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The Oklahoma Field Test: Air-Conditioning Electricity Savings from Standard Energy Conservation Measures, Radiant Barriers, and High-Efficiency Window Air Conditioners

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THE OKLAHOMA FIELD TEST: AIR-CONDITIONING ELECTRICITY SAVINGS FROM STANDARD ENERGY CONSERVATION MEASURES, RADIANT BARRIERS, AND HIGH-EFFICIENCY WINDOW AIR CONDITIONERS

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ABSTRACT

A field test involving 104 houses was performed in Tulsa, Oklahoma, to measure the air-conditioning electricity consumption of low-income houses equipped with window air conditioners, the reduction in this electricity consumption attributed to the installation of energy conservation measures (ECMs) as typically installed under the Oklahoma Weatherization Assistance Program (WAP), and the reduction achieved by the replacement of low-efficiency window air conditioners with high-efficiency units and the installation of attic radiant barriers.

Air-conditioning electricity consumption and indoor temperature were monitored weekly during the pre-weatherization period (June to September 1988) and post-weatherization period (May to September 1989). House energy consumption models and regression analyses were used to normalize the air-conditioning electricity savings to average outdoor temperature conditions and the pre-weatherization indoor temperature of each house.

The average measured pre-weatherization air-conditioning electricity consumption was 1664 kWh/year ($119/year). Ten percent of the houses used less than 250 kWh/year, while another 10% used more than 3000 kWh/year. An average reduction in air-conditioning electricity consumption of 535 kWh/year ($38/year and 28% of pre-weatherization consumption) was obtained from replacement of one low-efficiency window air conditioner (EER less than 7.0) per house with a high-efficiency unit (EER greater than 9.0). For approximately the same cost, savings tripled to 1503 kWh/year ($107/year and 41% of pre-weatherization consumption) in those houses with initial air-conditioning electricity consumption greater than 2750 kWh/year. For these houses, replacement of a low-efficiency air conditioner with a high-efficiency unit was cost effective using the incremental cost of installing a new unit now rather than later; the average installation cost for these houses under a weatherization program was estimated to be $786. The general replacement of low-efficiency air conditioners (replacing units in all houses without considering pre-weatherization air-conditioning electricity consumption) was not cost effective in the test houses. ECMs installed under the Oklahoma WAP and installed in combination with an attic radiant barrier did not produce air-conditioning electricity savings that could be measured in the field test.

The following conclusions were drawn from the study: (1) programs directed at reducing air-conditioning electricity consumption should be targeted at clients with high consumption to improve cost effectiveness; (2) replacing low-efficiency air conditioners with high-efficiency units should be considered an option in a weatherization program directed at reducing air-conditioning electricity consumption; (3) ECMs currently being installed under the Oklahoma WAP (chosen based on effectiveness at reducing space-heating energy consumption) should continue to be justified based on their space-heating energy savings potential only; and (4) attic radiant barriers should not be included in the Oklahoma WAP if alternatives with verified savings are available or until further testing demonstrates energy savings or other benefits in this type of housing.

EXECUTIVE SUMMARY

A cooperative field test was performed in Tulsa, Oklahoma, to determine

- the air-conditioning electricity consumption of low-income houses equipped with window air conditioners,
- the reduction in air-conditioning electricity consumption attributed to the installation of energy conservation measures (ECMs) as typically installed under the Oklahoma Weatherization Assistance Program (WAP), and
- the additional reduction achieved by the installation of two ECMs designed to reduce air-conditioning electricity consumption: replacement of low-efficiency window air conditioners with high-efficiency units and the installation of attic radiant barriers.

One hundred and four houses were monitored for the duration of the field test: 26 were assigned to a non-trealment group in which no ECMs were installed (control houses), 27 received ECMs performed under the Oklahoma WAP (weatherization-only houses), 27 received ECMs performed under the Oklahoma WAP plus a truss-mounted attic radiant barrier (radiant-barrier houses), and 24 received ECMs performed under the Oklahoma WAP plus a high-efficiency window air conditioner in replacement of a less efficient unit (air-conditioner replacement houses).

Under the Oklahoma WAP, a standard set of ECMs (selected specifically to reduce space-heating energy consumption) was installed by the normal weatherization crews in the three treatment groups of houses. General heat waste reduction included caulking and weatherstripping and, for the field test, airtightcning performed using a blower door. Attic insulation levels were increased to R-19, attic ventilation vents were added if necessary, and minor roof leaks were repaired. Storm windows with insect screens were installed on windows where no storm window existed or where the existing storm window was beyond repair. Minor repairs to the house were also performed under the program.

Radiant barriers (together with the standard set of ECMS installed under the Oklahoma WAP) were installed by a specially trained weatherization crew in just the radiant-barrier houses.

A radiant-barrier material with a kraft paper center and a thin aluminum coating on each side was used. The barrier was attached to the underside (faces) of the roof rafters or top chords of the roof trusses so that one reflective surface faced the attic floor and the other reflective surface faced the roof deck. The barrier was also installed on the gabled ends of the attic so that one reflective surface faced the attic space.

In the air-conditioner replacement houses, one window air conditioner per house with an energy efficiency ratio (EER) less than or equal to 7.0 was replaced by a high-efficiency unit (EER greater than or equal to 9.0) having about the same rated capacity as the original unit (the standard set of ECMs was also installed under the Oklahoma WAP). In houses with two existing units meeting this criterion, the unit with the greater pre-weatherization electricity consumption was replaced. All units older than four years were assumed to be eligible for replacement because actual EER ratings were not available. A minimum EER of 9.0 was selected for the replacement units to ensure that they met minimum efficiency standards for room air conditioners as stipulated by Congress (National Appliance Energy Conservation Act of 1987). Installations of the replacement units were performed by the organization from which the units were purchased.

The following weekly data were monitored for all houses during the pre-weatherization period (June to September 1988) and post-weatherization period (May to September 1989): house gas consumption (in only about half the houses), house electricity consumption, and air-conditioning electricity consumption (each air conditioner in a house was metered separately). Hourly indoor temperatures were monitored in each house and hourly weather data were monitored at three nearby sites. The indoor temperature was monitored in the room with the window air conditioner; if two air conditioners were in a house, indoor temperature was monitored in the room with the air conditioner operated the most. The following time-independent information was also collected or measured during the field test: house and occupant descriptive information, air leakages in all four groups of houses before and after ECMs were installed, and the ECMs installed in the houses and their costs.

Selection criteria limited the study to houses with occupants eligible for the Oklahoma WAP; that were single-family detached houses, but not mobile homes; that were occupied by the owner; that were cooled by only one or two electric window air conditioners in operating condition; and with occupants currently paying their own electric bills (bills could not be paid through vouchers) and that had regularly paid their bills in the past.

The ages of the houses used in the field test ranged between 4 and 75 years, and their average age was 41 years. Almost all the houses were built on crawlspaces 16 in. high and were single story. The total floor area of the houses averaged 1245 ft^2, with 60% being between 1000 and 1400 ft^2. Because the floor area cooled by window air conditioners was limited primarily to the room where the unit was present, the conditioned floor area was not likely equal to the total floor area. Sixty-four percent of the houses were cooled by one window air conditioner, 31% by two units, and 5% by three units (despite the selection criterion limiting the houses to one or two window air conditioners). The nameplatc cooling capacity of the units ranged from 5000 to 29,000 Btu/h, and averaged about 15,000 Btu/h. The age of the units ranged from 1 to 25 years old, with 70% being between 4 and 12 years old. The floors of 97% of the houses had no insulation, 54% had no wall insulation, and 9% had no attic insulation. The mean R-value of the houses with attic insulation was 7.3 °F-ft^2-h/Btu. Eighty-one percent of the existing window area in the houses was single-pane without a storm window. Seventy-one percent of the houses had only one or two occupants.

General heat waste reduction measures were performed in all the houses, storm windows were added in 90% of the houses, attic insulation was installed in 84% of the houses, and repair work was performed in 58% of the houses. The average costs for the weatherization work performed under the Oklahoma WAP were nearly the same in each group, averaging between $834 and $882 per house. Costs for individual houses ranged from $109 to $1296, with about half being between $900 and $1200.

Installation of the attic radiant barriers in the truss-mounted configuration averaged $394 per house and ranged between $385 and $435. Because the radiant-barrier material was donated, these costs include an estimated cost of $250 per house for material (approximately $0.20/$ft^2$ of radiant-barrier material).

The installation cost for the air conditioners (including labor and miscellaneous materials) ranged from $811 to $1487, and averaged $946. Air-conditioner installation costs are expected to be significantly less than this if performed routinely under a weatherization program. An average expected air-conditioner installation cost of $739 was estimated for a typical house if performed under a weatherization program.

The measured air-conditioning electricity savings were normalized to average annual outdoor temperature conditions and the pre-weatherization indoor temperature for each house. Normalized electricity savings were found by subtracting normalized post-weatherization consumption from normalized pre-weatherization consumption. The relation between weekly air-conditioning electricity consumption and a weekly "driving force" temperature (either average weekly outdoor temperature or outdoor-indoor temperature difference) includes transition and linear regions. Normalized annual air-conditioning electricity consumptions were estimated by analyzing data appropriate to each region. Data falling within the transition region were used to estimate a transition consumption constant for each house. Data falling within the linear region were analyzed using the following models and regression analyses:

$$E_{AC1} = A_1 + (B_1 * DT) \text{ and } E_{AC2} = A_2 + (B_2 * To)$$

where

E_{AC} — weekly electricity consumption of the air conditioner,
DT = average weekly outdoor-indoor temperature difference,
To = average weekly outdoor temperature,
A = intercept coefficient (determined by regression), and
B = slope coefficient (determined by regression).

Two models were needed because, in houses with two air conditioners, the monitored indoor temperature corresponded to only one of the units.

Pre-weatherization air-conditioning electricity consumptions averaged 1664 kWh/year ($119/year), ranging between 8 and 5708 kWh/year. One-third of the houses used less than 1000 kWh/year (about 10% used less than 250 kWh/year) and about 10% used 3000 kWh/year or more. Differences in the number and size of the air conditioners present, the portion of the house cooled by the units, the degree the air conditioners were used, indoor temperature maintained, and house differences (e.g., insulation levels and shading) all contributed to the large variation in consumption. These air-conditioning electricity consumptions were much lower than consumptions measured in larger, non low-income houses located in more southern climates and cooled by central air conditioners (which generally cool the entire living area rather than just one or two rooms as with window units).

Normalized air-conditioning electricity savings are shown in Table ES.1. At a 95% confidence level, the average savings of the air-conditioner replacement group was significantly different from zero. At this same confidence level, the average savings of the control group, weatherization-only group, and radiant-barrier group were not significantly different from zero. Again at the same confidence level, the average savings of the air-conditioner replacement group was determined to be significantly different from the other three groups and the average savings of the remaining three groups were not significantly different from each other. The average savings of 535 kWh/year measured in the air-conditioner replacement group was attributed to just the installation of high-efficiency air conditioners because no savings was measured in the weatherization-only group. The measured savings was close to an expected value of about 33%. A savings of 33% was expected assuming the new air conditioners (EER = 9.0) replaced units with EERs of about 6.

Each group included houses with positive and negative savings. There were eight houses with savings greater than 500 kWh/year in the air-conditioner replacement group, whereas only two or three such houses were in each of the other three groups. The air-conditioner replacement group had the fewest houses with negative savings and with large negative savings (greater than 500 kWh/year).

Air-conditioning electricity savings of the houses in the air-conditioner replacement group were dependent on the pre-weatherization air-conditioning electricity consumptions. For four air-conditioner replacement houses with pre-weatherization consumptions greater than 2750 kWh/year, the average savings of the replacements was 1503 kWh/year (41% of their average pre-weatherization consumption), which was nearly three times that observed for the group as a whole.

Table ES.1. Normalized air-conditioning electricity savings

Group	Average annual savings* (kWh)	Percent savings relative to the group's average pre-weatherization consumption (kWh)
Control	107	7%
Weatherization-only	-31	-2%
Radiant-barrier	-52	-4%
Air-conditioner replacement	535	28%

*Negative values indicate increased electricity consumption.

ECMs installed under the Oklahoma WAP and combined with a truss-mounted attic radiant barrier did not produce air-conditioning electricity savings that could be measured in the field test. This was indicated by the average savings of the weatherization-only group and radiant-barrier group being statistically the same as the control group and each other, and not statistically different from zero. Reasons for the lack of savings were not known. The groups of houses were generally equivalent. Post-inspections revealed that the radiant-barrier installations were of high quality. Emissivity measurements of radiant-barrier samples taken from four houses showed that the reflective surfaces had not degraded due to dust accumulation or other reasons. Possible explanations include:

- The savings produced by the ECMs installed under the Oklahoma WAP and by radiant barriers were smaller than the field test could measure. The expected savings of the ECMs were small for the test houses considering that the primary WAP ECMs only addressed two components of the total cooling load (attic insulation reduced heat flow through the ceiling and storm windows reduced conduction through the windows), a radiant barrier addressed one of the same components addressed by the WAP ECMs (reduced heat flow through the ceiling), and the pre-weatherization air-conditioning electricity consumptions were small.

- ECMs that kept heat out of the house also tended to keep heat in the house. This was an important consideration for window air conditioners that are controlled manually as well as by a thermostat. Low measured air-conditioning electricity consumptions and high indoor temperatures suggested that the occupants of these houses often ventilated their houses as much as possible and/or turned units off during unoccupied periods. If the installed ECMs trapped more heat in the house during unoccupied periods than before and/or reduced the effectiveness of ventilation, greater use of the air conditioners could have resulted to negate any potential savings.

The economics of replacing a low-efficiency air conditioner with a high-efficiency unit in the test houses was examined for a federally-sponsored weatherization program using a total resource test. The total resource test generally reflects the costs and benefits that would be experienced by all of society. In this test, costs and benefits are considered regardless of who pays for or receives them. Benefit-to-cost ratios were calculated for each house using the following assumptions:

- Benefits were limited to electricity savings.
- The cost for residential electricity was $0.07147/kWh.
- Service lifetimes of 10 and 15 years were estimated for new window air conditioners.
- When using a service lifetime of 10 years, the remaining lifetimes of the existing units were assumed to be 1, 5, or 10 years. Similarly, when using a service lifetime of 15 years, the remaining lifetimes were assumed to be 1, 5, 10, or 15 years.
- The occupants would install a replacement unit when the remaining lifetime of the existing unit was zero. The replacement units would have the same efficiency as the units installed under the field test.
- Costs were the incremental material and labor cost of replacing the air conditioners now rather than upon failure, because the total resource test does not consider who pays the costs.
- Discount factors adjusted for average fuel price escalation and based on a 4.6% discount rate were used in the calculations.

An interesting result of the analysis was that the benefit-to-cost ratio of the replacement was independent of the remaining lifetime of the existing unit. The benefit-to-cost ratio was very sensitive to the electricity cost and discount rate used in the calculations, and to the assumption that a replacement unit installed in several years by the occupant would have the same efficiency as the unit installed now under the weatherization program.

The general replacement of low-efficiency air conditioners with high-efficiency units (replacing units in all houses without considering pre-weatherization air-conditioning electricity consumption) was not cost effective in the test houses under the stated set of assumptions. The benefit-to-cost ratios were 0.41 and 0.55 depending on the service lifetime of the replacement air conditioner. The cost effectiveness of this approach was not more attractive primarily because the low pre-weatherization air-conditioning electricity consumptions generally observed in these houses offered low potential for savings; air conditioners costing $500 to $700 were installed in many houses that, for whatever reason, used less than $175/year to air condition.

Targeting houses based on high consumption made the replacements cost effective. Replacements were generally cost effective in houses with pre-weatherization consumption greater than about 3600 kWh/year if a 10-year service life was assumed and 2700 kWh/year if a 15-year service lifetime was assumed. For the subgroup of test houses with pre-weatherization consumption greater than 2750 kWh/year, replacement of the low-efficiency air conditioners was cost effective. The simple payback period for the replacements performed in this subgroup of houses was 7.3 years.

Cost effectiveness can be increased by requiring the occupants to help pay for the high-efficiency replacement units at the time of their installation. Such a program can be designed to be equitable, basing the occupant cost on the probability of a unit failure depending on its current age.

Four main conclusions were drawn from the field test results:

- Programs directed at reducing air-conditioning electricity consumption should be targeted at clients with high air-conditioning electricity consumption and/or streamlined to minimize costs in order to improve cost effectiveness. Current air-conditioning electricity consumptions provide a ceiling for the savings attainable by the program.

- Replacing low-efficiency air conditioners with high-efficiency units should be considered an option in a weatherization program directed at reducing air-conditioning electricity consumption, especially for houses with high air-conditioning electricity consumption. The cost-effectiveness of this measure should be verified in each house before installation. Savings from this ECM can be estimated fairly reliably for a group of houses knowing the rated efficiency of the existing and replacement units, and knowing the current air-conditioning electricity consumption.

- ECMs currently being installed under the Oklahoma WAP (chosen based on effectiveness at reducing space-heating energy consumption) should continue to be justified based on their space-heating energy savings potential only.

- Attic radiant barriers should not be included in the Oklahoma WAP if alternatives with verified savings are available or until further testing demonstrates energy savings or other benefits in this type of housing. Comfort improvements, especially in the portions of the houses that were not air conditioned, could not be addressed from this study and need to be further researched.

Issues remain, especially in low-income houses, concerning the potential for air-conditioning electricity savings. Additional research is needed to quantify the air-conditioning electricity consumption of low-income families using window air conditioners and the air-conditioning electricity savings achieved from weatherization programs in other southern states. Continued studies need to be performed to determine the air-conditioning electricity savings that occur from standard ECMs and those specifically designed to reduce air-conditioning electricity consumption. Because of the varied assumptions that must be made in performing an economic analysis, the cost effectiveness of replacement air conditioners should be analyzed further. A sensitivity analysis should be performed, the different perspectives of occupants and utilities should be examined in more depth, and the appropriate perspective of a federal weatherization program should be developed. Program options, such as having occupants help defray the cost of the new unit based on the estimated remaining lifetime of the existing unit, should be examined; these options could make air-conditioner replacements attractive in a broader range of houses.

A question raised but not answered from this study was whether air conditioning should be considered a necessity or luxury item in low-income weatherization programs. Unlike space-heating systems, the need for space-cooling systems to increase personal safety and reduce suffering is not generally accepted. Indoor temperature data from this and other studies need to be examined to quantify the discomfort and health risks associated with elevated indoor temperatures experienced in southern houses with inadequate or no space cooling, understand the operating strategies of the window units before and after weatherization, and develop program guidelines for addressing this issue.

THE OKLAHOMA FIELD TEST: AIR-CONDITIONING ELECTRICITY SAVINGS FROM STANDARD ENERGY CONSERVATION MEASURES, RADIANT BARRIERS, AND HIGH-EFFICIENCY WINDOW AIR CONDITIONERS

1. INTRODUCTION

1.1 BACKGROUND

An appreciable amount of the annual energy costs for families in southern climates can occur during the cooling season. However, research directed at improving the efficiency of buildings in such climates has not yet received the same level of attention and funding as in cold climates. The ability of commonly installed energy conservation measures (ECMs), such as attic insulation and storm windows, to reduce air-conditioning electricity consumption is not well documented by field tests. Further, the performance of thermal envelope and mechanical system measures specifically designed to reduce air-conditioning costs have not been thoroughly tested.

Weatherization programs performed by states and utilities in southern climates may be able to be improved by developing information about the performance of ECMs in reducing air-conditioning electricity consumption. Envelope ECMs widely used in heating climates (such as attic insulation, storm windows, and general heat waste reduction) are also typically performed under most Low-Income Weatherization Assistance Programs (WAPs) in the southern states. Although these ECMs may reduce air-conditioning costs, their inclusion in the WAPs is based primarily on their ability to reduce space-heating costs. The energy savings and cost effectiveness of these WAPs could be improved once the effect of these measures on air-conditioning electricity consumption is better understood. The WAPs might also be improved by including ECMs specifically designed to reduce air-conditioning costs. Utility programs may also suffer due to a lack of performance information because reliable recommendations cannot yet be made to homeowners on which measures are most effective.

Radiant barriers installed in attics of houses offer the potential of reducing residential cooling costs by reducing radiation heat transfer across the attic space. The recent status of research on attic radiant barriers is summarized by Wilkes and Yarbrough (1988):

"Experiments by a number of groups have clearly demonstrated that radiant barriers are effective in reducing heat flows through ceilings of buildings, especially under conditions where the building is cooled. While the results of the experiments are in qualitative agreement in indicating heat flow reductions, the quantitative thermal performance is still a subject of controversy."

A key research need identified by Wilkes and Yarbrough (1988) is

"to determine the seasonal and annual performance of radiant-barrier systems. Most of the existing field data have been obtained over time periods of a few days or weeks. Thus, the results of the field tests may not be directly interpretable into seasonal/annual performance."

Replacing a low-efficiency air conditioner with a more efficient unit offers the potential for reducing residential cooling costs by requiring less electricity consumption to provide the same amount of cooling. The efficiencies of air conditioners built today are two to three times that of units built before 1977, with some having a seasonal energy efficiency ratio[1] greater than 15. Congress passed the National Appliance Energy Conservation Act of 1987 to increase efficiency levels of residential appliances, including air conditioning equipment.

Previous studies have often focused on centrally cooled houses rather than houses cooled by window air conditioners. Results from modeling studies performed by McLain et al. (1985) and McLain, MacDonald, and Goldenberg (1985) confirm that significant electricity savings can be obtained economically by installing high-efficiency air conditioners in southern climates. In a recently completed field test performed in Austin, Texas using centrally-cooled houses, Hough and Burns (1990) found that 40% savings are achieved from replacing low-efficiency central air conditioners with high-efficiency units. From an analysis of data collected in 1982 on homes in Southern Florida and equipped with central air conditioners, Parker (1990) concluded the following:

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[1]Seasonal energy efficiency ratio (SEER) is used to express the efficiency of central cooling systems. The SEER is an estimate of the ratio of the total seasonal cooling requirements (Btu) and the total seasonal energy consumption (kWh). The higher the SEER, the more efficient the air conditioner. The efficiency value is developed in the laboratory by conducting up to four separate tests at various indoor and outdoor conditions, including a measure of performance under cyclic conditions (ASHRAE 1988).

"Savings from retrofits designed to save space-cooling energy use were substantial, averaging 35% on an annual basis. Of the implemented retrofit measures, replacement of old air conditioners with high seasonal energy efficiency ratio models, duct replacement and repair, and additions to ceiling insulation showed the greatest level of savings."

1.2 OBJECTIVES

A cooperative field test was performed in Tulsa, Oklahoma, to determine

- the air-conditioning electricity consumption of low-income houses equipped with window air conditioners,
- the reduction in air-conditioning electricity consumption attributed to the installation of ECMs as typically installed under the Oklahoma WAP, and
- the additional reduction achieved by the installation of two ECMs designed to reduce air-conditioning electricity consumption: replacement of low-efficiency window air conditioners with high-efficiency units and the installation of attic radiant barriers.

The field test was a cooperative effort performed by the Oak Ridge National Laboratory (ORNL), the Oklahoma Department of Commerce, Wa-Ro-Ma Tri-County Community Action Foundation, Public Service Company of Oklahoma, and the Alliance to Save Energy. Financial support was provided by the Oklahoma Department of Commerce; the U.S. Department of Energy, Office of Buildings Research (Existing Buildings Efficiency Research Program) and Office of Technical and Financial Assistance (WAP Division); and Public Service Company of Oklahoma.

The roles of the participating organizations are more thoroughly described in an experimental plan developed for the project (Ternes and Hu 1989). The Alliance to Save Energy and the Oklahoma Department of Commerce provided managerial support to the project. The Alliance to Save Energy developed the concept plan, disseminated information on the project, and helped resolve issues. The Oklahoma Department of Commerce was instrumental in formulating the field test and managed the field test at the state level. Wa-Ro-Ma Tri-County Community Action Foundation implemented the on-site portion of the field test by selecting houses, installing instrumentation, collecting data, and weatherizing the houses. Public Service

Company of Oklahoma helped install weather instrumentation, developed submetering installation details while working with code officials from Tulsa, collected weather data, and helped resolve issues. ORNL developed the experimental plan, supplied and helped install instrumentation, maintained a data base of all collected data, analyzed the data, and prepared technical reports.

The purpose of this report is to present information gathered during the field test and results obtained from analyses of this information. The experimental plan (Ternes and Hu 1989) identifies the detailed method of the project.[2]

[2]This plan was an invaluable tool that facilitated the organization of the project. A planning document of this type is recommended for all monitoring projects to document the field test design, define tasks and participant roles, identify research questions and analytical approaches, and resolve other planning issues.

2. FIELD TEST DESIGN

2.1 APPROACH

The field test was performed in Tulsa, Oklahoma. The summer climate in Tulsa is hot but not extreme, with annual cooling degree days of 1949 (base 65°F) and 1143 (base 70°F)[3] (Los Alamos Scientific laboratory 1980) and annual cooling degree hours of 26,468 (base 74°F)[4] (ASHRAE 1990).

Of 115 houses meeting the selection criteria identified in Sect. 2.2, 104 were monitored for the duration of the field test: 26 were assigned to a non-treatment group in which no ECMs were installed (control houses), 27 received ECMs performed under the Oklahoma WAP (weatherization-only houses), 27 received ECMs performed under the Oklahoma WAP plus a truss-mounted attic radiant barrier (radiant-barrier houses), and 24 received ECMs performed under the Oklahoma WAP plus a high-efficiency window air conditioner in replacement of a less efficient unit (air-conditioner replacement houses). A stratified random assignment procedure described in Sect 2.2 was used to help achieve pre-weatherization equality among the four groups. This one-way classification design allowed the effect of the treatments to be studied. The inclusion of a control group allowed factors other than the treatments that can affect air-conditioning electricity savings to be accounted for.

