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MARTIN MARIETTA

Monitoring and Evaluation of Foundation Insulation Retrofits in Single-Family Detached Houses in St. Paul and Minneapolis, Minnesota

M. J. Hewett
G. D. Nelson
M. T. Noble
D. A. Robinson
L. S. Shen
L. F. Goldberg

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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FINAL REPORT

March 1991

D.A. Robinson
Robinson Technical Services

G.D. Nelson
Gary Nelson and Associates

M.J. Hewett
Center for Energy and the
Urban Environment

M.T. Noble
Natural Resources Corporation

L.S. Shen and L.F. Goldberg
University of Minnesota

Research sponsored by the
Office of Existing Buildings Research Program,
Existing Buildings Efficiency Research Program
U.S. Department of Energy

Report prepared by
Robinson Technical Services
1821 University Avenue, Suite 151S
St. Paul, Minnesota 55104
Under
Purchase Order Number 86X-SA711V

for

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831
managed by
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U.S. DEPARTMENT OF ENERGY
under contract DE-AC05-84OR21400

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ACKNOWLEDGMENTS

The authors thank Tim Dunsworth of the Center for Energy and the Urban Environment for the analysis of utility gas heat content, PRISM program analysis checks, and for statistical assistance.

The staffs of the Center for Energy and the Urban Environment and the Natural Resources Corporation are warmly thanked for their support of this project.

The support of this work by the Oak Ridge National Laboratory under contract number 86X-SA711V is gratefully acknowledged. In particular we would like to thank Jeff Christian of ORNL for the loan of flux plates and for his helpful suggestions throughout the study.

Additional financial support was provided by the Underground Space Center from EXXON oil overcharge funds administered by the U.S. Department of Energy, and the Minnesota Department of Public Service, grant number DE-FG02-76C60014. This financial support is gratefully acknowledged, but the authors assume complete responsibility for the contents herein.

EXECUTIVE SUMMARY

BACKGROUND

Foundation insulation is typically one of the last and most costly retrofits added to an existing single family house. One earlier study (Quaid, 1988) found average space heat energy savings of 19.2 percent due to foundation insulation in fifteen otherwise well insulated houses in Minneapolis, Minnesota. Quaid's study, however, did not control for air sealing coincident with the retrofit, and relied on self-reported data with regard to basement heating.

OBJECTIVE

The objective of the present study was to measure the savings due to retrofit foundation insulation so that this retrofit could be recommended where it was found to be cost effective. The study was designed to evaluate the effectiveness of foundation insulation in reducing basement conductive heat loss, and to control for foundation air leakage and intentional basement heating.

METHODOLOGY

Since foundation insulation is a permanent retrofit, a before-after experimental method was used for the study. Twenty houses from the client bases of the Center for Energy and the Urban Environment (formerly the Minneapolis Energy Office) and the Natural Resources Corporation were selected to receive retrofits. Ten houses received interior retrofits, ten received exterior retrofits. Fiberglass insulated stud walls were used for eight of the interior retrofits, extruded polystyrene was used for two. All ten exterior retrofits were done using extruded polystyrene. For various reasons, such as change of owner/occupant, five houses were deleted from the final analysis.

To control for basement heating, basement supply and return registers were closed or sealed for the 21-month monitoring period of the study. As is common for the type of housing being studied, none of the basements was heated for comfort or used as daily living space. For all houses the basement was an uncontrolled zone without a thermostat.

Foundations were air sealed and energy use monitoring began in the fall of 1987. Foundation walls were insulated during the summer of 1988, and energy monitoring continued through June, 1989. Houses were visited quarterly to check homeowner meter readings, to service thermographs located in the basement and near the thermostat, and to observe any changes in basement usage. Homeowner read weekly data were collected on 18 houses for the duration of the study. Two houses were submetered using data acquisition systems.

Because the below grade environment adds a somewhat constant amount to the load of the house it appears as a negative internal gain. To account for this characteristic of the below grade environment, retrofit performance was evaluated by comparing the total energy input within the envelope before and after the retrofit. A linear two-parameter model (normalized thermal load model) of total load versus the outside temperature was used for this analysis.

RESULTS

On the average, the houses in the study achieved only about one-third of the whole-house energy savings that were predicted by a two-dimensional finite difference model used in the study. Savings may have been overpredicted by the model, since it assumed a constant and uniform basement air temperature and did not include effects of basement air stratification on whole-house energy use.

While energy savings were highly variable, all basements were warmer after retrofit than before, and the average basement temperature increased by 4.3 ^{o}F. In spite of variable savings, all homeowners were very pleased with their retrofits and reported an increased level of comfort in their basements.

The average energy savings for the interior and exterior retrofits were 92 and 24 therm/yr, respectively. These savings were 7.9 and 3.0 percent of the pre-retrofit space heat energy use.

The aggregate payback periods for the interior retrofits with and without a finished wall were 42 and 23 years, respectively, with minimum values of 23 and 12 years. The average costs for these retrofits were $2130 and $1173 with and without a finished wall, respectively. The aggregate payback period for the exterior retrofits was 129 years, with a minimum of 37 years. The average exterior retrofit cost was $1675.

Even though the foundation retrofits examined here improved comfort in all cases, model calculations showed that the application of retrofits to intentionally heated space is required to achieve payback periods of ten years or less. The accuracy of the model in this case was verified by comparing model results to measured data obtained from a uniformly heated below grade test module.

Regression analysis of savings as a function of the area insulated showed that the addition of a single parameter to the analysis yielded regression models for both the interior and exterior insulation cases that explained 80 percent or more of the reduction in observed savings. The parameters were the height of the house and the reciprocal of the depth of the insulation below grade for the interior and exterior insulation cases, respectively.

CONCLUSIONS AND RECOMMENDATIONS

We conclude that insulation applied in an uncontrolled basement produces highly variable results, and has the principal effect of increasing the temperature and comfort of the basement, rather than producing cost-effective whole-house energy savings.

Based on the savings observed in this study, and the current retrofit and energy costs ($5.50/MBtu) used here, we recommend that cold climate foundation retrofits be applied to unconditioned basements if increased comfort is desired. Using these same retrofit and energy costs and based on modeled energy savings, we further recommend that conditioned basements be insulated to enhance comfort and to obtain cost-effective energy savings.

The examination of alternative strategies to reduce the energy use of unconditioned or uninhabited basements is recommended. In particular, duct sealing and insulating, basement wall and basement ceiling air sealing, and basement ceiling insulation are strategies that could be examined.

The effect of air stratification and internal air movement on the effectiveness of foundation insulation needs further examination. Detailed basement temperature monitoring, and enhanced modeling of boundary conditions that include non-uniform basement air temperatures appear to be required for the accurate prediction of foundation retrofit savings for unconditioned basements.

