Title
RESULTS OF THE BONNEVILLE POWER ADMINISTRATION WEATHERIZATION AND TIGHTENING PROJECTS AT THE MIDWAY SUBSTATION RESIDENTIAL COMMUNITY

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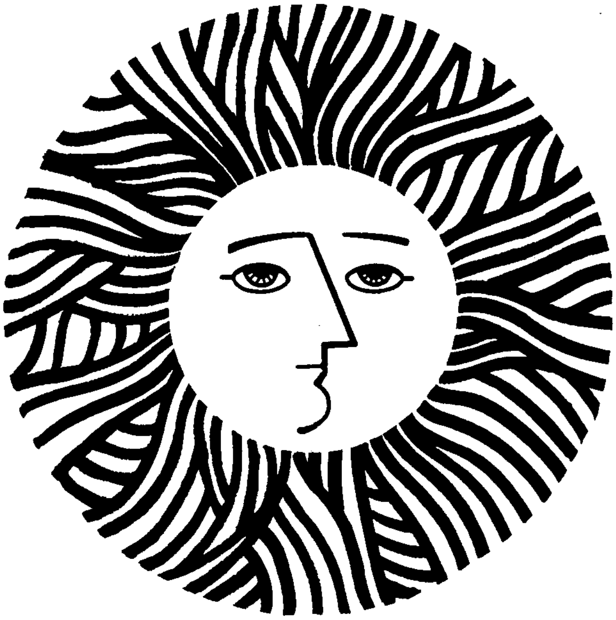

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ABSTRACT

As part of a regional conservation program, the Bonneville Power Adminstration retrofitted 18 houses at its Midway substation in central Washington and monitored the results for a three year period. The 18 houses were divided into three groups, or cells. During the first year of the project, energy consumption was monitored but no changes were made to the houses. Prior to the second year of the project, Cell 2 received attic and crawlspace insulation, foundation sill caulking, and increased attic ventilation. Cell 3 received these retrofits plus storm windows and doors, and Cell 1 served as the control group. Before the beginning of the project's third year, each house in Cell 1 received 22 hours of infiltration reduction weatherization or house tightening. Each house in Cell 3 received 10 hours of this same type of weatherization. Cell 2 served as the control group for the house doctoring phase of the project.

Energy consumption and weather data were monitored for the entire three year period. Before and after each set of retrofits, leakage area measurements were made using blower door fan pressurization, thereby allowing calculation of heating season infiltration rates. An energy use model correlating energy consumption with outside temperature was developed in order to determine improvements to the thermal conductance of the building envelope as a result of the retrofits. Energy savings were calculated based on the results of the energy use model and, as a check on these findings, the Computerized Instrumented Residential Analysis (CIRA) load calculation program developed at Lawrence Berkeley Laboratory provided a theoretical estimate of the savings resulting from the retrofits.

It was found that ceiling and crawlspace insulation had little effect upon leakage area, while storm windows reduced average leakage area for Cell 3 by 14%. Extended house doctoring reduced the average leakage area of Cell 1 by 27% while ordinary house doctoring reduced the average leakage area of Cell 3 by 20%. According to the energy use model, insulation reduced the thermal conductance parameter of Cell 2 by 7%, but this was not considered statistically significant. A reduction of 28% in the thermal conductance parameter of Cell 3 was observed as result of installation of insulation and storms. Extended house doctoring reduced the thermal conductance of Cell 1 by 14%, while a 27% reduction was noted in Cell 3 as a result of ordinary house doctoring. Changes in balance temperatures, the outside temperature at which space heating becomes necessary, were noted in all four instances. In some cases, these changes had the effect of masking energy savings that might otherwise have been observed. Energy savings observed as a result of the conservation retrofits were as follows: insulation only, 16%; insulation and storms, 42%; extended house doctoring, 9%; and ordinary house doctoring, no savings. Results of economic analyses showed that at current retail electricity prices in the Pacific Northwest (averaging $0.025/kWh), the insulation and storm window retrofits installed at Midway can be considered cost-effective if credit is given for salvage values. At this energy price, extended house doctoring is not cost-effective. However, if the retail price were to increase to $0.05/kWh (closer to the marginal cost of electricity), all of the retrofits that showed measurable energy savings would become cost-effective.

Key words: conservation, infiltration, insulation, retrofit, house doctor, thermal conductance, cost-effectiveness

INTRODUCTION

In recent years, demand for electrical energy in the Pacific Northwest has grown to consume all of the hydroelectric resources available in the region. Although the cost of generating this electricity is quite low, the projected cost of electricity from new capacity is so high that, in many instances, it is more economical to save energy through conservation. Furthermore, the United States Congress has ordered the Bonneville Power Administration (BPA), supplier of much of the region's electricity, to implement a region-wide power-sharing and energy conservation program. Because the majority of homes in the area are all-electric and consume a significant fraction of BPA's output, reducing energy consumption in the residential sector will be critical to the success of the conservation program. However, building new, energy-efficient homes is only part of the solution. The annual turnover in the housing stock of the United States is quite low; therefore, while new houses can be built to very high standards of energy efficiency [1,2], conservation efforts must concentrate on existing housing if annual electric energy consumption is to be reduced.

In 1978, the Bonneville Power Administration (BPA) initiated a residential conservation project in 18 occupied, BPA-owned houses at the Midway substation near Hanford, Washington to evaluate the energy savings and cost-effectiveness of several different conservation retrofits. Utility data were collected for all of the houses during the first year of the project to provide control data and during the following years to assess the effectiveness of the retrofits. In late 1979, BPA conducted a two-stage energy conservation retrofit program in the houses, insulating attics and crawlspaces, installing storm windows, and reducing infiltration [3,4]. Throughout the weatherization and tightening projects, the Energy Performance of Buildings (EPB) group of the Lawrence Berkeley Laboratory (LBL) provided advice and direct assistance in retrofit installation, monitoring, and performance analysis. (The Building Ventilation and Indoor Air Quality group at LBL also conducted pollutant surveys in the Midway houses [5].)

For a number of reasons, Midway is a useful site for an intercomparative study of energy conservation retrofits: the climate requires both heating and cooling; the houses are very similar in construction and size; they use only electricity as an energy source; and they have almost identical space heating and cooling equipment. Furthermore, because the houses are owned by BPA, it has been easy to ensure that all retrofit work is essentially the same. Finally, house occupants pay a flat monthly fee for electricity and therefore have no economic incentive to control their energy consumption. Therefore, any energy savings observed in these houses can be attributed to the energy conservation retrofits.

For the purposes of the project, the 18 houses were divided into three groups, or cells (with six houses per cell). Each cell received a different group of retrofits, and leakage area measurements were made on all houses before and after each phase of the project [4]. In Phase I of the project, Cell 1 served as a control group while Cells 2 and 3 received attic and crawlspace insulation, increased attic ventilation and foundation sill caulking. Cell 3 also was retrofitted with storm windows and doors. During Phase II, Cell 2 acted as the control group, while Cells 1 and 3 received two different programs of infiltration reduction (tightening) retrofits, or "house doctoring." The effectiveness of the Phase I retrofits were evaluated by means of an infrared scanner and by the post-retrofit measurements of leakage areas. The timeline below summarizes the phases of the project.

	1978-1979	PHASE I 1979-1980	PHASE II 1980-1981
CELL 1	Monitoring of Data	----> Control Group	-----> 22-hour house doctoring
CELL 2	Monitoring of Data	----> Insulation	-----> Control Group
CELL 3	Monitoring of Data	--> Insulation & Storms	-> 10-hour house doctoring

Utility and weather data were recorded during the three years of the project (and continue to be collected). From these data and leakage area measurements, improvements to the thermal conductance of the building shells and reductions in infiltration can be determined, and the energy and cost savings accruing from the project can be evaluated.

In this paper, we present the results of BPA's Midway Weatherization and Tightening Projects. We begin with a description of the houses and the conservation retrofit experiment. We then discuss the data collection and analysis procedures and the results of leakage area measurements, and evaluate the reductions in thermal conductance of the building shells as a result of the retrofits. Next, we present energy savings resulting from the retrofits as determined by an energy use model developed for this study and compare these savings with those calculated by the Computerized, Instrumented, Residential Analysis (CIRA), an energy load program developed at LBL [6]. We also discuss several analyses of the project's economic effectiveness. Finally, following conclusions concerning the Midway project, we offer recommendations for future activities in the Midway houses and elsewhere.

DESCRIPTION of WEATHERIZATION and TIGHTENING PROJECTS

Site and House Description

Midway is located in the arid southeastern part of Washington, along the banks of the Columbia River. It is about 37 miles northwest of Richland and 40 miles east of Yakima. The area experiences approximately 4,600 heating degree days (base 65 ^{O}F) and 450 cooling degree days (base 72 ^{O}F) per year. Wind velocities are low, averaging 7 mph throughout the year and blowing predominantly from the northwest. A high bluff to the south shades the community during late afternoon (after 2:00 PM solar time) during most of the winter.

The 18 Midway houses are all quite similar. They are located on two intersecting streets running north-south and east-west (see Figure 1). They are all wood frame, single-family, detached structures. Three have full basements, eight have basement/crawlspace combinations, and seven have full crawlspaces (see Table 1). The houses range in floor area from 1,110 to 1,329 square feet (excluding basements). Some of the construction differences are accounted for by the fact that the houses were built during three different periods--seven in 1943, eight in 1951, and three from 1965 to 1968. The first 15 houses were constructed with 2 inches of mineral wool insulation in the ceiling and exterior walls; the remaining three had 6 inches of fiberglass in the ceiling and 1.5 inch batts in the walls. The 15 older houses have double-hung wooden windows; the three newer ones, horizontal aluminum sliders. Prior to the retrofits, most of the double-hung windows had interlocking metal tracks that functioned as partial weatherstripping, and most exterior doorways had old, ineffective brass weatherstripping.

Table 1: The Midway Houses

House	Cell	Construction Date	Floor Area (ft^2)[a]	Floor Type[b]
1	2	1943	1161	CS
2	1	1943	1161	CS
3	1	1943	1161	CS
4	1	1943	1329	CS
5	3	1943	1161	CS
6	3	1943	1329	CS
7	1	1943	1329	CS
8	2	1951	1319	PB
9	3	1951	1319	PB
10	2	1951	1319	PB
11	1	1951	1319	PB
12	3	1951	1145	PB
13	3	1951	1319	PB
14	2	1951	1319	PB
15	2	1951	1145	PB
17	3	1965	1110	FB
19	3	1968	1110	FB
20	2	1968	2220[c]	FB

a. excluding basement floor area
b. CS = crawlspace; PB = partial basement; FB = full basement.
c. basement of House #20 has been remodeled into a conditioned space and is included in the floor area.

The letters within the boxes (houses) correspond to the conservation measures implemented; that is:

A = insulation level increased

B = insulated plus storm windows and doors installed

C = heat-pump water heater installed

D = solar water heater installed

E = point-of-use water heater installed

F = solar space heater installed

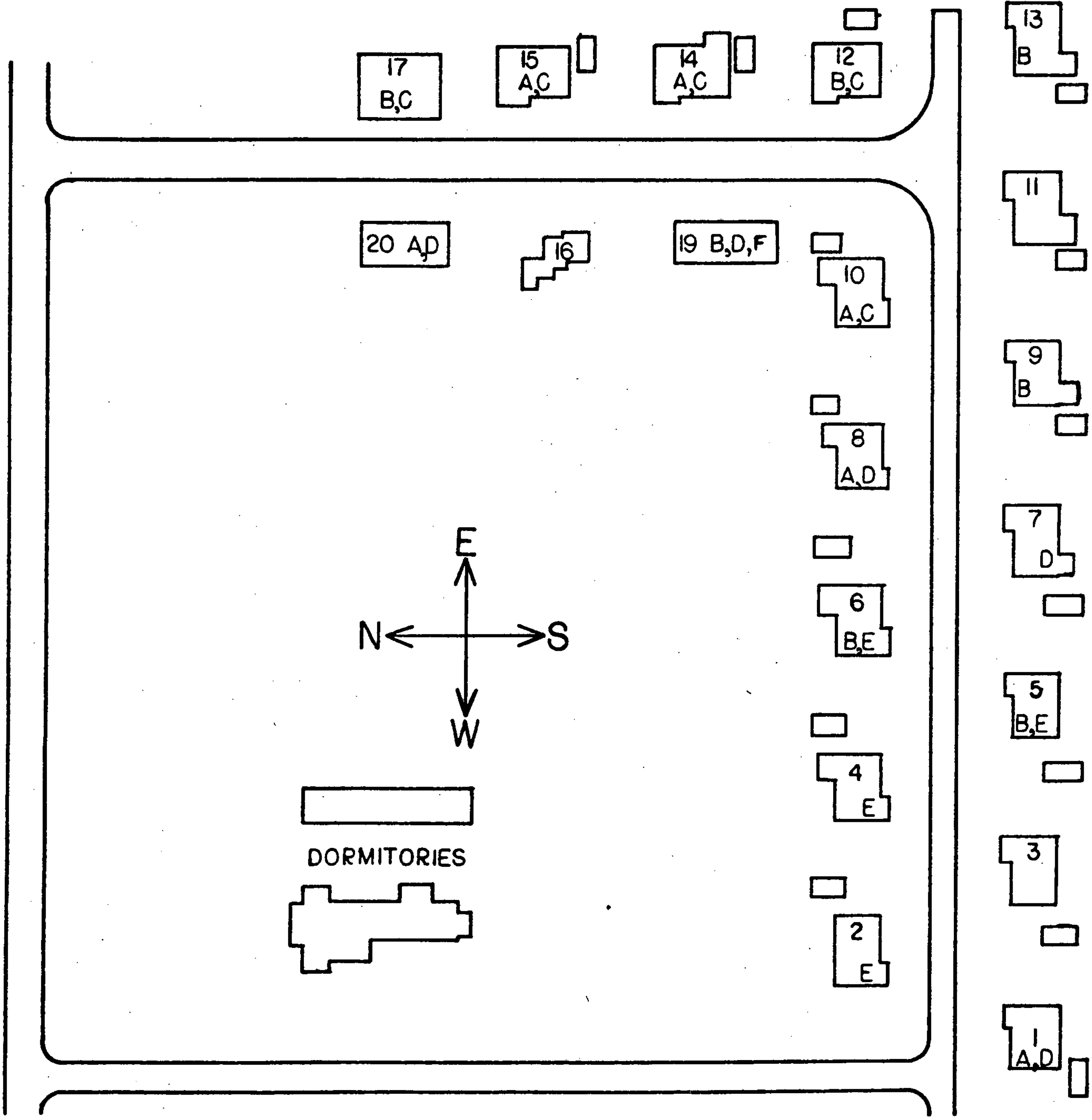

Figure 1: Midway Community Map

Retrofit Program - Phase I (1979-80)

In late 1979, BPA began its first set of conservation retrofits in Cell 2 and Cell 3 houses. (Cell 1 served as a control group for Phase I.) These retrofits consisted of:

1. An increase in attic insulation from approximately R-10 to R-30 with loose-fill fiberglass;
2. Installation of R-19 fiberglass batts in the crawlspace secured to the interior perimeter of the foundation wall and, where appropriate, a vapor barrier on the crawlspace floor;
3. An increase in attic ventilation through addition of soffit and ridge vents;
4. Caulking of the foundation sill plate; and
5. (Cell 3 houses only) installation of storm doors and windows.

A forced-air solar space heating system with ductwork in the basement and electric resistance backup was installed in one house in Cell 3. Prior to installation of these conservation measures, a two-person team from LBL measured leakage areas in the 18 houses using fan pressurization [4], accomplished with a "blower door," a large, door-mounted variable-speed fan able to blow air into (pressurize) or pull air out of (depressurize) a house. Leakage areas were remeasured after completion of Phase I of the project. (The fan pressurization technique is described in greater detail in Appendix B.)

Retrofit Program - Phase II (1980-1981)

In the fall of 1980, LBL researchers and BPA employees undertook the tightening or infiltration reduction element (also called "house doctoring") of the Midway Tightening Project in the houses of Cells 1 and 3 (with Cell 2 serving as the control). House doctoring is a combination energy audit and air infiltration reduction program developed by researchers at Princeton University and LBL. It includes many of the activities associated with a conventional energy audit, but also involves the use of certain diagnostic equipment to detect and eliminate places in the building shell where energy is lost through infiltration. A house doctor "team" of two trained technicians works for six to eight hours on a house.