The field test was conducted over a two-year period. A pre- and post-weatherization test design was employed: electricity consumption data were collected on the individual houses before and after weatherization and used to determine the change in air-conditioning electricity consumption. Pre- and post-weatherization testing was employed in order to determine the electricity consumption changes of individual houses (each house served as its own reference) and because other designs (such as an on-off design) were not feasible. Pre-weatherization data

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[3]For comparison, the annual cooling degree days (base 65°F and 70°F) are 3508 and 2797 for Phoenix, Arizona; 1589 and 778 for Atlanta, Georgia; and 4038 and 2613 for Miami, Florida.

[4]For comparison, the annual cooling degree hours (base 74°F) are 16,803 for Atlanta, Georgia, and 54,404 for Phoenix, Arizona.

were collected for all houses during one cooling season (June to September 1988). ECMs were installed in the three treatment groups of houses during the following winter. Post-weatherization data were collected during the following cooling season (May to September 1989).

Data and information collected during the field test basically adhered to the minimum data set specified in a residential monitoring protocol (with the exception of metered water-heating energy consumption) developed for research projects sponsored by the U.S. Department of Energy, Office of Buildings Research (Existing Buildings Efficiency Research Program) (Ternes 1987). The following weekly data were monitored for all houses during the two summer test periods:

- house gas consumption (meters could only be read in about half the houses),
- house electricity consumption, and
- air-conditioning electricity consumption (each air conditioner in a house was metered separately).

Hourly indoor temperatures were monitored in each house and hourly weather data (temperature, humidity, horizontal insolation, and wind speed) were monitored at three nearby sites. The indoor temperature was monitored in the room with the window air conditioner; if two air conditioners were in a house, indoor temperature was monitored in the room with the air conditioner operated the most (as reported by the occupants). The following time-independent information was also collected or measured during the field test:

- house and occupant descriptive information identified in Table 2.1 between November 1988 and February 1989,

- air leakages in all four groups of houses between November 1988 and July 1989 (before any ECMs were installed in the treatment and control houses) and again in October and November 1989 (after all ECMs were installed in the treatment and control houses), and

- the ECMs installed in the houses and their costs.

A more detailed description of the data parameters, instrumentation, and data management are provided in Appendix A.

2.2 HOUSE SELECTION AND ASSIGNMENT

The population of houses studied was limited to those having the following characteristics:

- occupants were eligible for the Oklahoma WAP;
- houses were located in Tulsa, Rogers, or Wagner Counties, Oklahoma;
- houses were single-family detached houses, but not mobile homes;
- houses were occupied by the owner;
- houses were cooled by only one or two electric window air conditioners in operating condition;
- houses were not scheduled to receive weatherization under any other program;
- occupants were not planning an extended stay away from the house during the summer monitoring periods (a 1-2 week vacation was acceptable);
- electric service was on and provided by Public Service Company of Oklahoma; and
- occupants were currently paying their own electric bills (bills could not be paid through vouchers) and that had regularly paid their bills in the past.

These criteria defined the population of houses needed to meet the basic objectives of the field test and narrowed the population to make the experiment easier to perform, improve the accuracy of the results, and help ensure that the four groups of houses were not significantly different. The importance of these criteria was described in detail in the experimental plan (Ternes and Hu 1989).

Because all the houses in the population of interest could not be studied, a sample of houses representing the population was chosen. Based primarily on cost considerations, the size of the initial sample was limited to 115 houses. Selection of the 115 houses was performed by identifying individual houses conforming to the selection criteria, determining if the occupants were willing to participate in the field test, and accepting them if they consented until the 115 house quota was reached. This quota sampling approach was chosen because a more formal statistical sampling technique such as random sampling required time and funds that were not available.

The houses were assigned to one of the four groups following the pre-weatherization period using a stratified random assignment procedure to help achieve pre-weatherization equality among the four groups. The strata were developed using two key variables that could significantly affect air-conditioning electricity consumption and savings. The number of window air conditioners existing in the house was an important criterion because (1) air-conditioning electricity consumption could have been affected, (2) occupants may have operate the systems differently if one or two units were present, and (3) only one air conditioner was replaced in the air-conditioner replacement group of houses. Pre-weatherization house electricity consumption during the summer was an important criterion because savings potential was dependent on initial consumption.

The house electricity consumption during the summer was estimated using the field test data. The house consumptions were compared to identify the high and low electricity users (houses in the upper and lower 50th percentiles, respectively). The houses were classified into one of the following four strata: high electricity user with one window air conditioner, high electricity user with two window air conditioners, low electricity user with one window air conditioner, and low electricity user with two window air conditioners. One-fourth of the houses from each stratum were then randomly assigned to each of the four test groups. The assignments were made after the pre-weatherization data were collected in order to minimize the effect attrition would have on creating unequal groups.

Of the 115 houses monitored at the start of the field test, 11 were dropped from the test for a variety of reasons: six were sold to new occupants, four installed a central air conditioner or an evaporative cooler, and one house burned down.

Table 2.1. House and occupant descriptive information

General
- Experimental program
- House identifier
- Interviewer
- Date of interview
- Occupant's name and phone number
- House location
- Utility distributors

House
- Type
- Number of floors
- Age
- Foundation and roof type
- Roof and exterior wall colors
- Number and description of rooms typically closed off
- Total and cooled floor areas

Occupancy
- Ownership
- Length of time at residence
- Permanent number by age group
- Average number at home during the day

Main cooling system
- Type
- Fuel
- Nameplate information (manufacturer, model, and output capacity)
- Location
- Age

Water-heating system
- Fuel
- Storage type
- Heater type
- Hot water temperature
- Nameplate information (manufacturer, model, tank size, input capacity, and recovery)
- Blanket thickness
- Location

Appliances
- Type
- Fuel
- Location

Table 2.1 (continued)

Insulation
Location and area
Construction
Type and thickness
Siding type (for walls)
Carpeted area (for subfloor)
Windows, glass doors, and non-glass exterior doors
Window type
Area measurements per external wall facing
Number of windows panes
Non-glass door type

3. OCCUPANT AND HOUSE CHARACTERISTICS

Occupant and house descriptive information was collected between November 1988 and February 1989 (between the two summer monitoring periods) for the 104 houses remaining in the field test. This information was obtained for each house through interviews with the homeowners, visual observations, and limited measurements.

3.1 OCCUPANT CHARACTERISTICS

The number of occupants in each house varied between 1 and 9 (see Fig. 3.1). Ninety-six percent of the houses had five or fewer occupants, and 71% had only one or two occupants. The average number of occupants per house was slightly more than two. The most common number of occupants per house was one.

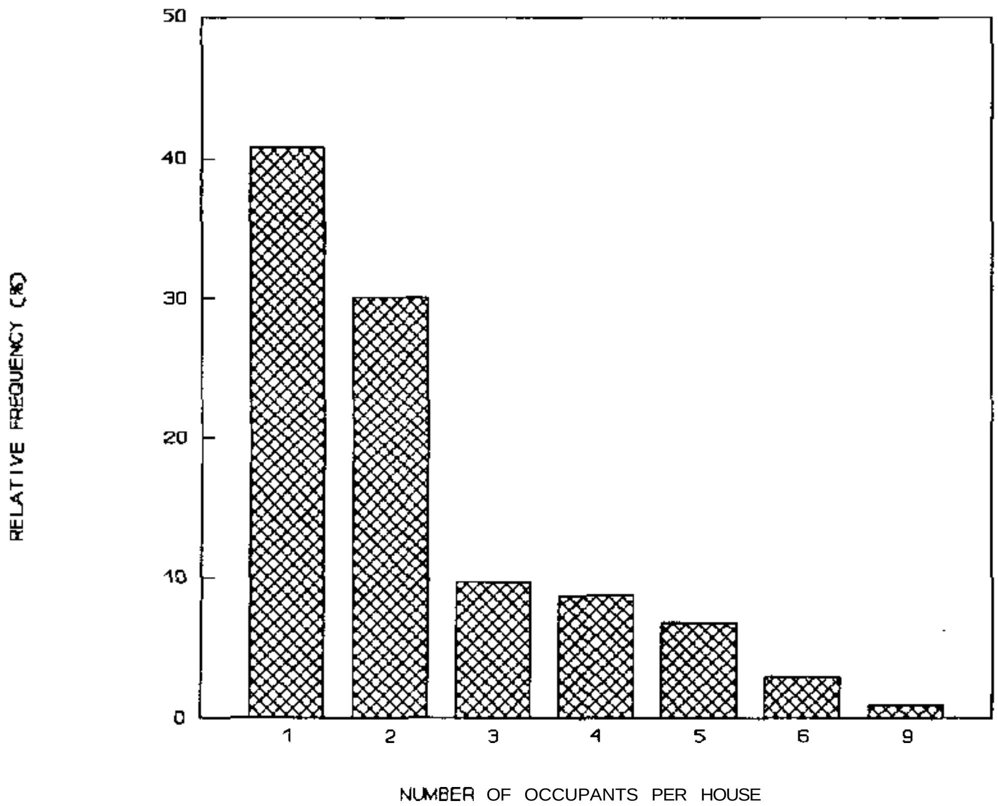

Fig. 3.1. Histogram of number of occupants per house for the test houses.

Figure 3.2 illustrates the number of people in each age group within each household size. The majority of the people in the households with only one or two occupants were retired adults; none were preschool-aged children. Among the 41% of the houses reporting one occupant, most were retired (88%) and the remaining were non-retired adults. As the household size increased beyond two, the presence of retired adults diminished (the houses were headed by non-retired adults) and the percentage of school-aged and preschool-aged children within the household increased.

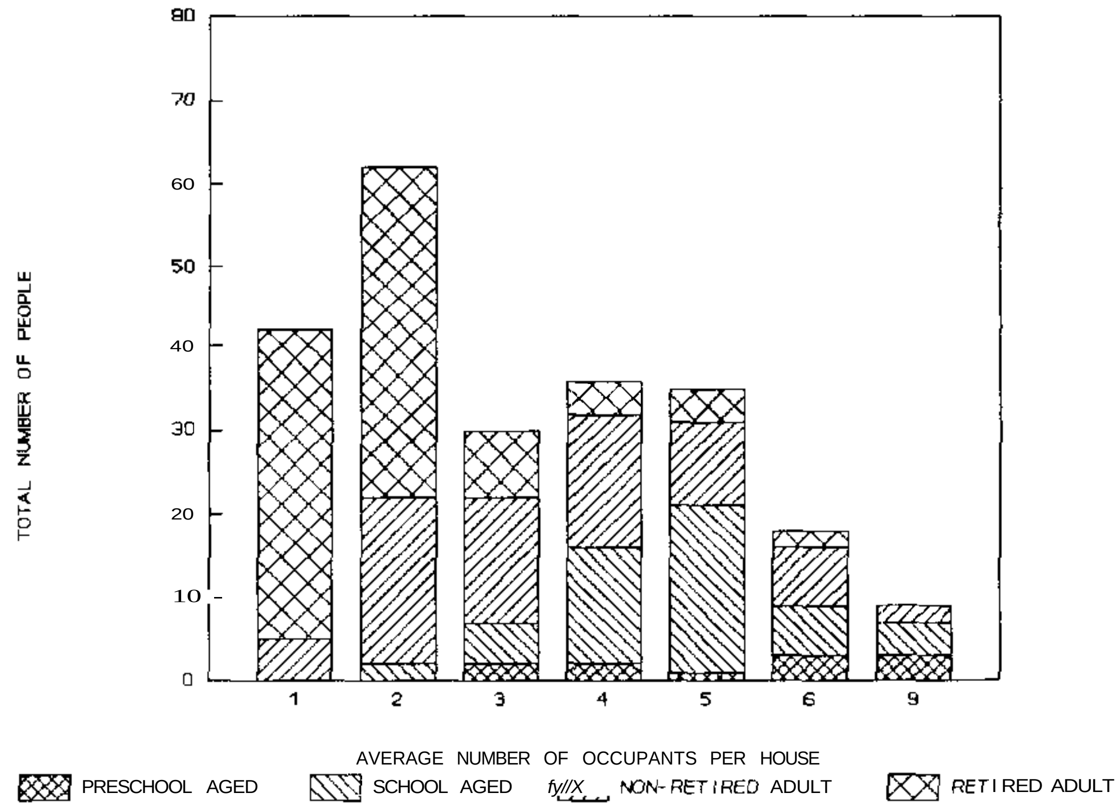

Fig. 3.2. For each occupancy level, total number of people by age group. For example, there were a total of 2 preschoolers, 14 school age, 16 non-retired adults, and 4 retired adults living in houses with four occupants.

The number of years each family had resided at their present address varied between 1 and 69 years, the mean being 21 years. Seventy-seven percent of the occupants had lived in the house between 10 and 40 years, and 17% less than 10 years.

3.2 HOUSE CHARACTERISTICS

The average house participating in the field test was approximately 41 years of age, single story, and built above a crawl space. The total floor area of the house averaged 1245 ft^2. The house was cooled by one window air conditioner. The house had less than R11 insulation in the attic and did not have wall or floor insulation.

Most houses in the field test were built during the 1930's through the 1950's. Their ages ranged between 4 and 75 years, and their average age was 41 years. Seventy-eight percent of the houses were evenly distributed between 26 and 55 years old (see Fig. 3.3). Only 12% of the houses were built in the last 25 years, and only 10% were built more than 55 years ago.

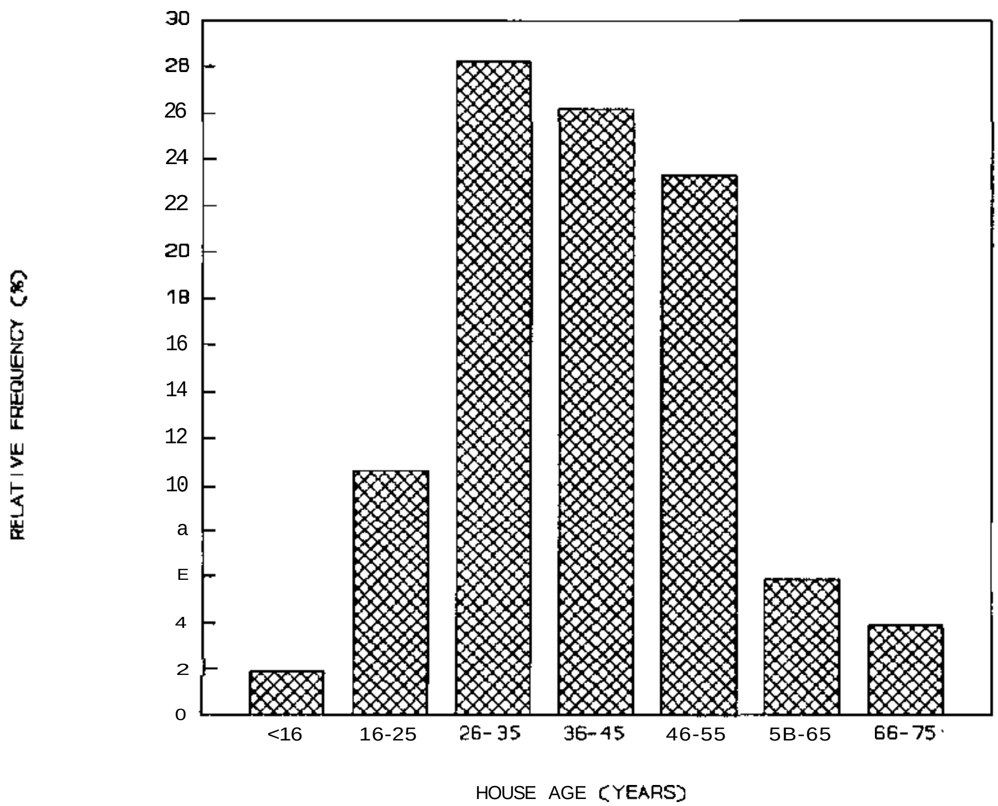

Fig. 33. Histogram of house agc for the test houses.

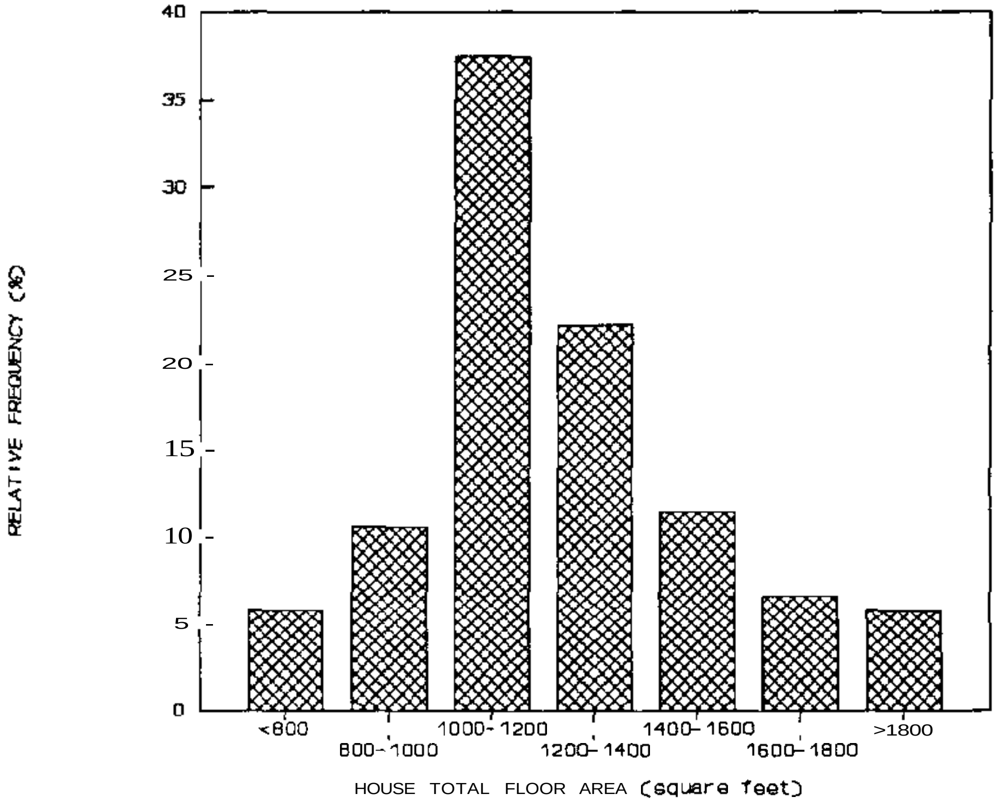

Fig. 3.4. Histogram of total floor area for the test houses.

A majority of the houses (97%) were built on crawlspaces (the foundations of two houses were combined crawlspace/basement systems, with the crawlspaces being the predominate structure). These crawlspaces were typically 16 in. high (the height of two concrete blocks). Most of the houses (95%) were single story (two houses with basements were considered multi-story).

The total floor area of the houses averaged 1245 ft^2 (this value included the basement floor areas of two houses). Although the total floor areas varied among the individual houses by as much as 1944 ft^2 (594 to 2538 ft^2), approximately 60% of the houses were between 1000 and 1400 ft^2. This distribution is shown in Fig. 3.4. Because the floor area cooled by window air conditioners was limited primarily to the room where the unit was present (and perhaps an adjacent room), conditioned floor area was not likely equal to total floor area. Conditioned floor area was not quantified, though.

The floor areas of the attics averaged 1202 ft^2, varying between 594 and 2313 ft^2. These values were close to the total floor areas of the houses because most houses were single-story structures. Most of the attics had a typical attic floor construction as opposed to kneewalls or sloped ceilings. Only 9% of the houses had no attic insulation; the remaining had their entire attic floor area insulated to some degree, mostly by blown cellulose. A distribution of the average R-value of the attic insulation in the houses at the start of the field test is shown in Fig. 3.5. Although a large percentage of homes had attic insulation at the start of the study, the R-value was greater than 10 °F-ft^2-h/Btu in only about 13% of the houses. Average R-values of 0, 3, 6, and 9 °F-ft^2-h/Btu (representing 0, 1, 2, and 3 in. of insulation present uniformly across the attic) were the most common individual insulation levels. The mean value for the 91% of the houses with some attic insulation was 7.3 °F-ft^2-h/Btu with extremes of 3 and 24 °F-ft^2-h/Btu.

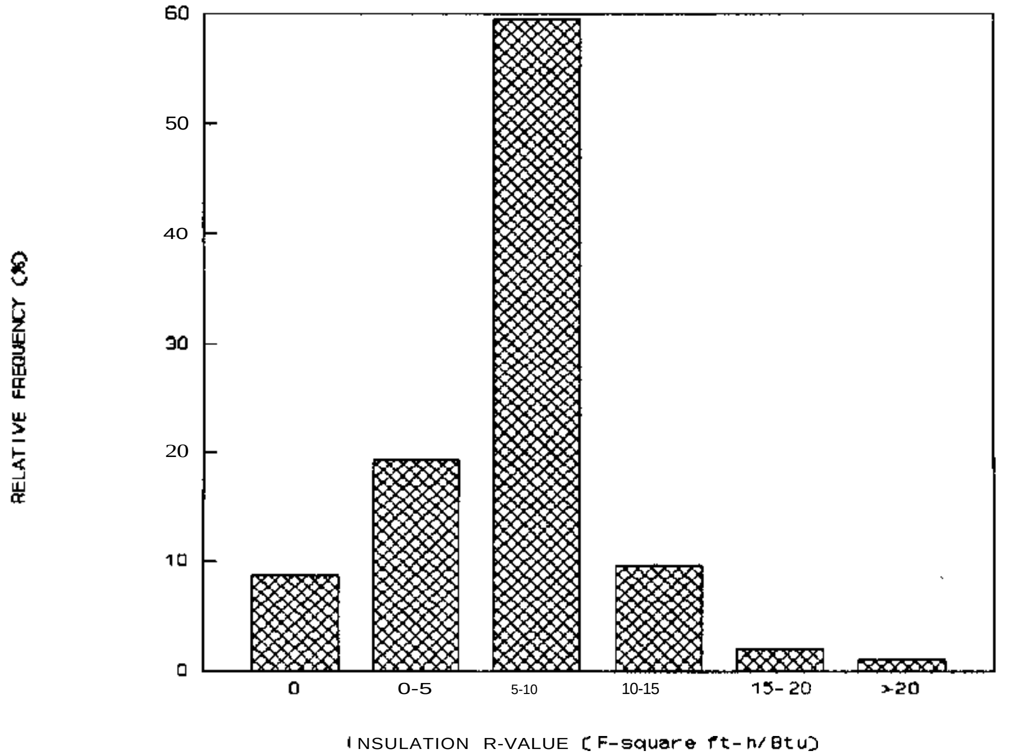

Fig. 3.5. Histogram of amount of attic insulation (average R-value of the insulation only) present in the test houses at the start of the experiment.

The houses were predominately made of frame construction and were sided with either wood, aluminum, shingle, or brick. Total exterior wall area averaged 1171 ft^2, ranging from 672 to 2220 ft^2. The wall cavity was not insulated in 54% of the houses. A distribution of the average R-valuc of the wall cavity insulation in the houses at the start of the field test is shown in Fig. 3.6. (Measuring wall insulation levels in the field was difficult because of limited access; thus, reported values were best estimatcs.) The most predominate insulation level (other than no insulation) was an R-value of 7.5 °F-ft^2-h/Btu, or about 2.5 in. of insulation (it was common practice in previous years to only insulate wall cavities with batts less than 3 in. thick). The mean value of the wall cavity insulation (predominately rock wool or fiberglass batts) in the 46% of the houses with some wall cavity insulation was 7.4 °F-ft^2-h/Btu.

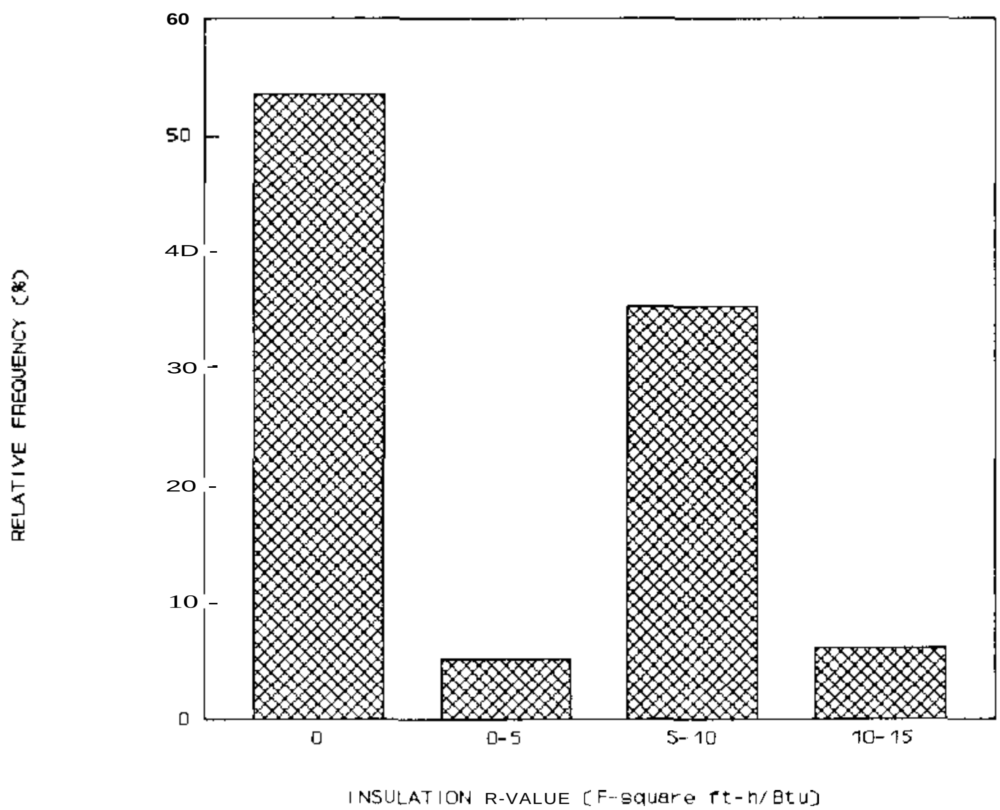

Fig. 3.6. Histogram of amount of wall cavity insulation (average R-value of the wall cavity insulation only) present in thc tcst houses at thc start of the cxpcriment.