Based on the regression results obtained here, interzone coupling and retrofit induced losses appear to be very important, but are poorly understood. In particular, the effect of basement air movement on losses due to the presence of a basement needs to be assessed. The distinction between basement heat loss - that is, soil conduction loss - and heat loss due to the presence of a basement - that is, whole house losses due to all other mechanisms - appears to be very important and in need of further clarification.

ABSTRACT

The effectiveness of foundation insulation retrofits in 15 Minnesota houses was evaluated using a before-after experimental method. Nine houses received interior retrofits, six exterior retrofits. Foundations were air sealed before the pre-retrofit heating season to control for inadvertent sealing during retrofit. Basement heating supply and return registers, where present, were closed for the 21 month monitoring period to control for heating of the basement area. Homeowners recorded gas and electric meter readings and furnace and water heater on-times weekly. A two-parameter linear regression model of total space heating load versus outside temperature was used to evaluate changes in energy use. The average whole-house energy savings for the interior and exterior cases were 92 and 24 therm per year, or 7.9 (range -0.6 to 17.8) and 3.0 (range -2.9 to 8.3) percent, respectively. Minimum payback periods for the interior and exterior cases were 12 and 37 years, respectively. For all houses the basement temperature increased between the pre- and post-retrofit periods, and all homeowners reported increased comfort in their basements. Average measured savings were about one-third of those predicted. The findings show that the application of insulation in an uncontrolled zone produces highly variable results, and has the principal effect of increasing the temperature and comfort of the basement, rather than producing cost effective whole-house energy savings. Model calculations for basements intentionally heated to 68°F yielded payback periods of 4 and 10 years for the interior and exterior retrofit cases. Regression analysis of measured savings points to the need for further understanding of the effect of basement heat loss on whole-house space heat energy use.

1. INTRODUCTION

The purpose of this study was to measure the savings due to retrofit foundation insulation applied to unconditioned basements so that this retrofit could be recommended where it was found to be cost effective. The study was designed to evaluate the effectiveness of foundation insulation in reducing basement conductive heat loss, and controlled for foundation air leakage and intentional basement heating. It is believed to be the first study of this type for foundation retrofits. One earlier study (Quaid, 1988) found average space heat energy savings of 19.2 percent due to foundation insulation in fifteen otherwise well insulated houses in Minneapolis, Minnesota. Quaid's study, however, did not control for air sealing coincident with the retrofit, and relied on self-reported data with regard to basement heating.

Foundation insulation is a permanent retrofit that insulates the basement of a house from the below grade environment. Because foundation insulation is a permanent retrofit, a before-after experimental method was used for the study. Twenty houses from the client bases of the Center for Energy and the Urban Environment (formerly the Minneapolis Energy Office) and the Natural Resources Corporation were selected to receive retrofits. Ten houses received exterior retrofits, ten received interior retrofits. Foundations were air sealed and energy use monitoring began in the fall of 1987. Foundation walls were insulated during the summer of 1988, and energy monitoring continued through June., 1989. Houses were visited quarterly to check homeowner meter readings, to service thermographs located in the basement and near the thermostat, and to observe any changes in basement usage.

Compared to the highly variable above grade environment, the below grade environment varies slowly in temperature and adds a somewhat constant amount to the load of the house. It thus appears as negative internal gain to the heating system. Because of this characteristic of the below grade environment, retrofit performance was evaluated by comparing the total energy input within the envelope before and after retrofit. That is, internal gains were included in the analysis. A simple linear two-parameter model of total load versus the outside temperature was used for this analysis.

Quantitative energy savings were found to be mixed and not particularly predictable; however, several qualitative results were clear. The most important are that retrofit insulation increases basement temperature and comfort, and that insulation applied to an uncontrolled zone produces highly variable results.

This report will present the methodology of the study; quantitative results, including economic analysis; and will speculate, with the assistance of regression analysis, about how real houses might be thermally attached to the ground.

2. DESCRIPTION OF HOUSES AND RETROFITS

2.1 SELECTION OF HOUSES

Houses were selected from the client bases of the Center for Energy and the Urban Environment (CEUE, formerly the Minneapolis Energy Office) and the Natural Resources Corporation (NRC). The CEUE provides weatherization services through its Operation Insulation program within the city of Minneapolis. Homeowners in the program contract for weatherization services and receive reduced interest loans to pay for the work done. Private contractors then install the specified retrofits to Operation Insulation standards. The NRC provides low income weatherization services to suburban Minneapolis through a county contract. Homeowners in the program are identified by their need for fuel assistance, and, if qualified, receive free weatherization services.

Since foundation insulation is usually the lowest priority retrofit installed, the first selection criterion for the houses was that each house be fully insulated, except for the foundation and the basement ceiling. The CEUE contacted 700 homeowners who had already thoroughly insulated their houses, except for the foundation. Of these homeowners, 92 expressed an interest in the project. The Natural Resources Corporation selected houses from its then current client base for weatherization. Since its contract allowed NRC to be paid for only completed jobs, a special agreement was negotiated with NRC's funding agencies so that the foundation insulation portion of the retrofit work required for these houses could be deferred for one year from the start of the study.

Candidate houses were initially visited by auditors from each agency, and a Candidate House Survey (see Appendix A) was completed for each house. These data were then used as a basis for house selection. Selection criteria are shown in Appendix B. Particular concerns were the general condition of the foundation, evidence or presence of moisture, accessibility of the foundation and rim joist for the application of insulation, and homeowner attitude towards participating in the study. Beyond these concerns, each house was required to have a deep basement as shown in Figure 2.1, and to be representative of the general housing stock available for foundation retrofit.

Based on the Candidate House Survey ten houses each from the CEUE and NRC client bases were selected for inclusion in the study. Eight CEUE and two NRC houses were selected for interior insulation retrofits. The remainder of the houses were selected for exterior retrofits. As a part of the selection process each homeowner was asked to sign an agreement to read his or her utility meters, plus one or two run-time meters, and to allow for the intrusions necessary for the study (Appendix C). In addition, CEUE homeowners were asked to sign an agreement that the installation of their insulation be delayed for one year (Appendix D). To control insulation costs and to encourage homeowner participation, fixed price contracts for the future retrofit work to be done were negotiated with the contractors for each CEUE site.