The blower door is the most important tool available to the house doctor. Pressurizing the house with such a device forces (warm) air to flow through the many cracks and openings in the building envelope. These leaks can be detected using "smokesticks" or an infrared scanner. Smokesticks are small, glass tubes containing a chemical that produces a smoke-like vapor upon contact with air. If held near a leakage site, the smoke will be drawn through the opening. The infrared scanner, an instrument similar to a television camera, is sensitive to contrasts between hot and cold surfaces and is used outside of the building to locate openings through which heat is escaping or inside to identify openings through which cold air is entering. These two instruments are the "stethoscopes" of the house doctor.

In general, the house doctor repairs only infiltration leaks; conduction leaks are quite difficult to eliminate. A typical house doctoring includes, but is not limited to: applying caulk (or polymeric foam or fiberglass) to cracks, joints, and spaces in attics, basements, along baseboards, around chimneys, flue pipes, plumbing and electrical penetrations, light fixtures, air conditioners, door and window frames, and so on; installing weatherstripping on doors, windows, attic and crawlspace hatches or doors; sealing dropped ceilings; installing foam gaskets in electrical outlets and switches; and closing of any apparent and easily accessible holes through the building envelope. If a furnace is present in the house (not the case at Midway), the house doctor may test its efficiency and perform a tuneup. He or she may also wrap the domestic water heater with fiberglass, install low-flow showerheads and faucet aerators, seal and insulate ductwork and perhaps even install plastic storm windows. None of these latter activities were performed at Midway, however. (<u>The House Doctor's Manual</u>, prepared as a supplement to this report [7], provides a detailed description of the house doctor procedure.)

For each of the Midway houses, a blower door was installed and pressurization and depressurization measurements were made. The house was then pressurized and important air leakage sites were located using smokesticks and an infrared scanner. Once the initial diagnosis was completed, the house doctor team went to the attic and began the necessary repair work. After a few hours in the attic, they continued their efforts in the basement or crawlspace, and eventually finished in the house interior. The house was then pressurized again and the previously sealed leakage sites were reinspected. Finally, when all work on the house was completed, pressurization and depressurization measurements were made once again. These measurements provide a basis for evaluating the effectiveness of the infiltration reduction program. Houses in Cell 1 received approximately 22 person-hours of house doctoring, while those in Cell 3 each received about 10 person-hours of work. A more detailed list of the retrofits performed on the houses in Cells 1 and 3 is presented in Table 2 and in Appendix A.

Table 2: Detailed List of House Doctor Retrofits to Midway Houses

	10-hour Program (Cell 3)	22-hour Program (Cell 1)
House Interior[a]		
Install outlet and switch plate gaskets	y	y
Caulk baseboard heaters	y	y
Caulk air conditioner penetration through wall	y	y
Cover air conditioner with polyethylene	n	y
Caulk circuit/fuse boxes	y	y
Caulk plumbing penetrations	y	y
Caulk electrical penetrations	y	y
Seal light fixtures	y	y
Caulk window and door frames	y	y
Weatherstrip windows and doors	y	y
Install door sweep	y	y
Caulk joints and cracks	y	y
Attic[a]		
Weatherstrip attic hatch	y	y
Caulk around plumbing vent pipes	n	y
Seal dropped ceilings	n	y
Stuff fiberglass into large openings	y	y
Caulk around light fixture penetrations	n	y
Caulk electrical penetrations	y	y
Seal wall/ceiling joints at top plate	n	y
Basement or Crawlspace[a]		
Weatherstrip crawlspace hatch or basement door	y	y
Weatherstrip crawlspace vent doors	y	n
Install or repair crawlspace vent doors	where necessary	
Caulk plumbing penetrations	y	y
Caulk electrical penetrations	y	y
Caulk cracks in subfloor	y	y
Seal joint between foundation and sill plate	n	y
Seal top and bottom of band joist	n	y
Weatherstrip basement windows	n	y
Caulk basement window frames	n	y
Stuff fiberglass into large openings	y	y

a. Detailed breakdown of activities in each house can be found in Appendix A.

Material and Labor Costs

Cost breakdowns for the two phases of the Midway retrofit program are given in Table 3. These are average costs for each house; obviously, actual costs varied from house to house, depending upon specific house doctor activities in a given house.

Table 3: Costs of Midway Retrofit Project

Phase I: Insulation and Storm Window Retrofits[a]

Conservation Measure	Cell 1	Cell 2	Cell 3
Attic Insulation		$ 764	$ 742
Attic Ventilation		205	203
Crawlspace Insulation and Vapor Barrier	Control	838	866
Foundation Sill Caulking		53	53
Storm Windows and Doors		N/A	2159
Total Cost Per House	N/A	$1860	$4023

Phase II: Infiltration Reduction Retrofits

	Cell 1	Cell 2	Cell 3
Cost of Materials	$ 120		$ 60
Cost of Labor (@ $10/hr)[b]	240		160
Capital Costs of Equipment (e.g., blower door, tools, etc.)	15	Control	15
Subtotal	375		235
Overhead (40% of costs)	150		94
Total Cost Per House	$525	N/A	$329

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a. Breakdown of materials and labor costs not available.

b. Labor costs reflect two person-days for Cell 3 and three person-days for Cell 1 rather than actual time spent on house doctoring.

ENERGY USE MODEL

To evaluate the reductions in energy consumption caused by the conservation retrofits, we employed an energy use model based on correlating average daily energy consumption with average daily exterior (outside) temperature. The rate of energy consumption by a house (in kWh/day) is given by the equation:

$$E = [K \cdot 24 \frac{hr}{day} (T_i - T_o)] - S - G \qquad (1)$$

where

E is the energy supplied for space heating (kWh/day);
K is the thermal conductance parameter of the house (kW/^oC);
S is the energy supplied by solar gain (kWh/day);
G is the energy supplied by internal sources such as people and appliances (kWh/day);
T_i is the interior temperature (^oC); and
T_o is the exterior temperature (^oC).

In other words, energy consumption is a linear function of the difference between the relatively constant interior and changing exterior temperatures (ΔT), where K (called the "thermal conductance parameter" in this paper) is a constant of proportionality equal to the heat loss rate of the house per degree Centigrade. The significance of K is seen most easily if space heating energy use divided by house floor area is plotted as a function of outdoor temperature (see Figure 2); the slope of the resulting line is K divided by house floor area (W/^oC-m^2), or "k." Rearranging Eq. 1 gives:

$$E = K(T_b - T_o) = KT_b - KT_o \qquad (2)$$

where

$$T_b = T_i - \frac{S + G}{K}$$

T_b is now the x intercept of the plot of energy use versus outside

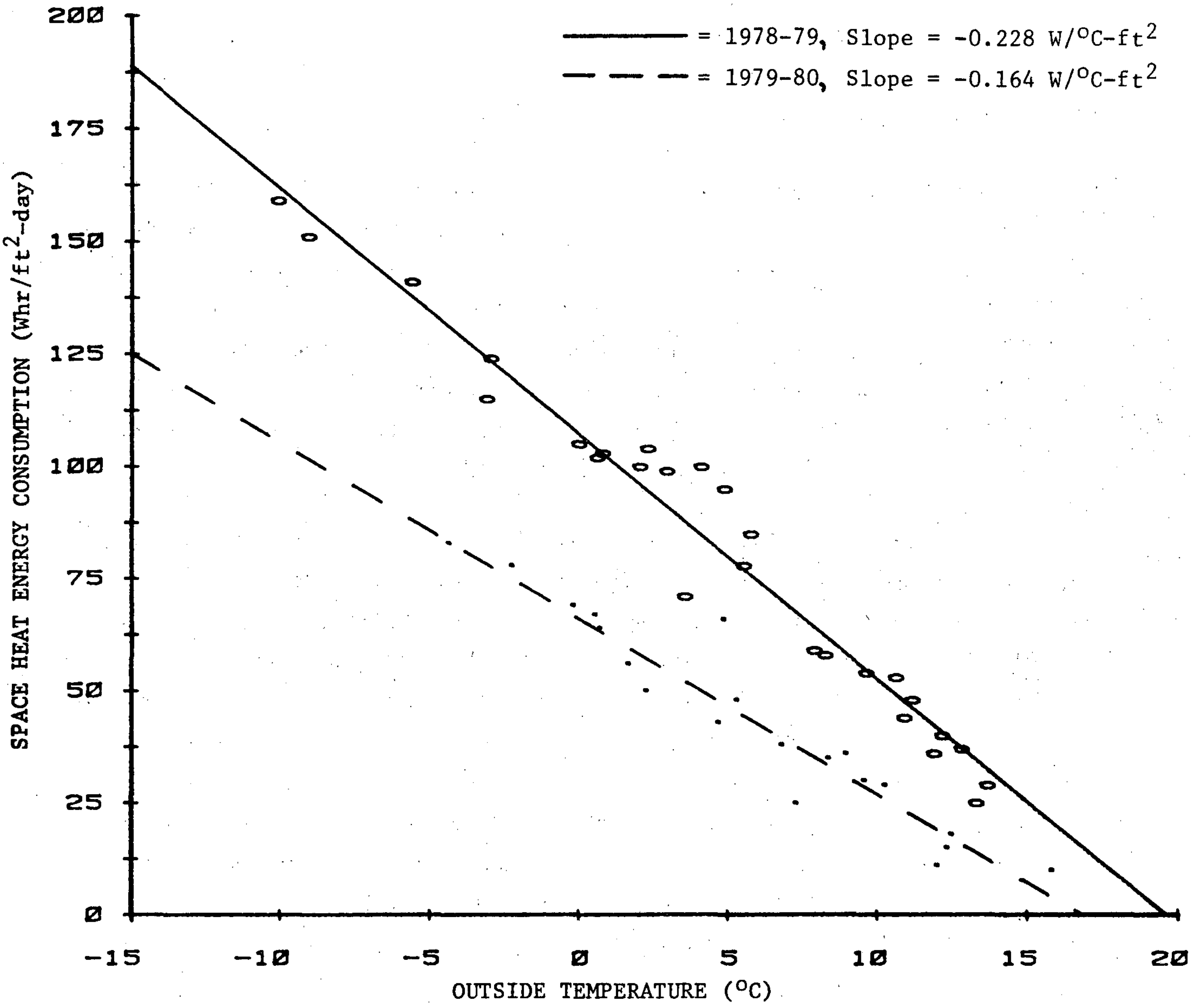

Figure 2: Space Heating Energy Consumption vs. Outside Temperature for Cell 3 before and after installation of insulation and storm windows and doors.

temperature, or the "balance temperature," which is the outdoor temperature at which space heating becomes necessary. Knowing two of the quantities in Equation 2 allows us to determine the third; in the case of Midway, we know E and T_o from utility meter and weather data. The value of T_o at which metered space heating energy consumption is zero is the balance temperature. Thus, for the purposes of this model, knowledge of T_i is not necessary.

Conservation retrofits affect the relationship between energy use and T_o in two ways: (1) the slope of the plot (k) is decreased, reflecting a lower heat loss rate per ^oC, and (2) assuming that T_i, S, and G remain fixed, the balance temperature of the house is reduced (as K decreases, $(S + G)/K$ increases, and $T_i - (S + G)/K$ decreases). The difference in the slope of the two pre- and post-retrofit plots is a measure of the effectiveness of the retrofits. Energy use is affected by both changes in K and changes in balance temperature.

K is actually composed of two terms: UA and I, where UA is the actual thermal conductance of the house (in $kW/^oC$) and I is the infiltration load (in this instance, also in $kW/^oC$). The thermal conductance is unique to a particular house and is the sum of the individual conductance terms of the windows, walls, ceiling, and floors. It remains the same as long as no changes are made to the shell. The infiltration load is composed of the individual infiltration terms from the many penetrations and cracks in the building shell. To a first order approximation, UA and I are independent of each other because improvements that affect conductance generally do not reduce infiltration, and vice versa. (Some retrofits, such as storm windows, do affect both conductance and infiltration.)

The actual thermal conductance (UA) of a house is the sum of the products of the transfer coefficients, U (in $W/^oC\text{-}m^2$), for each building component (floor, walls, ceilings, etc.) and the area of each component, A (in m^2). U is the inverse of R, which is commonly called "thermal resistance." An increase in the R of any component of a house--floor, walls, ceiling or windows--is equivalent to a decrease in U. The addition of insulation to the attics and crawlspaces of the Midway houses increases the R (or decreases the U) of the two components and should therefore be visible as a change in the slope of the energy consumption vs. outside temperature plot between the control and experimental years (1978-79,1979-80). Storm windows decrease both UA and I, however, because single-pane windows have a low R-value and are a large source of conductive heat loss, the addition of storms affects primarily the UA of a house. An example of the changes in slope and balance temperature as a result of retrofits to Cell 3 is shown graphically in Figure 2.

In windy areas, infiltration is more dependent upon wind velocity than upon temperature (assuming that wind speed is not correlated with temperature). Midway, however, has a low average wind speed and infiltration is therefore dominated by the stack effect, which is a function of temperature. A reduction in the infiltration term due to house doctoring should cause a change in the relationship of space-heating energy use vs. outside temperature from the second to the third years of the project (1979-80, 1980-81). Such a change would be visible as a decrease in slope in an energy use vs. outside temperature plot for the two years.

Internal heat contributions (G) such as appliance energy use, occupant metabolic heat, and solar gain are generally important in modeling energy use and must be accounted for. In the case of Midway, however, we found these sources of energy to have little, if any, importance in the evaluation of the conservation retrofits. When appliance usage in a house is significant, it must be included as a "free heat" contribution to space heating. Unless there is a correlation between appliance use and outside temperature, this contribution will appear only as a constant offset to energy use that does not affect the slope of the energy use plot (or the value of k). We found that appliance load patterns at Midway did not change appreciably during the course of the heating season (see Figure 3) and that whether or not appliance energy usage was included in the analysis, k varied little. Hence, we disregarded appliance usage. Metabolic heat from people was judged to be only a minor contribution and was also disregarded. Domestic hot water use was excluded as an internal load in this analysis since we assumed that most of the energy content of the hot water is lost through drains and the

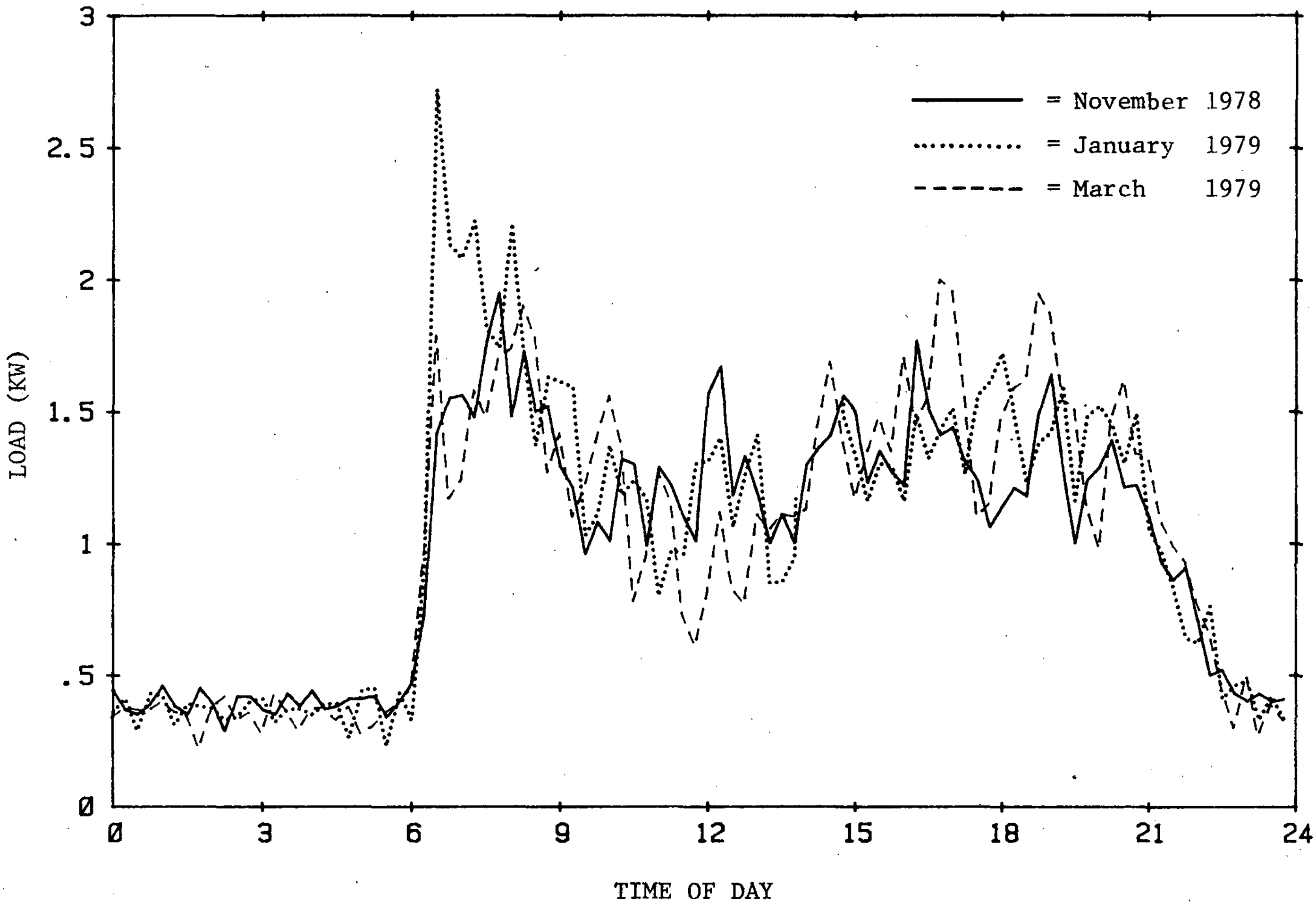

Figure 3: Typical Appliance Load vs. Time of Day for a House in Cell 3 during three months of the 1978-79 heating season in Midway, Washington

remaining free heat does not vary appreciably during the course of the heating season.