The foundation or floor of 97% of the houses was not insulated. The floors of three houses with crawlspaces were insulated with 2.5 to 3.5 in. of insulation. Crawlspaces that are only 16 in. high are difficult to insulate; this may be one reason why insulated floors were not common in the test houses.

Total window area for each house averaged 145 ft^2, varying between 48 and 443 ft^2. The window area of approximately 40% of the houses was between 100 and 159 ft^2. The predominate type of window present in the houses was single-pane without a storm window. Eighty-one percent of the total window area was single-pane without a storm window, 19% was single-pane with a storm window, and less than 1% was multipane without a storm window.

Consistent with the criterion presented in Sect. 2.2 that houses were to be cooled by only one or two electric window air conditioners, most of the houses were cooled by one (64%) or two (31%) window air conditioners. Despite this criterion, three window air conditioners were present in 5% of the houses. The nameplate cooling capacity of the units (or an estimated value based on physical appearance) ranged from 5000 to 29,000 Btu/h, and averaged about 15,000 Btu/h. A unit size of 18,000 Btu/h was most prevalent (40%). The age of the units as reported by the occupants ranged from 1 to 25 years old. Approximately 70% were between 4 and 12 years old.

A summary of the appliances located in the houses is provided in Table 3.1. All of the houses had water-heating systems fueled by natural gas, a cooking range, and conventional oven. Most of the houses had a conventional refrigerator/freezer, clothes washer, and clothes dryer. About half the houses had a microwave oven. Less than a third had a separate freezer or dishwasher.

Table 3.1. Appliance use and fuel type

Appliance	Percentage of houses	Percent gas	Percent electric
Water heater	100%	100%	0%
Cooking range	100%	93%	7%
Conventional oven	100%	93%	7%
Refrigerator/freezer	97%	0%	100%
Clothes washer	74%	0%	100%
Clothes dryer	68%	33%	67%
Microwave oven	50%	0%	100%
Separate freezer	32%	0%	100%
Dishwasher	11%	0%	100%

4. ENERGY CONSERVATION MEASURES

4,1. DESCRIPTION OF MEASURES

4.1.1 The Oklahoma Weatherization Assistance Program

With the exception of the control houses, all test houses received a standard set of ECMs (selected specifically to reduce space-heating energy consumption) as typically installed under the Oklahoma WAP. These measures were installed by the normal weatherization crews. This standard set of ECMs was composed of four components:

- General heat waste reduction or airtightening is an important part of the Oklahoma WAP. Typically, work is limited to caulking and weatherstripping. However, for the field test, airtightening was also performed using a blower door to locate major house leaks. A minimum ventilation guideline of 10 ACH50[5] (approximately 1850 cfm50 for a 1400 ft^2 house, 1600 cfm50 for a 1200 ft^2 house, and 1350 cfm50 for a 1000 ft^2 house) was used to avoid overtightening of houses which might cause moisture, health, and indoor air quality problems. Work was terminated when the minimum ventilation guideline was achieved, major leakage sites were sealed, or funds budgeted for general heat waste reduction were spent.[6] A specially trained, two-person weatherization crew performed this work.

- Attic insulation levels were increased to a thermal resistance of R-19 using blown cellulose insulation, attic ventilation vents were added if necessary, and minor roof leaks were repaired. The amount of ventilation area added, if any, was found by subtracting existing net free ventilation area from recommended values. The existing ventilation area was estimated by measuring the size of existing vents and accounting for area reductions due to screens and louvers. The recommended net free value ($in.^2$) was found by dividing the total attic area (ft^2) by 300. Vents were added as needed so that half of the total ventilation area was high (near the ridge) and half low. Most houses used in the study already had high gable vents. Thus, soffit vents (8 in. x 16 in., 4 in. x 16 in., or round hole vents) were usually installed. Mushroom vents installed either high or low on the roof were also employed.

[5]Current procedures commonly use a minimum ventilation guideline expressed in terms of cfm50 rather than ACH50. A value of 1500 cfm50 is typical. Explanation of the terms ACH50 and cfm50 are provided in Sect. 5.1.

[6]A cost-effective guideline was not used in this study to establish when to stop work.

- Storm window repair or installation was the final ECM performed. Existing storm windows were repaired, if possible. Storm windows with insect screens were installed on windows where no storm window existed or where the existing storm window was beyond repair.

- Other minor repairs to the house were also performed under the program. These repairs included patching floors, inside sheathing, outside walls, and foundation cracks.

A guideline of $1200 for materials and installation labor was used in order that the total house expenditure limit of $1600 set for the program (including costs for auditing, inspection, etc.) was not exceeded. Material and installation costs for attic insulation and storm windows were estimated at the time the house was audited, allowing budgets to be set for general heat waste reduction and repair work.

4.1.2 Attic Radiant Barrier

An attic radiant barrier consists of material with one or two low-emissivity surfaces. The barrier is designed to reduce thermal radiation heat transfer occurring between the roof deck and the top of the attic insulation, thereby reducing the total heat transfer through the ceiling. Radiant-barrier fact sheets developed by the Department of Energy (1991), Electric Power Research Institute (1988), and Faircy (1986) should be referred to for a more detailed discussion of what a radiant barrier is and how it operates.

Radiant barriers (together with the standard set of ECMs installed under the Oklahoma WAP) were installed in just the radiant-barrier houses. A radiant-barrier material with a kraft paper center and a thin aluminum coating on each side was used. Different manufacturers' materials were supplied by the Reflective Insulation Manufacturers Association. The barrier was attached to the underside (faces) of the roof rafters or top chords of the roof trusses so that one reflective surface faced the attic floor and the other reflective surface faced the roof deck. This installation is commonly termed a truss-mounted configuration and can be performed in the field in two ways as shown in Fig. 4.1. A gap of approximately 6 to 12 in. was left near the ridge and approximately 3 in. between the radiant barrier and the insulation near the cave. In this configuration, a channel through which warm air can move was created between the radiant

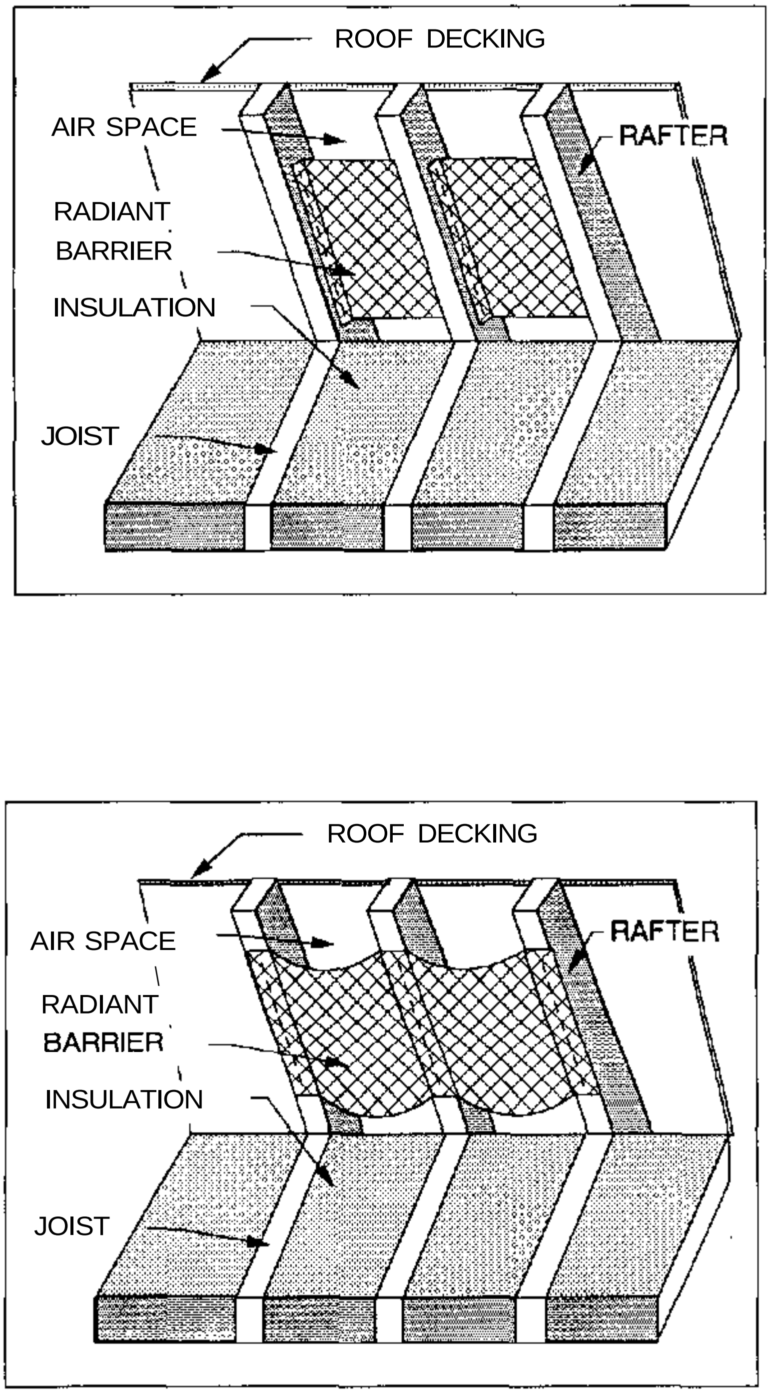

Fig. 4.1. Truss-mounted radiant-barrier configuration.

barrier and the roof deck. The only attic ventilation added to the houses was that performed under the Oklahoma WAP. The barrier was also installed on the gabled ends of the attic so that one reflective surface faced the attic space. A weatherization crew trained by the Reflective Insulation Manufacturers Association performed the installations. Costs for the radiant barrier were not counted toward the $1600 expenditure limit set for the Oklahoma WAP.

4.13 Air-Conditioner Replacements

In the air-conditioner replacement houses, one window air conditioner per house with an energy efficiency ratio (EER)[7] less than or equal to 7.0 was replaced by a high-efficiency unit (EER greater than or equal to 9.0) having about the same rated capacity as the original unit (the standard set of ECMs was also installed under the Oklahoma WAP). In houses with two existing units meeting this criterion, the unit with the greater pre-weatherization electricity consumption (as determined from the pre-weatherization field measurements) was replaced. All units older than four years were assumed to be eligible for replacement because actual EER ratings were not available. A minimum EER of 9.0 was selected for the replacement units to ensure that they met minimum efficiency standards for room air conditioners as stipulated by Congress (National Appliance Energy Conservation Act of 1987). The rated capacity of the replacement unit was the same as the original unit because savings could be artificially obtained by installing lower capacity units and increased electricity consumption could result from the installation of larger capacity units. Also, the original window air conditioners may not have been installed with the intention of providing air conditioning throughout the house, and calculating a "correct" size was complicated by the zoned nature of their use. Costs for the air conditioners were not counted toward the $1600 expenditure limit set for the Oklahoma WAP.

Installations of the replacement units were performed by the organization from which the units were purchased. Work generally included removal of the existing unit, mounting and

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[7]Energy efficiency ratio (EER) is used to express the efficiency of window air conditioners. EER is equal to the cooling output (Btu/h) divided by the power consumption (W). The higher the EER, the more efficient the air conditioner. EER differs from SEER in that laboratory measurements are made at only one indoor and outdoor test condition and cyclic operation is not considered.

securing the new unit in the window opening, and sealing spaces around the unit and window frame. Because units of the same rated capacity and voltage as the originals were used, no additional wiring was required.

4.2. INSTALLED MEASURES AND COSTS

The types of ECMs performed in each house and their costs are identified in Tables 4.1-4.4. Average costs for the groups are summarized in Table 4.5. Although the control group was not weatherized until after the field test was completed, cost for the control group are included to compare with the other three groups. The breakdown of weatherization costs into the four listed categories (general heat waste reduction, storm windows, attic insulation, and repair) can be misleading. The labor costs were usually calculated as a fixed percentage of the material costs for the ECM and, thus, may not reflect the actual cost to install the measure in that particular house. The total weatherization cost was less affected by this procedure and was relatively accurate. In Tables 4.1-4.4, houses listed at the bottom of the table (after the first average) were not used to calculate group electricity savings for reasons discussed in Sect. 7. For consistency, results in this section were based on just the houses used to calculate electricity savings; no significant differences would result if all houses had been used.

The installation frequency of weatherization measures performed in the test houses under the Oklahoma WAP is shown in Fig. 4.2. General heat waste reduction measures were performed in all the houses, storm windows were added in 90% of the houses, attic insulation was installed in 84% of the houses, and repair work was performed in 58% of the houses. These measures were installed consistently across the four groups, with the frequency of repair work being a minor exception. The average costs for the weatherization work performed under the Oklahoma WAP were nearly the same in each group, averaging between $834 and $882 per house. Costs for the four types of weatherization measures were also consistent across the four groups. Costs for individual houses ranged from $109 to $1296, with about half being between $900 and $1200.

A two-person weatherization crew installed the radiant barriers. After the first few installations, the crew could install the radiant barrier in a house in about half a day. Post-inspections showed that the installations were of high quality, demonstrating that weatherization

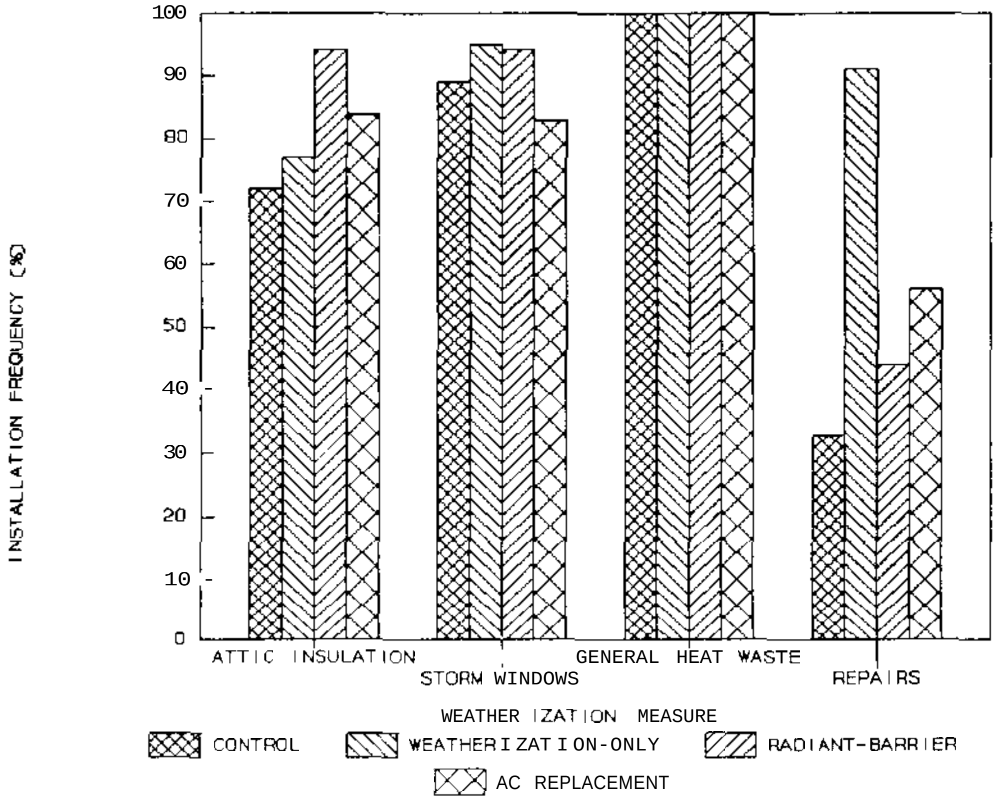

Fig. 4.2. Installation frequency of weatherization measures performed under the Oklahoma Weatherization Assistance Program.

crews can perform this ECM if properly trained. Installation of the attic radiant barriers in the truss-mounted configuration averaged $394 per house and ranged between $385 and $435 (see Table 4.3). Because the radiant-barrier material was donated, these costs included an estimated cost of $250 per house for material (approximately $\$0.20/ft^2$ of radiant-barrier material). Normalizing by the area of the attic, the average cost of the installation was $\$0.37/ft^2$. Because the area of the radiant-barrier material installed was greater than the area of the attic floor (considering roof pitch and area of the gable ends), this value would be slightly less if normalized by the area of the radiant-barrier material installed. The normalized costs compared favorably with the range of $\$0.20\text{-}0.45/ft^2$ of radiant-barrier material as identified in the Department of Energy's fact sheet (Department of Energy 1991).

Table 4.1. Energy conservation measure costs ($) for the control group

House	Weatherization: General heat waste	Weatherization: Storm windows	Weatherization: Attic insulation	Weatherization: Repair	Weatherization: Total	Radiant barrier	Replacement air conditioners	Total
17	450	565	106	72	1193	0	0	1193
25	166	655	0	0	821	0	0	821
30	362	80	0	0	442	0	0	442
31	348	446	155	0	949	0	0	949
37	119	436	126	0	681	0	0	681
40	584	600	102	0	1286	0	0	1286
43	357	209	218	28	812	0	0	812
50	234	508	82	0	824	0	0	824
51	307	288	174	24	793	0	0	793
52	257	835	184	20	1296	0	0	1296
57	286	203	92	263	844	0	0	844
67	247	705	127	0	1079	0	0	1079
68	419	581	0	54	1054	0	0	1054
90	387	501	122	0	1010	0	0	1010
109	248	0	0	0	248	0	0	248
111	251	0	160	0	411	0	0	411
118	373	654	0	0	1027	0	0	1027
120	559	467	113	0	1139	0	0	1139
Average:	331	430	98	26	884	0	0	884
Houses not used to calculate group electricity savings:								
4	136	529	0	0	665	0	0	665
9	495	501	136	64	1196	0	0	1196
19	93	86	174	0	353	0	0	353
21	382	525	109	0	1016	0	0	1016
39	471	400	136	37	1044	0	0	1044
80	397	527	0	0	924	0	0	924
107	354	78	0	28	460	0	0	460
Total average:	331	416	93	24	863	0	0	863

Note: Data for House 82 were not available (included in group electricity savings).

Table 4.2. Energy conservation measure costs ($) for the weatherization-only group

	Weatherization							
House	General heat waste	Storm windows	Attic insulation	Repair	Total	Radiant barrier	Replacement air conditioners	Total
3	257	374	93	20	744	0	0	744
7	425	382	0	41	848	0	0	848
15	417	492	131	85	1125	0	0	1125
23	296	486	164	40	986	0	0	986
24	348	503	0	111	962	0	0	962
41	312	408	159	61	940	0	0	940
42	211	402	122	16	751	0	0	751
47	590	396	93	93	1172	0	0	1172
48	445	400	126	43	1014	0	0	1014
53	195	674	215	15	1098	0	0	1098
54	415	749	0	33	1197	0	0	1197
59	266	419	169	21	875	0	0	875
61	405	340	136	122	1003	0	0	1003
62	255	83	126	20	484	0	0	484
69	129	293	92	0	514	0	0	514
71	268	167	252	21	708	0	0	708
75	414	83	93	33	623	0	0	623
89	605	221	89	207	1122	0	0	1122
97	162	142	189	12	505	0	0	505
103	520	457	136	127	1240	0	0	1240
104	88	242	0	7	337	0	0	337
110	109	0	0	0	109	0	0	109
Average:	324	351	108	51	834	0	0	834
Houses not used to calculate group electricity savings:								
5	248	855	0	0	1103	0	0	3103
10	263	125	234	21	643	0	0	643
34	619	599	131	112	1461	0	0	1461
70	452	455	150	158	1215	0	0	1215
102	457	196	165	36	854	0	0	854
Total average:	340	368	113	54	875	0	0	875

Table 43. Energy conservation measure costs ($) for the radiant-barrier group

	Weatherization							
House	General heat waste	Storm windows	Attic insulation	Repair	Total	Radiant barrier[1]	Replacement air conditioners	Total
14	330	293	98	0	722	435	0	1157
26	271	463	117	39	890	385	0	1275
27	467	499	126	72	1164	385	0	1549
32	210	209	122	0	541	385	0	926
35	423	438	189	0	1050	385	0	1435
38	443	504	93	107	1147	395	0	1542
55	387	362	165	0	914	385	0	1299
65	371	0	0	48	419	400	0	819
74	423	493	126	33	1075	385	0	1460
83	348	361	103	194	1006	385	0	1391
87	359	83	131	0	573	395	0	968
88	481	513	103	94	1191	390	0	1581
95	334	41	184	0	559	400	0	959
98	270	558	126	0	954	400	0	1354
106	444	373	131	0	948	390	0	1338
108	385	517	93	0	995	390	0	1385
115	215	282	116	0	613	400	0	1013
117	439	293	136	105	973	400	0	1373
Average:	367	349	120	38	874	394	0	1268
Houses not used to calculate group electricity savings:								
8	297	544	165	0	1006	400	0	1406
22	273	426	107	80	886	400	0	1286
28	371	720	93	0	1184	425	0	1609
46	408	473	89	0	970	390	0	1360
49	488	461	178	39	1166	445	0	1611
84	288	154	106	0	548	385	0	933
101	383	446	145	30	1004	420	0	1424
114	319	330	165	167	981	400	0	1381
Total average:	363	378	123	39	903	398	0	1301

[1]$250/house was assumed for materials because the radiant-barrier material was donated.
Note: Data for House 6 were not available (included in group electricity savings).

Table 4.4. Energy conservation measure costs ($) for the air-conditioner replacement group

	Weatherization							
House	General heat waste	Storm windows	Attic insulation	Repair	Total	Radiant barrier	Replacement air conditioners	Total
1	301	0	159	0	460	0	811	1271
2	277	500	179	0	956	0	898	1854
11	346	561	106	0	1013	0	1027	2040
13	312	564	140	25	1041	0	1487	2528
45	416	423	106	120	1065	0	811	1876
58	177	0	72	0	249	0	811	1060
60	133	0	0	0	133	0	927	1060
64	347	558	126	27	1058	0	811	1869
72	329	645	140	100	1214	0	1182	2396
78	495	482	131	0	1108	0	811	1919
79	3(X)	120	116	24	560	0	1364	1924
81	355	444	155	0	954	0	912	1866
85	128	366	92	10	596	0	811	1407
91	377	591	126	30	1124	0	811	1935
99	389	644	150	31	1214	0	811	2025
105	356	648	170	28	1202	0	955	2157
113	191	820	126	15	1152	0	877	2029
119	443	204	136	0	783	0	912	1695
Average:	315	421	124	23	882	0	946	1828
Houses not used to calculate group electricity savings:								
16	385	318	121	30	854	0	811	1665
20	295	554	136	0	985	0	0	985
56	391	0	0	31	422	0	877	1299
92	328	586	179	26	1119	0	811	1930
100	360	538	155	51	1104	0	927	2031
112	515	162	126	0	803	0	546	1349
Total average:	331	405	123	23	882	0	875	1757

Table 4.5. Comparison of average energy conservation measure costs ($) per group

Group	Weatherization: General heat waste	Weatherization: Storm windows	Weatherization: Attic insulation	Weatherization: Repair	Weatherization: Total	Radiant barrier[1]	Replacement air conditioners	Total
Control	331	430	98	26	884	0	0	884
Weatherization only	324	351	108	51	834	0	0	834
Radiant-barrier	367	349	120	38	874	394	0	1268
Air-conditioner replacement	315	421	124	23	882	0	946	1828

[1]$250/house was assumed for materials because the radiant-barrier material was donated.

Table 4.6 summarizes the rated capacities of the original and replacement air conditioners, the ages of the original units, and the EERs of the replacement units. As desired, the capacities of the original and replacement units were the same, and the EERs of the replacement units were all greater than or equal to 9.0. House 20 did not receive a replacement unit because the original unit was only a year old (and, thus, not likely to have an EER less than or equal to 7.0). The installation cost for the air conditioners ranged from $811 to $1487, and averaged $946 (see Table 4.4). This cost included the cost of the units, labor, and miscellaneous materials (the breakdown of this cost into these three categories was not known).

Air-conditioner installation costs arc expected to be significantly less than those incurred under the field test if performed routinely under a Weatherization program for the following reasons:

- Installation of the units would likely be performed by the regular Weatherization crews rather than the company selling the units. Under the field test, the company selling the units also performed the installations. This required an extra trip to each house (approximately 50 miles round trip) and extra coordination with the occupants that would not be required under a Weatherization program.
- The uncertainty associated with an experimental study led to increased costs. The company performing the installations was not familiar with the houses or the field test; therefore, the company's bid was made somewhat blindly.

Table 4.6. Specifications of the original and replacement air conditioners

	Original air conditioner		Replacement air conditioner	
House	Capacity (Btu/h)	Estimated age (years)	Capacity (Btu/h)	Energy Efficiency Ratio
1	18,000	5	18,000	9.0
2	16,500	8	16,400	9.0
11	10,600	12	10,300	12.0
13	25,000	8	27,000	9.0
45	18,000	6	18,000	9.0
58	18,000[a]	6	18,000	9.0
60	8,000	6	8,200	10.5
64	18,000	10	18,000	9.0
72	18,700	6	19,000	9.5
78	18,000[a]	8	18,000	9.0
79	24,000	10	24,000	9.1
81	15,000	6	15,000	9.0
85	18,000	6	18,000	9.0
91	18,000	25	18,000	9.0
99	18,000	10	18,000	9.0
105	13,500	4	13,000	9.7
113	12,000	20	12,300	9.7
119	14,000	6	15,000	9.0
Houses not used to calculate group electricity savings:				
16	18,000	10	18,000	9.0
20	20,000	1		
56	12,000	9	12,300	9.0
92	18,000	5	18,000	9.0
100	8,000	15	8,200	10.5
112	5,000		5,000	9.0

[a]Capacities were estimated based on physical appearance because nameplate information was missing.

- Air conditioners would be purchased in bulk under a competitive purchase order.