2.2 DESCRIPTION OF HOUSES

As described above, 20 houses were selected for the retrofit study. However, by the end of the program five NRC houses had been deleted from the study. Two were removed because of a change in ownership during the middle of the second heating season, and three

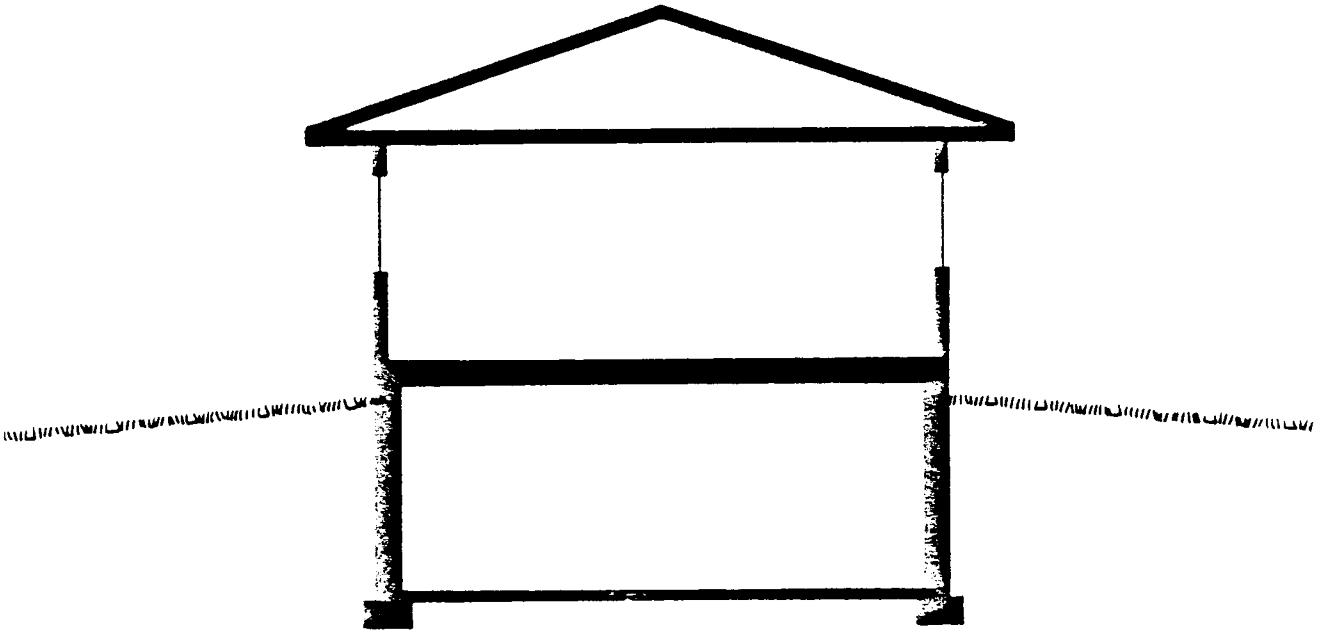

Fig. 2.1. Diagram of deep basement type.

Houses in study all had full area basements similar to the one shown here. All basements had an interior height of about eight feet, and an above grade exposure that ranged from 0.5 to 2.5 feet. All basement walls were constructed of cement block, except one that was built of limestone. To be selected for the study, all basements had to be dry and structurally sound.

were deleted because of irregular basement heating observed during quarterly visits to each site. Of the 15 remaining houses nine were insulated on the interior, six on the exterior. Characteristics of these houses, plus the five deleted houses, are shown in Table 2.1.

Most all of the ten CEUE houses were one and one-half to two stories, and, including the basement, had an average floor area of 2131 ft^2. The five NRC houses were largely one story with an average floor area of 1660 ft^2, including the basement. CEUE clients were middle income homeowners who paid for their own retrofit work. NRC clients were low-income homeowners who received no-cost retrofits through a county-funded weatherization program.

The primary heating fuel for all houses was natural gas. Ten houses had warm air heating systems (9 forced air, 1 gravity air), the remaining five, all CEUE houses, had hot water heating systems. All houses were equipped with gas water heaters, and all but three houses had gas cooking ranges. Two houses, ME03 and ME06 had gas space heaters that were used intermittently.

2.3 DESCRIPTION OF RETROFITS

Of the remaining houses eight of the interior retrofits were done using fiberglass batts; one used extruded polystyrene. For the fiberglass cases, insulation was installed in 2 by 4 stud wall cavities that were closed on each side with a vapor retarder. Most walls were insulated using R-13 fiberglass batts. In those cases where the foundation wall was especially irregular, an R-19 fiberglass batt was installed to ensure a continuous contact between the insulation and the existing basement wall, so that convection between the insulation and the wall would be minimized.

Table 2.1. Characteristics of 20 houses in retrofit study.

House Number	House Type	Total Floor Area (ft^2)	Heating System Type	Retrofit Description			
				Type	Area Insulated (ft^2)	R-Value	Material
MEO1	2 Story	2210	Pumped water	Int	936	13	Fiberglass
MEO2	1 1/2 Story	1625	Forced air	Int	840	13	Fiberglass
MEO3	1 1/2 Story	2584	Forced air	Ext	418	10	Polystyrene
MEO4	1 1/2 Story	2990	Pumped water	Int	968	13	Fiberglass
MEO5	2 Story	1970	Gravity water	Int	848	15	Fiberglass
MEO6	1 1/2 Story	2730	Pumped water	Int	895	15	Fiberglass
MEO7	2 Story	1890	Forced air	Int	832	15	Fiberglass
MEO8	1 1/2 Story	1520	Gravity air	Ext	367	10	Polystyrene
MEO9	1 Story	1820	Forced air	Int	944	13	Fiberglass
MEO10	1 1/2 Story	2125	Gravity water	Int	1072	15	Fiberglass
NRC1	1 Story	1340	Forced air	Int	864	8	Polystyrene
NRC2*	2 Story	2620	Forced air	Int	1112	8	Polystyrene
NRC3	1 1/2 Story	1535	Forced air	Ext	200	10	Polystyrene
NRC4	1 Story	1200	Forced air	Ext	217	10	Polystyrene
NRC5*	Split-level	2000	Forced air	Ext	494	10	Polystyrene
NRC6*	1 Story	1926	Forced air	Ext	248	10	Polystyrene
NRC7*	1 Story	2184	Forced air	Ext	321	10	Polystyrene
NRC8	1 Story	1776	Forced air	Ext	234	10	Polystyrene
NRC9	1 Story	1344	Forced air	Ext	258	10	Polystyrene
NRC10*	1 Story	1440	Gravity air	Ext	148	10	Polystyrene

Notes: Total floor area includes area of basement. R-15 fiberglass insulation is estimated value for nominal R-19 fiberglass batt compressed into 4 inch cavity. Houses from the Center for Energy and the Urban Environment (formerly the Minneapolis Energy Office) client base are labeled with the prefix MEO. Houses marked with asterisk were deleted from final analysis.