Solar gain through windows, walls and ceilings can contribute significantly to internal heating. For the Midway houses, we plotted weekly solar insolation values against the difference between measured weekly energy consumption and estimated weekly energy consumption (as determined by the energy use model). A visible correlation between these two values would indicate the solar contribution to internal gains to be significant. A random relationship would indicate no significant contribution. We found a random relationship between these values and therefore concluded that solar gain was not an important input to the energy model of the Midway houses.

While internal heat sources do not affect K in this analysis, they can alter the balance temperature. As can be seen from equation 2, if G increases, $(S + G)/K$ gets larger and T_b decreases. However, what is important in the analysis of energy savings is not the absolute value of T_b but rather the change in this quantity over two successive years. The percentage change in ΔT_b from one year to the next should remain the same even if internal gains are excluded from the analysis.

DATA COLLECTION and ANALYSIS

Energy Consumption Measurements

Until the beginning of the Midway project, the houses had no electric meters. In 1978, BPA installed four electric submeters on all 18 houses in order to monitor total electric and water heat, space heat and air conditioning energy consumption. (The energy consumed by appliances is obtained by subtracting the three submetered quantities from the total consumption.) Energy use was measured in watt-hours. Air temperature, wind speed and direction, and solar insolation for the Midway houses were measured by an on-site weather station. Measurements were made at 15-minute intervals, stored in a computer at Midway, and periodically transmitted by microwave to BPA headquarters in Portland, Oregon. House interior temperatures have not been monitored by BPA, although the data collection system has the capacity to store and transmit such information.

Leakage Area Measurements

Leakage area measurements were made in September 1979, at the end of the project's first year and just before installation of the Phase I measures, and in May 1980, under conditions as similar as possible to the pre-retrofit measurements, to determine whether any reductions had occurred. Leakage area measurements were also made on houses in Cells 1 and 3 just before and after house tightening (Phase II) in November 1980. Houses in Cell 2 (the Phase II control group) were not remeasured at this time.

From the leakage areas and appropriate weather data, both average annual and heating season infiltration rates can be calculated by means of an infiltration model developed at LBL [see Appendix B]. For the present report, weather data collected at Midway was used to calculate energy savings. In order to determine average pre- and post-retrofit infiltration rates, however, 30-year average weather data from Yakima, Washington was used. This allowed comparison of infiltration rates during differing climatic years.

Data Analysis Procedure

For analysis purposes, utility data on computer tape for each house were consolidated into four daily values: space heating, cooling, domestic hot water, and total electricity consumption. Average daily values for temperature, wind speed, wind direction and solar insolation were also determined from the data.

Because of the great scatter that is typical of day-to-day energy consumption in an occupied house (due to variability in occupant behavior, solar gain, wind speed, and so on), averages of seven consecutive days of energy consumption and outside temperature data were calculated for each house. If data for a particular day were missing, the day was not included in the count. (Hence, the seven days were not always consecutive.) Days during which space heating consumption was less than 5 kWh or air conditioning was used were also excluded from the analysis. (Days with low space heating consumption often had average temperatures greater than 20 °C and could not be included in the analysis. Table 5 shows the number of data points used in the analysis; each data point represents seven days.) Seven-day energy consumption values for a single house were divided by floor area to allow averaging of data for all houses in a cell. The normalized seven-day energy consumption values for the houses in a cell were then added together, averaged over identical seven-day periods and plotted against outside temperature. A linear regression was fit to the data, and average thermal conductance parameters (k values) and balance temperatures were found for each cell for each year. Data from house 9 were not included in the analysis because of monitoring problems, while data from houses 17, 19 and 20 were excluded because of many occupancy changes during the project.

Energy Savings

To compare energy consumption between warmer and colder years all data were normalized to a "standard" heating season. Our standard heating season was 1978-79 (which happened to correspond very closely to the average heating season for the area; see reference 3). The average outdoor temperature (4.8 °C) for the standard heating season was subtracted from the balance temperature for each cell for each year. The resulting quantity was then multiplied by the appropriate k value derived from the energy model. This quantity, in turn, was multiplied by the average floor area of the houses in the particular cell and by the number of heating days in the standard heating season (196, which represents the number of seven-day data points multiplied by seven, and is equivalent to the number of days during which more than 5 kWh of space heating energy were required). While this number of days might slightly underestimate the number of heating days in the average year, it does cover the period from roughly October through mid-April and should approximate the heating season at Midway.

The equation used to calculate energy consumption is:

$$E = k\,(T_b - T_o) \times (\text{floor area}) \times (\#\ \text{of heating days}) \tag{3}$$

where all variables are the same as previously defined.

Economic Analyses

Four different types of economic analyses were applied to the data in order to evaluate the cost-effectiveness of the conservation improvements made to the Midway houses. The first three--net benefits, benefit-to-cost ratio, and internal rate of return--are discussed in Marshall and Ruegg [8]. The fourth technique--cost of conserved energy--is described in Wright, et al. [9]. The four analyses (described briefly below and in greater detail in Appendix C are:

1. Net Benefits: the difference between the lifetime energy savings (in dollars) of an energy conservation investment and the lifetime costs. An investment with a net benefit greater than zero is considered worthwhile.

2. Benefit-to-Cost Ratio: the ratio of dollars saved to dollars spent for an investment. If this ratio is greater than one, the investment is considered worthwhile.

3. Internal Rate of Return: the rate of return on an investment, that is, the interest rate for which lifetime savings are equal to lifetime costs. This rate of return calculated for an investment must be compared to the minimum rate of return acceptable to an

investor-- generally equal to the real discount rate-- in order to determine the desirability of the investment.

4. Adjusted Cost of Conserved Energy: the total lifecycle cost of a conservation investment divided by the annual energy savings resulting from the investment, which is then adjusted to account for the real escalation rate of energy prices. For the investment to be worthwhile, the adjusted cost of conserved energy must be less than the current price of supplied energy to the homeowner or the current marginal cost of energy to the utility.

All analyses were performed in terms of a real (or constant-dollar) discount rate and a real energy escalation rate so as to avoid difficulties in choosing appropriate interest and inflation rates. In doing the analyses, we varied both the real discount rate and real energy escalation rate in order to assess the sensitivity of the results to such changes. We varied the real discount rates from 2.7% to 7.3% and the real energy escalation rate (the annual rate at which the cost of energy increases after accounting for inflation) from 1% to 3%. We assumed two energy costs: 2.5 and 5.0 cents/kWh. The first value is a typical retail price of electricity in the Pacific Northwest, while the second value is somewhat higher than the highest retail rate to be found in the region, and might be comparable to the marginal cost of electricity from new generating capacity. We calculated economic results including and excluding the 15% federal energy conservation tax credit. The former situation would apply to a homeowner and the latter to a utility. We also performed economic analyses incorporating BPA's planned "Energy Buy-Back Weatherization Program." [10] Under this program, BPA will make a one-time payment to the consumer of 29.2 cents per estimated total annual kilowatt-hours saved by installed conservation measures, or the actual cost of those measures, whichever is less.

Our base economic case reflects probable economic conditions and the rate of increase in electricity prices in the Pacific Northwest as new generating capacity is brought on line: a real discount rate of 2.7% and a real energy escalation rate of 1.8%. Our base case also assumes amortization periods of 30 years for insulation and storm retrofits and 10 years for house doctoring, however, we varied the amortization period to test the sensitivity of the analyses to this factor. The base case assumes the following salvage values for the conservation measures at the end of the amortization period: insulation, 75%; storms, 50%; house doctoring, 0%. We also performed the analyses with salvage values excluded, since the homeowner generally does not account for salvage value when assessing the cost-effectiveness of a conservation measure.

RESULTS and DISCUSSION

The results of our analysis of the Midway data are presented below in five sections: 1) leakage areas and infiltration rates; 2) energy model results (changes in k and balance temperature as defined earlier in this paper); 3) predicted and observed energy savings; 4) economic analyses of the retrofits; and 5) discussion. (Aggregated results of leakage areas and infiltration rates for each cell are presented here; data on individual houses may be found in Appendix D.

(1) Leakage Areas and Infiltration Rates

Table 4 presents leakage areas (in cm^2) measured during Phases I and II of the Midway project, specific leakage areas (leakage area divided by house floor area, in cm^2/m^2) and average heating season infiltration rates (in air changes per hour) derived from the leakage area measurements.

During Phase I, the average leakage area of Cell 1--the control group--increased from 484 cm^2 to 491 cm^2, or 1%, a statistically insignificant change. For Cell 2--the insulation-only group--there was a negligible decrease in leakage area, from 411 cm^2 to 406 cm^2. Because attic and crawlspace insulation affects only conduction, this result was expected. Cell 3--recipient of both insulation and storm windows--showed a 14% decrease in leakage area, from 411 cm^2 to 355 cm^2.* Storm

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*The discrepancy between this value and the one reported in reference 4 is due to recalibration and use of different blower doors for the two measurements.

Table 4: Leakage Areas and Heating Season Infiltration Rates: Midway Houses

	Leakage Areas (cm^2)		Specific Leakage Areas (cm^2/m^2)		Heating Season Infiltration Rates (ACH)	
PHASE I	Pre-retrofit	Post-retrofit	Pre-retrofit	Post-retrofit	Pre-retrofit	Post-retrofit
CELL 1 Control Group (5 Houses) Avg. age: 36.4 yr Area: 1,260 ± 90 ft^2	484 ± 75	491 ± 88	4.1 ± 0.7	4.2 ± 0.8	0.42 ± 0.07	0.43 ± 0.08
CELL 2 Attic Insulation (6 Houses) Avg. age: 28.5 yr Area: 1,418 ± 403 ft^2	411 ± 73	406 ± 40	3.4 ± 1.1	3.2 ± 0.8	0.35 ± 0.12	0.33 ± 0.08
CELL 3 Attic Insulation & Storm Windows (6 Houses) Avg. age: 27.9 yr Area: 1,213 ± 104 ft^2	411 ± 107	355 ± 126	3.5 ± 0.8	3.2 ± 0.9	0.36 ± 0.08	0.33 ± 0.10
PHASE II						
CELL 1 Extended House Doctoring (6 Houses) Avg. age: 32.5 yr Area: 1235± 101	487 ± 41	358 ± 54	4.3 ± 0.5	3.1 ± 0.4	0.44 ±0.05	0.32 ± 0.05
CELL 3 Ordinary House Doctoring (6 Houses) Avg. age: 27.9 yr Area: 1,213 ± 104 ft^2	396 ± 81	318 ± 69	3.4 ± 0.6	2.8 ± 0.5	0.35 ±0.05	0.28 ± 0.05

windows affect both conduction and infiltration; hence, this level of decrease is not surprising.

When Phase I pre-retrofit leakage areas are divided by the average floor area for each cell to give specific leakage areas, Cell 1 (4.1 cm^2/m^2) is seen to have been somewhat leakier than Cells 2 (3.4 cm^2/m^2) and 3 (3.5 cm^2/m^2), perhaps because the average age of the houses in Cell 1 is greater than those of the houses in the other cells. We would expect older houses to be somewhat leakier. This relative difference did not change greatly with Phase I post-retrofit leakage areas.

The heating season infiltration rates presented in Table 4 were calculated using the LBL infiltration model (described in Appendix B. Infiltration rates calculated for Phase I of the project generally parallel the changes observed in leakage areas. Cell 1 infiltration rates remained roughly the same, while those for Cell 2 decreased by 6% and those for Cell 3 decreased by 8%.

During Phase II, only the leakage areas of Cells 1 and 3 were measured. Leakage areas for Cell 2 (control houses) were assumed to be unchanged from Phase I. Cell 1, which received extended house doctoring, showed an average decrease of 27% in leakage area, from 487 cm^2 to 358 cm^2. The average reduction for houses in Cell 3--recipients of ordinary house doctoring--was 20%, from 396 cm^2 to 318 cm^2.*

As a result of the house doctor retrofits, the specific leakage area of houses in Cell 1 was reduced from 4.3 to 3.1 cm^2/m^2, while in Cell 3, the specific leakage area was reduced from 3.4 to 2.8 cm^2/m^2. The difference in specific leakage areas observed between Cells 1 and 3 during Phase I was reduced after Phase II of the project, presumably because more time was spent on sealing leaks in Cell 1. Similar changes were seen in Phase II heating season infiltration rates: for Cell 1,

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*The difference in leakage areas measured for Cell 3 at the end of Phase I and beginning of Phase II--355 cm^2 vs. 396 cm^2--results from the use of different blower doors. This difference--41 cm^2 or 10%--is within the error generally attributed to leakage area measurements.

this rate was reduced from 0.44 to 0.32 ach, while the infiltration rate was reduced from 0.35 to 0.28 ach in Cell 3.

Figures 4 and 5 compare pre- and post-retrofit specific leakage areas and infiltration rates for the Midway houses with the same quantities measured for other groups of houses in North America [11]. Even before retrofitting, in terms of specific leakage area the Midway houses were among the tightest measured and compared favorably with two groups of new, energy-efficient houses in Eugene, Oregon [1] and Rochester, N.Y. [2]. Because infiltration rates are a function of local weather conditions, the Midway houses in Figure 5 should only be compared to the Oregon houses.

Energy Modeling Results

Table 5 presents results obtained from the energy-use model described earlier in this paper. These results are presented in terms of the normalized thermal conductance parameter k (Watts/^{o}C-m^{2}), which is K (Watts/^{o}C) divided by cell floor area. Also shown in the table are the average outside temperatures for each cell for each year as calculated from the data points, average daily energy use for each cell, the number of data points making up the samples, the R-squared (goodness of fit) for each regression analysis and the results of a t-test on the k values. The t-test is a measure of the statistical significance of the difference between two values of the same variable [12]. For this project, a t-value greater than 2.02 implies a statistically significant difference at a confidence level of 95 percent. A t-value greater than 2.73 corresponds to a confidence level of 99 percent.

During Phase I of the project, the control group, Cell 1, showed a small increase in k and a small decrease in the balance temperature (1.1^{o}C). Data for the first two years (both were "control" years) were averaged, hence, the slight change in the two parameters is of no statistical significance.