If performed under a weatherization program, an average expected air-conditioner installation cost of $739 was estimated for all the houses comprising the air-conditioner replacement group ($786 for just those houses with pre-weatherization air-conditioning electricity consumption greater than 2750 kWh/year) based on the following analyses and assumptions:

- Current costs for various capacity window air conditioners with EERs between 9.0 and 9.2 were obtained from two discount suppliers in Knoxville, Tennessee (units were manufactured by three nationally recognized companies). A linear relation between capacity and cost was observed for these units.[8] Based on the known capacity of the air conditioner actually installed in each house, an expected cost for the unit was estimated using this linear relation. Using this approach, the average expected cost for just the units themselves was estimated to be $639 for all the houses and $686 for the subgroup of houses.[9]

- A cost of $100 per house was assumed to be reasonable to cover costs for labor and miscellaneous materials to install the units. This cost was sufficient to allow a two-person crew two hours to install the replacement unit.

These estimated costs, rather than costs incurred under the field test, were used in the economic analysis presented in Sect. 7.3 because we did not feel that the field test costs accurately reflected expected program costs.

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[8]COST($) = [0.021453 x CAPACITY(Btu/h)] + 276.47

[9]This approach still did not consider cost reductions that could occur due to bulk purchases.

5. AIR-LEAKAGE RESULTS

Air leakages were measured twice in all the houses. Pre-weatherization measurements were made between November 1988 and July 1989. Post-weatherization measurements were made in October and November 1989. Because the control houses had already been weatherized by October 1989, the measurements in these houses included the effect of the work performed (these houses did not serve as a "control" for this measurement).

Air leakages measured in the control, weatherization-only, radiant-barrier, and air-conditioner replacement houses are summarized in Tables 5.1-5.4, respectively. Average values for the groups are summarized in Table 5.5. In Tables 5.1-5.4, houses listed at the bottom of the table (after the first average) were not used to calculate group electricity savings for reasons discussed in Sect. 7. For consistency, results in this section were based on just the houses used to calculate electricity savings; no significant differences would have resulted if all houses had been used.

5.1 ANALYSIS METHOD

The air leakages reported in Tables 5.1-5.5 were the air-flow rate (cfm50) and house air changes per hour (ACH50) at 50 Pa pressure difference across the building shell. Both cfm50 and ACH50 are airtightness ratings useful for studying the effectiveness of airtightening work. ACH50 results are discussed in this report because the airtightening procedure used a minimum ventilation guideline expressed in terms of ACH50. Results are also presented in terms of cfm50 because this quantity is currently being used more frequently in airtightening procedures.

These indicators were calculated from data collected from fan pressurization (blower door) testing. A series of air flow measurements (Q) were made at different pressure differences between the inside and outside of the house (AP) (nominally 10 Pa to 60 Pa in increments of 10 Pa). These data follow the power law form

$$Q = C\,(\Delta P)^{N} \qquad \text{(Eq. 5-1)}$$

Table 5.1. Air-leakage measurements for the control group

	Air leakage (cfm50)			Air leakage (ACH50)			
House	Pre	Post	Change	Pre	Post	Change	Comments
17	1807	1791	-16	12.87	12.76	-0.11	
25	2016	1651	-365	10.77	8.82	-1.95	
30	3481	2022	-1459	26.29	15.27	-11.02	
31	5896	2445	-3451	37.79	15.67	-22.12	
37	1767	1431	-336	12.27	9.94	-2.33	
40	2699	2883	184	10.63	11.36	0.72	
43	4261	1984	-2277	18.92	8.81	-10.11	
50	2515	2320	-195	16.04	14.80	-1.24	
51	4518	2120	-2398	34.23	16.06	-18.17	
52	10602	9336	-1266	35.25	31.04	-4.21	
57	4815	4087	-728	26.06	22.12	-3.94	
67	3858	3222	-636	24.73	20.65	-4.08	
68	5486	3904	-1582	32.19	22.91	-9.28	
82	2200	1224	-976	18.33	10.20	-8.13	
90	4734	2067	-2667	33.72	14.72	-19.00	
109	4650	4036	-614	29.58	25.67	-3.91	
111	4891	3195	-1696	32.61	21.30	-11.31	
118	3645	2757	-888	28.13	21.27	-6.85	
120	3734	1478	-2256	22.23	8.80	-13.43	
Average:	4083	2840	-1243	24.35	16.43	-7.92	
Houses not used to calculate group electricity savings:							
4	4320	2116	-2204	31.21	15.29	-15.92	
9	4985	1728	-3257	32.51	11.27	-21.24	
19	2013	1603	-410	9.32	7.42	-1.90	
21	4675	2041	-2634	30.92	13.50	-17.42	Pre n = .495
39	3320	1714	-1606	25.15	12.98	-12.17	
80	4926	2825	-2101	25.34	14.53	-10.81	
107	6547	2125	-4422	26.83	8.71	-18.12	
Total average:	4168	2619	-1548	24.77	15.23	-9.54	

Table 5.2. Air-leakage measurements for the weatherization-only group

	Air leakage (cfm50)			Air leakage (ACH50)			
House	Pre	Post	Change	Pre	Post	Change	Comments
3	2726	1469	-1257	25.81	13.91	-11.90	
7	4819	2474	-2345	22.23	11.41	-10.82	
15	3366	1460	-1906	31.88	13.83	-18.05	
23	3305	2160	-1145	21.74	14.21	-7.53	
41	49%	3120	-1876	32.53	20.31	-12.21	
42	2595	1528	-1067	18.02	10.61	-7.41	
47	2645	1414	-1231	14.79	7.91	-6.88	
48	2658	1850	-808	19.09	13.29	-5.80	
53	5818	5111	-707	39.42	34.63	-4.79	
54	3834	2281	-1553	22.50	13.39	-9.11	
59	1675	1542	-133	10.47	9.64	-0.83	
61	6226	5168	-1058	45.91	38.11	-7.80	
62	1685	1587	-98	14.18	13.36	-0.82	
69	1888	955	-933	15.73	7.96	-7.77	
71	5980	1870	-4110	33.22	10.39	-22.83	
75	3159	2370	-789	19.03	14.28	-4.75	
89	5939	5353	-586	74.99	67.59	-7.40	
97	2200	1411	-789	14.03	9.00	-5.03	
103	2625	2117	-508	18.70	15.08	-3.62	
104	4290	1876	-2414	25.00	10.93	-14.07	
110	1060	868	-192	8.18	6.70	-1.48	
Average:	3499	2285	-1215	25.12	16.98	-8.14	
Houses not used to calculate group electricity savings:							
5	6479	3660	-2819	21.01	153	-9.14	
10	5130	2906	-2224	28.50	157	-12.36	
34	5328	3868	-1460	27.75	193	-7.60	
70	6343	4475	-1868	45.18	317	-13.30	
Total average:	3871	2516	-1355	26.00	146	-8.53	

Note: Data for House 24 were not available (included in group electricity savings).

Table 5.3. Air-leakage measurements for the radiant-barrier group

House	Air leakage (cfm50) Pre	Post	Change	Air leakage (ACH50) Pre	Post	Change	Comments
6	5388	1499	-3889	56.13	15.61	-40.51	
14	4426	1765	-2661	29.27	11.67	-17.60	
26	2387	1850	-537	15.79	12.24	-3.55	
27	3479	2019	-1460	22.65	13.14	-9.51	
32	2178	2387	209	25.93	28.42	2.49	
35	3340	2653	-687	16.47	13.08	-3.39	
38	3431	1812	-1619	19.86	10.49	-9.37	
55	2921	2457	-464	17.39	14.63	-2.76	
65	1759	1646	-113	12.22	11.43	-0.78	
74	3777	2383	-1394	24.98	15.76	-9.22	
83	2901	2569	-332	30.22	26.76	-3.46	
87	1930	1379	-551	10.31	7.37	-2.94	
88	8250	6168	-2082	41.25	30.84	-10.41	prc n = .39
95	3624	3258	-366	26.13	23.50	-2.64	
98	3878	2461	-1417	25.65	16.28	-9.37	
106	3017	2125	-892	27.94	19.68	-8.26	
108	4511	4186	-325	25.51	23.68	-1.84	
115	1642	1246	-396	12.67	9.61	-3.06	
117	4173	4445	272	21.73	23.15	1.42	
Average:	3527	2543	-984	24.32	17.23	-7.09	
Houses not used to calculate group electricity savings:							
22	3906	3678	-228	28.72	27.04	-1.68	
28	2505	1742	-763	16.57	11.52	-5.05	
46	4055	2664	-1391	20.86	13.70	-7.16	
49	3803	1938	-1865	12.78	6.51	-6.27	
84	3129	2458	-671	22.87	17.97	-4.90	
114	2371	2050	-321	14.82	12.81	-2.01	
Total average:	3471	2514	-958	23.15	16.68	-6.47	

Table 5.4. Air-leakage measurements for the air-conditioner replacement group

	Air leakage (cfm50)			Air leakage (ACH50)			
House	Pre	Post	Change	Pre	Post	Change	Comments
1	1693	1358	-335	11.20	8.98	-2.22	
2	3897	2629	-1268	22.55	15.21	-7.34	
11	4043	1784	-2259	27.07	11.95	-15.13	
13	2175	1602	-573	15.49	11.41	-4.08	
45	2585	1590	-995	19.23	11.83	-7.40	
58	4338	3756	-582	20.08	17.39	-2.69	
60	7241	6201	-1040	46.18	39.55	-6.63	
64	3422	2054	-1368	19.94	11.97	-7.97	
72	4816	1771	-3045	27.12	9.97	-17.15	
78	3624	1759	-1865	25.81	12.53	-13.28	
79	2589	2298	-291	13.39	11.89	-1.51	
81	3171	2064	-1107	13.35	8.69	-4.66	
85	1589	1429	-160	12.95	11.65	-1.30	
91	5156	1940	-3216	30.69	11.55	-19.14	
99	5852	1857	-3995	32.27	10.24	-22.03	
105	6627	2661	-3966	19.58	7.86	-11.72	
113	80%	3916	-4180	42.17	20.40	-21.77	
119	2436	1548	-888	14.05	8.93	-5.12	
Average:	4075	2345	-1730	22.95	13.44	-9.51	
Houses not used to calculate group electricity savings:							
16	6919	3304	-3615	34.94	16.69	-18.26	
20	2370	1585	-785	14.96	10.01	-4.96	
56	7450	3130	-4320	34.75	14.60	-20.15	
92	6255	2952	-3303	28.96	13.67	-15.29	
100	3891	2413	-1478	23.16	14.36	-8.80	
112	4670	3815	-855	28.83	23.55	-5.28	
Total average:	4371	2476	-1895	24.11	13.95	-10.16	

Table 5.5. Comparison of air-leakage measurcmcnts pcr group

	Air leakage (cfm50)			Air leakage (ACH50)		
Group	Pre	Post	Change	Pre	Post	Change
Control	4083	2840	-1243	24.35	16.43	-7.92
Weatherization-only	3499	2285	-1215	25.12	16.98	-8.14
Radiant-barrier	3527	2543	-984	24.32	17.23	-7.09
Air-conditioner replacement	4075	2345	-1730	22.95	13.44	-9.51
Average[1]:	3785	2500	-1285	24.22	16.08	-8.15

[1]Averages were weighted by the number of houses for each group.

where C and N arc constants. Bccause ln(Q) vs ln(AP) is a linear relation, these valucs were regressed by the method of weightcd least squares to determine the best values of C and N. The equations and weighting factors used in this analysis are presented in Standard CAN/CGSB-149.10-M86 (CGSB 1986). The cfm50 value was calculated using Eq. 5-1, the bcst values of C and N, and 50 Pa as the value of AP. The ACH50 value was calculated from the cfm50 value and known house volumes.

5.2 RESULTS

The averagc pre-weathcrization air leakage of the four groups ranged from 3527 to 4083 cfm50, and the wcighted average of the groups was 3785 cfm50 (the avcrage was weighted by thc numbcr of houscs in each group). The average decrease in air leakage of the four groups following wcatherization ranged from 984 to 1730 cfm50 and the weighted average was 1285 ct'm50. At a 95% confidence lcvcl, there was no difference in the pre-wcatherization air leakage or air lcakage changc measured in the four groups (at a 75% confidencc level, thcrc was no diffcrcnce in the prc-wcatherization air lcakagcs measured in thc four groups, but there was in the changcs of the air leakages). Thc agreement in the pre-weathcrization values of the four groups indicated that the four groups wcrc cquivalcnt with regard to their air tightness. The only specificd difference in the ECMs pcrformed in the four groups of houses was the installation of radiant barriers and high-efficiency air conditioners in two of the groups. Because these two measures should not significantly affect house air leakage, no difference among groups in the air leakage change following the installation of ECMs was expected. Because of the equivalency among groups, the remaining analyses focus on the houses as a group to examine the effect of the weatherization work performed under the Oklahoma WAP and the blower-door guided airtightening performed for the field test.

As shown in Fig. 5.1, pre-weatherization air leakages ranged from less than 10 ACH50 to greater than 40 ACH50, with the majority of houses (88%) evenly distributed between 10 and 35 ACH50. In terms of cfm50, houses were fairly evenly distributed between 1500 and 5000 cfm50. On average, these houses had greater air leakages than houses used in other field tests in more northern climates. The average air leakage of 3785 cfm50 for the houses in this study was greater than the average of 2483 cfm50 measured in houses used in the M200 Program (Shen et al. 1990) and the average of 3179 cfm50 from an ORNL field test performed in New York (Ternes et al. 1991).[10]

Significant decreases in air leakages occurred due to weatherization work performed under the Oklahoma WAP and using the blower-door guided airtightening procedure. This is evident from Fig. 5.1, where post-weatherization air leakages in the majority of the houses (63%) were between 5 and 15 ACH50 (68% were between 1000 and 2500 cfm50). Air leakage decreases in most houses (67%) were between 0 and 10 ACH50 (see Fig. 5.2); the decreases were between 0 and 1500 cfm50 in 65% of the houses. Decreases of more than 15 ACH50 occurred in 15% of the houses (more than 2500 cfm50 in 13% of the houses) and an increase was measured in 4% of the houses (reasons for an increase were not known). The air leakage reductions occurring in the houses were due to a combination of measures. Although the blower-door guided airtightening and caulking and weatherstripping performed under the Oklahoma WAP were directed specifically at air leakage reduction, reductions also occurred from the storm windows installed, and possibly the attic insulation and the repair work performed.

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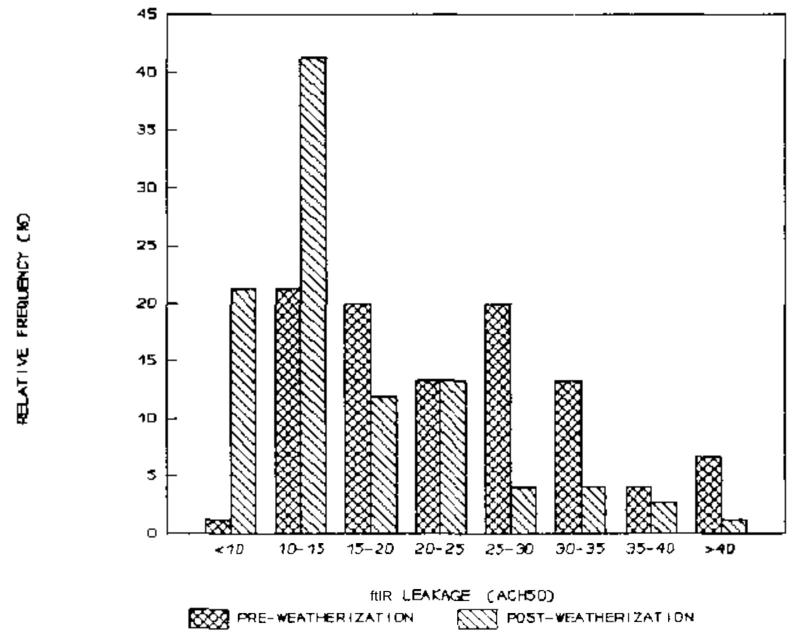
[10]The average house used in the New York Field Test had two floors buiit above a concrete block basement. In this study, houses were generally single-story and built above a crawl space. Average non-basement floor areas were similar: 1305 ft^2 for the New York Field Test compared to 1245 ft^2 for this study.



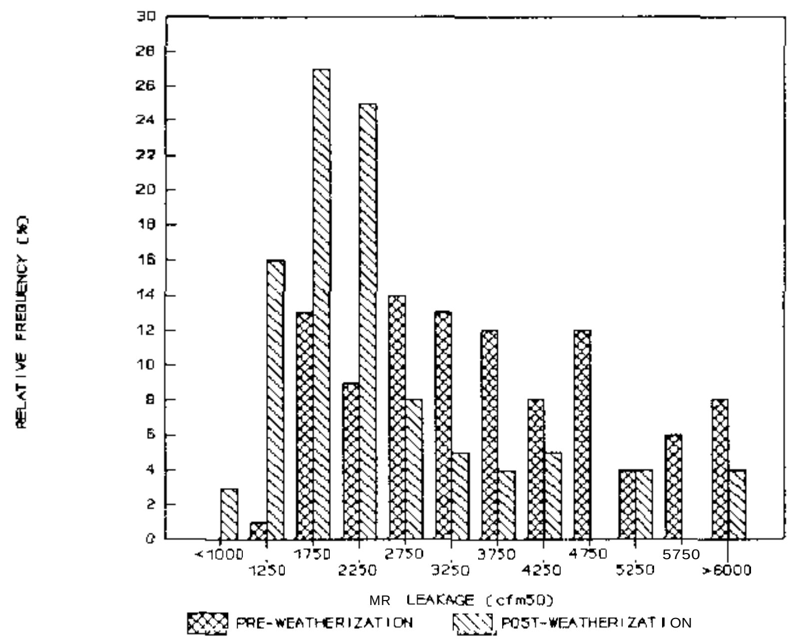


Fig. 5.1. Histogram of pre- and post-weatherization air leakages. The top graph presents results in units of ACH50 and the bottom graph in units of cfm50. Listed air-leakage values in the bottom graph represent ranges (e.g., 2250 cfm50 represents a range of 2000-2499 cfm50).

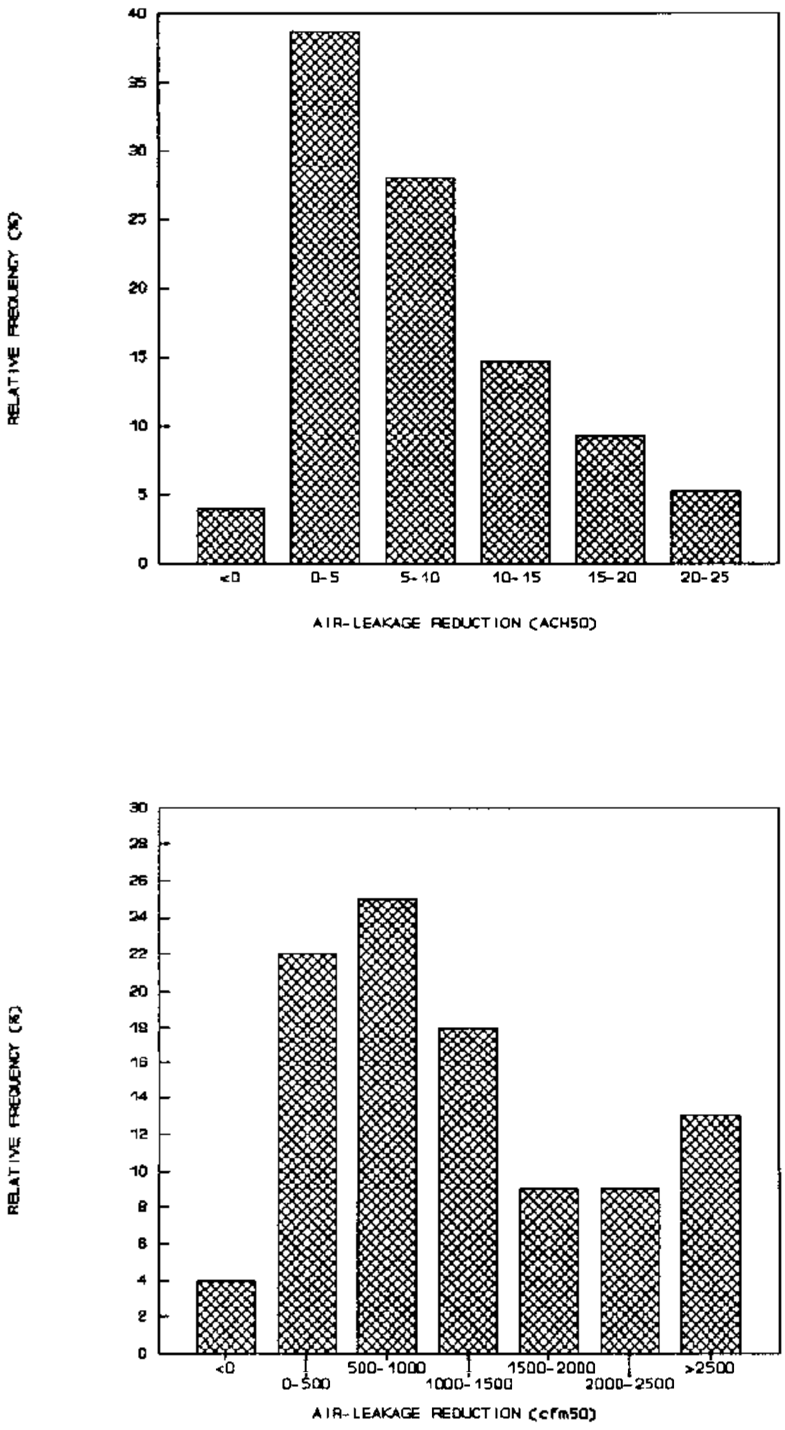


Fig. **5.2.** Histogram of air-leakage reductions following **weatherization. The** top graph presents results in units of **ACH50** and the bottom graph in units of **cfm50.**

Examination of the air-leakage reductions achieved as a function of thc prc-weatherization air leakage (Fig. 5.3) revealed two general trends (dashed and dotted lines). These trends were developed visually and were not results of regression analyses. In the top graph of Fig. 5.3, the solid line represents maximum desired air-leakage reductions to achieve a post-weatherization air leakage of 10 ACH50 (the minimum value as stipulated by the minimum ventilation guideline in the airtightening procedure). The trend shown by the dashed line represents the majority of the houses, houses in which significant reductions werc achieved from the combined measures installed in the houses. In these houses, post-weathcrization air leakages were nearly equal to or approaching 10 ACH50 (in the range of 10 to 20 ACH50). The trend shown by the dotted line represents a fewer number of houses, houses in which small reductions were achieved (much smaller reductions than those represented by the previous trend for a given prc-weatherization air leakage). In these houses, reductions of less than 10 ACH50 were achieved, although pre-weatherization air leakages were often greater than 20 ACH50.

Similar trends are exhibited in the bottom graph of Fig. 5.3, where the solid line represents maximum desired air-leakage reductions to achieve a post-wcathcrization air leakage of 1500 cfm50; 1500 cfm50 is a commonly used value for the minimum ventilation guideline (Schlegcl 1990). Thc dashed line represents houses with post-weatherization air leakages in the range of 1500-2500 cfm50. The final air leakages achieved in these houses werc similar to those achieved in houses under the M200 Program (Shcn et al. 1990). Thc dotted line represcnts houses with pre-weatherization air leakagcs greater than 3000 cfm50 in which reductions of less than 1500 cfm50 were achieved.

The trends observed in Fig. 5.3 indicated that major leakage sites werc being scaled in most of the houscs (about 80%). After weatherization, some of these houses were still slightly leakier than desired (air leakages werc greater than 20 ACH50 or 2500 cfm50). In the remaining houses (the 20% represented by the dotted lines), major leakage sites were not sealcd. This may have occurred because work had to be stoppcd to remain within budget constraints, some major leakage sites could not bc found, or some leakage sites could not be sealed using techniques available to the weatherization crew. Additional training and use of altcrnative techniques (such as high-density wall insulation) might improve upon the reductions already achieved. Inclusion of

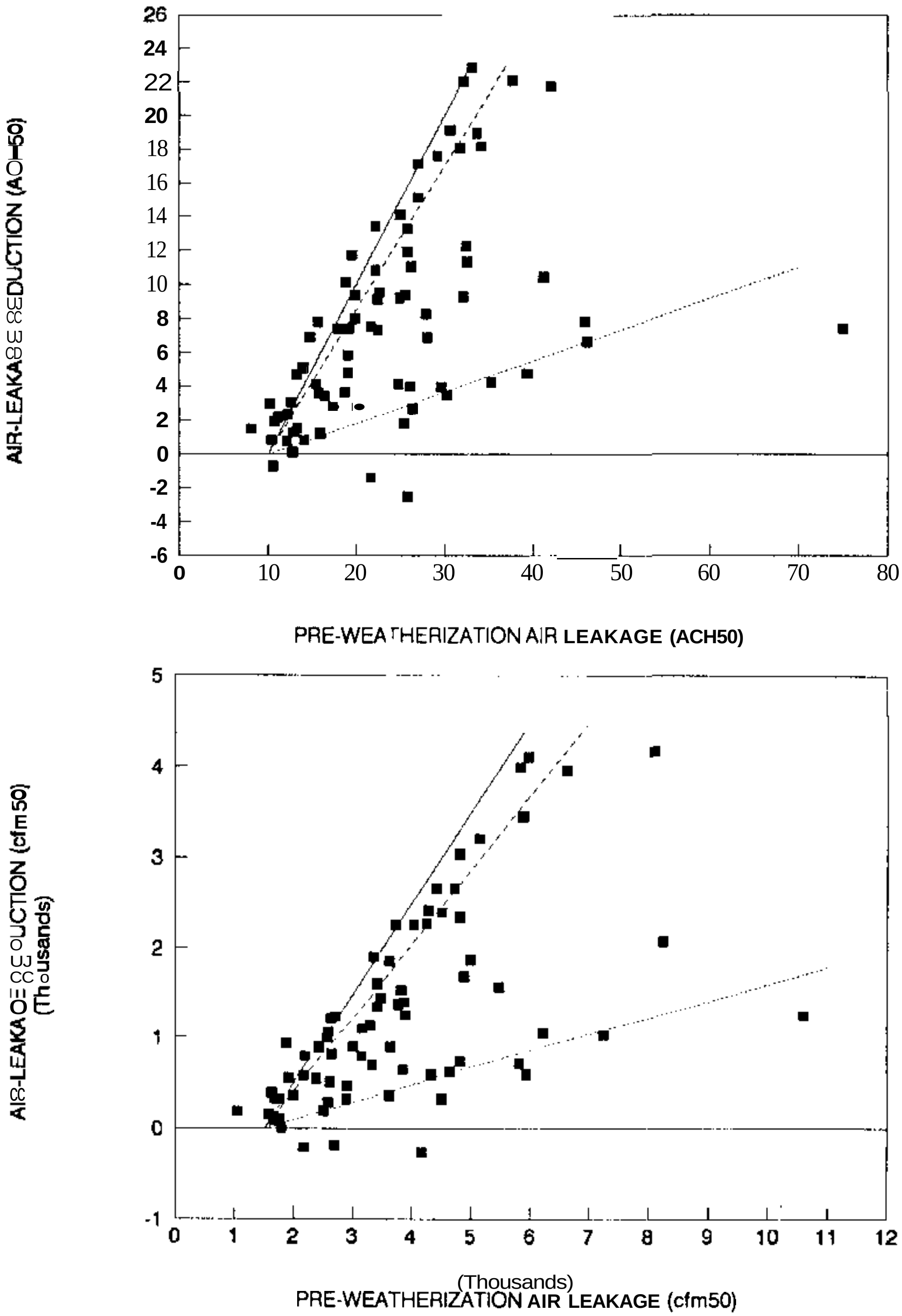


Fig. 53. Comparison of the air-leakage reduction for each house to its pre-weatherization air leakage. The top graph presents results in units of ACH50 and the bottom graph in unils of cfm50. The solid lines represent maximum desired air-leakage reductions. The dashed lines represent the majority of the houses in which nearly optimum reductions were achieved. The dotted lines represent a fewer number of houses in which small reductions were achieved. The dashed and dotted lines were developed visually and were not results of regression analysis.

cost-effective guidelines in the blower-door procedure (Schlegel 1990) may have allowed additional cost-effective work to be performed in some of these houses.