For the polystyrene case, z-channel was used to attached extruded polystyrene to the basement wall. In all cases, walls were finished with gypsum board wall covering.

The six remaining exterior retrofits all used R-10 extruded polystyrene attached to the exterior of the foundation. In two cases the polystyrene was extended to cover the rim joist. The average total width of the applied insulation was 2.8 feet, and it was buried to an average depth below grade of 1.1 feet. Four houses were insulated using polystyrene protected with factory-applied rock aggregate. For the remaining two houses the insulation was protected using a site-applied trowel-on stucco in one case and a spray-on coating in the second. Details of both the interior and exterior retrofits are shown in Appendix E.

Prior to retrofit installation, contractors were trained to correctly perform the required retrofits and were given work standards to maintain. On-site inspections were conducted throughout the retrofit installation period, and after completion all retrofits received an infrared inspection.

3. EXPERIMENTAL METHOD

3.1 BEFORE-AFTER METHOD

Because foundation insulation is a permanent retrofit, a before-after experimental method was used for the study. Using this method, each house was monitored for one heating season before and after the application of the foundation insulation. Monitoring began in the fall of 1987, and basements were insulated during the summer of 1988. A second heating season of monitoring began in the fall of 1988 and concluded in the summer of 1989.

3.2 CONTROLLED CONDITIONS

The central purpose of the study was to evaluate the effectiveness of foundation insulation in reducing conduction losses from basements. Since the application of foundation insulation may also decrease the air leakage of the foundation, each foundation was air sealed before the start of the pre-retrofit monitoring season. The basement of each house, with a special emphasis on the rim joist area, was sealed so that the reduction in conductive heat loss would not be confounded by any simultaneous reduction in basement air leakage. To control for changes in stack loss that could occur due to warmer basement temperatures, the attic floor of each house was also air sealed before the pre-retrofit period. Changes in air leakage rate due to the above pre-retrofit sealing are shown in Table 3.1 For the final sample set of 15 houses, the average air leakage reduction measured at 50 Pa was 1.1 and 3.8 air changes per hour for the CEUE and NRC houses, respectively. NRC houses had greater reductions in air leakage, since they received wall insulation and whole house air sealing at the same time.

Table 3.1. Changes in air leakage rate due to air sealing.

House Number	Air Leakage Rate (Air Change/Hour at 50 Pa)					
	Pre-Retrofit Sealing			Sealing Due to Retrofit		
	Before	After	Change	Before	After	Change
ME01	8.2	8.0	0.2	7.7	8.0	-0.3
ME02	11.3	9.5	1.8	5.5	5.2	0.3
ME03	6.9	5.0	1.9	6.2	5.5	0.7
ME04	6.4	5.7	0.7	6.1	5.5	0.6
ME05	9.2	7.6	1.6	8.3	7.2	1.1
ME06	7.1	6.1	1.0	7.0	6.1	0.9
ME07	8.7	7.9	0.8	9.0	7.8	1.2
ME08	7.8	7.3	0.5	7.8	7.4	0.4
ME09	7.5	6.2	1.3	6.7	6.6	0.1
ME010	13.2	12.2	1.0	10.9	10.0	0.9
NRC1	5.0	4.4	0.6	3.6	4.3	-0.7
NRC2*	13.7	10.8	2.9	9.8	10.0	-0.2
NRC3	13.6	8.3	5.3	9.2	8.3	0.9
NRC4	9.4	5.6	3.8	5.5	4.5	1.0
NRC5*	9.4	7.1	2.3	6.2	6.1	0.1
NRC6*	10.5	6.2	4.3	6.3	7.0	-0.7
NRC7*	5.2	3.8	1.4	4.3	4.1	0.2
NRC8	13.8	6.6	7.2	6.3	6.4	-0.1
NRC9	8.9	6.7	2.2	8.2	7.1	1.1
NRC10*	7.9	4.1	3.8	5.2	5.3	-0.1

Notes: Pre-retrofit sealing was measured using fan depressurization. Sealing due to retrofit was based on the average value of pressurization and depressurization measurements. Houses marked with asterisk were deleted from final analysis.

To control for basement heating, return and supply registers were closed or sealed in as many houses as possible for the 21 month monitoring period of the study. This could not be done in all houses, and house NRC4 had three open supply registers, and houses NRC8 and ME03 each had one open return register in the basement. As is common for the type of housing being studied, none of the basements was heated for comfort or used as daily living space.

The effect of furnace fan operation on basement pressure was measured in eight of the ten houses heated with forced air systems. Even though house NRC4 had three open supply registers, when the furnace fan was operating the basement pressure decreased to -7 Pa with respect to the first floor of the house. This was the largest negative pressure measured, and indicates that house NRC4 had a great deal of return duct leakage. The second largest negative pressure (-3.5 Pa) was measured in house ME02. The remainder of the houses ranged from -2.0 to 0.0 Pa, except for NRC9 that showed a positive pressure of 0.5 Pa. Houses ME08 and ME09 were not measured. Of the houses deleted from the study, all showed pressure differences between -1.0 and 0.5 Pa, except for NRC10 that was not measured.

3.3 SITE INSPECTIONS

To maintain site control over the houses, each house was visited six times during the duration of the program. During each of these site visits the recording thermographs were serviced, all meters were read as a check on the homeowner's readings, and observations relating to the use of each basement were recorded in a log book. These visits were also used to carry out the other activities required by the study, such as: measuring the steady state efficiencies and input rates of all furnaces, boilers, and water heaters; performing pre- and post-retrofit fan pressurization tests and a post-retrofit infrared inspection on all houses; and conducting an exit interview with each homeowner.

4. MEASUREMENTS

4.1 WEEKLY DATA

Weekly data were collected for 18 of the 20 houses in the study. For each house, the gas meter, the electric meter, and a furnace or boiler run-time meter were read and recorded once each week. If the house had a gas cooking range (15 out of 20 houses), the water heater was also submetered with a run-time meter. Water heater run-times were recorded so that internal gains due to cooking could be found by subtracting the hot water and space heat gas use from the total gas consumption.

Meters were read by homeowners who, as a part of the house selection process, were asked to do this task for the 21 month period of the study. Each homeowner was asked to sign the Foundation Research Homeowner Agreement shown in Appendix C. Homeowners were paid $20/month to read their own meters. Data were recorded once a week and mailed monthly to the principal investigator on special self-mailing forms. To maintain program credibility, checks were mailed to the homeowners within one or two days after their data sheet had been received. The data reporting rate remained high throughout the program, with overall reporting rates of 94 and 91 percent for the pre- and post-retrofit periods, respectively. Most post-retrofit data loss was due to one homeowner (NRC10) who became very unreliable during the second half of the post-retrofit period. The pre-retrofit data for this house was excellent, indicating that it is hard to predict how cooperative homeowners will be over an extended period of time. The remainder of the homeowners behaved in a consistent fashion throughout the study.