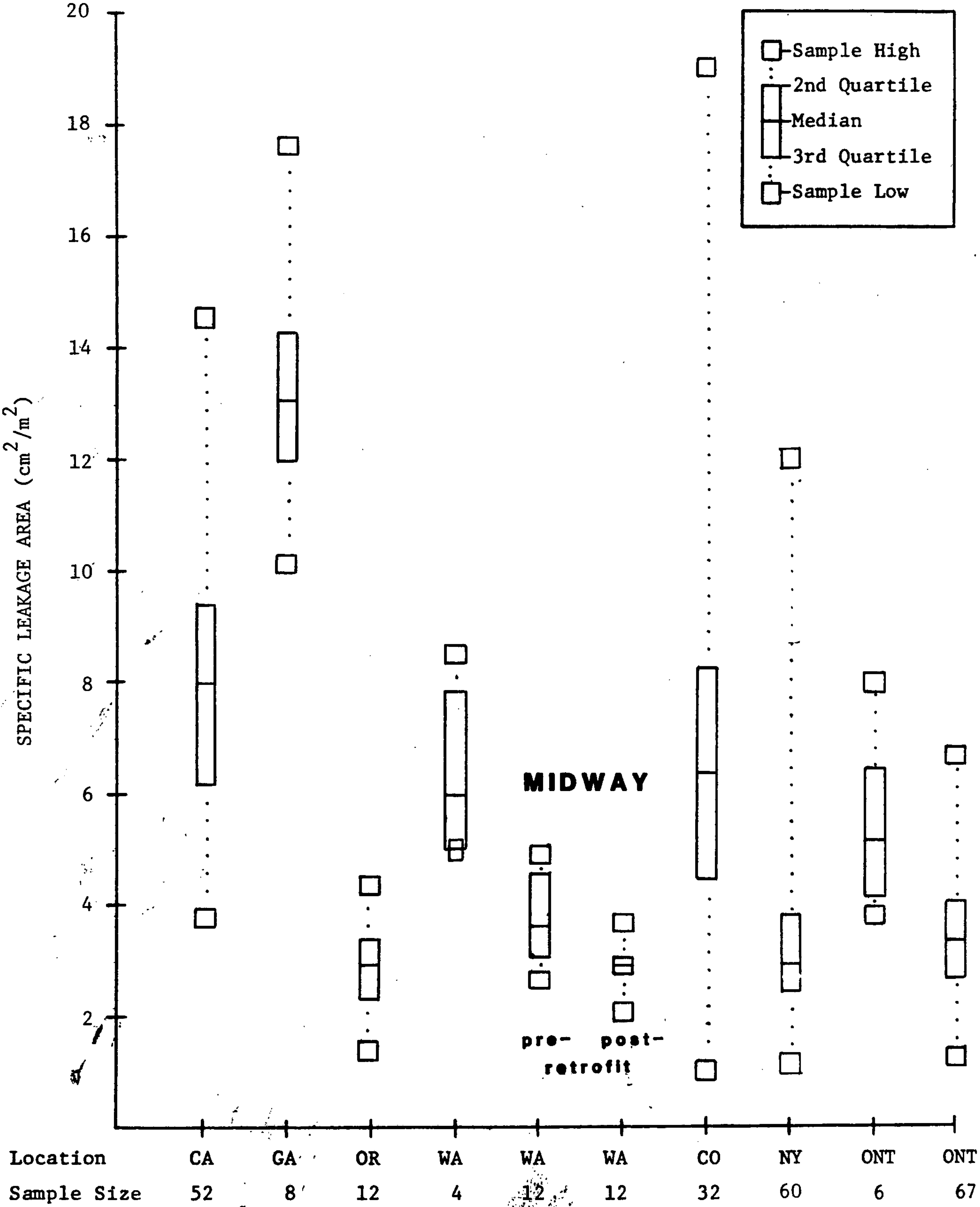

Figure 4 : Specific Leakage Areas for Selected Groups of Houses Tested by LBL Researchers and Others [11]

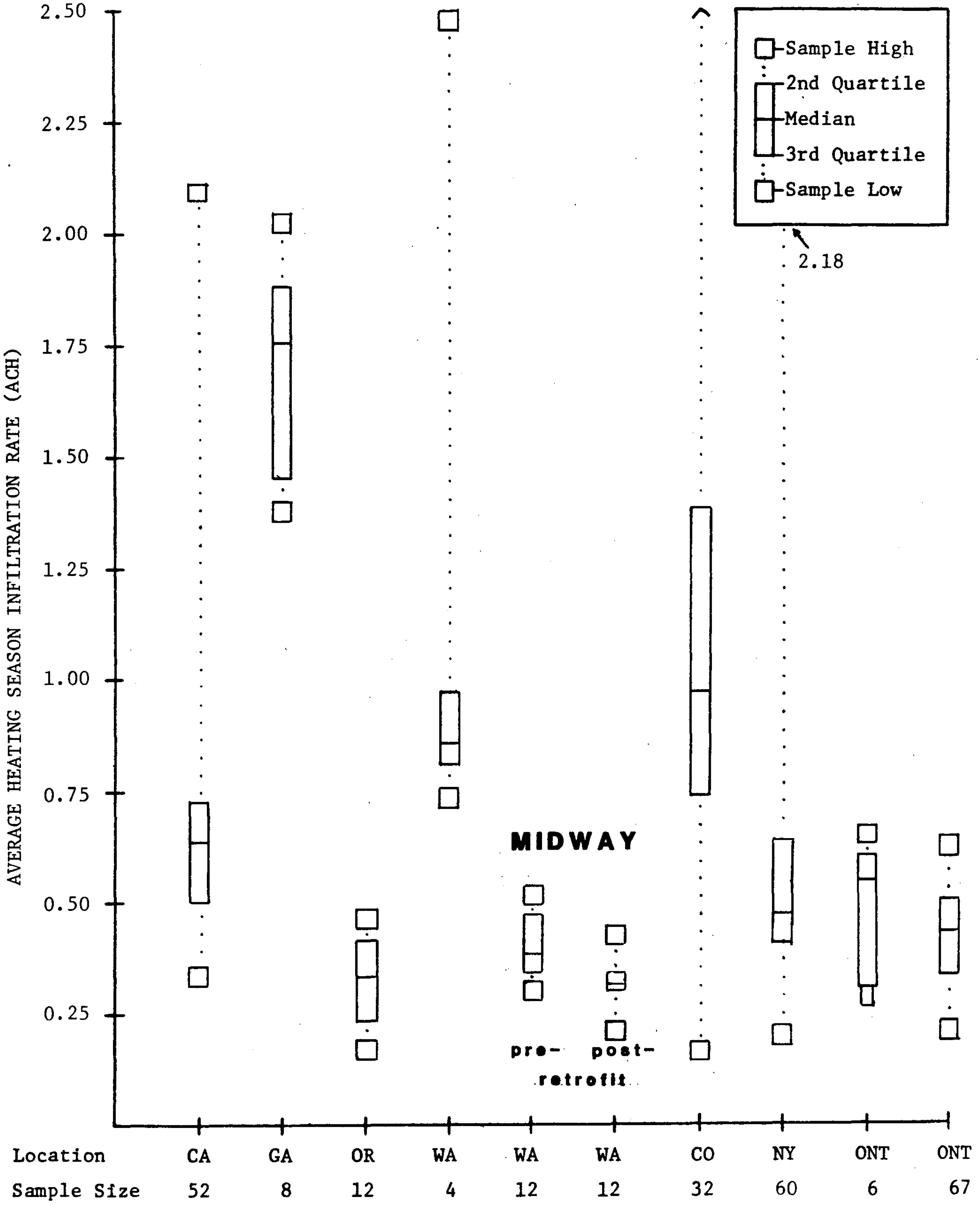

Figure 5 : Heating Season (November-March) Infiltration Rates for Selected Groups of Houses Tested by LBL Researchers and Others [11]

Table 5: Energy Modelling Results: Midway Houses

	k ($W/^{o}C\text{-}m^2$)	Balance Temperature (^{o}C)	Average Outside Temperature (^{o}C)	Avg. Daily Energy Use ($kWh/day\text{-}m^2$)	R^2, # of Data Points	t-Test on change in k (year-to-year)
CELL 1						
Control: 1978-79	2.50 ± 0.08	19.2 ± 0.5	4.8	0.86	0.98, 28	t(1-2): 2.66
Phase I: 1979-80	2.74 ± 0.11	18.1 ± 0.6	6.2	0.78	0.97, 21	t(2-3): 4.08
Phase II: 1980-81	2.24 ± 0.14	19.5 ± 1.0	9.0	0.57	0.95, 17	t(1-3): 2.50
CELL 2						
Control: 1978-79	2.64 ± 0.12	18.5 ± 0.8	4.6	0.88	0.96, 27	t(1-2): 1.48
Phase I: 1979-80	2.46 ± 0.13	17.1 ± 0.7	6.3	0.65	0.95, 21	t(2-3): 0.81
Phase II: 1980-81	2.58 ± 0.17	16.9 ± 1.1	9.1	0.48	0.94, 17	t(1-3): 0.41
CELL 3						
Control: 1978-79	2.45 ± 0.10	19.6 ± 0.8	4.6	0.88	0.96, 27	t(1-2): 6.48
Phase I: 1979-80	1.76 ± 0.12	16.8 ± 1.1	5.8	0.47	0.92, 20	t(2-3): 4.36
Phase II: 1980-81	1.29 ± 0.09	21.5 ± 1.3	9.1	0.39	0.93, 17	t(1-3): 12.60

In Cell 2, a 7% decrease in k, from 2.64 to 2.46 W/°C-m^2, accompanied by a moderate decrease in balance temperature (1.4°C) was observed. According to the T-test, this decrease is not statistically significant. However, calculations done with the Computerized Instrumented Residential Analysis (CIRA) [7] for Cell 2 indicate that the decrease in k as a result of increasing insulation in the attic and crawlspace insulation levels should be on the order of 25%.

A decrease of 28% in k from 2.45 to 1.76 W/°C-m^2 was observed for Cell 3--recipient of insulation and storm windows--during Phase I of the project, accompanied by a large drop in balance temperature (3.8°C). CIRA calculations suggest that the decrease in k as a result of the insulation and storms should be on the order of 36%.

During Phase II of the project, the extended house-doctored group, Cell 1, showed a statistically significant decrease of 14% in k from 2.74 to 2.24 W/°C-m^2 and a decrease of 0.9 °C in balance temperature. Cell 2, the control group during Phase II, showed an increase in k but it was not found to be statistically significant. Cell 3 showed a statistically significant decrease of 27% in k from 1.76 to 1.29 W/°C-m^2 accompanied by a statistically significant increase in balance temperature (4.7°C). (It should be noted that because of the exclusion of the four houses from the analysis, the change in k resulting from house doctoring of Cells 1 and 3 do not parallel in size the reductions in leakage areas shown in Table 4.)

Energy Savings

Table 6 compares modeled (actual) and estimated energy consumption and savings resulting from the conservation retrofits. Actual energy savings were found by using k values and balance temperatures obtained from the energy use model, and heating season weather data normalized to the standard heating season, as previously described. Estimated energy consumption figures for the three cells were calculated by CIRA. Table 6 also shows the standard errors in the actual energy consumption. Figure 6 shows graphically the actual energy use with error bars. The overlap between the possible extremes in energy use during the different years should be noted.

Table 6: Comparison of Actual and Estimated Energy Consumption and Savings: Midway Houses

	Actual Energy Use [a] (kWh/yr)	Reduction in Energy Use Due to Retrofits (kWh/yr)	Reduction in Energy Use Due to Retrofits (%)	Estimated Energy Use [b] (kWh/yr)	Reduction in Energy Use Due to Retrofits (kWh/yr)	Reduction in Energy Use Due to Retrofits (%)
CELL 1						
Control: 1978-79	19,980 ± 1,580			20,835		
Phase I: 1979-80				N/A[c]		
Phase II: 1980-81	18,130 ± 1,680	1,840	9.2	19,995	840	4.0
CELL 2						
Control: 1978-79	19,800 ± 1,470	3,240	16.3	17,950	4,460	24.8
Phase I: 1979-80	16,560 ± 1,290	--	--	13,490		
Phase II: 1980-81	17,090 ± 1,920			N/A[c]		
CELL 3						
Control: 1978-79	19,650 ± 1,330	8,200	41.7	17,950	6,510	36.3
Phase I: 1979-80	11,450 ± 1,310	--	--	11,440	465	4.1
Phase II: 1980-81	11,670 ± 1,220			10,975		

a. Energy use calculated as described in the text and normalized to "standard" year; these values do not represent the amount of energy actually consumed.

b. Estimated energy consumption as calculated by Computerized, Instrumented Residential Analysis (CIRA).

c. Not applicable because these control years were the same as preceding years.

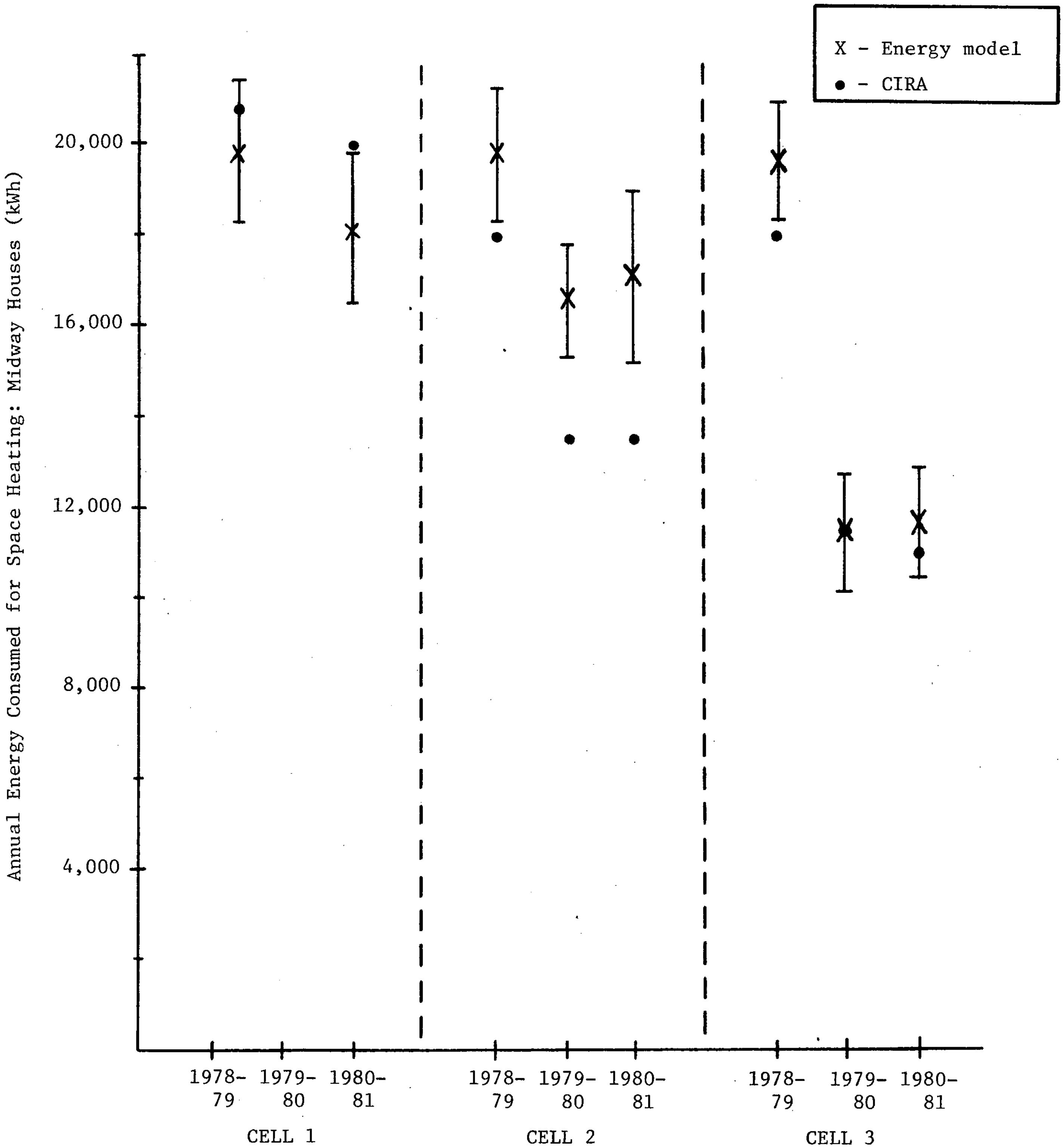

Figure 6: Energy Consumption Data Normalized for the Three Years of the Midway Study

We have averaged energy use during the first two years (normalized to the standard year) for Cell 1, the Phase I control group. Energy use during the first year of the project (as shown in Table 6) varied by only about 2% among the three cells. Cell 1 showed the highest energy use, perhaps due to the greater age of the houses in the cell. As a result of increased insulation levels, a 16.3% reduction in energy use, or 3,240 kWh, was observed in Cell 2. CIRA predicted a reduction of 4,460 kWh, or 24.8%. On the other hand, installation of storm windows and insulation in Cell 3 resulted in savings of 8,200 kWh, a 41.7% reduction in energy use whereas CIRA predicted a reduction of 6,510 kWh, or 36.3%. Therefore, storm windows appear to have saved some 4960 kWh.

During Phase II, no change in energy use was observed in Cell 2, the control group. A 9.2% reduction in energy use was seen in Cell 1, recipient of the extended house doctor treatment (1,840 kWh) as compared to the CIRA estimate of 840 kWh, or 4%. However, despite the 10 hours of house doctoring received by the houses in Cell 3, and the significant decrease in k (see Table 5), no reduction in energy use was observed. CIRA, on the other hand, predicted a savings of 465 kWh, or 4.1%. The balance temperature for this cell increased so much as to mask any energy savings that might otherwise have been observed. We believe this increase in balance temperature to have been caused by occupant behavior (discussed below).