Houses with low pre-weatherization air leakages should not have needed a significant amount of airtightening and, thus, should have had lower than average expenditures for general heat waste reduction.[11] Expenditures for general heat waste reduction averaged $246 for the houses with pre-weatherization air leakages less than 2000 cfm50, compared to an average expenditure of $315 to $367 for each of the four groups. The air leakage reductions achieved in this subgroup of houses averaged 297 cfm50 compared to 1285 cfm50 for all the houses combined. Inclusion of a cost-effective guideline in the blower-door directed procedure might reduce the amount of general heat waste reduction work performed in already tight houses while achieving about the same average reductions, saving additional funds in the process.

The relation between expenditure for general heat waste reduction and air-leakage reduction was further examined using Fig. 5.4. Little correlation existed between expenditure and reduction, when one would expect increased reductions from increased expenditures. Although air-leakage reductions were generally small (less than 100 cfm50) when expenditures for waste heat reduction were small (less than $200), large expenditures did not necessarily produce larger than average reductions.

As seen from Fig. 5.1, post-weatherization air leakages in 21% of the houses were less than 10 ACH50, the minimum value established for the airtightening procedure (15% were less than 9 ACH50). Likewise, 19% of the houses were less than 1500 cfm50. Tightening below 10 ACH50 may have resulted indirectly from installation of attic insulation and storm windows after the airtightening work had been performed. Care should be taken in the future not to overtighten houses to avoid problems and reduce expenditures.

Storm windows are designed to reduce air leakage while also reducing heat loss through conduction. Although no strong relation between the expenditure for storm windows and the

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[11]It should be noted that costs attributed to general heat waste reduction included many items, including items that were hard to distinguish between repair and airtightening.

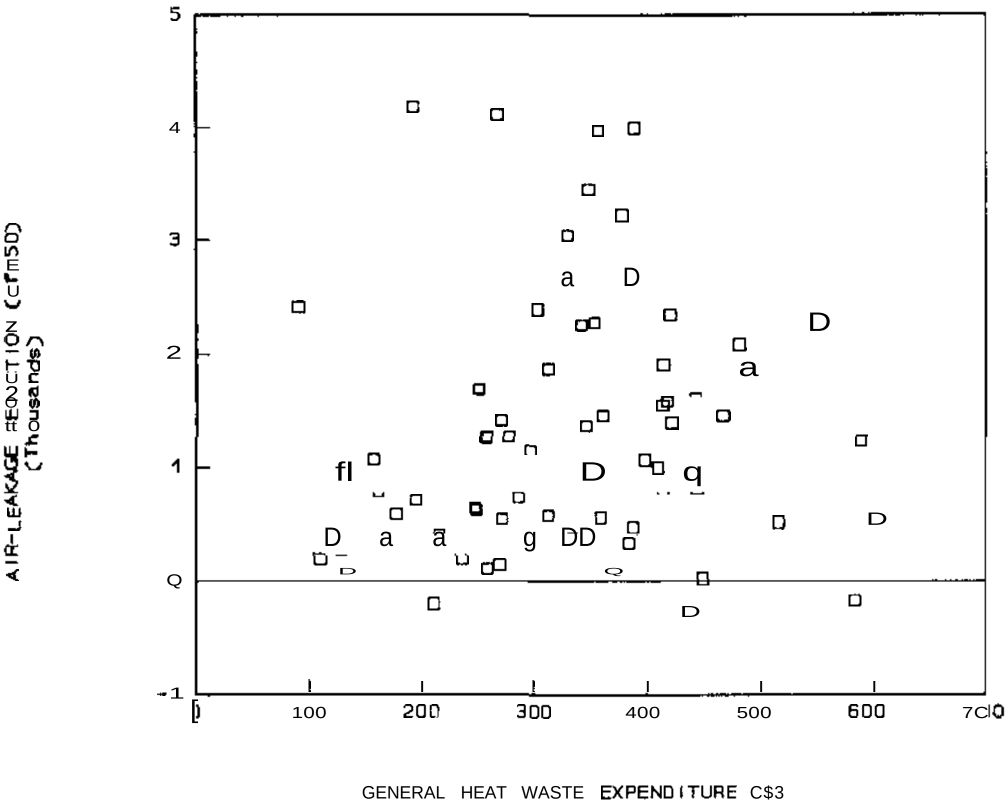

Fig. 5.4. Comparison of the air-leakage reduction for each house to the expenditure for general heat waste reduction in the house.

overall air-leakage reduction is demonstrated in Fig. 5.5, the overall reduction was generally less in houses in which $150 or less was spent on storm windows. Less than $150 was spent on storm windows in 18% of the houses, indicating that these houses already had storm windows or double pane windows. The average pre-weatherization air leakage was 3164 cfm50 in these houses (slightly less than the average value for all the houses) and the average reduction due to all installed measures was 637 cfm50 (about half the average of all the houses).

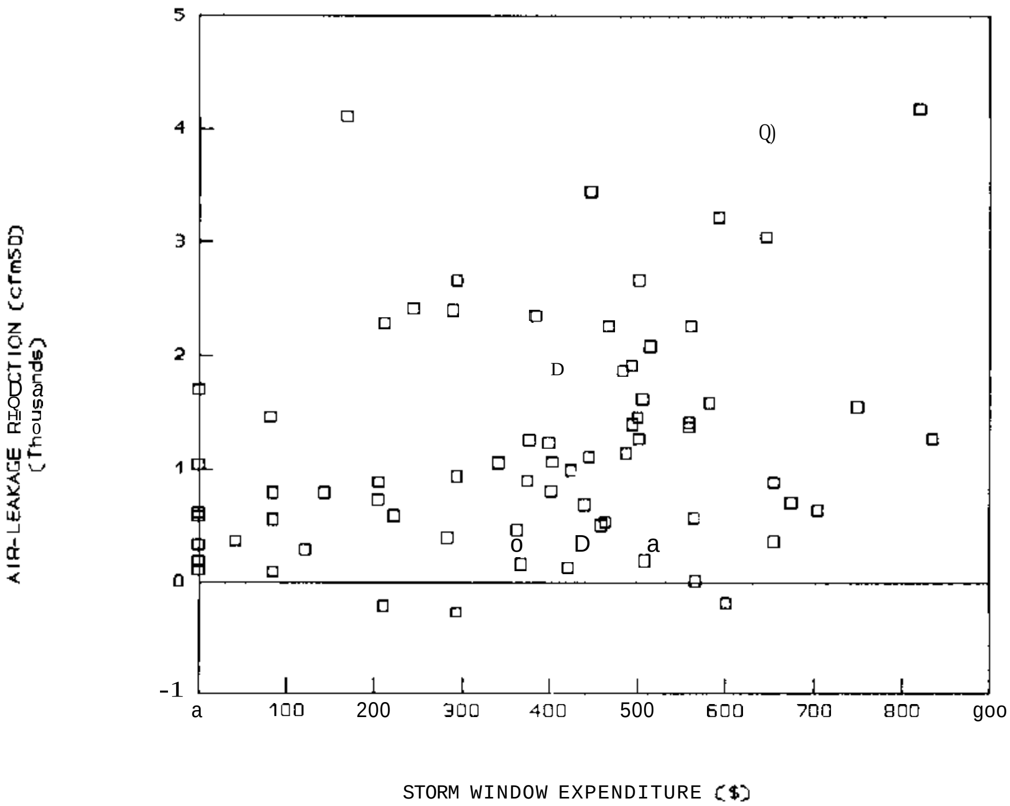

Fig. 5.5. Comparison of air-leakage reduction for each house following weatherization to the expenditure for storm windows in the house.

6. AIR-CONDITIONING ELECTRICITY ANALYSES

Energy savings is defined by Fracastoro and Lyberg (1983) as "the amount of energy saved by a retrofit if everything is kept constant except for the retrofit itself, and changes in the behavior of the occupants induced by the retrofit." This definition is applicable when the actual savings due to the ECMs installed is of interest. The savings defined in this manner is not the same as the observed annual energy savings, because this latter savings is influenced by differences in outdoor and indoor climate, occupant behavior changes (such as changes in internal loads, room closures, and window and door opening practices) due to factors other than the ECMs installed, and changes in occupancy following weatherization. Determining if an occupant behavior change is due to the ECMs installed or an outside factor can be difficult.

Consistent with this definition, air-conditioning electricity savings was defined to be the annual savings normalized to an average weather year for Tulsa, Oklahoma, and the average pre-weatherization indoor temperature for each house. Comparison of the normalized savings for the treatment houses to the normalized savings for the control houses was used to account for occupant behavior changes caused by factors other than ECMs installed. This comparison assumed that the treatment houses responded equivalently to the control houses to a factor other than the ECMs installed. In this study, the measured savings were not influenced by changes in occupancy because the few houses that did have new occupants were dropped from the study.

The savings were normalized to the pre-weatherization indoor temperature for each house rather than a standard temperature (such as 78°F) to obtain the savings for the houses as they were initially operated. Thus, variability in savings among houses was due, in part, to the different indoor temperatures. This normalization assumed that all indoor temperature changes were due to factors other than the ECMs installed. If a change was induced by the ECM, both pre- and post-weatherization temperatures should have been used. Researchers theorize that occupants of houses receiving an attic radiant barrier might increase their indoor temperature following weatherization to maintain equivalent comfort conditions because the ceiling is not as warm, although research has not substantiated this theory. In this study, indoor temperature changes resulting from the installation of radiant barriers could not be separately identified from indoor temperature changes resulting from another factors; thus, pre-weatherization temperatures only were used in the normalizations.

Normalized annual air-conditioning electricity consumptions used to calculate normalized savings were estimated from the pre- and post-weatherization data using air-conditioning electricity consumption models and regression analysis described below to account for the following factors: time periods over which data were collected were unequal and did not cover entire summer periods, pre- and post-weatherization outdoor temperature conditions were different and not equal to the typical outdoor temperatures desired for normalization, and post-weatherization indoor temperatures were not equal to pre-weatherization temperatures.

An idealized relation between weekly air-conditioning electricity consumption and a weekly "driving force" temperature (either average weekly outdoor temperature or outdoor-indoor temperature difference) has three regions (see Fig. 6.1): no air conditioning is required at sufficiently low temperatures, electricity consumption is non-zero but not a function of temperature in a transition region, and a electricity consumption and temperature are linearly related at higher temperatures.

The electricity usage behavior exhibited in the transition region is due to many reasons. The effect of excluding factors affecting air-conditioning electricity consumption other than outdoor temperature (such as solar radiation, indoor and outdoor humidity, and night sky radiation cooling) becomes more critical at cooler outdoor temperatures. An additional important reason is the use of a weekly average temperature to characterize the driving force. This is especially important with window air-conditioning units because their use can be more intermittent than central systems.

Except in the warmest climates, cool periods several days in duration are likely to occur during the summer when air-conditioning is not required. The relationship between air-conditioning electricity consumption and the temperature driving force is different for weeks that include these cool periods than for those that do not. This occurs because the effect of these

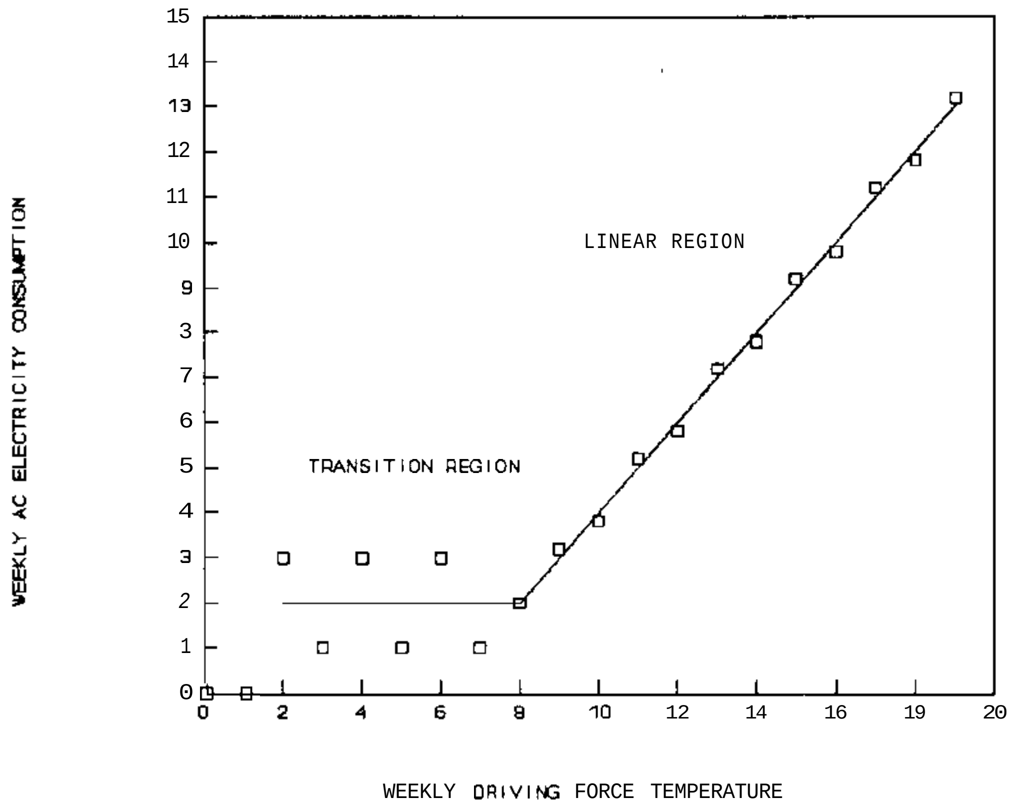

Fig. **6.1.** Weekly **air-conditioning** electricity consumption as a function of a **weekly** "driving force" temperature (either average weekly outdoor temperature or outdoor-indoor temperature difference) for an idealized **situation.**

cool periods on electricity consumption is limited (electricity consumption cannot drop below zero) but their effect on the driving force temperature is not **limited.**[12]

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[12]**For** example, assume that 35 **kWh** is used to cool a house on a day with an average outdoor temperature of **85°F** and that the daily outdoor temperature for the next six days is sufficiently low so that no air conditioning is needed. The average air-conditioning electricity consumption for this period is 35 **kWh/week.** If the average outdoor temperature of the remaining six days is **80°F,** the average weekly temperature is **81°F,** whereas the average weekly temperature is **76°F** if the daily temperature for the six days is **75°F.** Thus, weekly electricity consumption becomes unrelated to the weekly outdoor temperature under this situation. Because the house indoor temperature can float below the thermostat setpoint (the thermostat only controls above its setpoint), the same behavior occurs even if outdoor-indoor temperature difference is considered.

In addition to cool periods of several days duration when air conditioning is not required during the summer, outdoor temperatures often rise above typically maintained indoor temperatures during the day and below at night, on a daily basis, especially at cooler average outdoor temperatures. Use of an average temperature cannot completely capture the complex dynamics of heat flow reversal as occurs under these conditions. This behavior is somewhat analogous to space-heating energy consumption during "swing" periods (when outdoor temperatures rise above indoor and house balance point temperatures for short periods of time) which usually occurs near the beginning and end of the heating season. The difference is that "swing" periods often occur throughout the summer when cooling is considered.

Data for each house were examined individually to identity the data appropriate for the three electricity consumption-temperature regions defined above from Fig. 6.1. Data falling within the transition region were used to estimate a transition consumption constant for each house. This constant was zero in many houses (there was not a discernible transition region). Data falling within the linear region were used with the house models described below to develop regression equations. Although judgements were involved in making these decisions, there was statistical and physical validity to them.

Two air-conditioning electricity consumption models were used. The models assumed that the electricity consumption of each air conditioner was linearly related to either the temperature difference between the inside and outside of the house or to only the outdoor temperature. Two models were needed because the indoor temperature was monitored in just one room of the house and, in houses with two air conditioning units, this temperature corresponded to only one of the units. With window units, one unit is typically located in a living room and the other in a bedroom. These units are intended to cool only the room in which they are located (and perhaps an adjacent room) and arc typically operated independently from one another, so that the temperatures maintained in the rooms in which they are located may be quite different.

In houses with two air conditioners, the indoor temperature was monitored in the room with the air conditioner that the occupants reported was operated the most (labeled AC1 for the field test). Consequently, the electricity consumption of this air conditioner (presumably a larger electricity consumption than the second unit) was normalized to both indoor and outdoor temperature using the outdoor-indoor temperature difference. The second air conditioner (AC2) was only normalized to outdoor temperature. The models used were

$$E_{AC1} = A_1 + (B_1 * DT) \quad \text{and} \tag{Eq. 6-1}$$

$$E_{AC2} = A_2 + (B_2 * To) \tag{Eq. 6-2}$$

where

E_{AC} = weekly electricity consumption of the air conditioner,
DT — average weekly outdoor-indoor temperature difference,
To = average weekly outdoor temperature,
A = intercept coefficient (determined by regression), and
B = slope coefficient (determined by regression).

Linear regression techniques were used to estimate the parameters, A and B, for the pre- and post-weatherization periods for each air conditioner using the pre- and post-weatherization data, respectively, and the appropriate model for each unit. Although the electricity consumption data were collected primarily on a weekly basis, the collection periods did vary in duration (especially if a weekly reading for a given house was missed). Consequently, the electricity consumptions used in the regression analysis were normalized to weekly consumptions by dividing the electricity consumption for the period by the duration of the period in weeks. The temperatures used in the analysis were the average temperature for the period, and the average temperature difference between hourly indoor and outdoor temperatures for the period.

Weeks with little or no air-conditioning electricity consumption in the, linear region were not ignored in the analysis. This is exemplified in Fig. 6.2, where weekly electricity consumption for a hypothetical air conditioner is plotted versus an average weekly outdoor-indoor temperature difference. Weeks with no consumption indicated times when occupants chose not to operate the air conditioner even though a large temperature difference existed and they tended to operate the unit at this temperature difference at other times. Including these data in the regression retained occupant behavior within the analysis, although coefficients of determination (R^2) decreased and

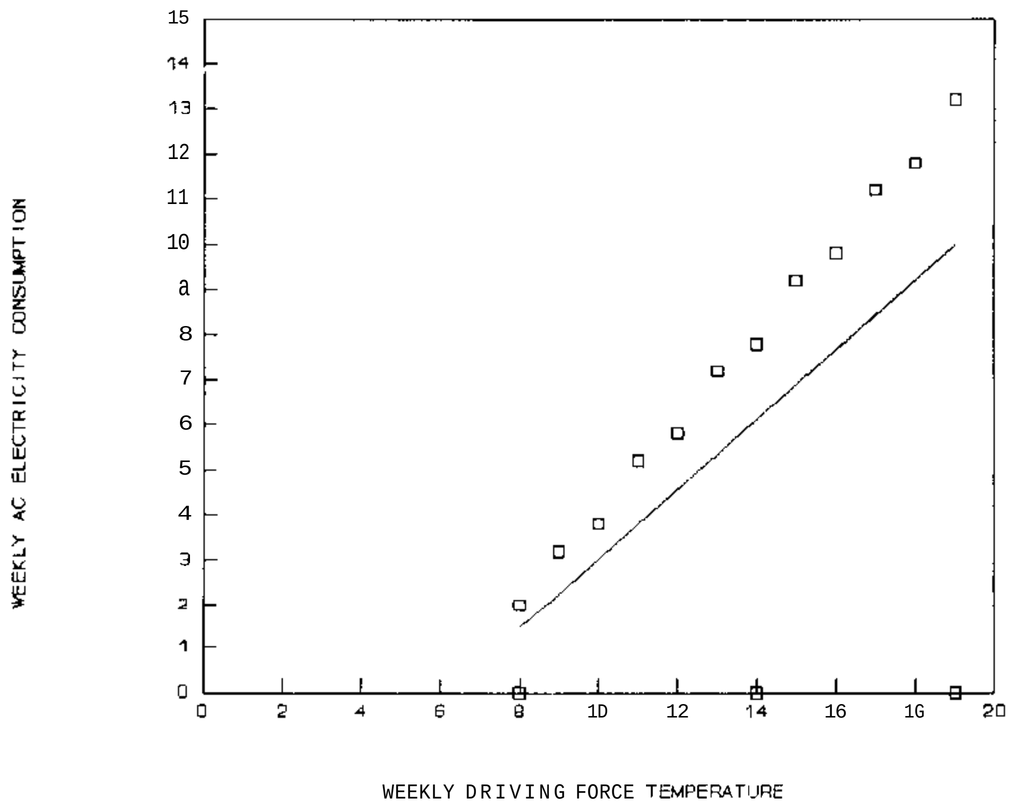

Fig. 6.2. Weekly air-conditioning electricity consumption in the linear region as a function of an average weekly outdoor-indoor temperature difference exemplifying a typical, occupied house. The solid line is a simple linear regression line for the indicated data, including the three data points with no air-conditioning electricity consumption.

uncertainty increased. An alternative approach would he to ignore these data, effectively modeling the house just when the occupants chose to operate the air conditioning units. Occupant effects would remain excluded from the analysis if the regression results were used directly to determine electricity consumptions and savings, hut could he restored in the final analysis if a "usage" factor were employed.[13] This alternative approach was examined but not used because we wanted to retain these occupant influences and because of the difficulties in determining the usage factor as described in Footnote 13.

Pre- and post-weatherization normalized annual electricity consumptions for each air conditioner were calculated using the estimated pre- and post-weatherization regression values for A and B found for each air conditioner, the transition electricity consumption constants identified for each air conditioner, outdoor temperatures from a Typical Meteorological Year (TMY) weather tape for Tulsa, Oklahoma (assumed to be a representative weather year), and the average pre-weatherization indoor temperature for each house (applicable for the AC1 units only). Weekly average outdoor temperatures and temperature differences were calculated using the pre-weatherization indoor temperature and TMY outdoor temperature data for dates between April 23 and October 14. This 25-week summer period was chosen because the average outdoor temperatures were generally greater than 70° F and, thus, air conditioning was likely required. This choice excluded the electricity consumption-temperature region when no air conditioning was required at sufficiently low temperatures. Each average weekly outdoor temperature or temperature difference was then used with values for A and B for each air conditioner to estimate a weekly air-conditioning electricity consumption. If the electricity consumption determined using the regression coefficients was less than the transition consumption constant, the weekly value was set equal to the transition value. The weekly values were summed to obtain an estimate of the normalized annual electricity consumption of each air conditioner. Normalized annual electricity savings were then found by subtracting the normalized post-weathcrization consumption from the normalized pre-weatherization consumption.

[13]Basically, a "usage" factor reflects the number of weeks the unit is allowed to run compared to the total number of weeks the unit could be operated. Referring to Fig. 5.2, a total of 15 weeks of data were collected, but the air conditioner was used for only 12 of those weeks, making the "usage" factor equal to 0.8 for this unit. The determination of the "usage" factor in actual houses is more difficult than this example because of complications regarding the inclusion or exclusion of small, non-zero consumptions. Additionally, the data to be excluded are concentrated (usually near the balance point) and, thus, are not representative across all temperatures.

7. MR-CONDITIONING ELECTRICITY CONSUMPTIONS AND SAVINGS

Using the models and analysis approaches presented in Sect. 6, normalized annual air-conditioning electricity consumptions and savings were estimated for each house. Results for 81 of the 104 houses are presented in Tables 7.1 to 7.4. Twenty-three houses were dropped from this phase of the analysis for a variety of reasons:

- 17 houses had an air conditioner that was not submetered as determined from survey information or examination of baseload electricity consumption (a unit was added to the house during the study without our knowledge or was plugged into an unmetered outlet);
- four houses had inadequate data for analyses (post-weatherization data were missing, submetered and house electricity data were inconsistent, or indoor temperature data were missing); and
- two houses did not use their air-conditioners at all during the study (either by choice or because the only existing unit was broken).

The dropped houses were evenly distributed across the four study groups: six from the control group, five from the weatherization-only group, eight from the radiant-barrier group, and six from the air-conditioner replacement group.[14] Thus, the attrition should not affect the validity of the study.