Data were entered into dBASE files using a data checking program to detect values that were out of the expected range. As each reading was entered, the use per day for the present and past periods was calculated and displayed. Meter readings that showed uses that differed by a factor of ten or more beyond the expected use were adjusted to yield a use on the same order as the one expected. The justification for this method rests on the observation that the use per day values being compared are based on the differences between cumulative meter readings, and, if a single meter reading is in error, then a paired high-low value is created. Our correction to the meter reading in this case is based on the conservative assumption that high-low values that are an order of magnitude greater or less than the expected value are an artifact of the data and not representative of the performance of the house.

Because the measured consumptions ranged in magnitude from zero to 100, the above method detected errors in the hundreds place and greater. Meter reading errors on the same or lower order (tens and one place) as the actual consumption could not be detected with the above method, and required a further examination of regression residuals for the presence of high-low pairs. This process, and the criteria used for data rejection in this study, is discussed in Section 5.1. A sample weekly dBASE file appears in Appendix F.

4.2 HOURLY DATA

Hourly data were collected at two sites (ME02 and NRC7) using Fowlkes data acquisition systems. Eight temperatures, two thermal fluxes, the electrical use, and the furnace and water heater run-times were monitored at each site. These data were collected to assist in the calibration of the foundation heat loss model being developed at the Underground Space Center at the University of Minnesota.

The Fowlkes data acquisition system consisted of an analog-to-digital converter that was controlled by a portable computer. Each channel was scanned about ten times per minute, and average values of each measured quantity were stored in the computer once each hour. Data were retrieved on a weekly basis using modem communication with the monitored site. The daily ASCII files obtained in this manner were copied into a single ASCII file that was then imported into a dBASE file for analysis. Daily and weekly files of summed and average data were then prepared using dBASE programs. The weekly data prepared this way were then analyzed the same as the weekly homeowner read data.

Weekly files of summed and averaged hourly data for the pre- and post-retrofit periods are shown for these two houses in Appendix G. House ME02 received an interior retrofit, and the flux plates were placed on the floor, so that they could be readily retrieved after the retrofit was installed. House NRC7 received an exterior retrofit, and the flux plates were placed on the wall. Both houses were chosen because they had simple rectangular geometries, fully accessible walls, and no attached garage.

The pre-retrofit fluxes for house ME02 show that during the middle of the winter the heat flux reversed with heat flowing from the ground into the house. In the post-retrofit period all of the fluxes are positive and somewhat larger, reflecting a greater basement air temperature and a lower ground temperature due to lower wall heat loss. This is particularly noticeable for the corner heat flux (FLUX2).

The data for house NRC7 are not as useful as that for ME02, since the owners decided to finish about half of the basement area into a recreation room and a third bedroom during the summer between the pre- and post-retrofit seasons. This was done to accommodate an unexpected change in the family, and was largely out of the control of the research program. Because of this change in usage pattern, this house was dropped from the analysis.

4.3 AIR LEAKAGE

The air leakage rate of each house was measured before and after the application of the foundation retrofit to determine the amount of air sealing that was coincident with the retrofit. Air leakage rates were based on the average value of fan pressurization and depressurization measurements. Measured air leakage rates before and after retrofit are shown in Table 3.1. The average air leakage rates before retrofit for the 15 final sample houses were 7.5 and 6.6 air changes per hour at 50 Pa for the CEUE and NRC houses, respectively. The average reduction in air leakage rate due to the retrofit, again for the 15 final houses, was 0.6 and 0.4 air changes per hour at 50 Pa for the CEUE and NRC houses.

4.4 TEMPERATURE

The temperature near the thermostat and at mid-height in the basement of each house was measured during both the pre-and post-retrofit period. Temperatures were recorded using battery powered bimetallic thermographs, and were measured to an accuracy of +/- $1^{o}F$. Each thermograph tape recorded for a period of 12 weeks, and an average temperature was assigned to each measurement by examining the entire tape for the period. The results of these measurements are shown in Table 4.1 and Figure 4.1. For the basement, fall temperatures were measured from November through January, and spring temperatures were measured from February through April. Temperatures near the thermostat were found by averaging the measured fall and spring values. In general, the basements follow a pattern of being cooler in the spring than the fall, and being warmer after the retrofit than before. The average increase in basement temperature was 4.3 ^{o}F. Except for the two houses that changed owners, set point temperatures remained nearly the same throughout the study.

Table 4.1. Basement and setpoint temperatures.

House Number	Basement Temperature (°F)				Set Point Temperature (°F)	
	Pre-Retrofit		Post-Retrofit		Pre-Retrofit	Post-Retrofit
	Fall	Spring	Fall	Spring		
ME01	62	57	66	62	63	64
ME02	58	56	61	62	65	66
ME03	57	52	60	54	67	66
ME04	62	62	68	67	67	68
ME05	62	60	65	63	65	65
ME06	60	52	60	58	66	66
ME07	57	54	61	59	67	66
ME08	58	56	61	59	62	63
ME09	61	59	68	65	70	72
ME010	60	52	64	64	70	72
NRC1	61	61	63	61	68	68
NRC2*	61	63	66	56	71	72(65)
NRC3	56	53	61	59	67	67
NRC4	61	59	66	66	72	71
NRC5*	65	62	68	62	70	72(65)
NRC6*	67	64	64	64	70	68
NRC7*	61	60	67	66	72	72
NRC8	58	58	62	60	74	73
NRC9	54	50	57	54	68	67
NRC10*	70	69	64	63	74	74

Notes: Basement fall temperatures were measured from November through January. Basement spring temperatures were measured from February through April. Basement temperatures were measured at mid-height in basement and setpoint temperatures were measured near the house thermostat. Temperatures shown in parentheses are setpoint temperatures for second owners of houses NRC2 and NRC5. Houses marked with asterisk were deleted from final analysis.