Results of the Economic Analyses

Tables 7 through 9 present the results of the analyses of the base economic case: a real discount rate of 2.7%, a real energy escalation rate of 1.8%, energy costs of 2.5 and 5.0 cents/kWh, amortization periods of 20 and 30 years for insulation and storm retrofits and 10 and 20 years for house doctoring, and the following salvage values: 75%, insulation; 50%, storms; 0%, house doctoring. (Salvage values are expressed as discounted terms in the tables.) The tables also present the results of the economic analyses if salvage values are excluded, if the 15% federal energy conservation tax credit is included, and if the BPA "Energy Buy-Back Weatherization Program" is applied.

Table 7 : Results of Economic Analyses of Attic and Crawlspace Insulation

Retrofit Cost: $ 1,860

Amortization Period: See below

Tax Credit Value: $ 279

Energy Savings: 3,240 kWh/yr.

Maintenance Cost: $ 0 /yr.

BPA "Buyback Value: $ 946

Real Discount Rate: 2.7 %

Energy Escalation Rate: 1.8 %

Amortization Period: 30 yrs

Discounted Salvage Value:$ 627

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	894	3,020	1,173	3,299	1,840	3,966
Benefit/Cost Ratio	1.48	2.62	1.74	3.09	3.01	5.34
Internal Rate of Return (%)	5.1	10.2	6.2	11.9	10.8	19.8

*Adjusted Cost of Conserved Energy: 1.4 ¢/kWh

Real Discount Rate: 2.7 %

Energy Escalation Rate: 1.8 %

Amortization Period: 20 yrs

Discounted Salvage Value:$ 819

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	438	1,917	717	2,196	1,384	2,863
Benefit/Cost Ratio	1.24	2.03	1.45	2.39	2.51	4.13
Internal Rate of Return (%)	4.4	9.6	5.7	11.5	11.0	19.9

*Adjusted Cost of Conserved Energy: 1.8 ¢/kWh

Real Discount Rate: 2.7 %

Energy Escalation Rate: 1.8 %

Amortization Period: As noted

Discounted Salvage Value:$ 0

	20 years*		30 years			
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0		
Net Benefits ($)	-381	1,098	266	2,392		
Benefit/Cost Ratio	0.80	1.59	1.14	2.29		
Internal Rate of Return (%)	0	7.9	3.7	9.7		

*Adjusted Cost of Conserved Energy: 3.1 ¢/kWh

Table 8 : Results of Economic Analyses of Storm Windows and Doors

Retrofit Cost: $ 2,159

Amortization Period: See below

Tax Credit Value: $ 324

Energy Savings: 4,960 kWh/yr.

Maintenance Cost: $ 50 /yr.

BPA "Buyback Value: $ 1,448

Real Discount Rate: 2.7 %

Energy Escalation Rate: 1.8 %

Amortization Period: 30 yrs

Discounted Salvage Value: $ 486

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	562	3,817	886	4,141	2,010	5,265
Benefit/Cost Ratio	1.18	2.20	1.31	2.45	2.16	4.04
Internal Rate of Return (%)	4.1	11.0	5.1	12.8	13.3	30.7

*Adjusted Cost of Conserved Energy: 2.1 ¢/kWh

Real Discount Rate: 2.7 %

Energy Escalation Rate: 1.8 %

Amortization Period: 20 yrs

Discounted Salvage Value: $ 634

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	- 26	2,238	298	2,562	1,422	3,686
Benefit/Cost Ratio	0.99	1.76	1.11	1.98	1.96	3.50
Internal Rate of Return (%)	2.6	10.0	3.9	12.1	13.3	30.7

*Adjusted Cost of Conserved Energy: 2.5 ¢/kWh

Real Discount Rate: 2.7 %

Energy Escalation Rate: 1.8 %

Amortization Period: As noted

Discounted Salvage Value: $ 0

	20 years *		30 years			
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0		
Net Benefits ($)	-381	1,098	266	2,392		
Benefit/Cost Ratio	0.80	1.59	1.14	2.29		
Internal Rate of Return (%)	0	9.0	2.9	10.7		

*Adjusted Cost of Conserved Energy: 3.2 ¢/kWh

Table 9 : Results of Economic Analyses of Extended House Doctoring

Retrofit Cost: $ 525
Amortization Period: See below
Tax Credit Value: $ 79
Energy Savings: 1,840 kWh/yr.
Maintenance Cost: $ 25 /yr.
BPA "Buyback Value: $ 525

Real Discount Rate: 2.7 %
Energy Escalation Rate: 1.8 %
Amortization Period: 20 yrs
Discounted Salvage Value: $ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	- 68	772	11	851	457	1,297
Benefit/Cost Ratio	0.93	1.85	1.01	2.03	2.20	4.39
Internal Rate of Return (%)	1.4	13.9	2.9	16.7	50+	50+

*Adjusted Cost of Conserved Energy: 2.7 ¢/kWh

Real Discount Rate: 2.7 %
Energy Escalation Rate: 1.8 %
Amortization Period: 10 yrs
Discounted Salvage Value: $ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-303	135	-224	214	222	660
Benefit/Cost Ratio	0.59	1.18	0.66	1.32	2.02	4.05
Internal Rate of Return (%)	0	7.2	0	10.8	50+	50+

*Adjusted Cost of Conserved Energy: 4.2 ¢/kWh

Note: In all the tables on economic analysis, values of internal rates of return less than 1% appear as 0%.

Note that a cost-effective investment is one for which: 1) the net benefits are positive; 2) the internal rate of return is equal to or greater than the real discount rate for that case; 3) the benefit-to-cost ratio is greater than one; or 4) the adjusted cost of conserved energy is less than or equal to the price of the energy paid by the consumer or displaced by the measure.

<u>Attic and Crawlspace Insulation</u>. Table 7 presents the results of the economic analyses for this set of conservation measures. They can be considered cost-effective if credit is taken for the salvage value. If however, the salvage value is excluded, a 20 year amortization with a present energy price of 2.5 cents/kWh yields unfavorable results. (This change underscores the fact that inclusion of the salvage value greatly enhances the cost-effectiveness of a particular retrofit.)

<u>Storm Windows and Doors</u>. Table 8 presents the results of the economic analyses for these retrofits. For the base case conditions, the storms are found to be cost-effective, however, if the amortization period is reduced to 20 years, the storms cannot be considered cost-effective at an energy price of 2.5 cents/kWh, even if the salvage value is included.

<u>Extended House Doctoring</u>. Table 9 presents the results of the economic analyses for this conservation measure. Under the base case economic conditions with an energy price of 2.5 cents/kWh, extended house doctoring cannot be considered cost-effective. Even with inclusion of the federal tax credit, the economic indicators are still relatively unfavorable. (The BPA Buyback program would pay for the complete cost of the retrofit.) However, if the energy price is raised to 5.0 cents/kWh, this measure becomes cost-effective.

In general, if the price of energy is 5.0 cents/kWh or more, all of the conservation measures can be considered cost-effective no matter what the amortization period, real discount rate, or energy escalation rate.

Discussion of Results

Leakage Area Measurements. For the most part, measured results conformed to expectations. However, reductions in leakage area due to house doctoring, and consequent energy savings, were somewhat less than might have been expected, given the amount of time spent on the procedure. (It is generally assumed that house doctoring will reduce leakage areas by 20 to 40 percent, resulting in energy savings on the order of 7.5 to 15 percent [13].) This can be explained by the fact that the Midway houses were quite tight to begin with (as evidenced by Figures 4 and 5) and provided little opportunity for significant tightening.

Energy Modeling Results. The values obtained from modeling of energy use are in some ways the most puzzling results of the Midway project. According to the model, houses with changes to the shell--due to increased insulation or decreased infiltration--should show decreases in both k and the balance temperature. The changes observed were not consistent with this expectation. The addition of insulation to Cell 2 houses resulted in a statistically insignificant reduction in k but a significant reduction in balance temperature. On the other hand, the addition of insulation and storm windows to Cell 3 houses resulted in statistically significant decreases in both k and balance temperature. These changes suggest the storm windows to have been an important retrofit measure, but the large changes in Cell 3 might also be partially attributable to changes in occupant window use. That is, prior to installation of the storm windows, occupants might have opened windows to relieve overheating, thus causing increased heat loss. However with the storm windows in place, occupants might have opened the interior windows but not the storms, such that less heat would be lost.

In Cells 1 and 3, the decreases in k as a result of house doctoring were statistically significant, but these changes were countered by significant increases in the balance temperatures. We are unable to account for this increase except to ascribe it to occupant behavior and occupancy changes. (The phenomenon of occupants increasing indoor temperatures as a response to conservation retrofits has been observed in both England and Sweden, and may have occurred here [14].) Cell 3 underwent a large number of occupancy changes during Phase II of the project, which may have affected the results.

Energy Savings. Another unexpected result was the uncertainty in energy savings in Cells 1 and 3 as a consequence of house doctoring. Measured energy savings in Cell 1 were 1840 ± 2300 kWh while CIRA predicted 840 kWh. Cell 3 energy "savings" were -200 ± 1800 kWh (CIRA predicted 465 kWh). In both cases the measured savings are consistent with the predicted savings. Based upon the energy savings and leakage area reductions observed in Cell 1, we would have expected to see an annual energy savings of approximately 750 kWh in Cell 3. Because energy consumption and consequent savings are very sensitive to small variations in k and the balance temperature, it is possible for the estimated standard error in energy consumption to mask energy savings. The estimated standard errors shown in Table 6 and Figure 6 point up the sensitivity of energy savings to small variations in k and balance temperature. A change of a few percent in either of these quantities could lead to energy savings or energy losses.

Given the estimated standard error for actual energy consumption--approximately 1,250 kWh--for the comparison years (1979-80 vs. 1980-81), it is not surprising that energy savings were not detected. Had we used an average balance temperature for the two years for Cell 3, for example, we would have observed some energy savings.

Economic Analyses. Although the base case economic parameters show two of the three conservation measures (insulation and storms) to be cost-effective at an energy price of 2.5 cents/kWh, these results should be interpreted with some caution. Inclusion of a salvage value in the analyses does improve a measure's cost-effectiveness, but the salvage value is a quantity that a homeowner may never "see." That is, the salvage value reflects the expectations that a retrofit will continue to save energy long after the amortization period ends and that the original homeowner occupies the house for years after the amortization period ends (or that the homeowner's investment has been sufficiently repaid upon sale of the house). However, the investor may experience a negative cash flow for a number of years, until such time as energy prices have escalated sufficiently to offset the negative flow. Therefore, while a particular measure may be cost-effective from the long-term point of view, the homeowner, with a relatively short planning horizon, may nonetheless perceive the measure to be unattractive.

* * *

The results of these projects should not be generalized to other locations or housing stocks. The Midway houses are atypical for at least two reasons: first, as noted previously the Midway houses were initially quite tight, hence the energy savings realized by house doctoring were not great. Second, Midway residents pay a low flat monthly fee for electricity and have no incentive to conserve. Indeed, Midway residents consume much more electricity than the average for the BPA service region, and there is some reason to believe that retrofits could induce them to be even more liberal with their energy use. In places where people pay a set rate for each kilowatt-hour consumed and are penalized for excessive consumption, conservation efforts are likely to show greater returns.

Sources of Error

Sources of error in the Midway analysis lie in: 1) the experiments themselves; 2) data acquisition; and 3) statistical analysis of the data.

Experimental Error. Experimental errors occur as a result of: change of control cell from year to year, variable occupant behavior, occupancy changes, and differences between houses and retrofits within a cell.

The control group in an experiment provides baseline data against which to compare subject group data. For the Midway project the control group was not the same throughout the three year period. Also, because of gaps in the data and warmer weather during the third year of the project, the individual effects of the retrofits cannot be determined easily.

Regarding the second major source of experimental uncertainty, it has been noted in other studies [15], that differences in occupant behavior can account for a variation in energy use in identical houses of 2 to 1 with a standard deviation of 15%. In the Midway houses, we noted that despite similar floor areas and numbers of occupants, energy use patterns differed significantly from house to house over the course of the same month.

Large changes in the number of people residing in a house, or a complete turnover in occupancy, can also affect the quality of the data. Here, such changes were compensated for somewhat by omitting part of the data for the years in which major occupancy changes took place. In some instances, however, data extending across occupancy changes was used.

Finally, the data has been treated as though all retrofits in a given cell were identical--probably not the case for the house doctoring. As evidenced by the logs in Appendix A, activities were not identical from house to house and the reductions in leakage area were not the same for houses in a single cell.

Data Acquisition. Inspection of the Midway data tapes show periods during which data was not collected or was incorrect for one or more input channels. Although an attempt was made to eliminate incorrect or faulty readings, some incorrect data has probably been incorporated into the analysis.

A significant problem with all of the Midway data is the absence of interior temperatures for the 18 houses. As a substitute, we calculated the balance temperatures for the houses. The balance temperature can be determined from an energy use vs. outside temperature regression. However, the value that emerges cannot be considered as accurate as one derived from direct measurement of inside temperature.

Finally, the data base for the third year of the project is fairly limited as a result of a short, mild winter (9 °C average temperature for 1980-81 as opposed to 4.8 °C for 1978-79, with 17 weeks of usable data for the former compared to 27 for the latter). We assume that data collected during very cold weather is statistically more accurate than that collected during warmer weather because space heating dominates energy use and overheating generally does not occur. Consequently, the lack of cold weather data for 1980-81 resulted in a poorer statistical analysis of the data.

Data Analysis. Uncertainties in the energy use model itself are the remaining source of error. We have discussed previously some of the factors which, ideally, should be included in the analysis, such as appliance energy use, metabolic heat and solar gain. We have also pointed out that certain patterns of energy consumption, such as increased appliance usage in the winter, could influence the accuracy of the energy model. The omission of these inputs may introduce an additional error of as much as 10%. The ranges of energy use presented in Table 6, it should be noted, are based only on the standard errors in k and the balance temperature as derived from the regression analysis. These standard errors are on the order of 7 to 10%. The resulting standard error in energy use is therefore on the order of 10 to 14%.

CONCLUSIONS and RECOMMENDATIONS

In summary, the goal of the BPA Midway Weatherization and Tightening Projects has been to evaluate the energy and cost savings accruing from conservation measures installed in a group of 18 monitored houses. The measures chosen were: attic and crawlspace insulation; storm windows and doors; and two levels of house tightening (or house doctoring). These measures were divided among three groups of houses and spread over a period of three years. The insulation retrofits were expected to reduce conduction losses through the building shell, the house tightening to reduce infiltration, and the storm windows, both. In all cases, measurable energy savings were expected to result.

Our analysis of the utility data and leakage area measurements from the Midway houses yielded mixed results. We found a significant reduction (14%) in leakage area due to the installation of storm windows but no reduction as a result of installing insulation. The "ordinary" house tightening program (10 person-hours of work) reduced the average leakage area of houses in Cell 3 by 20%, whereas the "extended" program (22 person-hours of work) led to a reduction of 27%. In general, the reduction in leakage area due to house doctoring was less than expected.

Application of an energy use model to the energy consumption data from the Midway houses showed that all four conservation measures reduced the thermal conductance parameter, k, although in the insulation-only houses the reduction was not statistically significant. Installation of both insulation and storm windows and doors resulted in a decrease of 28% in k (as opposed to a 7% reduction in houses receiving only insulation) and a large decrease in balance temperature (in contrast to a more moderate decrease following simple insulation). Extended house doctoring resulted in a 14% decrease in k while the ordinary house doctoring program produced a decrease of 27%. (The latter group of houses already showed a reduced thermal conductance parameter at the time of the house doctoring. Thus, in absolute terms, the reduction in k for both house doctoring programs was about the same. Furthermore, increases in the calculated balance temperatures for the two cells suggest the effect of the extended house doctoring to have been greater than that of the ordinary house tightening.)

According to our energy use model, significant energy savings were realized by three of the four conservation measures. Insulation saved 3,240 kWh/year, the insulation and storm window combination saved 8,200 kWh/year (suggesting that the storms alone may have reduced energy consumption by almost 5,000 kWh/year) and extended house doctoring saved 1,840 kWh/year. No energy savings were found as a result of ordinary house doctoring, in spite of the 20% reduction in leakage area, although the estimated standard error in the results was larger than the energy savings gained from this measure.