Results for three houses included in Tables 7.1-7.4 were not used to compute the group average consumptions and savings to be discussed in the following sections. Two houses (one from the control group and one from the weatherization-only group) were excluded because their air-conditioning electricity savings were not within four standard deviations of the average of their respective group. These houses deviated so greatly from the norm of their group that they were considered outliers (untypical of the rest of the results). A third house, part of the

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[14]For review, no ECMs were installed in the control houses, ECMs as currently performed under the Oklahoma WAP were installed in the weatherization only houses, ECMs as currently installed under the Oklahoma WAP plus a truss-mounted attic radiant barrier were installed in the radiant-barrier houses, and ECMs as currently installed under the Oklahoma WAP plus a high-efficiency window air conditioner in replacement of a less efficient unit were installed in the air-conditioner replacement houses.

Table 7.1. Normalized air-conditioning electricity consumptions and savings for the control group

	Regression information						Normalized annual electricity consumption						Normalized annual electricity savings**			
	Pre-weatherization			Post-weatherization			Pre-weatherization			Post-weatherization						
	Weeks of data	Coefficient of determination		Weeks of data	Coefficient of determination											95% confidence interval
House		AC1	AC2		AC1	AC2	AC1 (kWh)	AC2 (kWh)	Total (kWh)	AC1 (kWh)	AC2 (kWh)	Total (kWh)	AC1 (kWh)	AC2 (kWh)	Total (kWh)	(kWh)
17	9	0.11		15	0.76		1385	0	1385	493	0	493	892	0	892	339
25	10	0.95		15	0.93		3038	0	3038	3333	0	3333	-295	0	-295	170
30	7	0.64		15	0.68		390	0	390	446	0	446	-56	0	-56	162
31	14	0.65		15	0.82		523	0	523	261	0	261	263	0	263	152
37	10	0.59		12	0.06		8	0	8	9	0	9	-1	0	-1	306
40	12	0.56	0.27	15	0.61	0.72	238	38	275	258	95	353	-21	-57	-78	216
43	12	0.92		14	0.89		1663	0	1663	1320	0	1320	343	0	343	185
50	13	0.88		8	0.48		1300	0	1300	929	0	929	371	0	371	372
51	12	0.88		13	0.90		863	0	863	1170	0	1170	-307	0	-307	177
52	13	0.87		15	0.90		2711	0	2711	2688	0	2688	23	0	23	271
57	13	0.17	0.37	16	0.33	0.25	4536	1172	5708	4324	1995	6320	212	-823	-611	597
67	13	0.92	0.60	13	0.93	0.71	435	322	757	429	591	1019	6	-268	-262	171
68	13	0.84		15	0.84		640	0	640	792	0	792	-152	0	-152	205
82	11	0.35	0.00	16	0.81	0.00	1556	209	1764	1280	0	1280	275	209	484	381
90	14	0.87		15	0.90		2150	0	2150	2996	0	2996	-847	0	-847	205
109	12	0.81		13	0.25		305	0	305	122	0	122	183	0	183	400
111	11	0.88		12	0.79		1261	0	1261	1003	0	1003	257	0	257	164
118	13	0.34		16	0.89		2500	0	2500	1477	0	1477	1024	0	1024	237
120	12	0.94		16	0.00		835	0	835	38	0	38	797	0	797	74
Average:									1478			1371			107	290
19*	9	0.94	0.55	15	0.90	0.00	4998	328	5326	2081	0	2081	2917	328	3245	200

*This house was not used to calculate average group savings because its savings was not within tour standard deviations of the average.
**Negative values indicate increased electricity consumption.

Table 7.2. Normalized air-conditioning electricity consumptions and savings for the weatherization-only group

	Regression information						Normalized annual electricity consumption						Normalized annual electricity savings**			
	Pre-weatherization			Post-weatherization			Pre-weatherization			Post-weatherization						
House	Weeks of data	Coefficient of determination AC1	Coefficient of determination AC2	Weeks of data	Coefficient of determination AC1	Coefficient of determination AC2	AC1 (kWh)	AC2 (kWh)	Total (kWh)	AC1 (kWh)	AC2 (kWh)	Total (kWh)	AC1 (kWh)	AC2 (kWh)	Total (kWh)	95% confidence interval (kWh)
3	12	0.88		14	0.80		1471	0	1471	1279	0	1279	192	0	192	130
7	12	0.88		15	0.73		2910	0	2910	2348	0	2348	562	0	562	244
15	6	0.88		15	0.84		1684	0	1684	1510	0	1510	174	0	174	176
23	12	0.69		16	0.73		2188	0	2188	1848	0	1848	340	0	340	336
24	10	0.83		15	0.86		2007	0	2007	3084	0	3084	-1078	0	-1078	284
41	12	0.92	0.54	16	0.40	0.58	1439	2508	3947	1432	2091	3523	6	417	424	187
42	12	0.59		16	0.76		1847	0	1847	1302	0	1302	545	0	545	157
47	14	0.80		0	0.00		211	0	211	0	0	0	211	0	211	109
48	11	0.93		5	0.95		1012	0	1012	2428	0	2428	-1416	0	-1416	72
53	13	0.68		16	0.77		2720	0	2720	3314	0	3314	-595	0	-595	325
54	9	0.84		15	0.89		852	0	852	662	0	662	190	0	190	141
59	14	0.89	0.00	15	0.67	0.10	1219	0	1219	603	206	809	616	-206	410	155
61	12	0.43	0.12	15	0.36	0.00	1051	431	1483	886	124	1009	166	308	473	631
62	12	0.38		16	0.92		1529	0	1529	1688	0	1688	-159	0	-159	214
69	14	0.41		16	0.79		1780	0	1780	4230	0	4230	-2450	0	-2450	147
71	12	0.28		16	0.00		154	0	154	25	0	25	128	0	128	109
75	11	0.92		15	0.96		2539	0	2539	2240	0	2240	299	0	299	106
89	14	0.66		15	0.83		1462	0	1462	1113	0	1113	349	0	349	134
97	6	0.93		15	0.91		648	0	648	1361	0	1361	-713	0	-713	147
103	11	0.80		15	0.94		1719	0	1719	691	0	691	1028	0	1028	263
104	11	0.47		15	0.64		4209	0	4209	4203	0	4203	5	0	5	402
110	12	0.81		16	0.93		2080	0	2080	1690	0	1690	391	0	391	140
Average:									1803			1834			-31	393
102*	13	0.47	0.66	4	0.69	0.73	2356	813	3170	6705	1317	8022	-4349	-503	-4852	798

*This house was not used to calculate average group savings because its savings was not within four standard deviations of the average.
"Negative values indicate increased electricity savings.

Table 7.3. Normalized air-conditioning electricity consumptions and savings for the radiant-barrier group

	Regression information						Normalized annual electricity consumption						Normalized annual electricity savings*			
	Pre-weatherization			Post-weatherization			Pre-weatherization			Post-weatherization						
House	Weeks of data	Coefficient of determination AC1	Coefficient of determination AC2	Weeks of data	Coefficient of determination AC1	Coefficient of determination AC2	AC1 (kWh)	AC2 (kWh)	Total (kWh)	AC1 (kWh)	AC2 (kWh)	Total (kWh)	AC1 (kWh)	AC2 (kWh)	Total (kWh)	95% confidence interval (kWh)
6	12	0.85		15	0.88		492	0	492	403	0	403	89	0	89	124
14	12	0.57	0.51	14	0.95	0.07	768	129	897	1373	247	1621	-605	-119	-724	287
2ft	13	0.75	0.00	13	0.64	0.24	2495	98	2593	1358	65	1423	1137	33	1170	482
27	13	0.94		14	0.90		2328	0	2328	3419	0	3419	-1091	0	-1091	169
32	13	0.89		15	0.95		444	0	444	340	0	340	104	0	104	95
35	13	0.55		12	0.71		728	0	728	1516	0	1516	-788	0	-788	387
38	12	0.44		15	0.71		177	0	177	109	0	109	68	0	68	134
55	14	0.79		10	0.87		2323	0	2323	1963	0	1963	360	0	360	184
65	10	0.91		15	0.89		750	0	750	766	0	766	-16	0	-16	93
74	13	0.90		15	0.91		4221	0	4221	4494	0	4494	-273	0	-273	308
83	14	0.89		12	0.75		564	0	564	696	0	696	-132	0	-132	196
87	12	0.91		14	0.92		1488	0	1488	1491	0	1491	-3	0	-3	146
88	12	0.71		15	0.83		1009	0	1009	1186	0	1186	-177	0	-177	533
95	14	0-84	0.33	7	0.96	0.00	707	398	1105	238	167	405	470	230	700	235
98	13	0.84		9	0.86		3922	0	3922	3668	0	3668	254	0	254	256
106	12	0.66		13	0.87		1446	0	1446	1826	0	1826	-380	0	-380	193
108	12	0.35		14	0.75		103	0	103	115	0	115	-12	0	-12	282
115	11	0.15		16	0.83		883	0	883	978	0	978	-95	0	-95	444
117	13	0.79		15	0.76		2106	0	2106	2142	0	2142	-36	0	-36	200
Average:									1452			1503			-52	299

*Negative values indicate increased electricity consumption.

Table 7.4. Nonnalizcd air-conditioning electricity consumptions and savings for the air-conditioner replacement group

House	Regression information: Pre-weatherization: Weeks of data	Pre-weatherization: Coefficient of determination AC1	Pre-weatherization: Coefficient of determination AC2	Post-weatherization: Weeks of data	Post-weatherization: Coefficient of determination AC1	Post-weatherization: Coefficient of determination AC2	Normalized annual electricity consumption: Pre-weatherization AC1 (kWh)	Pre-weatherization AC2 (kWh)	Pre-weatherization Total (kWh)	Post-weatherization AC1 (kWh)	Post-weatherization AC2 (kWh)	Post-weatherization Total (kWh)	Normalized annual electricity savings**: AC1 (kWh)	AC2 (kWh)	Total (kWh)	95% confidence interval (kWh)
1	11	0.88	0.71	16	0.86	0.21	2337	165	2502	1521	189	1710	815	-24	792	195
2	8	0.92		16	0.93		4701	0	4701	2976	0	2976	1725	0	1725	140
11	14	0.13		14	0.71		516	0	516	232	0	232	285	0	285	287
13	12	0.90	0.00	15	0.85	0.25	2720	0	2720	1978	43	2021	743	-43	699	117
45	13	0.91	0.36	15	0.53	0.37	1849	587	2436	2427	701	3129	-579	-115	-693	220
58	13	0.71	0.72	15	0.76	0.83	589	208	797	514	399	914	74	-191	-117	158
60	12	0.88		15	0.46		187	0	187	115	0	115	72	0	72	167
64	12	0.89	0.00	15	0.97	0.00	2768	181	2949	1569	61	1629	1200	120	1320	173
72	12	0.84		12	0.89		1244	0	1244	431	0	431	813	0	813	186
78	12	0.89		16	0.91		2584	0	2584	2611	0	2611	-27	0	-27	169
79	13	0.86		15	0.88		3701	0	3701	2452	0	2452	1248	0	1248	181
81	12	0.00		15	0.89		31	0	31	123	0	123	-92	0	-92	336
85	10	0.89		16	0.77		3158	0	3158	1438	0	1438	1720	0	1720	145
91	13	0.80		15	0.77		798	0	798	370	0	370	428	0	428	180
99	14	0.83		16	0.95		2215	0	2215	2282	0	2282	-67	0	-67	97
105	12	0.00		14	0.14		322	0	322	13	0	13	309	0	309	61
113	10	0.79	0.84	14	0.92	0.55	1127	4%	1623	659	554	1213	467	-58	409	191
119	13	0.92		15	0.91		1953	0	1953	1156	0	1156	797	0	797	154
Average:									1913			1379			535	362
20*	14	0.84		16	0.91		1043	0	1043	1758	0	1758	-716	0	-716	166

"This house was not used to calculate average group savings because a replacement air conditioner was not installed in this house.
"Negative values indicate increased electricity consumption.

air-conditioner replacement group, was dropped because thc existing air conditioner did not quality for replacemcnt. By excluding this house, the savings achieved from actual replacements rather than a replacement program (in which all houses would not qualify) was studied. To some degree, this house could be considcrcd a weatherizcd only house, although such an approach was not followed. Although the threc houses were excluded because of air-conditioning electricity savings considerations, thcy were also excluded from thc analysis of pre-wcatherization air-conditioning electricity consumptions for consistency.

Coefficients of determination (R^2) for thc regressions are presented in Tables 7.1-7.4. Over half the coefficients of determination for the AC1 modcls (which uscd outdoor-indoor temperature diffcrcncc) were greater than 0.8 and most wcrc greatcr than 0.6: the coefficient was greater than 0.6 in 74% of the houses for the prc-weathcrization period and in 85% for the post-weathcrization period. Coefficients for the AC2 models (which used only outdoor temperature) wcrc not as high: thc coefficient was greater than 0.5 in only 56% of the houses for the prc-weatherization period and in 44% for the post-weatherization period.

Coefficicnts of determination for space-healing analyses are generally greatcr than those obtained for this space-cooling analysis. Coefficients are greater than 0.8 in more than 90% of thc houses studicd in a previous experiment using submetered space-heating energy consumption and indoor tcmperaturc (Tcrnes et al. 1991). Several reasons for this difference are proposed:

- Air-conditioning consumption is influenced by at least three weathcr variablcs (tcmperaturc, humidity, and solar radiation), whereas space-heating energy consumption is strongly dependent on tcmpcraturc alone. Prior experience and exploratory investigations indicated that multiple rcgrcssion analysis of wcckly air-conditioning consumption data docs not considerably improve correlations. Regrcssion coefficients often lack physical meaning, making extrapolations unccrtain.

- Swing pcriods, when average outdoor and indoor tcmpcraturcs arc ncar equality, can distort regressions. These periods usually occur near the start and cnd of thc winter (especially in colder climates) and are often ignored in spacc-hcating analyscs (Mcicr et al. 1986). Summers can he constant swing periods bccause outdoor temperatures oftcn oscillate abovc and below house indoor temperature over a day and cool periods occurring in the summer allow air conditioners to bc turned off for short periods.

- Control of window air conditioners is likeiy more occupant dependent and sporadic than that of central heating systems.

Therefore, the relatively high coefficients of determination obtained for the AC1 models (regressions were based on outdoor-indoor temperature differences) were surprising. Coefficients for the AC2 models were not as good because the regressions were based on outdoor temperature only. Additionally, these second air conditioners were used much less frequently than the main AC1 air conditioners. We theorize that the use of these second air conditioners is more highly dependent on occupant choices that are made on factors other than outdoor temperature. The high coefficients for the AC1 models supported the importance of measuring indoor temperature and lent credibility to the field study results.

The pre-weatherization summer period was considerably hotter than the post-weatherization summer. For the period between June 1 and September 19 when field data were predominately collected, the average pre-weatherization outdoor temperature was 82.0° F and the cooling degree hours (base 74° F) were 24,565. For the same calendar dates, the average post-weatherization outdoor temperature was 77.6° F and the cooling degree hours were 15,563. The normalization technique employed in the analysis was designed to account for this difference in pre- and post-weatherization conditions. Comparison of results to the control houses eliminated any secondary effects caused by the weather differences.

7.1 AIR-CONDITIONING ELECTRICITY CONSUMPTION

Total (ACl and AC2) pre-weatherization air-conditioning electricity consumptions of the 78 test houses averaged 1664 kWh/year (the median value was 1485 kWh/year), ranging between 8 and 5708 kWh/year. Figure 7.1 shows that one-third of the houses used less than 1000 kWh/year (about 10% used less than 250 kWh/year) and about 10% used 3000 kWh/year or more. Differences in the number and size of the air conditioners present, the portion of the house cooled by the units. the degree the air conditioners were used, indoor temperature maintained, and house differences (e.g., insulation levels and shading) all contributed to this large variation in consumption.

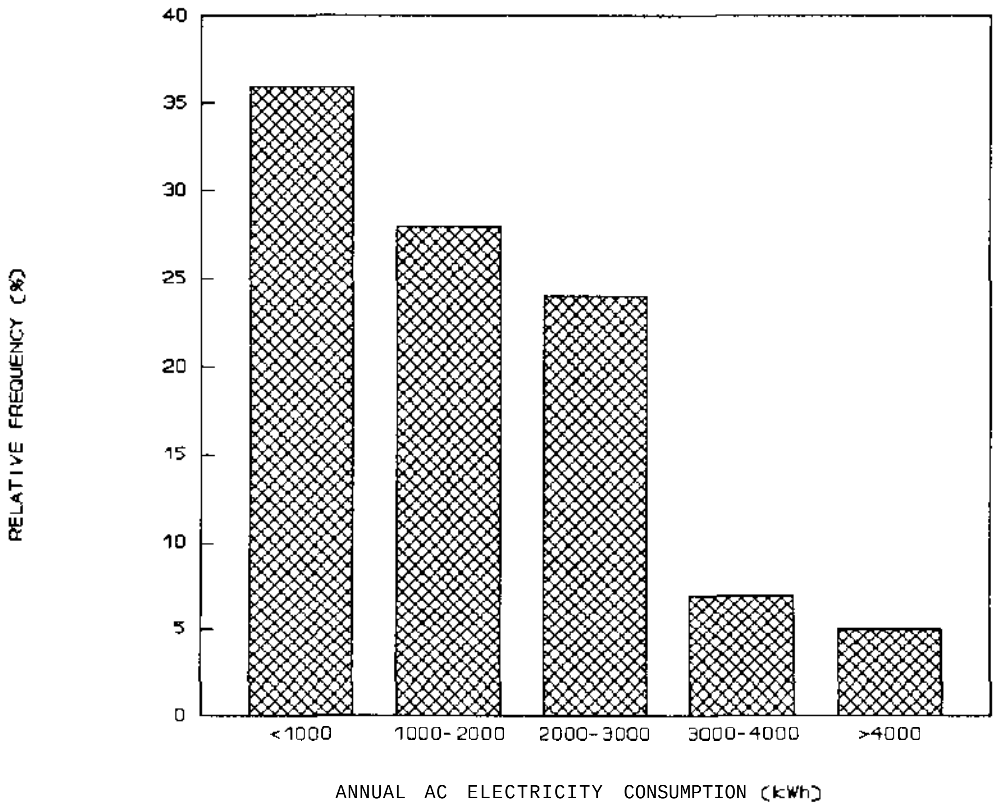

Fig. 7.1. Histogram of normalized annual pre-weatherization air-conditioning electricity consumption.

These air-conditioning electricity consumptions were much lower than consumptions measured in larger, non low-income houses located in more southern climates and cooled by central air conditioners (which generally cooled the entire living area rather than just one or two rooms as with window units). Parker (1990) measured consumptions ranging from 144 to 21,934 kWh/year (the average was 8163 kWh/year) in 25 houses with an average floor area of 1891 ft^2 located in Palm Beach County, Florida. Hough and Burns (1990) predicted an average consumption from measured data of 5110 kWh/year for 14 houses with a floor area of 1503 ft^2 located in Austin, Texas.

Figure 7.2 shows that the average pre-weatherization air-conditioning electricity consumptions of the four groups differed by only several hundred kWh/year: 1478 kWh/year for

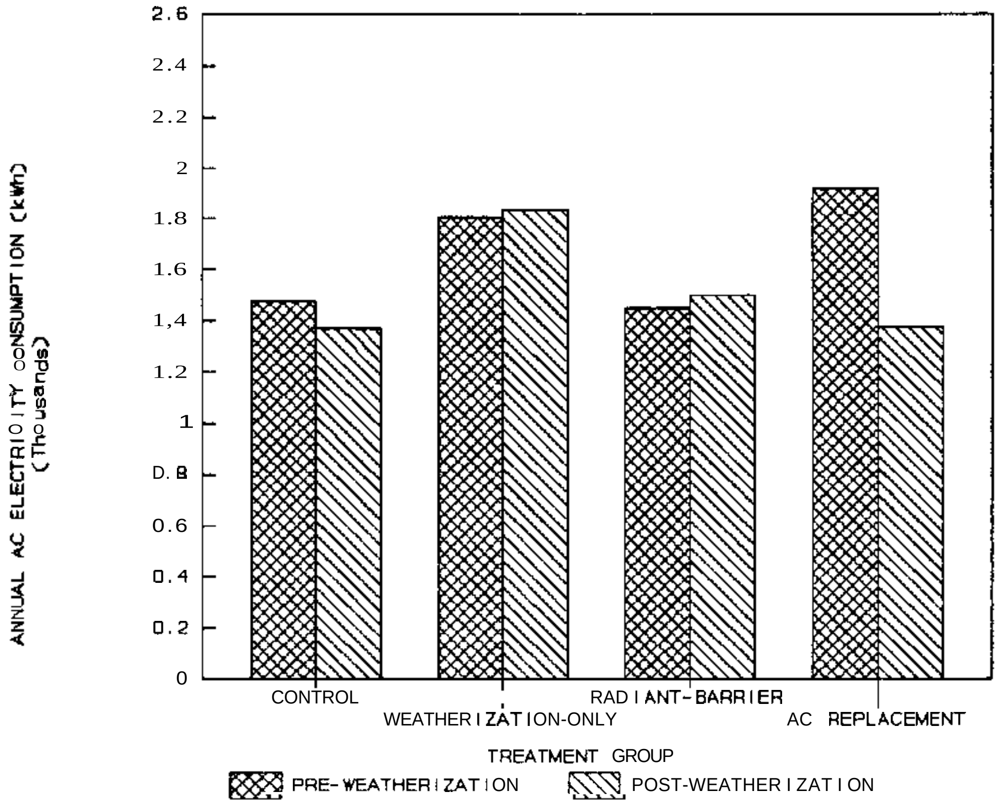

Fig. **7.2.** Average normalized prc- and **post-weatherization** annual **air-conditioning electricity** consumptions for the four groups of test houses.

the control houses, 1803 kWh/year for the weatherization-only houses, 1452 kWh/year for the radiant-barrier houses, and 1913 kWh/year for the air-conditioner replacement houses. An analysis of variance indicated that there were no differences among these average pre-weatherization consumptions at a 95% confidence level (a statistically significant difference could not be concluded even at a 75% confidence level). Median values showed more disparity between groups: 1281 kWh/year for the control houses, 1718 kWh/year for the weatherization-only houses, 1009 kWh/year for the radiant-barrier houses, and 2084 kWh/year for the air-conditioner replacement houses.

The 1990 (and still current) cost for residential electricity in the Tulsa area during the summer months (June to September) was $0.06447/kWh for the first 1000 kWh used in a house and $0.07147/kWh for any monthly consumption above 1000 kWh. Using the higher rate to calculate a maximum possible cost, the average air-conditioning electricity cost was $119/year.

The following analysis was performed to put an upper bound on the air-conditioning electricity cost savings that could he reasonably expected from ECMs applied to the housing stock used in the field test. Assuming the average air-conditioning consumption can be reduced 50% by an optimum set of ECMs (even though the best group savings in the field test was less than 30%), a savings of about 800 kWh/year ($57/year) would be expected for these houses. Although only 10% of the houses used more than 3000 kWh/year, a savings of 1500 kWh/year ($107/year) would be expected if houses with this level of consumption were targeted. The potential savings for the test houses were limited because of the small house sizes, the non-extreme cooling climate, the use of window air conditioners which generally cooled only small portions (one or two rooms) of the houses, and the operating strategies of the air conditioners chosen by the occupants. Considering the wide variation in air-conditioning electricity consumptions, this analysis also indicated the importance of targeting houses with high consumption to obtain the most cost-effective installations of ECMs.

In houses with two air conditioners, the average electricity consumption of the AC1 air conditioners was 1615 kWh/year and the AC2 air conditioners was 434 kWh/year. With only one exception, the AC1 consumption was always greater than the AC2 consumption for a given house. In the one exception, the ACl consumption was 1439 kWh/year and the AC2 consumption was 2508 kWh/year. These results implied that the air conditioner with the greatest electricity consumption in each house was properly identified by the occupants at the start of the study and that indoor temperature was monitored in the zone conditioned by the more important unit from an electricity consumption perspective.

7.2 AIR-CONDITIONING ELECTRICITY SAVINGS

Normalized air-conditioning electricity savings averaged 107 kWh/year (7% of pre-weatherization consumption) for the control group, -31 kWh/year (-2%) for the weatherization-only group, -52 kWh/year (-4%) for the radiant-harrier group, and 535 kWh/year (28%) for the air-conditioner replacement group. These savings arc shown in Fig. 7.2, where the average pre-weatherization electricity consumptions are compared to post-weatherization consumptions for each group. Both pre- and post-weatherization AC1 consumptions were normalized to the pre-weatherization indoor temperature measured in each house, which averaged 81° F. Median values of the savings showed similar results: 103 kWh/year for the control group, 192 kWh/year for the weatherization-only group, -16 kWh/year for the radiant-barrier group, and 419 kWh/year for the air-conditioner replacement group.

At a 95% confidence level, the average savings of the air-conditioner replacement group (535 kWh/year) was significantly different from zero. At this same confidence level, the average savings of the control group, weatherization-only group, and radiant-barrier group were not significantly different from zero. The 95% confidence intervals listed in Tables 7.1-7.4 for the average group savings included uncertainty associated with the individual savings for each house in addition to uncertainty from the variation in savings among houses. The variation in savings among houses (and, hence, the group confidence levels) were large because of many factors, including the wide variation that occurred in the pre-weatherization air-conditioning electricity consumptions of the houses and differences in the ECMs installed within each group.

An analysis of variance indicated that, at the 95% confidence level, there were significant differences among the average air-conditioning electricity savings of the four groups. Using Duncan's multiple range test at the same confidence level, the average savings of the air-conditioner replacement group was determined to be significantly different from the other three groups and the average savings of the remaining three groups were not significantly different from each other. These analyses were performed without considering the uncertainty in the individual house savings estimates (i.e., the analyses were performed assuming the individual house savings were known without error). This should not be critical because the uncertainty in individual house savings increased the 95% confidence levels of the groups by only about 15%.