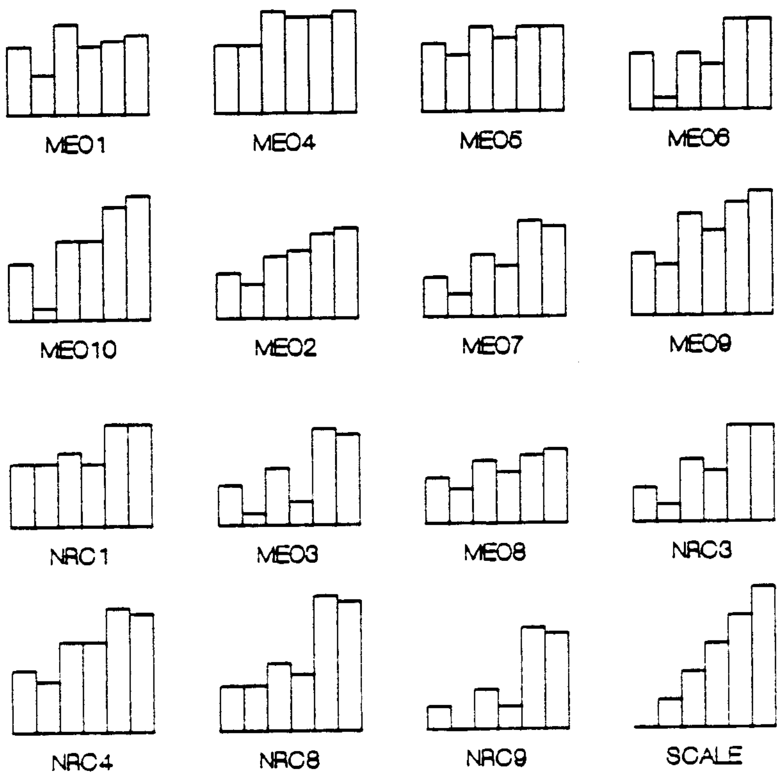

Fig. 4.1. Pre- and post-retrofit temperatures.

From left to right the six bars show the following temperatures: pre-retrofit basement, fall; pre-retrofit basement, spring; post-retrofit basement, fall; post-retrofit basement, spring; pre-retrofit setpoint; post-retrofit setpoint. Fall temperatures were measured from November through January, spring temperatures from February through April. Setpoint temperatures were temperatures measured near house thermostat. Lower right SCALE icon shows temperature scale from 50 °F baseline to 75 °F by five degree increments.

5. ANALYSIS OF ENERGY SAVINGS

5.1 NORMALIZED THERMAL LOAD ANALYSIS

Load savings were evaluated using a two-parameter linear least-squares model to calculate a weather normalized pre- and post-retrofit annual thermal load for each house (Robinson, 1986). The annual thermal load is defined as the total energy input within the house envelope, including all energy due to space heating, cooking, and electric use, that is required to maintain the house at its setpoint temperature for a full heating season.

Thermal inputs due to boilers and furnaces were calculated using the measured steady state efficiencies shown in Table 5.1. Gas cooking and electric use were assumed to be 100 percent efficient. Cooking gas use was found by subtracting measured space and water heating gas use from total gas use. By using the steady state furnace efficiency in this calculation, we are assuming that the difference in energy use that we are seeking is provided by the furnace at its marginal or steady state efficiency, and that any shifting of load from the furnace to cooking or electric sources is adequately represented by using the steady state efficiency rather than the seasonal efficiency.

Metabolic gains from house occupants were assumed to be the same for both the pre- and post-retrofit periods. Of the fifteen houses in the final analysis, all were occupied by the same families throughout the study. Of these households, the number of occupants changed in only two, and in these cases each household decreased by one adult member during the measurement period. All energy used for domestic water heating was assumed to leave the

Table 5.1. Input rates and efficiencies of gas space heating equipment and water heaters.

House Number	Gas Input Rate (kBtu/Hour)			Steady State Efficiency (unitless)		
	Heating System		Water Heater	Heating System		Water Heater
	Primary	Secondary		Primary	Secondary	
ME01	150		53	0.74		0.77
ME02	116		38	0.74		0.78
ME03	90	15	36	0.81	0.75	0.76
ME04	96		40	0.88		0.86
ME05	167		51	0.78		0.76
ME06	111	23	43	0.78	0.75	0.76
ME07	144		38	0.79		0.83
ME08	89		31	0.74		0.84
ME09	82		39	0.87		0.78
ME010	95		44	0.80		0.77
NRC1	83		43	0.78		0.77
NRC2*	97		29	0.76		0.73
NRC3	101		44	0.84		0.74
NRC4	59		43	0.75		0.74
NRC5*	90		43	0.79		0.75
NRC6*	85		48	0.75		0.77
NRC7*	112		33	0.78		0.80
NRC8	88		34	0.75		0.80
NRC9	76		29	0.75		0.82
NRC10*	79	36	50	0.79	0.75	0.78

Notes: Secondary heating systems were submetered gas space heaters. House NRC10 was deleted from study because space heater was not used in post-retrofit heating season. Houses marked with asterisk were deleted from final analysis.

house, either as flue or gray water losses (Nelson, 1986). Total energy use for clothes drying, and the fraction of this energy leaving the house, was assumed to be the same for the pre- and post-retrofit periods.

By using the definition of the thermal load as described above, and the measured weekly data described in Section 4.1, weekly loads could be calculated for each measurement period. These loads were then used in a linear least-squares model that fit the weekly loads to the average outdoor temperatures recorded for each measurement period at the Minneapolis-St.Paul airport. The model yielded two performance parameters: an average base use per day, and an average use per degree-day. The weather normalized load was calculated by multiplying these parameters (using the absolute value for the average use per degree-day) by the average number of days and the average number of degree-days below the set point temperature of the house, respectively, and then adding the results. A custom least-squares weather normalization program following this technique (Robinson, 1986) was written in a compiled data base language for this calculation. This method was chosen over the alternative normalized annual consumption program, PRISM (Fels, 1986), because it explicitly includes internal gains due to thermal sources other than the furnace or boiler, it normalizes for thermostat setpoint, and it is a heating-only model that does not require non-heating season data. When compared using synthetic heating only data (Shen, 1990), the PRISM program and the above two-parameter model produced numerical results that were in close agreement.

The results of the above analysis are shown in Tables 5.2 and 5.3. Pre-retrofit thermal loads are shown in Table 5.2, and post-retrofit thermal loads are shown in Table 5.3. Because many houses

Table 5.2. Results of pre-retrofit analysis using two-parameter normalized thermal load model.