The energy savings predicted by LBL's Computerized Instrumented Residential Analysis program (CIRA) were within the uncertainty in energy savings calculated by the energy use model (see discussion of energy savings results). According to CIRA, the insulation retrofit should have saved 4,460 kWh/year, 1,220 kWh more than calculated by the energy-use model. The insulation and storms, on the other hand, should have saved 6,510 kWh/year according to CIRA, some 1,700 kWh less than calculated by the energy-use model. CIRA's estimate of savings from the extended house doctoring was 840 kWh/year, about 1,000 less than the number derived from the energy use model. Estimated savings due to the ordinary house doctoring were 465 kWh/year, according to CIRA, while the energy use model found no savings.

In terms of economics, the cost-effectiveness of each of the Midway retrofits is very sensitive to the energy escalation rate, if the real discount rate is relatively low. If, however, the real discount rate is greater than 4% and the energy escalation rate is less than about 1.5%, cost-effectiveness is more dependent upon the price of energy. (Cost-effectiveness is, of course, adversely affected by low energy prices.) Because the real discount rate at the present time is rather high and is likely to remain so (in the range of 4%), the economics of conservation in the Pacific Northwest will be strongly influenced by energy prices and the real energy escalation rate. In those areas where electricity prices are already 4.0 cents/kWh or more, consumers will need little incentive to invest in conservation. Where electricity is cheaper, conservation will be attractive only if either the real rate of increase in energy price is 3% or more per year or the marginal cost of electricity (to the utility) is greater than about 4.0 to 5.0 cents/kWh. In the latter situation, it may make sense for a utility to underwrite conservation investments (as is being done by some of the private utilities in the region and by BPA).

These findings lead to the following conclusions:

1. The addition of storm windows seems to be an effective retrofit because it reduces both conduction and infiltration losses. In the case of the Midway houses, we believe the storm windows to have greatly reduced energy loss through open windows (see Discussion).

2. Additional levels of attic and crawlspace insulation (from R-10 to R-30) are also cost-effective retrofits in terms of energy savings, although they appear to save less overall than the storm windows.

3. House doctoring results in marginal energy savings if done on houses that are already tight or are located in regions with low infiltration rates (due to low average wind velocities) as is the case at Midway.

5. Assuming a marginal cost of electricity from new generating facilities greater than about 4.0 to 5.0 cents/kWh, the three conservation retrofits that showed energy savings in the Midway project can be considered a cost-effective means of "creating" new supplies of energy. Given the great uncertainties in the current marginal cost of electricity, the advantages of obtaining "new" supplies through conservation at a known cost should not be disregarded.

As regards the future of the Midway project, or other similar experiments, we make the following recommendations:

1. Monitoring of utility data at Midway should continue in order to provide more data with which to evaluate the conservation measures. BPA should install indoor temperature sensors in all 18 houses as soon as possible. As a matter of good practice, the location and positioning of all outdoor sensors (temperature and solar insolation) should be checked to ensure that they are giving accurate readings. The outdoor temperature sensor should be positioned so that it is completely shielded from the sun. The pyranometer should be located so that it more accurately reflects the shading of the Midway community by the bluff to the south.

2. We believe the Midway project has demonstrated the effectiveness of certain types of conservation retrofits--specifically, attic insulation and storm windows, whether installed individually or in combination-- and that no further formal studies need be conducted on these two retrofits. Because these retrofits may be less effective in housing styles other than those characteristic of Midway, BPA might consider studying a selection of houses more representative of the entire housing stock of the Pacific Northwest.

3. As far as house doctoring is concerned, we recommend that BPA establish an experimental program of infiltration reduction retrofits for houses leakier than the Midway houses. Such a program should also incorporate other proven cost-effective conservation measures that were not included in the Midway project, such as insulation of water heaters, installation of low flow showerheads and, where appropriate, furnace tuneups. Furthermore, in order to evaluate the effectiveness of house doctoring in reducing leakage area in a more representative selection of the housing stock, an infiltration reduction program might be established as a follow-up to an energy use and indoor air quality monitoring program, should such a program be established by BPA. For a house-doctoring program to be successful in the long run, it is important that quality control measures be built into the program. For example, the quality of a house doctor training program and pre- and post-retrofit evaluation with a blower door are critical to ensuring that expected energy savings are actually realized.

APPENDIX A

MIDWAY HOUSE DOCTORING ACTIVITY LOGS

Table A1: Ordinary House Doctoring Activity Log

Activity	House Identification Number					
	5	6	9	12	13	17
Install outlet gaskets	y	y	y	y	n	n
Install switch plate gaskets	y	y	y	y	n	n
Caulk baseboards	y	n	n	n	y	y
Caulk baseboard heaters	y	y	y	n	y	n
Caulk air conditioner penetration	y	n	y	y	y	y
Cover air conditioner with polyethylene sheet	n	n	n	n	n	n
Caulk circuit/fuse boxes	y	y	y	y	y	n
Caulk or seal light fixtures	y	y	n	y	n	y
Caulk electrical penetrations	y	n	y	y	y	y
Caulk plumbing penetrations	y	n	y	y	y	y
Caulk or plug vent or chimney penetrations	n	n	n	n	n	n
Caulk window and door frames	y	n	y	n	y	y
Weatherstrip windows and doors	y	door	door	y	n	y
Weatherstrip attic and crawlspace hatches/doors	y	y	attic	y	y	n
Seal and insulate dropped ceilings	y	n	n	n	y	n
Caulk cracks in attic and crawlspace	n	y	n	y	n	y
Caulk cracks in floors, subfloors, walls	n	n	n	n	n	y
Stuff fiberglass into large openings and bypasses	y	y	n	y	n	y
Install or repair crawlspace vent covers	y	n	y	n	n	n
Tape heating system ducts	n	n	n	n	n	n
Caulk wall-wall, wall-ceiling joints	y	y	y	n	y	n
Person-hours spent on house doctoring	11	12	12	10	10	10

Table A2: Extended House Doctoring Activity Log

Activity	House Identification Number					
	2	3	4	7	11	19
Install outlet gaskets	y	y	y	y	y	n
Install switch plate gaskets	y	y	y	y	y	n
Caulk baseboards	n	n	n	n	n	y
Caulk baseboard heaters	y	n	n	y	n	n
Caulk air conditioner penetration	y	y	y	y	n	y
Cover air conditioner with polyethylene sheet	y	y	y	n	y	n
Caulk circuit/fuse boxes	y	y	n	y	n	n
Caulk or seal light fixtures	y	y	y	y	y	y
Caulk electrical penetrations	y	y	y	y	y	y
Caulk plumbing penetrations	y	y	y	y	y	y
Caulk or plug vent or chimney penetrations	n	n	n	y	n	n
Caulk window and door frames	y	y	n	n	y	y
Weatherstrip windows and doors	n	y	y	y	y	y
Weatherstrip attic and crawlspace hatches/doors	y	y	y	n	y	n
Seal and insulate dropped ceilings	y	y	y	y	y	y
Caulk cracks in attic and crawlspace	y	y	n	n	n	y
Caulk cracks in floors, subfloors, walls	y	y	y	n	y	n
Stuff fiberglass into large openings and bypasses	y	y	y	y	y	n
Install or repair crawlspace vent covers	n	n	n	n	n	n
Tape heating system ducts	n	n	n	n	n	y
Caulk wall-wall, wall-ceiling joints	y	y	y	n	y	n
Person-hours spent on house doctoring	26	22	19	24	23	20

APPENDIX B

THE LBL INFILTRATION MODEL

With the LBL infiltration model, local weather data and a few building and site parameters are all that is needed to calculate infiltration rates in residential buildings. The model is specifically designed for simplicity, that is, the number of input parameters has been limited to make it usable in a programmable calculator. Presented here is an overview of the model; readers interested in more detail should consult references 16 and 17.

The model has two important parts: 1) determination of "effective leakage area;" and 2) calculation of infiltration airflow rates. Leakage areas are measured by blower door fan pressurization. The flow rates are determined by using leakage area measurements in conjunction with temperature, local windspeed, building height, and various shielding factors. Both components are discussed here.

Fan Pressurization and the Determination of Leakage Area

Infiltration through a building envelope is the process of air passing through openings and cracks in the structure, such as those around windows, doors, plumbing and electrical penetrations, ducts and flue pipes, fireplaces and chimneys, baseboards and so on. The quantity of air that passes through a single opening depends upon such factors as ambient weather, location of the opening within the building, shielding of the various sides of the building, the nature of the surrounding terrain and detailed geometry of the opening. Consequently, because several of these factors are variable, air flow through a particular opening is not constant from day to day nor is it the same from structure to structure.

Natural infiltration typically is driven by pressure differences (ΔP) across the building shell in the range of 0 to 10 Pascals (Pa) and is characterized by large, short-term fluctuations. Fan pressurization uses a door-mounted, variable-speed fan capable of moving large volumes of air into or out of a structure. When ΔP is held constant, all air flowing through the fan must also be flowing through the building envelope. When ΔP is much greater than 10 Pa, fan flow dominates natural infiltration and the latter may be disregarded. At a given pressure differential and fan speed (in RPM), the flow of air through the fan is determined by means of a previously established calibration curve. For each house, measurements are taken under conditions of both pressurization and depressurization at a series of fixed pressure differentials (for example, from 10 to 70 Pa at 10 Pa intervals), generating a pressure-versus-flow curve. These data are then used to find the effective leakage area of the house.

Air flow through a building envelope is a combination of viscous flow and turbulent flow. The former is proportional to ΔP while the latter is proportional to the square root of ΔP. Empirically, we find that the mixture of flows through the envelope produces a characteristic curve that is well represented by the function ΔP^n, where n is an exponent between 0.5 and 1.0.

The curves generated by fan pressurization are extrapolated to a ΔP of 4 Pa (representative of natural infiltration). It is assumed that in the pressure differential ranges characteristic of natural infiltration (-10 to +10 Pa), the flow-versus-pressure behavior of a building more closely resembles square-root (turbulent) than linear (viscous) flow. Using this assumption, air flow through the building shell is a function of the product of $\Delta P^{1/2}$ and a quantity called the "effective leakage area" of the structure. The effective leakage area, or A_{eff}, characterizes the air leakage of a structure and can be used in conjunction with other parameters (as described below) to calculate infiltration into the building. A more detailed explanation of leakage area can be found in Reference 1.

Calculating Infiltration

To calculate infiltration, two important separable quantities must be determined: wind-induced infiltration and stack-induced infiltration. The former is the passage of air through the building shell caused by a wind-induced pressure difference across the shell. The stack effect is due to the temperature difference between the interior and exterior of a building; the buoyancy of warm air causes a pressure difference across the building shell that drives infiltration. The basic form of the model relates infiltration (Q) to the effective leakage area and the square root of the sum of wind- and stack-induced infiltration. The general form of the model is:

$$Q = A_{eff} \sqrt{(\text{stack term}) + (\text{wind term})}$$

The wind and stack terms break down in the following ways. The wind term is of the form $[(f_w^2)(v^2)]$, where f_w is the "wind parameter" and v is the wind velocity measured at a local meteorological station. The stack term is of the form $[(f_s^2)(\Delta T)]$, where f_s is the "stack parameter" and ΔT is the indoor-outdoor temperature difference.

The Wind Parameter. The wind parameter is of the following general form:

$$f_w = [\text{shielding factor}] \times [\text{vertical leakage factor}] \times [\text{terrain factor}]$$

The shielding factor describes the degree to which a structure is protected from the wind by surrounding buildings, fences, trees, and so on. The more obstructions located around a particular house, the less effect the wind has upon the structure. The model divides shielding into five classes, Class I being the totally unobstructed case, such as open water, while Class V is a highly obstructed situation, such as might occur in the center of a large city.

The <u>vertical leakage factor</u> accounts for the fact that the leakage area in a structure is divided between the floor, ceiling, and walls. The model assumes that the floor and ceiling are shielded from the influence of the wind and, as leakage area is shifted from the walls to the floor and ceiling, the effect of the wind is proportionately reduced. This factor is of the form:

$$(1 - R)^{1/3}$$

where R is defined as the ratio of the sum of the floor and ceiling leakage area to the total leakage area of the house, that is:

$$R = \frac{(A_{ceiling} + A_{floor})}{A_{total}}$$

The <u>terrain factor</u> accounts for the difference between the wind velocity, as measured on a weather tower (usually at an airport), and the effective wind speed at the house. Standard wind engineering formulae are used to translate wind velocity in one terrain at one height to another terrain at another height. This is possible only if no large obstructions, such as hills, intervene between the two sites.

<u>The Stack Parameter</u>. The stack parameter is of the general form:

$$f_s = [\text{horizontal leakage factor}] \times [\text{null pressure factor}] \times [\text{stack velocity}]$$

The <u>horizontal leakage factor</u> is analagous to the vertical leakage factor; it determines the relative importance of infiltration through the ceiling and floor and is of the form:

$$\frac{(1 + R/2)}{3}$$

The null pressure factor accounts for the fact that, given a temperature difference between the interior and exterior of a structure and a vertical temperature gradient through the structure, there will be a height in the building at which the pressure differential across the building shell will be zero. The approximate form of this term is

$$\left[1 - \frac{X^2}{(2 - R)^2}\right]^{3/2}$$

where R is the same factor as described above and

$$X = \frac{A_{ceiling} - A_{floor}}{A_{total}}$$

Finally, the stack velocity term is roughly analogous to the speed at which air is flowing vertically through the structure as a result of the stack effect.

A useful physical interpretation of the infiltration model is that it converts the complex pressure distributions across the shell of a building caused by the wind and stack effects into an equivalent single pressure across an opening with the same effective leakage area as the building. The wind and stack effects are then added by superimposing the equivalent flows resulting from each effect, that is

$$Q_{total} = \sqrt{Q^2_{stack} + Q^2_{wind}}$$

where Q is the combined infiltration in cubic meters per second. The infiltration rate for a given structure is therefore

$$\frac{Q}{V} = \sqrt{\frac{Q^2_{stack} + Q^2_{wind}}{V^2}}$$

where V is the house volume in cubic meters.

APPENDIX C

ECONOMIC ANALYSES

In order to evaluate the economic effectiveness of the Midway project, four standard economic analyses were applied to the data. These were: net benefit analysis; benefit/cost ratio; internal rate of return; and adjusted cost of conserved energy. This appendix describes what assumptions were made in applying the four analyses and how each one is used. A useful discussion of these economic analysis techniques applied to energy can be found in Marshall and Ruegg [8] and Wright, et al [9].

In order to use these economic analyses properly, certain assumptions must be made about discounting factors, the cost of funds, alternative investment possibilities, energy price escalation, and other factors. These are discussed below.

Discounting Factors

Present Worth Factor. For the purposes of this study, all costs and savings were converted to constant dollars (as opposed to nominal dollars). Present value is defined as the equivalent value of past and future dollars corresponding to a base year. To convert future dollars to a present value, both an interest rate and an inflation rate, or a "real" discount rate, must be taken into account through the application of a present worth factor. The present worth factor can be used to convert future costs such as replacement costs and salvage values to present values.

The present worth factor is found by the following formula:

$$PWF = \frac{1}{(1 + D)^N}$$

where

PWF is the present worth factor;
D is the real discount rate; and
N is the number of discounting periods.

In this case, the real discount rate is determined either by the costs of borrowing money or the return from alternative investments, corrected for inflation. The formula for calculating the real discount rate is:

$$D = \frac{(I - K)}{(1 + K)}$$

where

D is the real discount rate;
I is the interest rate; and
K is the inflation rate.

For example, if the interest rate is 14% and the inflation rate is 11%, the real discount rate is 2.7%. Choosing the appropriate combination of interest and inflation rates can be difficult. We avoided this problem in our analyses simply by assuming different real discount rates ranging from 2.7 to 7.3%.

Uniform Present Worth Factor. The uniform present worth factor is used to find the present value of a uniform series of payments that are made over N periods at a real discount rate, D. The yearly maintenance costs are multiplied by this factor in order to get the present value of the maintenance costs over the period of the investment. It is assumed that these yearly costs remain the same in constant dollars.

The uniform present worth factor is found using the following formula:

$$UPW = \frac{[\,1 \,/\, (1 + D)\,]^{N} - 1}{1 - (1 + D)}$$

where

UPW is the uniform present worth factor;
D is the real discount rate; and
N is the number of discounting periods.

Energy Escalation Factor. The energy escalation factor is a modified form of the uniform present worth factor. The only difference between the two is that the energy escalation factor takes into account the rate of escalation of the periodic payment or receipt that is being discounted over N periods or years. For example, if you wish to find the present value of the energy savings (in dollars) from a conservation measure which has a useful life of N years, you would want to account for the yearly fuel price escalation rate (above and beyond inflation) in addition to discounting the yearly savings. The first year energy cost savings are multiplied by the energy escalation factor to get the present value of the energy savings over the period of the investment.