The average savings of 535 kWh/year ($38/year and 28% of pre-weatherization air-conditioning electricity consumption) measured in the air-conditioner replacement group was attributed to just the installation of high-efficiency air conditioners because no average savings was measured in the weatherization-only group. There is some question as to whether these savings should be adjusted by the control group or the weatherization-only group; consequently, no adjustments are presented in this report. The measured savings were close to an expected value of about 33%. A savings of 33% was expected assuming the new air conditioners (EER = 9.0) replaced units with EERs of about 6 and the second air conditioners present in some houses were infrequently used.

The distribution of individual house air-conditioning electricity savings for each group is shown in Fig. 7.3. Each group included houses with positive and negative savings. There were eight houses with savings greater than 500 kWh/year in the air-conditioner replacement group, whereas only two or three such houses were in each of the other three groups. The only two houses with savings greater than 1500 kWh/year were both in the air-conditioner replacement

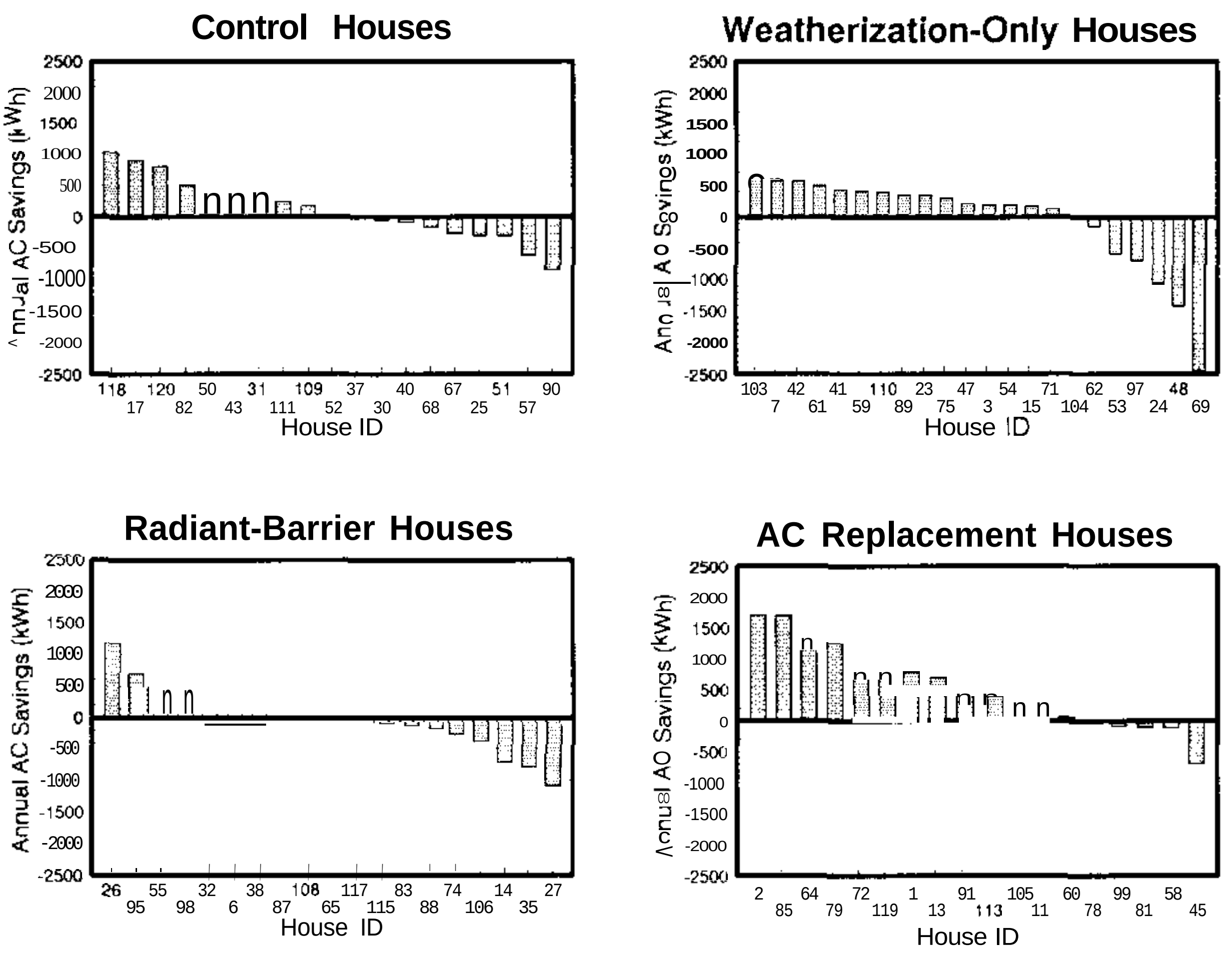

Fig. 7.3. Distribution of individual normalized annual house air-conditioning electricity savings for the four groups of test houses.

group. The air-conditioner replacement group had the fewest houses with negative savings and with large negative savings (greater than 500 kWh/year). Although a large percentage (about 75%) of the houses in the weatherized only group experienced positive savings (about the same percentage as found in the air-conditioner replacement group), the magnitude of the negative savings experienced in the remaining weatherization-only houses was quite large (larger than the other three groups).

Air-conditioning electricity savings of the houses in the air-conditioner replacement group were dependent on the pre-weatherization air-conditioning electricity consumptions, as indicated from Fig. 7.4. Three houses with pre-weatherization consumptions of approximately 2500 kWh/year had negative savings. Reasons for these houses not following the trend for the other houses were not known. If these three houses were considered to be outliers, the correlation between savings and pre-weatherization consumption was greatly improved (R^2 raised from 0.39 to 0.82). The average savings of the replacements was 694 kWh/year if the three outlier houses were not considered, compared to 535 kWh/year. For the four (of 18) air-conditioner replacement houses with pre-weatherization consumptions greater than 2750 kWh/year, the average savings of the replacements was 1503 kWh/year (41% of their average pre-weatherization consumption), which was nearly three times that observed for the group as a whole.

No correlation ($R^2 < 0.06$) was found between savings and pre-weatherization consumptions for the other three groups. Because even radiant-barrier houses with high pre-weatherization air-conditioning electricity consumptions did not demonstrate significant savings, the fact that this group's average pre-weatherization air-conditioning electricity consumption was lower than the other three groups does not likely affect the overall results.

ECMs installed under the Oklahoma WAP and combined with a truss-mounted attic radiant barrier did not produce air-conditioning electricity savings that could be measured in the field test. This was evidenced by the average savings of the weatherization-only group and radiant-barrier group being statistically the same as the control group and each other, and not statistically different from zero. Some savings were expected from these ECMs even though the ECMs installed under the Oklahoma WAP are justified for space-heating rather than air-conditioning electricity reductions.

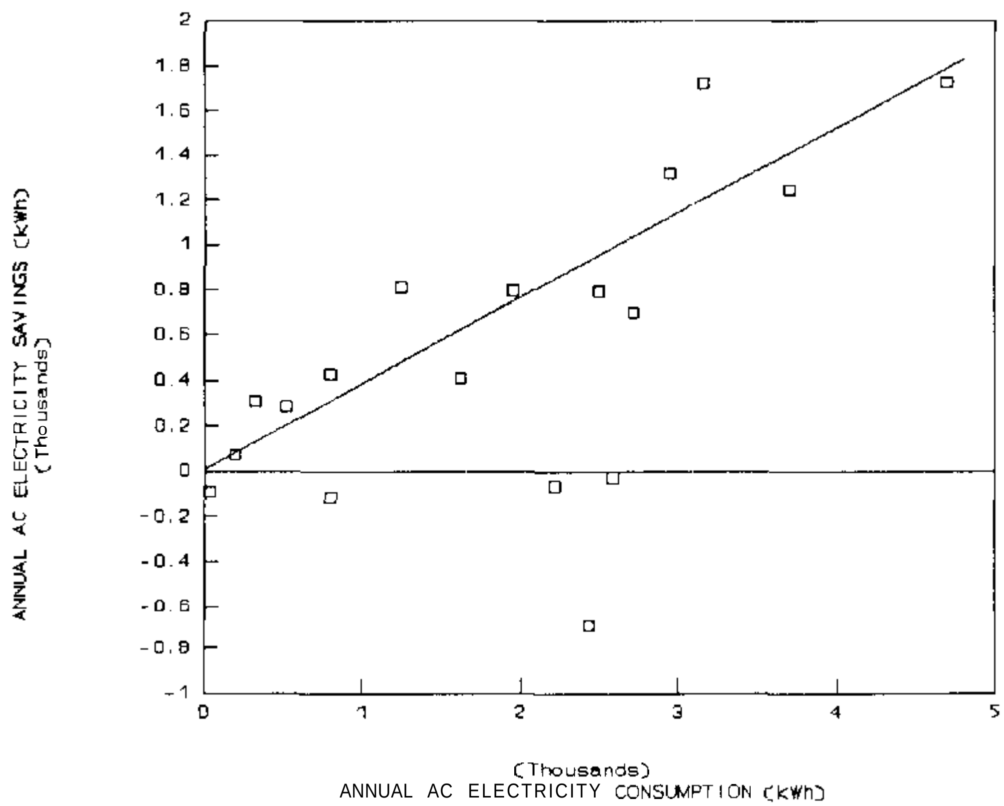

Fig. 7.4. Comparison of normalized annual air-conditioning electricity savings for the air-conditioner replacement houses to their annual pre-weatherization air-conditioning electricity consumptions. The solid line is a simple linear regression line for the measured data, excluding the three data points with pre-weatherization electricity consumptions of about 2500 kWh/year and negative savings.

Reasons for the lack of savings were not known. The lack of equivalency among the groups was not a likely factor because a random assignment process was followed, pre-weatherization consumptions were statislically the same, and costs for ECMs installed under the Oklahoma WAP were the same (implying the houses required approximately the same degree of improvement). Post-inspections revealed that the radiant-harrier installations were of high quality. Emissivity measurements of radiant-barrier samples taken from four houses (see Appendix B) showed that the reflective surfaces had not degraded due to dust accumulation or other reasons (the emissivity of the radiant-barrier surface facing downward was less than or equal to its manufactured value of 0.05 in all four houses). Possible explanations include:

- The savings produced by the ECMs installed under the Oklahoma WAP and by radiant barriers were smaller than the field test could measure. The expected savings of the ECMs were small for the test houses considering that the primary WAP ECMs only addressed two components of the total cooling load (attic insulation reduced heat flow through the ceiling and storm windows reduced conduction through the windows), a radiant barrier addressed one of the same components addressed by the WAP ECMs (reduced heat flow through the ceiling), and the pre-weatherization air-conditioning electricity consumptions were small. The field test results were only sufficiently accurate to show that the savings of the weatherization-only and radiant-barrier groups were less than 362 kWh/year and 247 kWh/year, respectively, at a 95% confidence level. A weakness with this explanation is that the best estimate of the average measured savings of the control group houses was about 150 kWh/year greater than that for the weatherization-only and radiant-barrier groups.

- ECMs that kept heat out of the house also tended to keep heat in the house. This was an important consideration for window air conditioners that were controlled manually as well as by a thermostat. Low measured air-conditioning electricity consumptions and high indoor temperatures suggested that the occupants of these houses often ventilated their houses as much as possible and/or turned units off during unoccupied periods. If the installed ECMs trapped more heat in the house during unoccupied periods than before and/or reduced the effectiveness of ventilation, greater use of the air conditioners could have resulted to negate any potential savings.

7.3 SAVINGS ECONOMICS

The economics of replacing a low-efficiency air conditioner with a high-efficiency unit in the test houses are examined in Sect. 7.3.1 for a federally-sponsored weatherization program. The application of these results to a utility program and occupant are discussed in subsequent sections.

73.1 Federally-Sponsored Weatherization Program

The economics of replacing a low-efficiency air conditioner with a high-efficiency unit in the test houses to improve their energy efficiency was examined for a federally-sponsored weatherization program using a total resource test. The total resource test generally reflects the costs and benefits that would be experienced by all of society. In this test, costs and benefits are considered regardless of who pays for or receives them. Examination of the economics of this replacement was made complicated by the fact that the existing units were still operational, with a remaining lifetime less than that for a new unit. Additionally, it was likely that the existing units would he replaced with higher-efficiency units at the time of their failure if they were not replaced at the time of the field test. Ceiling insulation, for example, does not have these complicating factors: an uninsulated ceiling will likely remain uninsulated for the duration of its life (especially in low-income houses), and uninsulated and insulated ceilings have the same lifetimes.

Benefit-to-cos! ratios were calculated for each house using the following assumptions:

- Benefits were limited to electricity savings obtained from replacing low-efficiency window air conditioners (EER assumed to he less than 6.0) with high-efficiency units (EER equal to 9.0 or greater). Benefits did not include consideration of improved comfort, health, or safety. Externalities such as reduced environmental pollution, increased economic activity, and improved national security were also not considered.

- 1990 (and still current) costs for residential electricity in the Tulsa area during the summer months (June to September) were used to convert electricity savings in energy units to dollars. This cost was $0.07147/kWh, which is the cost for any monthly consumption above 1000 kWh.

- Service lifetimes of 10 and 15 years were estimated for new window air conditioners. Ten years is the median lifetime reported by ASHRAE (1991) for window air conditioners, while lifetimes of 15 years were reported for other air conditioning equipment. Field observations indicate that window air conditioners may be used longer than average in low-income houses.

- When using a service lifetime of 10 years, the remaining lifetimes of the existing units were assumed to be 1, 5, or 10 years. The average age of the existing units was 9 years. Assuming the existing units have total lifetimes the same as new units, then remaining lifetimes would be 1 year. A remaining lifetime of 10 years was used to be equal to lifetimes of new units, and 5 years was used as an intermediate value. Similarly, when using a service lifetime of 15 years, the remaining lifetimes of the existing units were assumed to be 1, 5, 10, or 15 years.

- The occupants would install a replacement unit when the remaining lifetime of the existing unit was zero. The replacement units would have the same efficiency as the units installed under the field test.[15] The National Appliance Energy Conservation Act of 1987 stipulated that window air conditioners manufactured after January 1, 1990 had to meet minimum efficiency standards. The air conditioners installed under the field test generally had efficiencies equal to the minimum stipulated values.

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[15]This was a conservative assumption that decreased cost effectiveness.

- Costs were the incremental material and labor cost of replacing the air conditioners now rather than upon failure. The total resource test does not consider who pays the costs. *The* occupants of the houses will likely buy a new air conditioner whenever the present unit fails. For a new unit installed now under a weatherization program, this will be after 10 or 15 years depending on the assumed lifetime; if the current unit was not replaced, then this will occur earlier. Other costs devoted to the measure, such as administration costs, were not included. Installation costs estimated for a weatherization program were used rather than costs actually incurred under the field test (see Sect. 4.2).

- Discount factors adjusted for average fuel price escalation and based on a 4.6% discount rate were used in the calculations. These factors were consistent with those recommended by Lippiatt (1991) for Federal energy conservation projects.

Sample calculations are provided in Appendix C to demonstrate the method employed. An interesting result of the analysis was that, for an existing unit with a fixed efficiency, the benefit-to-cost ratio of the replacement was independent of the remaining lifetime of the existing unit (although it was dependent on the service lifetime of the new unit).[16] Although the incremental cost associated with installing the replacement unit now rather than in the future increased as the remaining lifetime increased, there were more years over which electricity savings occurred. This is proven in Appendix C.

The general replacement of low-efficiency air conditioners with high-efficiency units (replacing units in all houses without considering pre-weatherization air-conditioning electricity consumption) was not cost effective in the test houses under the stated set of assumptions. The benefit-to-cost ratios were 0.41 and 0.55 (Table 7.5) depending on the service lifetime of the replacement air conditioner.[17] The cost effectiveness of this approach was not more attractive primarily because the low pre-weatherization air-conditioning electricity consumptions generally observed in these houses offered low potential for savings; air conditioners costing $500 to $700 were installed in many houses that, for whatever reason, used less than $175/year to air condition.

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[16]The benefit-to-cost ratio is indirectly dependent on the remaining lifetime of the existing unit. In general, the older the existing unit, the fewer remaining years the unit has. Because older units are likely to be less efficient than newer units, annual savings estimated for a high-efficiency replacement will likely be higher for an older unit than a newer unit. Thus, older units will more likely be economical to replace.

[17]To be cost effective, the benefit-to-cost ratio must be greater than or equal to 1.0.

Table 7.5. Economics of air-conditioner replacements

	All houses	Houses with pre-weatherization air-conditioning electricity consumption greater than 2750 kWh/year
Average annual savings[1]	535 kWh	1503 kWh
	$38.23	$107.42
Average estimated installation cost[2]	$739	$786
Benefit-to-cost ratio[3]:		
10-year service lifetime	0.41	1.08
15-year service lifetime	0.55	1.47
Simple payback period	19.3 years	7.3 years

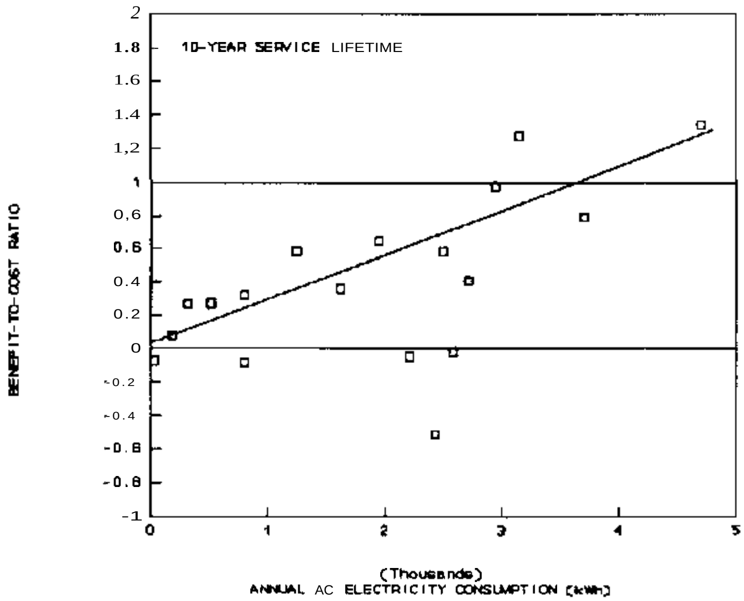
[1]Dollar savings were based on an electricity cost of $0.07147/kWh. This was the 1990 (and current) cost for electricity in the Tulsa area during the summer months for any monthly consumption above 1000 kWh.

[2]Installation costs were estimated for a weatherization program. We felt that costs actually incurred under the field test were high because of the experimental nature of the study.

[3]Discount factors adjusted for average fuel price escalation and based on a 4.6% discount rate were used in the calculations.

Targeting houses based on high consumption made the replacements cost effective. As with the electricity savings, the benefit-to-cost ratio for the replacement performed in each house was dependent on the pre-weatherization air-conditioning electricity consumption, as indicated from Fig. 7.5. For the houses tested, a clear trend was established depending on the assumed service lifetime: replacements were generally cost effective in houses with pre-weatherization consumptions greater than about 3600 kWh/year if a 10-year service life was assumed and 2700 kWh/year if a 15-year service lifetime was assumed. For the subgroup of test houses with pre-weatherization consumptions greater than 2750 kWh/year, replacement of the low-efficiency air conditioners was cost effective, as indicated by the benefit-to-cost ratios of 1.08 and 1.47 (see Table 7.5). The simple payback period for the replacements performed in this subgroup of houses was 7.3 years.

The benefit-to-cost ratio was very sensitive to the electricity cost and discount rate used in the calculations, and the assumption that a replacement unit installed in several years by the occupant would have the same efficiency as the unit installed now under the weatherization



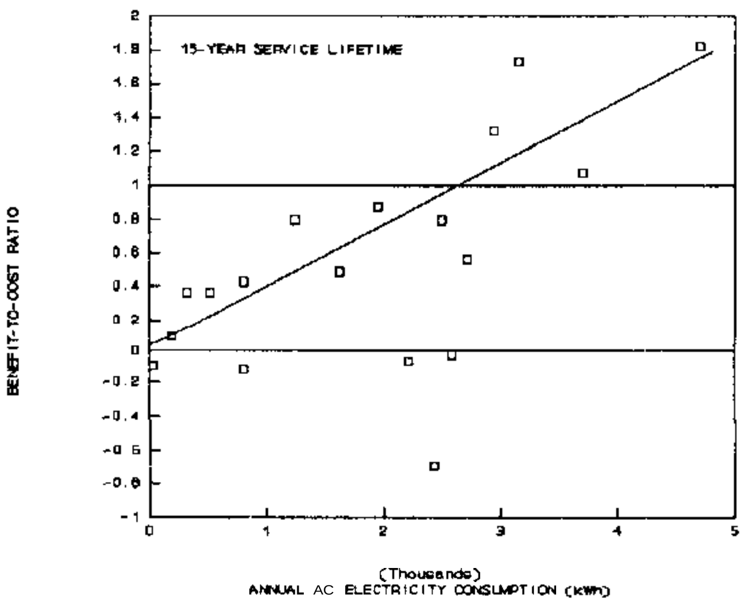


Fig. 7.5. Comparison of the **benefit-to-cost** ratios calculated for the **air-conditioner** replacement houses to their annual **pre-weatherization air-conditioning** electricity consumptions. The service lifetime of a new air conditioner was assumed to be 10 years in the top graph and 15 years in the bottom graph. The solid line in both graphs is a simple linear regression line for the calculated values, excluding **the three** data points with prc-weatherization **electricity** consumptions of about 2500 **kWh/year** and negative **benefit-to-cost** ratios.

program. Percentage changes in the cost of electricity would directly change the benefit-to-cost ratios calculated. For example, a *20%* increase in the electricity cost from $0.07147/kWh to $0.08576/kWh would increase the calculated benefit-to-cost ratios by 20%. Using discount factors developed in 1990 for Federal energy conservation projects, which were based on a *1%* discount rate, the benefit-to-cost ratios would be about 13% less than those calculated. The National Appliance Energy Conservation Act of 1987 does not address used equipment. Replacement units purchased by occupants (especially low-income occupants) may be used rather than new equipment (although the extent that this might occur is unknown and would need to be investigated). If these used units were manufactured before 1990, they would likely have lower efficiencies than those installed under the field test. In this case, electricity savings would occur even after the occupants performed the replacement, increasing the benefits of performing the replacement now.[18]

An alternative approach to the total resource test is to perform the analysis from a program perspective. In this method, the full cost of the replacement unit is charged to the weatherization program and used in the calculations, rather than the incremental cost of replacing the unit now instead of later. This alternative arises because the costs are paid from two different sources: the program and the occupant. In using the incremental cost, program costs are reduced by the future costs to be incurred by the occupant to purchase a replacement unit if a new unit is not installed now. In this case, the occupant becomes somewhat of a "free rider", receiving a new air conditioner under the weatherization program when a new unit would have to be purchased anyway in several years. Program economics become very dependent on the remaining lifetime of the existing units if the full cost is charged to the program: the shorter the remaining lifetime, the less time there is for savings to occur to offset the total cost. For the test houses, replacement was not cost effective in any house if the full cost of the replacement had to be recovered and the remaining lifetime was assumed to be less than five years.

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[18]If the occupant will replace the existing unit in five years with a new unit having an EER of 9.0, then the unit installed during weatherization will only have five years of energy saving benefits. If the occupant will replace the existing unit in five years with an old, used unit having an EER of 6.0, then the unit installed during weatherization will provide energy savings benefits over the entire lifetime.

If the program is charged full price for the replacements, cost effectiveness can be increased by requiring the occupants to help pay for the high-efficiency replacement units at the time of their installation. With the occupants assistance, program costs can be decreased significantly. Such a program can be designed to be equitable, basing the occupant cost on the probability of a unit failure depending on its current age.

13.2 Utility Sponsored Programs

The economics of utility-sponsored energy conservation programs are generally evaluated using four economic tests, which evaluate the program from different utility perspectives. These tests are:

- the rate impact test (perspective of a non-participating ratepayer),
- the participant test (perspective of a participating ratepayer),
- the utility cost test (perspective of the utility company), and
- the total resource test (perspective of all of society).

In all of these tests except the participant test, benefits should include costs that the utility avoids by not having to generate and deliver electrical power; externalities should also be considered in the total resource test. Examination of the economics of replacement air conditioners for a utility was beyond the scope of this study, although the basic savings information would be applicable to such an analysis.

7.3.3 Occupant Perspective

In the absence of a weatherization program, occupants must decide between replacing an existing, low-efficiency unit with a higher-efficiency unit now rather than later, upon failure. The economic results presented in Sect. 7.3.1 for the total resource test are generally applicable to an occupant in this case (because the occupant bears all the costs and receives the benefit of energy savings), with the exception that a higher discount rate may be more appropriate.

8. CONCLUSIONS AND RECOMMENDATIONS

Primary conclusions and recommendations of the study are most pertinent to the Oklahoma WAP and similar low-income programs interested in reducing air-conditioning electricity consumption. These conclusions and recommendations are:

- Programs directed at reducing air-conditioning electricity consumption should be targeted at clients with high air-conditioning electricity consumption and/or streamlined to minimize costs in order to improve cost effectiveness. Current air-conditioning electricity consumptions provide a ceiling for the savings attainable by a program. The average measured air-conditioning electricity consumption for the 81 houses studied in this field test was 1664 kWh/year ($119/year), which is low compared to larger houses located in more southern states that are occupied by non low-income people and are cooled by central air conditioners. Ten percent of the houses used less than 250 kWh/year, while another 10% used more than 3000 kWh/year.

- Replacing low-efficiency air conditioners with high-efficiency units should be considered an option in a weatherization program directed at reducing air-conditioning electricity consumption, especially for houses with high air-conditioning electricity consumption. This ECM produced measurable savings, with increased savings achieved in houses with high initial air-conditioning electricity consumption. This measure was cost-effective under appropriate conditions. The cost-effectiveness of this measure should be verified in each house before installation.

  An average reduction in air-conditioning electricity consumption of 535 kWh/year ($38/year and 28% of pre-weatherization consumption) was obtained from replacement of one low-efficiency window air conditioner (EER less than 7.0) per house with a high-efficiency unit (EER greater than 9.0). For approximately the same cost, savings tripled to 1503 kWh/year ($107/year and 41% of pre-weatherization consumption) in those houses with initial air-conditioning electricity consumptions greater than 2750 kWh/year. Savings from this ECM can be estimated fairly reliably for a group of houses knowing the rated efficiencies of the existing and replacement units, and knowing the current air-conditioning electricity consumptions.