BUILDING LABEL	BEGIN DATE	END DATE	NUMBER OF DAYS	NUMBER OF RDNGS	SET POINT TEMP	NORMAL TEMP	R*R	SLOPE (Use per d-day)	STD ERROR SLOPE	BASE (use per day)	STD ERROR BASE	NRMLZD THRML LOAD	STD ERROR NTL
HOUSE-MEO1	10/04/87	05/01/88	210	26	63	64	0.970	-0.112	0.004	0.35	0.14	967	16
HOUSE-MEO2GSM	01/06/88	04/28/88	113	14	65	66	0.957	-0.064	0.004	0.44	0.16	656	19
HOUSE-MEO3	01/06/88	05/02/88	117	11	67	66	0.982	-0.095	0.004	0.13	0.19	825	26
HOUSE-MEO4	10/03/87	04/30/88	210	25	67	68	0.991	-0.133	0.003	-0.79	0.10	952	12
HOUSE-MEO5	10/12/87	05/02/88	203	27	65	65	0.950	-0.121	0.005	0.03	0.20	980	23
HOUSE-MEO6	12/23/87	04/27/88	126	17	66	66	0.981	-0.122	0.004	-0.48	0.17	879	21
HOUSE-MEO7	10/06/87	05/04/88	211	25	67	66	0.990	-0.107	0.002	-0.15	0.08	851	9
HOUSE-MEO8F	10/05/87	05/02/88	210	26	62	63	0.989	-0.079	0.002	-0.45	0.06	478	6
HOUSE-MEO9	10/11/87	05/15/88	217	23	70	72	0.970	-0.083	0.003	0.18	0.12	896	17
HOUSE-MEO10	10/04/87	05/15/88	224	18	70	72	0.907	-0.103	0.008	0.11	0.23	1076	23
HOUSE-NRC1	10/01/87	04/28/88	210	25	68	68	0.974	-0.061	0.002	0.22	0.09	606	10
HOUSE-NRC2*	10/18/87	05/17/88	212	23	71	72	0.971	-0.187	0.007	-1.21	0.29	1506	39
HOUSE-NRC3F	11/14/87	04/30/88	168	21	67	67	0.916	-0.061	0.004	0.17	0.16	576	18
HOUSE-NRC4	10/08/87	05/19/88	224	30	72	71	0.978	-0.062	0.002	-0.11	0.07	570	9
HOUSE-NRC5F*	12/14/87	05/17/88	155	17	70	72	0.915	-0.128	0.009	-0.05	0.39	1281	52
HOUSE-NRC6*	10/06/87	05/17/88	224	24	70	68	0.987	-0.093	0.002	0.05	0.09	844	11
HOUSE-NRC7SM*	11/01/87	05/15/88	196	26	72	72	0.966	-0.088	0.003	-0.45	0.15	745	21
HOUSE-NRC8F	10/08/87	05/19/88	224	30	74	73	0.984	-0.073	0.002	-0.43	0.07	620	10
HOUSE-NRC9	10/06/87	05/03/88	210	27	68	67	0.984	-0.059	0.001	0.18	0.06	557	7
HOUSE-NRC10*	01/01/88	05/21/88	141	14	74	74	0.964	-0.066	0.003	0.35	0.16	827	26

Notes: Analysis of houses MEO2 and NRC7 that were submetered for hourly data, was done using the weekly average data shown in Appendix G. House NRC7 and houses with F suffix in their label were equipped with electric kitchen ranges, and the furnace was the only gas combustion appliance considered in the analysis of these houses. The setpoint temperature was the temperature measured near the thermostat in each house. The normal temperature is equal to the post-retrofit set point temperature and was used to normalize the pre-retrofit thermal load to the same temperature as the post-retrofit load. Negative slope indicates that as the outdoor temperature decreases the thermal load on the house envelope increases. Units for the slope and base are therm/^{o}F-day and therm/day, respectively. Normalized thermal load is annual load in therm/year. Houses marked with asterisk were deleted from final analysis.

Table 5.3. Results of post-retrofit analysis using two-parameter normalized thermal load model.

BUILDING LABEL	BEGIN DATE	END DATE	NUMBER OF DAYS	NUMBER OF RDNGS	SET POINT TEMP	NORMAL TEMP	R*R	SLOPE (Use per d-day)	STD ERROR SLOPE	BASE (use per day)	STD ERROR BASE	NRMLZD THRML LOAD	STD ERROR NTL
HOUSE-MEO1	10/02/88	05/07/89	217	27	64	64	0.956	-0.104	0.004	0.42	0.16	922	17
HOUSE-MEO2GSM	01/05/89	05/11/89	126	14	66	66	0.956	-0.066	0.004	0.09	0.15	571	20
HOUSE-MEO3	01/08/89	05/08/89	120	15	66	66	0.970	-0.082	0.004	0.29	0.15	767	18
HOUSE-MEO4	10/01/88	05/13/89	224	27	68	68	0.990	-0.120	0.002	-0.55	0.09	906	11
HOUSE-MEO5	10/17/88	05/03/89	198	22	65	65	0.936	-0.104	0.006	0.24	0.23	904	24
HOUSE-MEO6	12/14/88	05/03/89	140	17	66	66	0.978	-0.116	0.004	-0.35	0.19	872	22
HOUSE-MEO7	10/04/88	05/09/89	217	25	66	66	0.992	-0.121	0.002	-0.53	0.08	856	10
HOUSE-MEO8F	10/03/88	05/08/89	217	31	63	63	0.961	-0.074	0.003	-0.42	0.10	447	10
HOUSE-MEO9	09/18/88	05/14/89	238	28	72	72	0.954	-0.083	0.003	-0.19	0.15	779	20
HOUSE-MEO10	10/02/88	05/14/89	224	28	72	72	0.954	-0.089	0.004	0.13	0.16	938	22
HOUSE-NRC1	09/29/88	04/13/89	196	23	68	68	0.952	-0.050	0.002	0.18	0.10	498	12
HOUSE-NRC2FO*	09/22/88	01/20/89	120	13	72	72	0.951	-0.171	0.011	-1.71	0.43	1179	53
HOUSE-NRC3F	11/12/88	04/22/89	161	20	67	67	0.923	-0.076	0.005	-0.21	0.22	592	25
HOUSE-NRC4	09/22/88	05/11/89	231	28	71	71	0.927	-0.049	0.003	0.24	0.11	558	14
HOUSE-NRC5FOF*	09/21/88	01/27/89	128	14	72	72	0.877	-0.120	0.012	-0.20	0.51	1153	64
HOUSE-NRC6*	10/04/88	05/09/89	217	21	68	68	0.868	-0.086	0.007	0.37	0.27	873	31
HOUSE-NRC7SM*	11/01/88	05/11/89	191	25	72	72	0.922	-0.070	0.004	0.51	0.19	874	27
HOUSE-NRC8F	09/22/88	04/27/89	217	31	73	73	0.981	-0.065	0.002	-0.12	0.08	638	10
HOUSE-NRC9	09/27/88	05/09/89	224	27	67	67	0.957	-0.051	0.002	0.26	0.08	511	10
HOUSE-NRC10*	08/28/88	03/18/89	202	12	74	74	0.760	-0.039	0.006	0.76	0.30	668	43