The energy escalation factor is found by the following formula:

$$EEF = \frac{[(1 + E) / (1 + D)]^N - 1}{1 - (1 + D) / (1 + E)}$$

where

EEF is the energy escalation factor;
E is the real energy escalation rate;
D is the real discount rate; and
N is the number of discounting periods.

Economic Analysis Techniques

Net Benefit Analysis. Net benefit analysis allows one to determine the difference between the lifetime energy savings (in dollars) of an energy conservation investment and the lifetime costs. The analysis may be used to compare the benefits of making an investment with those of foregoing it, or it may be used to compare competing investments. An investment with a net benefit greater than zero is considered worthwhile. The formula for calculating the net benefit is:

$$NB = EC(EEF) + TI - [P - S(PWF) + M(UPW) + R(PWF)]$$

where

NB are the net benefits or savings;

EC is the reduction in energy costs due to the investment;

EEF is the energy price escalation factor;

TI are any tax or economic incentives applicable to the investment;

P are the differential purchase and installation costs;

S is the differential salvage value;

PWF is the present worth factor;

M are the differential maintenance and repair costs;

UPW is the uniform present worth factor; and

R is the differential replacement cost during the investment lifetime.

In order for an investment to be economically worthwhile, its net benefit must be greater than zero. Strictly speaking, for an energy conservation investment to be cost-effective the net benefit must be greater than or equal to zero, however, due to the distribution of benefits over the period of the investment, a net benefit that is not much greater than zero may not be considered economically appealing to the investor.

Net benefit analysis can also be used to determine the economically efficient size of a conservation investment. If the net benefit increases with additional investment, it is profitable to increase the investment. Net benefit analysis does not, however, indicate the economic return on an investment dollar. This analysis technique cannot distinguish between large and small investments that result in the same dollar savings nor can it be used to rank competing non-mutually exclusive investments because it may not indicate the highest total net benefits for a limited budget.

Benefit-to-Cost Ratio (B/C). Benefit-to-Cost analysis is very similar to net benefit analysis, except that it evaluates the ratio of energy savings to system costs. A project with a benefit-to-cost ratio greater than 1 is considered a worthwhile investment. There are several possible formulas for benefit-to-cost ratio, depending on whether the benefits are added in the numerator or subtracted from the denominator. The formula used here for calculating the benefit-to-cost ratio is:

$$B/C = \frac{EC(EEF) + S(PWF)}{(P - TI) + R(PWF) + M(UPW)}$$

where

B/C is the ratio of benefits to costs;
EC is the reduction in energy costs due to the investment;
EEF is the energy price escalation factor;
P are the differential purchase and installation costs;
TI are any tax or economic incentives applicable to the investment;
S is the differential salvage value;
R is the differential replacement cost during the investment lifetime;
PWF is the present worth factor;
M are the differential maintenance and repair costs; and
UPW is the uniform present worth factor.

In general, benefit-to-cost ratio utilizes the same benefit and cost values as net benefit analysis and has special application in comparing different purpose projects competing for the same budget, to which end it is often used in conjunction with internal rate of return analysis.

Internal Rate of Return (IRR). The internal rate of return determines the economic return on an investment, that is, the interest rate for which lifetime savings for a project are equal to lifetime costs (in other words, the return for the period over which an investment pays for itself). In order to determine the desirability of an investment, the internal rate of return must be compared to the minimum rate of return acceptable to the investor. In general, the minimum acceptable rate of return is equal to the real discount rate at the time of the investment. Any project with an internal rate of return greater than the acceptable

Any project with an internal rate of return greater than the acceptable minimum rate is considered desirable. The general formula for this type of analysis is:

$$\text{Find } i \text{ such that } EC(EEF) - [(P - TI) + [(R - S)(PWF)] + M(UPW)] = 0$$

where

EC is the reduction in energy costs due to the investment;
EEF is the energy escalation factor;
P are the differential purchase and installation costs;
TI are any tax or economic incentives applicable to the investment;
R is the differential replacement cost during the investment lifetime;
S is the differential salvage cost;
PWF is the present worth factor;
M are the differential maintenance and repair costs; and
UPW is the uniform present worth factor.

The internal rate of return is generally calculated by an iterative process that seeks the interest rate for which the net value of the investment is equal or close to zero. This analysis technique can also be used to evaluate two projects competing for the same budget; the project with the higher return is the more favorable investment.

Adjusted Cost of Conserved Energy. Analysis of the cost of conserved energy allows one to determine the cost of energy saved by a conservation investment. This is done by dividing the annualized cost of the investment by the annual energy savings and the energy escalation factor. A worthwhile investment is one for which the adjusted cost of conserved energy is less than the cost of supplied energy. For the homeowner, this is the price of energy; for the utility, it is the marginal cost of energy from new production facilities. The formula is:

$$ACCE = \frac{[P + M(UPW) - S(PWF)]}{ES(EEF)}$$

where

ACCE is the cost of conserved energy;

P is the purchase and installation cost of the investment;

M is the value of the yearly maintenance and repair costs;

UPW is the uniform present worth factor;

S is the salvage value;

PWF is the present worth factor;

ES are the energy savings resulting from the investment; and

EEF is the energy escalation factor.

The adjusted cost of conserved energy is a useful tool because it allows one to determine the cost-effectiveness of a conservation measure by a simple comparison. As long as the adjusted cost of conserved energy is less than or equal to the retail price of utility-supplied electricity to the homeowner, or the marginal cost of electricity to the utility, the conservation measure can be considered cost-effective.

Table C1 : Attic and Crawlspace Insulation (1.0% Energy Escalation Rate)

Retrofit Cost: $ 1,860 Energy Savings: 3,240 kWh/y
Amortization Period: 30 yrs. Maintenance Cost: $ 0 /yr.
Tax Credit Value: $ 279 BPA "Buyback Value: $ 946

Real Discount Rate: 2.7 %
Energy Escalation Rate: 1.0 % Discounted Salvage Value:$ 627

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	663	2,559	942	2,838	1,609	3,505
Benefit/Cost Ratio	1.36	2.38	1.60	2.79	2.76	4.83
Internal Rate of Return (%)	4.6	9.4	5.6	11.1	10.0	18.9

*Adjusted Cost of Conserved Energy: 1.6 ¢/kWh

Real Discount Rate: 4.5 %
Energy Escalation Rate: 1.0 % Discounted Salvage Value:$ 372

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	9	1,505	288	1,784	955	2,451
Benefit/Cost Ratio	1.00	1.81	1.18	2.13	2.04	3.68
Internal Rate of Return (%)	4.6	9.4	5.6	11.1	10.0	18.9

*Adjusted Cost of Conserved Energy: 2.5 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 1.0 % Discounted Salvage Value:$ 168

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-604	483	-325	762	342	1,429
Benefit/Cost Ratio	0.68	1.26	0.79	1.48	1.37	2.56
Internal Rate of Return (%)	4.6	9.4	5.6	11.1	10.0	18.9

*Adjusted Cost of Conserved Energy: 3.9 ¢/kWh

Table C1 : Attic and Crawlspace Insulation (1.0% Energy Escalation Rate)

Retrofit Cost: $ 1,860 Energy Savings: 3,240 kWh/yr.
Amortization Period: 20 yrs. Maintenance Cost: $ 0 /yr.
Tax Credit Value: $ 279 BPA "Buyback Value: $ 946

Real Discount Rate: 2.7 %
Energy Escalation Rate: 1.0 % Discounted Salvage Value:$ 819

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	325	1,690	622	1,988	1,271	2,637
Benefit/Cost Ratio	1.17	1.91	1.40	2.27	2.39	3.88
Internal Rate of Return (%)	3.9	8.9	5.4	11.0	10.4	19.1

*Adjusted Cost of Conserved Energy: 1.9 ¢/kWh

Real Discount Rate: 4.5 %
Energy Escalation Rate: 1.0 % Discounted Salvage Value:$ 578

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-127	1,208	170	1,325	819	1,974
Benefit/Cost Ratio	0.93	1.55	1.11	1.85	1.90	3.16
Internal Rate of Return (%)	3.9	8.9	5.4	11.0	10.4	19.1

*Adjusted Cost of Conserved Energy: 2.8 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 1.0 % Discounted Salvage Value:$ 341

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-608	304	-311	601	338	1,250
Benefit/Cost Ratio	0.67	1.16	0.80	1.38	1.37	2.37
Internal Rate of Return (%)	3.9	8.9	5.4	11.0	10.4	19.1

*Adjusted Cost of Conserved Energy: 4.2 ¢/kWh

Table C2 : Attic and Crawlspace Insulation (1.8% Energy Escalation Rate)

Retrofit Cost: $ 1,860
Energy Savings: 3,240 kWh/y
Amortization Period: 30 yrs.
Maintenance Cost: $ 0 /yr.
Tax Credit Value: $ 279
BPA "Buyback Value: $ 946

Real Discount Rate: 4.5 %
Energy Escalation Rate: 1.8 %
Discounted Salvage Value:$ 627

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	174	1,835	453	2,114	1,120	2,781
Benefit/Cost Ratio	1.09	1.99	1.29	2.34	2.22	4.04
Internal Rate of Return (%)	5.1	10.2	6.2	11.9	10.8	19.8

*Adjusted Cost of Conserved Energy: 2.2 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 1.8 %
Discounted Salvage Value:$ 372

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-501	688	-222	967	444	1,634
Benefit/Cost Ratio	0.73	1.37	0.86	1.61	1.49	2.79
Internal Rate of Return (%)	5.1	10.2	6.2	11.9	10.8	19.8

*Adjusted Cost of Conserved Energy: 3.6 ¢/kWh

Table C2 : Attic and Crawlspace Insulation (1.8% Energy Escalation Rate)

Retrofit Cost: $ 1,860
Energy Savings: 3,240 kWh/yr.
Amortization Period: 20 yrs.
Maintenance Cost: $ 0 /yr.
Tax Credit Value: $ 279
BPA "Buyback Value: $ 946

Real Discount Rate: 4.5 %
Energy Escalation Rate: 1.8 %
Discounted Salvage Value:$ 578

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	- 37	1,208	242	1,487	909	2,154
Benefit/Cost Ratio	0.98	1.65	1.15	1.94	1.99	3.36
Internal Rate of Return (%)	4.4	9.6	5.7	11.5	11.0	19.9

*Adjusted Cost of Conserved Energy: 2.6 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 1.8 %
Discounted Salvage Value:$ 341

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-543	432	-264	712	403	1,378
Benefit/Cost Ratio	0.71	1.23	0.83	1.45	1.44	2.51
Internal Rate of Return (%)	4.4	9.6	5.7	11.5	11.0	19.9

*Adjusted Cost of Conserved Energy: 3.9 ¢/kWh

Table C3 : Attic and Crawlspace Insulation (3.0% Energy Escalation Rate)

Retrofit Cost: $ 1,860
Energy Savings: 3,240 kWh/yr
Amortization Period: 30 yrs.
Maintenance Cost: $ 0 /yr.
Tax Credit Value: $ 279
BPA "Buyback Value: $ 946

Real Discount Rate: 2.7 %
Energy Escalation Rate: 3.0 %
Discounted Salvage Value: $ 627

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	1,310	3,853	1,589	4,132	2,256	4,799
Benefit/Cost Ratio	1.70	3.07	2.00	3.61	3.47	6.25
Internal Rate of Return (%)	6.0	11.4	7.1	13.2	11.8	21.2

*Adjusted Cost of Conserved Energy: 1.2 ¢/kWh

Real Discount Rate: 4.5 %
Energy Escalation Rate: 3.0 %
Discounted Salvage Value: $ 372

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	470	2,427	749	2,706	1,416	3,373
Benefit/Cost Ratio	1.25	2.30	1.47	2.71	2.55	4.69
Internal Rate of Return (%)	6.0	11.4	7.1	13.2	11.8	21.2

*Adjusted Cost of Conserved Energy: 1.9 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 3.0 %
Discounted Salvage Value: $ 168

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-320	1,051	- 41	1,330	626	1,997
Benefit/Cost Ratio	0.83	1.56	0.97	1.84	1.68	3.18
Internal Rate of Return (%)	6.0	11.4	7.1	13.2	11.8	21.2

*Adjusted Cost of Conserved Energy: 3.1 ¢/kWh

Table C3 : Attic and Crawlspace Insulation (3.0% Energy Escalation Rate)

Retrofit Cost: $ 1,860
Energy Savings: 3,240 kWh/yr.
Amortization Period: 20 yrs.
Maintenance Cost: $ 0 /yr.
Tax Credit Value: $ 279
BPA "Buyback Value: $ 946

Real Discount Rate: 2.7 %
Energy Escalation Rate: 3.0 %
Discounted Salvage Value: $ 819

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	629	2,300	908	2,579	1,575	3,246
Benefit/Cost Ratio	1.34	2.24	1.57	2.63	2.72	4.55
Internal Rate of Return (%)	5.0	10.6	6.4	12.6	11.8	21.1

*Adjusted Cost of Conserved Energy: 1.6 ¢/kWh

Real Discount Rate: 4.5 %
Energy Escalation Rate: 3.0 %
Discounted Salvage Value: $ 578

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	115	1,512	394	1,791	1,061	2,458
Benefit/Cost Ratio	1.06	1.81	1.25	2.13	2.16	3.69
Internal Rate of Return (%)	5.0	10.6	6.4	12.6	11.8	21.1

*Adjusted Cost of Conserved Energy: 2.3 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 3.0 %
Discounted Salvage Value: $ 341

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-435	649	-156	928	511	1,595
Benefit/Cost Ratio	0.77	1.35	0.90	1.59	1.56	2.74
Internal Rate of Return (%)	5.0	10.6	6.4	12.6	11.8	21.1

*Adjusted Cost of Conserved Energy: 3.5 ¢/kWh

Table C4 : Storm Windows and Doors (1.0% Energy Escalation Rate)

Retrofit Cost: $ 2,159
Amortization Period: 30 yrs.
Tax Credit Value: $ 324
Energy Savings: 4,960 kWh/yr
Maintenance Cost: $ 50 /yr.
BPA "Buyback Value: $ 1,448

Real Discount Rate: 2.7 %
Energy Escalation Rate: 1.0 %
Discounted Salvage Value: $ 486

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	210	3,112	534	3,436	1,658	4,560
Benefit/Cost Ratio	1.06	1.98	1.19	2.20	1.96	3.64
Internal Rate of Return (%)	4.6	9.4	5.6	11.1	10.0	18.9

*Adjusted Cost of Conserved Energy: 2.3 ¢/kWh

Real Discount Rate: 4.5 %
Energy Escalation Rate: 1.0 %
Discounted Salvage Value: $ 288

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-394	1,896	- 70	2,220	1,053	3,344
Benefit/Cost Ratio	0.87	1.64	0.97	1.84	1.69	3.19
Internal Rate of Return (%)	4.6	9.4	5.6	11.1	10.0	18.9

*Adjusted Cost of Conserved Energy: 2.9 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 1.0 %
Discounted Salvage Value: $ 130

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-966	698	-642	1,022	482	2,146
Benefit/Cost Ratio	0.65	1.25	0.74	1.42	1.37	2.63
Internal Rate of Return (%)	4.6	9.4	5.6	11.1	10.1	18.9

*Adjusted Cost of Conserved Energy: 4.0 ¢/kWh

Table C4 : Storm Windows and Doors (1.0% Energy Escalation Rate)

Retrofit Cost: $ 2,159
Amortization Period: 20 yrs.
Tax Credit Value: $ 324
Energy Savings: 4,960 kWh/yr.
Maintenance Cost: $ 50 /yr.
BPA "Buyback Value: $1,448

Real Discount Rate: 2.7 %
Energy Escalation Rate: 1.0 %
Discounted Salvage Value: $ 634

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-199	1,892	125	2,216	1,249	3,340
Benefit/Cost Ratio	0.93	1.65	1.05	1.85	1.85	3.26
Internal Rate of Return (%)	1.0	9.2	3.2	11.2	12.4	29.5

*Adjusted Cost of Conserved Energy: 2.7 ¢/kWh

Real Discount Rate: 4.5 %
Energy Escalation Rate: 1.0 %
Discounted Salvage Value: $ 448

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-594	1,174	-270	1,498	854	2,622
Benefit/Cost Ratio	0.79	1.42	0.89	1.60	1.63	2.93
Internal Rate of Return (%)	1.0	9.2	3.2	11.2	12.4	29.5

*Adjusted Cost of Conserved Energy: 3.3 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 1.0 %
Discounted Salvage Value: $ 264

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-1,017	378	-693	702	431	1,826
Benefit/Cost Ratio	0.62	1.14	0.70	1.30	1.35	2.49
Internal Rate of Return (%)	1.0	9.2	3.2	11.2	12.4	29.5