  For houses with pre-weatherization air-conditioning electricity consumptions greater than 2750 kWh/year, replacement of a low-efficiency air conditioner with a high-efficiency unit was cost effective for 10 and 15-year lifetimes using the incremental cost of installing a new unit now rather than later (the benefit-to-cost ratios were equal to 1.08 and 1.47, respectively); the average installation cost for these houses under a weatherization program was estimated to be $786. At an estimated cost of $739 per house, the general replacement of low-efficiency air conditioners (replacing units in all houses without considering pre-weatherization air-conditioning electricity consumption) was not cost effective in the test houses.

- ECMs currently being installed under the Oklahoma WAP (chosen based on effectiveness at reducing space-heating energy consumption) should continue to be justified based on their space-heating energy savings potential only. No air-conditioning electricity savings were measured from these ECMs.

- Attic radiant barriers should not be included in the Oklahoma WAP if alternatives with verified savings arc available or until further testing demonstrates energy savings or other benefits in this type of housing. No air-conditioning electricity savings were measured from combining a truss-mounted attic radiant barrier with ECMs currently being installed under the Oklahoma WAP. Comfort improvements, especially in the portions of the houses that were not air conditioned, could not be addressed from this study and need to be further researched.

Because of the varied assumptions that are made in performing an economic analysis, the cost effectiveness of replacement air conditioners should be analyzed further. The cost effectiveness of replacement air conditioners was determined from a total resource test and using the incremental cost of installing a replacement unit now rather than a similar unit later when the existing unit fails. To broaden this analysis, a sensitivity analysis should be performed, the different perspectives of occupants and utilities should be examined in more depth, and the appropriate perspective of a federal weatherization program should be developed. Program options, such as having occupants help defray the cost of the new unit based on the estimated remaining lifetime of the existing unit, should be examined; these options could make air-conditioner replacements attractive in a broader range of houses.

The conclusions and recommendations arc limited to air-conditioning electricity savings. Space-heating energy consumption data were not collected in the field test, even though space-heating energy savings were expected from ECMs installed under the Oklahoma WAP. Therefore, total annual savings and economics of the weatherization work performed under the Oklahoma WAP and radiant barriers were not addressed in this study.

Application of these conclusions and recommendations to other state weatherization programs or more generally for houses in "cooling" climates must be carefully considered because of differences in houses, occupants, and climate. Houses in this field lest were cooled by one or two window air conditioners, and only a portion of the living space was typically cooled. Larger houses with a larger portion of their living space cooled by central air-conditioning equipment (or multiple window units) likely have higher air-conditioning electricity consumptions than those in the field test and, thus, a higher potential for electricity savings. Low-income families as encountered in this study may have budget concerns that affect their operation of the air conditioners differently from families that are not low-income. Although hot summer days definitely occur in Tulsa, the duration and intensity of summer temperatures and humidities are less than that which occurs in other southern states.

Issues remain, especially in low-income houses, concerning the potential for air-conditioning electricity savings. Additional research is needed to quantify the air-conditioning electricity consumption of low-income families using window air conditioners and the air-conditioning electricity savings achieved from weatherization programs in other southern states. A research project currently underway in North Carolina (Sharp and Ternes 1990) is a start at further addressing this issue. Continued studies need to be performed to determine the air-conditioning electricity savings that occur from standard ECMs and those specifically designed to reduce air-conditioning electricity consumption. Measures of interest include wall insulation, window shading devices and window treatments, and duct leakage repair. Projects focusing on air-conditioning electricity savings obtained from standard ECMs and duct leakage repair are being performed by the Florida Solar Energy Center at this time. ORNL is currently conducting a study of exterior masonry wall insulation as a retrofit measure.

A question raised but not answered from this study was whether air conditioning should be considered a necessity or luxury item in low-income weatherization programs. Unlike space-heating systems, the need for space-cooling systems to increase personal safety and reduce suffering is not generally accepted. Indoor temperature data from this and other studies need to be examined to quantify the discomfort and health risks associated with elevated indoor temperatures experienced in southern houses with inadequate or no space cooling, understand the operating strategies of the window units before and after weatherization, and develop program guidelines for addressing this issue.

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APPENDIX A. FIELD TEST IMPLEMENTATION

A.1 DATA PARAMETERS AND MONITORING INSTRUMENTATION

The data collected in this field test can be divided into two classifications: time-independent information and time-dependent measurements. The time-independent information was data collected before, during, or after the experiment through discussions with the occupants, visual observations, and some limited measurements. Time-dependent measurements were monitored continuously with instrumentation throughout the experimental period.

A.1.1 Time-Independent Information

The following information was collected:

- house and occupant descriptive information,
- air leakages in all four groups of houses, and
- the ECMs installed in the houses and their costs.

Descriptive information was collected on all houses to document the physical characteristics of the houses and air-conditioning equipment, as well as the characteristics of the occupants. Table 2.1 lists the specific information collected. These data were collected between November 1988 and February 1989 (between the two summer monitoring periods).

Air-leakage measurements were made in all houses using one blower door to characterize the air tightness of the houses before and after ECMs were installed (control houses were also tested during the pre- and post-wcatherization periods). The fan pressurization technique using a blower door was used because repeatable results can be obtained at standard conditions. The houses were measured in their normal leakage condition. Under this condition, only those openings in the envelope that could naturally be sealed (such as windows, external doors, fireplace dampers) were closed for the test rather than sealing all possible openings in the envelope (such as vents, animal gates, and window air conditioners). Reasons for this choice were:

- to represent the "as found" condition of the house,
- to test the house in the condition requiring the least modification by testing personnel to limit the time required for setup of the house, and
- to reduce the number of special leakage areas sealed for the pre-weatherization test that had to be replicated for the post-weatherization test to ensure comparable results.

Measurements were made between November 1988 and July 1989 (before any ECMs were installed in the treatment houses) and again in October and November 1989 (after all ECMs were installed in the treatment and control houses).

The ECMs installed in the houses and their costs were documented when the installations were completed. The quality of the installations was checked through visual inspections. If an ECM was not installed correctly, additional work was performed until the installation was satisfactory.

A.1.2 Time-Dependent Measurements

Four data parameters were monitored in each house: house gas consumption (in only about half the houses), house electricity consumption, air-conditioning electricity consumption (each air conditioner in a house was metered separately), and indoor temperature. Weather data (temperature, humidity, horizontal insolation, and wind speed) were monitored at three nearby sites. Meters used to monitor the three energy consumptions were read weekly. Hourly indoor temperature data and weather data were stored internally in the monitoring instrumentation and collected once a month.

A recently calibrated, digital electric billing meter was installed in each house in replacement of the existing billing meter. The new meter was used to measure the house electricity consumption. A meter with a digital display was specifically selected to avoid meter reading errors caused by dial-type meters.

The existing gas billing meter in each house was used to monitor the house gas consumption. These meters could only be read in about half the houses for a variety of reasons: the meters were not found, meters were located in unaccessible areas, and meter faces were clouded with moisture.

A recently calibrated, digital watt-hour meter (billing-type meter) was installed with a dedicated circuit to monitor the electricity consumption of each air conditioner found in the houses. A new circuit enclosed in approved outdoor conduit was run from the customer side of the house billing meter, along the outside wall of the house, to a new receptacle at each window air conditioner. A watt-hour meter and circuit breaker were wired into the new circuit. Installation of a new circuit was determined to be the least expensive approach to submetering the air conditioners while ensuring that the submetering was safe and met all building codes; an additional benefit of this approach was that the house wiring was improved and made safer (the wiring in many of the homes was not designed for loads imposed by large window air conditioners). The circuit was initiated from the customer side of the billing meter because the electrical panel boxes were located inside most homes, the electrical panels were a four fuse design and had no available circuits, and wiring into the electrical panels did not always meet building code.

The indoor temperature of each house was monitored using a single-channel recording device that included a temperature sensor and microprocessor based electronics to calculate and store average hourly temperature. On average, calibration tests found that the temperatures measured by these devices were about 0.75° F lower than actual; the temperatures measured by individual devices were generally within 0.75° F of the average. The devices were located in the room with the air conditioner; if two air conditioners were in a house, the device was located in the room with the air conditioner operated the most (as reported by the occupants). The devices were placed to minimize their exposure to radiant energy heat sources. The same device was used in each house for both summers.

Ambient weather parameters were monitored at three Public Service Company of Oklahoma's electric substations. The parameters monitored were temperature, humidity, horizontal insolation, and wind speed. The parameters were monitored using battery powered data loggers, type T (copper-constantan) thermocouples, humidity sensors, pyranometers, and radiation shields. The three sites were distributed among the test houses (in fact, the houses were located in north Tulsa, within about 10 miles of each other).

A.2 DATA COLLECTION AND MANAGEMENT

After the time-independent information and time-dependent data were collected in the field, they were sent to ORNL in various formats and on various media for analyses. A data management system was developed to prepare these data for analyses. The system was designed to transfer the field data onto microcomputer databases, check the validity of the data, convert the data into files that can be managed and manipulated by the Statistical Analysis Software (SAS), and merge individual tiles into one master file for data and statistical analyses.

All data management and analyses were performed in a microcomputer environment. A menu-driven system was developed to facilitate and minimize the data processing effort. The main menu system was invoked by a DOS command and allowed the user to enter either the SAS or the dBASE III Plus software environment, depending on the task and the function to be performed. Previous knowledge of cither software was not required.

The field data can be divided into three categories based on the frequency and time at which the data were collected: weekly household energy consumption, hourly indoor and outdoor temperatures, and house and occupant descriptive information. Data management and validation procedures, developed for the individual categories, will be discussed, along with how individual files were merged into one master file. Additionally, field experiences and data quality will also be discussed.

A.2.1 Weekly Household Energy Consumption Data

Three data parameters were collected weekly from each test house: house gas consumption, house electricity consumption, and air-conditioning electricity consumption (two consumptions if two air conditioners were present). The field data were recorded by data collection personnel onto data sheets designed by ORNL and forwarded to ORNL for processing.

Upon receiving the data, ORNL project staff entered the data into a dBASE III Plus database using a full screen data entry system. The quality of the data was checked as they were entered. Values for the house ID, date, time, and meter readings had to be within a feasible range. Values outside the established ranges were not accepted by the system.

The dBASE III Plus files were converted to SAS files using a SAS utility program. The following variables were created for subsequent statistical analyses:

1. household identification (ID) which uniquely identified individual households,
2. date when the meter data were recorded,
3. air-conditioning electricity consumption between this and the previous reading (a consumption for each air conditioner present),
5. house electricity consumption between this and the previous reading,
6. house gas consumption between this and the previous reading,
7. elapsed time in hours between this and the previous reading, and
8. five error check flags.

Weekly energy consumptions were determined by concatenating incoming meter readings to readings of the previous week and calculating their difference. Elapsed times between two consecutive readings were calculated in order to standardize the energy consumptions per unit time. During these calculations, the following quality checks were performed (using the error check flags):

1. Negative values for the four calculated energy consumptions were identified. This occurred most often when the billing meters were replaced (because new meters were initially set at zero) and due to misreading of the meters,
2. Inconsistent data were identified. Inconsistency was defined to be when the weekly house electricity consumption was less than the sum of the air-conditioning electricity consumptions.

A printout listing all weekly records containing invalid data was generated. ORNL staff corrected all "correctable" errors, recalculated the energy consumptions, and then rechecked the quality of the data. Non-correctable errors were set as being "missing" in order that weekly records with "missing" data could be skipped, if desired, in future analyses. Causes for the non-correctable errors were identified and, to the extent possible, were fixed in the field by Wa-Ro-Ma Community Action Foundation personnel.

A.2.2 Indoor Temperature and Weather Data

A temperature recorder was installed in every participating house to record and store house-specific hourly indoor temperatures. These data were processed to obtain a database for each house containing the following variables: recorder ID, time and date for each temperature reading, and hourly temperature readings (in units of °F), for the entire summer monitoring period. The recorder ID uniquely identified the recorder and, with information maintained and updated by Wa-Ro-Ma Community Action Foundation, the test house in which it was installed.

Field personnel downloaded the data from the recorders to floppy diskettes once a month and forwarded the diskettes to ORNL. Individual house indoor temperature data were stored in separate data files on the diskettes. The data stored on diskette were transferred to the microcomputer using software developed by the manufacturer of the temperature devices. These files were assigned file names identifying their respective recorder ID and the month they were collected. The recorder ID was also a data variable contained within each file.

Special software was developed in SAS to combine the monthly files for each house and to overcome three complicating factors. First, the indoor temperature files were not formatted in a way that the data could be easily extracted. The SAS software parsed the file in order to retain the recorder ID with the corresponding hourly temperatures. The recorder ID was retained to serve as the identification link between the temperature and energy consumption files. Second, data were redundantly stored because the recorders stored the latest 83 days of hourly indoor temperature data, but the data were collected monthly. Additionally, the data for each house extended over different time frames because the data were collected at various dates and times. To avoid processing duplicate data and to increase efficiency, a "benchmark" date was sought for each house. This "benchmark" date was the time and date when the most recent hourly indoor temperature was recorded and processed. When processing the next month's data, only data recorded later than the "benchmark" date was processed.

The validity of the hourly indoor temperatures were checked. Acceptable values were defined to be within the range of 55° F and 100° F. The data were also checked for repetitiveness by identifying cases where ten consecutive indoor temperatures were identical. Repetitiveness of this order likely indicated that the recorder was not functioning properly. Flags were raised if an invalid range or if constant readings were detected. Output was generated to list all invalid data so that ORNL project staff could manually inspect the list and make appropriate corrective actions.

Weather data were collected at three sites to represent the weather at each test house. The instruments measured the average hourly outdoor temperature, humidity, horizontal insolation, and wind speed, and automatically stored the data onto a cassette tape at periodic intervals. Field personnel collected the tapes from the sites once a month and forwarded them to ORNL. These data were further processed to obtain a database for each site containing the following data: weather station ID, time and date for each set of readings, hourly outdoor temperature readings (in units of °F), hourly relative humidity (in units of %), hourly horizontal insolation (in units of $Btu/h\text{-}ft^2$), and hourly wind speed (in units of mph) for the entire summer monitoring period.

Data were transferred from cassette to the microcomputer and stored in ASCII format using software developed by the manufacturer of the data logger. These data were then converted to spreadsheet files and visually examined, both individually and comparatively between sites. The instrumentation status and battery voltage were also checked, although these data were not stored. The batteries in the data logger needed to be replaced if the voltage level was below 10 volts. The programming of the data logger had been tampered with if the instrumentation status was not equal to a predetermined constant.

A.2.3 Household Survey Data

An interview conducted between monitoring periods established the house and air-conditioning system characteristics of the test houses, and the behavioral characteristics and demographics of the occupants. Field personnel interviewed heads of the test households, visually inspected and measured house structural and physical characteristics, and recorded the information on survey forms designed and provided by ORNL. A full screen interactive data entry system was designed using dBASE III Plus software to facilitate data entry onto computer databases. This data entry system displayed screens which simulated the survey forms, and prompted the user to fill in the blanks. Simple range checks were implemented during data entry so that errors could be corrected immediately. SAS files were created from the dBASE III Plus files for further data analyses.

A.2.4 Merging Files

In order to normalize the energy consumptions and savings, the household energy databases were merged with the indoor and outdoor temperature data files. This required establishing links (such as house ID, recorder ID, and weather station ID) among the different data bases. The survey and audit related data were analyzed separately and, thus, were not merged with the other data sets.

Outdoor temperature was merged rather readily with indoor temperature. Because of the closeness of the houses and consistency among the outdoor temperatures measured at each weather station, a single outdoor temperature file was created to represent all the houses. For each house, the outdoor and indoor temperatures were merged using the time (to the nearest hour) and date when temperatures were recorded.

While the energy consumption data were merged with the hourly temperature data, a temperature variable was calculated corresponding to the time period represented by the energy consumption data. Two temperature variables were calculated: the average difference between hourly indoor and outdoor temperatures for the period, and the average difference after setting negative hourly differences equal to zero. Using the house and recorder IDs, the temperature and consumption files for each house were merged and temperature variables calculated. Calculating this difference was complicated by the fact that the recording interval for the energy consumption data varied week to week for a given house and also varied among houses. During this process, the energy consumptions were also normalized to time by dividing the consumptions by their respective recording intervals. In this manner, average weekly consumptions for each period were obtained. This normalization was required because the recording intervals varied (especially if a weekly reading for a given house was missed) even though data were collected on primarily a weekly basis. This merged data set was then used in subsequent analyses.

A.2.5 Data Quality

The majority of the errors that were detected in the consumption data were due to the house gas consumption being less than zero. This was caused primarily by meter reading errors. The house electricity consumption was less than zero in one house for an unknown reason. A new electric and gas billing meter were installed in two houses, causing a data error and loss of a week of data.

Air-conditioning electricity consumption data were lost for periods of time in some houses for a variety of reasons; the wrong house was metered at the start of the study in one case; an air conditioner was replaced by a unit with a different voltage in two houses, requiring a new submeter; an air conditioner was not present at the beginning of the summer in two houses; an air conditioner was not plugged into the metered outlet in two houses; the submeter failed in one house; and meters could not be read in two houses because of access problems. These problems caused insufficient data to be collected for analyses in four houses. For those weeks in which meter readings were lost or not obtainable, the weekly record was set as missing.

Indoor temperature data were lost for the last few weeks of the post-weatherization period in four houses because of data transfer problems. Weather data were occasionally lost, primarily due to lightning strikes near the instrumentation. Because of the redundancy in the weather stations, a continuous set of weather data could be constructed by combining the three sites.

APPENDIX B. RADIANT-BARRIER EMISSIVITY MEASUREMENTS

Radiant-barrier samples were removed from the attics of four houses (selected randomly) in May 1991, more than two years after being installed. The emissivities of both the top and bottom facing surfaces were measured (the top surface faced the roof deck and the bottom surface faced the attic insulation). These measurements, along with observations made when the samples were removed from the attics, are summarized in Table B.1.

Table **B.1. Radiant-barrier emissivity** measurements

House	Emissivity		Comment
	Top face	Bottom face	
14	0.35	0.03	Top surface visibly dusty.
28	0.07	0.03	Some dust apparent on top surface.
114	0.05	0.05	
117	0.17	0.03	Attic fan used in house. Attic insulated with blown fiberglass installed before the field test.

In all four houses, no dust accumulation was apparent on the bottom surface of the radiant barrier; in fact, the bottom surfaces appeared to be quite clean. Dust accumulation was readily observable on the top surface of the radiant barriers installed in two of the four houses.

These observations were confirmed by the emissivity measurements. In all four houses, the emissivity of the bottom surface of the radiant barrier was between 0.03 and 0.05, which is the expected range for new radiant-barrier material. The top surfaces had emissivities greater than or equal to the bottom surfaces. Dust accumulation likely contributed to these increases. For House 14, the top surface of the radiant barrier was different from the bottom surface and had a higher emissivity initially. The following conclusions are drawn from these results:

- The performance of the radiant barriers installed in the test houses were not affected by dust accumulation because the bottom surfaces remained clean. In the truss-mounted configuration, the performance of a radiant-barrier material should remain unchanged if the emissivity of the bottom surface remains equal to its initial value regardless of changes that may occur to the top surface.

- Dust accumulations occurred on top surfaces of the radiant barriers, with a resultant increase in the emissivity of the surfaces. In the truss-mounted configuration, a reflective surface must face downward to avoid performance degradation. In a horizontal application, dust accumulation on the top surface is likely.

APPENDIX C ECONOMIC CALCULATIONS

Two sample calculations are provided to illustrate the manner in which the economic calculations were performed. The simplest calculation occurred when the remaining lifetime of the existing unit was assumed to be the same as the service lifetime of a new unit (see Fig. C.1). The calculation was more complex when the remaining lifetime was assumed to be less than the service lifetime. An example of this is provided in Fig. C.2 using a remaining lifetime of one year.

In completing the analysis, we found that the benefit-to-cost ratios were the same for each of the remaining lifetimes assumed (the benefit-to-cost ratio calculated in Fig. C.1 was the same as that calculated in Fig. C.2 for a 301-year analysis period). This was confirmed by examining the basic economic equations used in the calculations. Using the calculation in Fig. C.2 as a guide, the benefit-to-cost ratio was equal to

$$BCR = \frac{\text{(annual savings)(electricity cost)(UPW)}}{\text{(installation cost)(sum of SPW for replacement - sum of SPW for base case)}}$$

where

UPW = uniform present worth factor and
SPW = single payment present worth factor.

Annual savings, electricity cost, and unit installation cost remained constant for different assumed remaining lifetimes. Thus, the ratio of the UPW to the difference in sums of the SPW must also remain constant for the benefit-to-cost ratio to be independent of the remaining lifetime. This ratio can be expressed and reduced as follows:

$$\frac{UPW}{\sum SPW\,for\ replacement - \sum SPW\,for\ base\ use} \qquad \text{(Eq. C-1)}$$

$$\frac{\dfrac{(1+i)^n-1}{i(1+i)^n}}{\displaystyle\sum_{x=0}^{\infty}\frac{1}{(1+i)^{xL}}-\sum_{x=0}^{\infty}\frac{1}{(1+i)^{n+xL}}} \qquad \text{(Eq. C-2)}$$

where:

where:	i	= discount rate
	n	= remaining lifetime of the existing unit
	L	= service lifetime of a new unit

$$\frac{(1+i)^n-1}{i(1+i)^n\left(\displaystyle\sum_{x=0}^{\infty}\frac{1}{(1+i)^{xL}}-\sum_{x=0}^{\infty}\frac{1}{(1+i)^n(1+i)^{xL}}\right)} \qquad \text{(Eq. C-3)}$$

$$\frac{(1+i)^n-1}{i\left(\displaystyle\sum_{x=0}^{\infty}\frac{(1+i)^n}{(1+i)^{xL}}-\sum_{x=0}^{\infty}\frac{1}{(1+i)^{xL}}\right)} \qquad \text{(Eq. C-4)}$$

$$\frac{(1+i)^n-1}{i\displaystyle\sum_{x=0}^{\infty}\frac{(1+i)^n-1}{(1+i)^{xL}}} \qquad \text{(Eq. C-5)}$$

$$\frac{1}{i\displaystyle\sum_{x=0}^{\infty}\frac{1}{(1+i)^{xL}}} \qquad \text{(Eq. C-6)}$$

Because the final form of this ratio (Eq. C.6) did not include n, the remaining lifetime of the existing unit, the ratio was independent of this value.

Base case:
existing window air conditioner has a remaining lifetime of 15 years
existing unit will be replaced in 15 years with a window air conditioner having the same efficiency as the unit installed under the replacement option

Replacement option:
new window air conditioner has a service lifetime of 15 years
in 15 years, the new unit will be replaced with a window air conditioner having the same efficiency as the original replacement
energy savings is 1725 kWh/year for 15 years

Timeline:

Year	Base case	Replacement option
0		Install new air conditioner
1		Energy savings = 1725 kWh
2		Energy savings = 1725 kWh
3		Energy savings = 1725 kWh
4		Energy savings = 1725 kWh
5		Energy savings = 1725 kWh
6		Energy savings = 1725 kWh
7		Energy savings = 1725 kWh
8		Energy savings = 1725 kWh
9		Energy savings = 1725 kWh
10		Energy savings = 1725 kWh
11		Energy savings = 1725 kWh
12		Energy savings = 1725 kWh
13		Energy savings = 1725 kwh
14		Energy savings — 1725 kWh
15	Install new air conditioner	Energy savings = 1725 kWh; install new air conditioner
16		

Economic parameters:
installation cost is $728
electricity cost is $0.07147/kWh
UPW = 10.73 (15 years, 4.6% discount rate adjusted for average fuel escalation)

Calculation: The analysis only needs to be performed considering the first 15 years because equivalent conditions occur after the fifteenth year.

BCR = (1725 kWh/year)($0.07147/kWh)(10.73)/($728) = 1.817

Fig. C.l. Sample calculation assuming the remaining lifetime of the existing unit is equal to the service lifetime of the new unit

Base case:

existing window air conditioner has a remaining lifetime of 1 year

existing unit will be replaced in 1 year with a window air conditioner having the same efficiency as the unit installed under the replacement option

Replacement option:

new window air conditioner has a service lifetime of 15 years

in 15 years, the new unit will be replaced with a window air conditioner having the same efficiency as the original replacement

energy savings is 1725 kWh/year for 1 year

Timeline:

Year	Base case	Replacement option
0		Install new air conditioner
1	Install new air conditioner	Energy savings = 1725 kWh
2		
3		
4		
5		
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15		Install new air conditioner
16	Install new air conditioner	

Fig. C.2. Sample calculation assuming the remaining lifetime of the existing unit is equal to the service lifetime of the new unit.

Economic parameters:

installation cost is \$728

electricity cost is \$0.07147/kWh

UPW = 0.96 (1 year, 4.6% discount rate adjusted for average fuel escalation)

SPW:	1.000 0 years	0.956 1 year
	0.509 15 years	0.487 16 years
	0.259 30 years	0.248 31 years
	0.132 45 years	0.126 46 years
	0.067 60 years	0.064 61 years
	0.034 75 years	0.033 76 years
	O.Q17 90 years	0.017 91 years
	2.018	1.931

Calculation: At the end of 15 years, the unit installed under the base case still has one more year of useful life. The calculation could be performed assuming a salvage value for this unit. To avoid this assumption, the analysis can be performed for an infinite number of years, replacing units in both options every 15 years and bringing these costs to a present value.

$$BCR = \frac{(1725\ kWh/year)(\$0.07147/kWh)(0.96)}{(\$728)(1+...+.017) - (\$728)(.956+...+017)}$$

$$= 1.869$$

If the analysis is carried out for 301 years, the sums of the SPWs are 2.038152 and 1.948520, making the BCR equal to 1.814.

Fig. C.2. Continued.

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