*Adjusted Cost of Conserved Energy: 4.3 ¢/kWh

Table C5 : Storm Windows and Doors (1.8% Energy Escalation Rate)

Retrofit Cost: $ 2,159
Energy Savings: 4,960 kWh/y
Amortization Period: 30 yrs.
Maintenance Cost: $ 50 /yr.
Tax Credit Value: $ 324
BPA "Buyback Value: $ 1,448

Real Discount Rate: 4.5 %
Energy Escalation Rate: 1.8 %
Discounted Salvage Value: $ 288

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-142	2,402	182	2,726	1,306	3,850
Benefit/Cost Ratio	0.95	1.81	1.07	2.03	1.86	3.52
Internal Rate of Return (%)	4.1	11.0	5.1	12.8	13.3	30.7

*Adjusted Cost of Conserved Energy: 2.6 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 1.8 %
Discounted Salvage Value: $ 130

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-809	1,013	-485	1,337	639	2,461
Benefit/Cost Ratio	0.71	1.37	0.80	1.55	1.49	2.87
Internal Rate of Return (%)	4.1	11.0	5.1	12.8	13.3	30.7

*Adjusted Cost of Conserved Energy: 3.6 ¢/kWh

Table C5 : Storm Windows and Doors (1.8% Energy Escalation Rate)

Retrofit Cost: $ 2,159
Energy Savings: 4,960 kWh/yr.
Amortization Period: 20 yrs.
Maintenance Cost: $ 50 /yr.
Tax Credit Value: $ 324
BPA "Buyback Value: $1,448

Real Discount Rate: 4.5 %
Energy Escalation Rate: 1.8 %
Discounted Salvage Value: $ 448

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-456	1,450	-132	1,774	992	2,898
Benefit/Cost Ratio	0.84	1.52	0.95	1.71	1.73	3.13
Internal Rate of Return (%)	2.6	10.0	3.9	12.1	13.3	30.7

*Adjusted Cost of Conserved Energy: 3.1 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 1.8 %
Discounted Salvage Value: $ 264

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-919	575	-595	899	529	2,024
Benefit/Cost Ratio	0.66	1.21	0.75	1.38	1.43	2.65
Internal Rate of Return (%)	2.6	10.0	3.9	12.1	13.3	30.7

*Adjusted Cost of Conserved Energy: 4.0 ¢/kWh

Table C6 : Storm Windows and Doors (3.0% Energy Escalation Rate)

Retrofit Cost:	$ 2,159	Energy Savings:	4,960 kWh/yr
Amortization Period:	30 yrs.	Maintenance Cost:	$ 50 /yr.
Tax Credit Value:	$ 324	BPA "Buyback Value:	$ 1,448

Real Discount Rate: 2.7 %

Energy Escalation Rate: 3.0 % Discounted Salvage Value: $ 486

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	1,201	5,094	1,525	5,418	2,649	6,542
Benefit/Cost Ratio	1.38	2.60	1.53	2.90	2.53	4.78
Internal Rate of Return (%)	6.0	11.4	7.1	13.2	11.8	21.2

*Adjusted Cost of Conserved Energy: 1.7 ¢/kWh

Real Discount Rate: 4.5 %

Energy Escalation Rate: 3.0 % Discounted Salvage Value: $ 288

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	311	3,308	635	3,632	1,759	4,756
Benefit/Cost Ratio	1.10	2.11	1.24	2.37	2.15	4.12
Internal Rate of Return (%)	6.0	11.4	7.1	13.2	11.8	21.2

*Adjusted Cost of Conserved Energy: 2.2 ¢/kWh

Real Discount Rate: 7.3 %

Energy Escalation Rate: 3.0 % Discounted Salvage Value: $ 130

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-531	1,568	-207	1,892	917	3,016
Benefit/Cost Ratio	0.81	1.57	0.91	1.78	1.70	3.30
Internal Rate of Return (%)	6.0	11.4	7.1	13.2	11.8	21.2

*Adjusted Cost of Conserved Energy: 3.1 ¢/kWh

Table C6 : Storm Windows and Doors (3.0% Energy Escalation Rate)

Retrofit Cost:	$ 2,159	Energy Savings:	4,960 kWh/yr.
Amortization Period:	20 yrs.	Maintenance Cost:	$ 50 /yr.
Tax Credit Value:	$ 324	BPA "Buyback Value:	$1,448

Real Discount Rate: 2.7 %

Energy Escalation Rate: 3.0 % Discounted Salvage Value: $ 634

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	267	2,825	591	3,149	1,715	4,273
Benefit/Cost Ratio	1.09	1.97	1.23	2.21	2.16	3.89
Internal Rate of Return (%)	3.8	11.3	4.9	13.5	14.8	32.5

*Adjusted Cost of Conserved Energy: 2.2 ¢/kWh

Real Discount Rate: 4.5 %

Energy Escalation Rate: 3.0 % Discounted Salvage Value: $ 448

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-223	1,915	100	2,239	1,225	3,363
Benefit/Cost Ratio	0.92	1.68	1.04	1.90	1.90	3.47
Internal Rate of Return (%)	3.8	11.3	4.9	13.5	14.8	32.5

*Adjusted Cost of Conserved Energy: 2.8 ¢/kWh

Real Discount Rate: 7.3 %

Energy Escalation Rate: 3.0 % Discounted Salvage Value: $ 264

Energy Cost (¢/kWh)	No Tax Credit*		Tax Credit		BPA "Buyback"	
	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-753	906	-429	1,230	695	2,354
Benefit/Cost Ratio	0.72	1.34	0.82	1.52	1.56	2.92
Internal Rate of Return (%)	3.8	11.3	4.9	13.5	14.8	32.5

*Adjusted Cost of Conserved Energy: 3.6 ¢/kWh

Table C7 : Extended House Doctoring (1.0% Energy Escalation Rate)

Retrofit Cost: $ 525
Amortization Period: 20 yrs.
Tax Credit Value: $ 79
Energy Savings: 1,840 kWh/yr.
Maintenance Cost: $ 25 /yr.
BPA "Buyback Value: $ 525

Real Discount Rate: 2.7 %
Energy Escalation Rate: 1.0 %
Discounted Salvage Value: $ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-132	644	- 53	723	393	1,169
Benefit/Cost Ratio	0.85	1.71	0.94	1.87	2.03	4.06
Internal Rate of Return (%)	1.0	12.8	1.0	15.5	50+	50+

*Adjusted Cost of Conserved Energy: 2.9 ¢/kWh

Real Discount Rate: 4.5 %
Energy Escalation Rate: 1.0 %
Discounted Salvage Value: $ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-194	461	-115	540	331	986
Benefit/Cost Ratio	0.77	1.54	0.85	1.70	2.02	4.03
Internal Rate of Return (%)	1.0	12.8	1.0	15.5	50+	50+

*Adjusted Cost of Conserved Energy: 3.2 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 1.0 %
Discounted Salvage Value: $ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-266	251	-187	330	259	776
Benefit/Cost Ratio	0.66	1.32	0.73	1.47	2.00	4.00
Internal Rate of Return (%)	1.0	12.8	1.0	15.5	50+	50+

*Adjusted Cost of Conserved Energy: 3.8 ¢/kWh

Table C7 : Extended House Doctoring (1.0% Energy Escalation Rate)

Retrofit Cost: $ 525
Amortization Period: 10 yrs.
Tax Credit Value: $ 79
Energy Savings: 1,840 kWh/yr.
Maintenance Cost: $ 25 /yr.
BPA "Buyback Value: $ 525

Real Discount Rate: 2.5 %
Energy Escalation Rate: 1.0 %
Discounted Salvage Value: $ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-321	99	-243	177	204	624
Benefit/Cost Ratio	0.57	1.13	0.63	1.27	1.94	3.88
Internal Rate of Return (%)	1.0	6.1	1.0	9.7	50+	50+

*Adjusted Cost of Conserved Energy: 4.4 ¢/kWh

Real Discount Rate: 4.5 %
Energy Escalation Rate: 1.0 %
Discounted Salvage Value: $ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-340	44	-261	122	185	569
Benefit/Cost Ratio	0.53	1.06	0.60	1.19	1.94	3.87
Internal Rate of Return (%)	1.0	6.1	1.0	9.7	50+	50+

*Adjusted Cost of Conserved Energy: 4.7 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 1.0 %
Discounted Salvage Value: $ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-363	- 29	-285	50	162	496
Benefit/Cost Ratio	0.48	0.96	0.54	1.08	1.93	3.87
Internal Rate of Return (%)	1.0	6.1	1.0	9.7	50+	50+

*Adjusted Cost of Conserved Energy: 5.2 ¢/kWh

Table C8 : Extended House Doctoring (1.8% Energy Escalation Rate)

Retrofit Cost: $ 525
Energy Savings: 1,840 kWh/yr
Amortization Period: 20 yrs.
Maintenance Cost: $ 25 /yr.
Tax Credit Value: $ 79
BPA "Buyback Value: $ 525

Real Discount Rate: 4.5 %
Energy Escalation Rate: 1.8 %
Discounted Salvage Value:$ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-143	564	- 64	643	382	1,089
Benefit/Cost Ratio	0.83	1.66	0.92	1.83	2.17	4.35
Internal Rate of Return (%)	1.4	13.9	2.9	16.7	50+	50+

*Adjusted Cost of Conserved Energy: 3.0 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 1.8 %
Discounted Salvage Value:$ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-230	325	-151	404	295	850
Benefit/Cost Ratio	0.71	1.41	0.79	1.57	2.14	4.28
Internal Rate of Return (%)	1.4	13.9	2.9	16.7	50+	50+

*Adjusted Cost of Conserved Energy: 3.5 ¢/kWh

Table C8 : Extended House Doctoring (1.8% Energy Escalation Rate)

Retrofit Cost: $ 525
Energy Savings: 1,840 kWh/yr.
Amortization Period: 10 yrs.
Maintenance Cost: $ 25 /yr.
Tax Credit Value: $ 79
BPA "Buyback Value: $ 525

Real Discount Rate: 4.5 %
Energy Escalation Rate: 1.8 %
Discounted Salvage Value:$ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-323	76	-244	155	202	601
Benefit/Cost Ratio	0.55	1.10	0.62	1.24	2.02	4.04
Internal Rate of Return (%)	0	7.2	0	10.8	50+	50+

*Adjusted Cost of Conserved Energy: 4.5 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 1.8 %
Discounted Salvage Value:$ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-350	- 1	-271	78	175	523
Benefit/Cost Ratio	0.50	1.00	0.56	1.12	2.01	4.02
Internal Rate of Return (%)	0	7.2	0	10.8	50+	50+

*Adjusted Cost of Conserved Energy: 5.0 ¢/kWh

Table C9 : Extended House Doctoring (3.0% Energy Escalation Rate)

Retrofit Cost: $ 525   Energy Savings: 1,840 kWh/yr.
Amortization Period: 20 yrs.   Maintenance Cost: $ 25 /yr.
Tax Credit Value: $ 79   BPA "Buyback Value: $ 525

Real Discount Rate: 2.7 %
Energy Escalation Rate: 3.0 %   Discounted Salvage Value:$ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	41	990	120	1,069	566	1,515
Benefit/Cost Ratio	1.04	2.09	1.14	2.29	2.48	4.96
Internal Rate of Return (%)	3.7	15.6	5.0	18.4	50+	50+

*Adjusted Cost of Conserved Energy: 2.4 ¢/kWh

Real Discount Rate: 4.5 %
Energy Escalation Rate: 3.0 %   Discounted Salvage Value:$ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	- 57	736	22	815	468	1,261
Benefit/Cost Ratio	0.93	1.87	1.03	2.06	2.44	4.88
Internal Rate of Return (%)	3.7	15.6	5.0	18.4	50+	50+

*Adjusted Cost of Conserved Energy: 2.7 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 3.0 %   Discounted Salvage Value:$ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-168	447	- 89	526	357	972
Benefit/Cost Ratio	0.78	1.57	0.87	1.75	2.38	4.76
Internal Rate of Return (%)	3.7	15.6	5.0	18.4	50+	50+

*Adjusted Cost of Conserved Energy: 3.2 ¢/kWh

Table C9 : Extended House Doctoring (3.0% Energy Escalation Rate)

Retrofit Cost: $ 525   Energy Savings: 1,840 kWh/yr.
Amortization Period: 10 yrs.   Maintenance Cost: $ 25 /yr.
Tax Credit Value: $ 79   BPA "Buyback Value: $ 525

Real Discount Rate: 2.7 %
Energy Escalation Rate: 3.0 %   Discounted Salvage Value:$ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-274	193	-195	272	251	718
Benefit/Cost Ratio	0.63	1.26	0.70	1.41	2.16	4.32
Internal Rate of Return (%)	0	8.9	0	12.5	50+	50+

*Adjusted Cost of Conserved Energy: 4.0 ¢/kWh

Real Discount Rate: 4.5 %
Energy Escalation Rate: 3.0 %   Discounted Salvage Value:$ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-298	128	-218	206	227	653
Benefit/Cost Ratio	0.59	1.18	0.66	1.32	2.15	4.30
Internal Rate of Return (%)	0	8.9	0	12.5	50+	50+

*Adjusted Cost of Conserved Energy: 4.2 ¢/kWh

Real Discount Rate: 7.3 %
Energy Escalation Rate: 3.0 %   Discounted Salvage Value:$ 0

	No Tax Credit*		Tax Credit		BPA "Buyback"	
Energy Cost (¢/kWh)	2.5	5.0	2.5	5.0	2.5	5.0
Net Benefits ($)	-328	42	-250	120	197	567
Benefit/Cost Ratio	0.53	1.06	0.60	1.19	2.14	4.27
Internal Rate of Return (%)	0	8.9	0	12.5	50+	50+

*Adjusted Cost of Conserved Energy: 4.7 ¢/kWh

APPENDIX D

MIDWAY HOUSE LEAKAGE AREAS and HEATING SEASON INFILTRATION RATES

Table D1: Individual Midway House Leakage Areas and Infiltration Rates (Phase I)

PHASE I	House ID	Leakage Areas (cm^2) Pre-retrofit	Leakage Areas (cm^2) Post-retrofit	Specific Leakage Areas (cm^2/m^2) Pre-retrofit	Specific Leakage Areas (cm^2/m^2) Post-retrofit	Heating Season Infiltration Rates (ACH) Pre-retrofit	Heating Season Infiltration Rates (ACH) Post-retrofit
CELL 1	2	495	533	4.6	4.9	0.47	0.51
	3	490	481	4.5	4.5	0.46	0.45
	4	499	521	4.0	4.2	0.41	0.43
	7	572	573	4.6	4.6	0.47	0.47
	11	365	345	3.0	2.8	0.30	0.29
CELL 2	1	532	466	4.9	4.3	0.51	0.44
	8	384	394	3.1	3.2	0.32	0.33
	10	367	383	3.0	3.1	0.31	0.32
	14	446	443	3.6	3.6	0.37	0.37
	15	417	362	3.9	3.4	0.40	0.34
	20	321	385	1.6	1.9	0.16	0.19
CELL 3	5	521	418	4.8	3.9	0.49	0.40
	6	566	532	4.6	4.3	0.47	0.44
	9	382	341	3.1	2.8	0.32	0.28
	12	311	248	2.9	2.3	0.30	0.34
	13	367	407	3.0	3.3	0.30	0.34
	17	318	182	3.1	1.8	0.31	0.18
	19*	327	403	3.2	3.9	0.32	0.40

*Solar heating system was installed in house between measurements, increasing leakage area.

Table D2: Individual Midway House Leakage Areas and Infiltration Rates (Phase II)

		Leakage Areas (cm^2)		Specific Leakage Areas (cm^2/m^2)		Heating Season Infiltration Rates (ACH)	
PHASE II	House ID	Pre-retrofit	Post-retrofit	Pre-retrofit	Post-retrofit	Pre-retrofit	Post-retrofit
CELL 1	2	527	398	4.9	3.7	0.50	0.38
	3	460	322	4.3	3.0	0.43	0.30
	4	528	360	4.3	2.9	0.44	0.30
	7	513	442	4.2	3.6	0.42	0.36
	11	433	301	3.5	2.5	0.36	0.25
	19	460	322	4.5	3.1	0.46	0.32
CELL 3	5	379	290	3.5	2.7	0.36	0.28
	6	468	441	3.8	3.6	0.39	0.37
	9	399	315	3.3	2.6	0.33	0.26
	12	259	237	2.4	2.2	0.25	0.23
	13	487	338	4.0	2.8	0.40	0.28
	17	383	290	3.7	2.8	0.37	0.28

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