Notes: Analysis of houses MEO2 and NRC7 that were submetered for hourly data, was done using the weekly average data shown in Appendix G. House NRC7 and houses with F suffix in their label were equipped with electric kitchen ranges, and the furnace was the only gas combustion appliance considered in the analysis of these houses. Houses NRC2 and NRC5 changed owners during the last week of January, 1989. Results for these houses are based on performance while the houses were occupied by their first owners only. For this analysis the normal temperature is set equal to the setpoint temperature, so that these results may be directly compared to the pre-retrofit load (see Table 5.2). Negative slope indicates that as the outdoor temperature decreases the thermal load on the house envelope increases. Units for the slope and base are therm/^{o}F-day and therm/day, respectively. Normalized thermal load is annual load in therm/year. Houses marked with asterisk were deleted from final analysis.

demonstrate a seasonal component to their energy use (Fels, 1986), the pre- and post-retrofit analysis periods were matched for all but three houses in the study. Houses NRC2 and NRC5 could not be period matched because of a change in the owner/occupant of the house, and house NRC10 could not be period matched due to missing post-retrofit data. Houses NRC2 and NRC5 were deleted from the final analysis because of their change in owner/occupant, and NRC10 was deleted because the basement was heated during the pre-retrofit season, but not during the post-retrofit season.

So that the data for each house would be treated the same, the following two-step data editing routine was used throughout the analysis. The first data edit focused on meter reading errors. A first run was done using the raw data compiled as described in section 4.1 of this report. The residuals from this first regression analysis were then examined, and any high-low pairs in the tens place were corrected. Also, if the reader had a history of irregular reading, but had a regular life style, two to three readings might be averaged. These data adjustments are judged to be conservative, since no data were deleted, and, as discussed previously, all data were from cumulative meters. The data resulting from this edit was then run a second time, and the residuals were again examined. For the second edit, the focus was on household variability, and single outliers were deleted. A single meter reading was deleted if its residual exceeded two times the standard error of the estimate. A typical house had one or two high-low pairs that were corrected, and one or two single values that were deleted. Many of the deleted readings were for periods during the holiday season when household activity was highly variable.

5.2 NORMALIZED ANNUAL CONSUMPTION ANALYSIS

The Princeton PRISM program was also used to analyze the meter data collected in this study, and the results of this analysis are shown in Table 5.4 and Table 5.5. The analysis shown in these tables was based on metered gas consumption only, and was carried out as an overall check on the retrofit savings found in this study. Data for this analysis were edited using the same technique as described in section 5.1 above, and the pre and post periods were again matched to reduce the effects of seasonality.

5.3 MEASURED SAVINGS

Measured savings in load for the 15 final analysis houses are shown in Table 5.6. The normalized thermal loads shown in this table are from Tables 5.2 and 5.3. These same load data are shown in Figure 5.1. In this figure, houses for which the load decreased between the pre- and post-retrofit period are shown by the points below the diagonal line. Of the 15 houses in Figure 5.1, ten show a significant (more than one standard error) reduction in measured load. The remainder of the houses, except for one, show no significant (less that one standard error) difference between the pre- and post-retrofit measured loads.

The average space heat energy savings for the load savings shown in Table 5.6 are shown in Table 5.7. The average pre- and post-retrofit space heat energy consumptions shown in Table 5.7 were calculated from the loads shown in Table 5.6 by dividing the loads in Table 5.6 by an estimated Annual Fuel Utilization Efficiency (AFUE) of 0.75. So that the cost effectiveness of the retrofits may be directly compared, a single value for the AFUE is used here rather than the steady state efficiency values shown in

Table 5.4. PRISM program results for pre-retrofit data.

********************* PRISM-Heating Only (HO) *********************

UNIT ID	PRE OR POST	SAMP TYPE	TIME PERIOD	# PDS	# DAYS	RAW CONS X	RXR	TREF	BASE LEVEL X PER DAY	HEAT SLOPE X PER HDD	HEATING PART X PER YEAR	NAC X PER YEAR
HOUSE-ME01	PRE	I	10/04/87-06/19/88	34	239	995C	0.984	58.3(1.5)	0.75(0.15)	0.153(0.005)	973.(41.)	1248.(25.)
HOUSE-ME02	PRE	I	01/06/88-06/30/88	24	176	471C	0.970	63.1(3.3)	0.51(0.16)	0.091(0.006)	688.(52.)	875.(28.)
HOUSE-ME03	PRE	E	10/11/87-06/30/88	30	251	779C	0.974	61.4(2.3)	0.62(0.15)	0.107(0.005)	759.(44.)	985.(25.)
HOUSE-ME04	PRE	I	10/03/87-06/25/88	34	237	905C	0.993	57.6(0.9)	0.68(0.09)	0.148(0.003)	921.(23.)	1169.(15.)
HOUSE-ME05	PRE	I	10/12/87-06/21/88	34	239	1169C	0.966	56.0(2.1)	1.17(0.24)	0.167(0.007)	975.(60.)	1404.(39.)
HOUSE-ME06	PRE	I	10/07/87-06/29/88	37	259	1063C	0.982	55.7(1.4)	0.92(0.14)	0.159(0.005)	919.(35.)	1257.(24.)
HOUSE-ME07	PRE	I	10/06/87-06/28/88	34	251	913C	0.992	62.1(1.1)	0.39(0.09)	0.132(0.003)	966.(26.)	1108.(14.)
HOUSE-ME08	PRE	E	10/12/87-06/27/88	36	252	747C	0.986	56.8(1.3)	0.69(0.09)	0.110(0.003)	661.(22.)	913.(15.)
HOUSE-ME09	PRE	I	10/11/87-06/26/88	32	252	799C	0.975	62.7(2.1)	0.55(0.14)	0.102(0.004)	757.(41.)	956.(21.)
HOUSE-ME010	PRE	I	10/04/87-06/26/88	37	259	1067C	0.980	59.5(1.6)	1.16(0.13)	0.130(0.004)	862.(37.)	1286.(22.)
HOUSE-NRC1	PRE	I	10/01/87-06/30/88	34	273	711C	0.992	64.2(1.3)	0.54(0.06)	0.078(0.002)	611.(20.)	808.(10.)
HOUSE-NRC2*	PRE	I	10/18/87-07/25/88	31	268	1645C	0.985	59.5(1.6)	1.08(0.20)	0.239(0.009)	1590.(58.)	1983.(38.)
HOUSE-NRC3	PRE	E	10/10/87-05/28/88	33	231	775C	0.964	60.9(2.7)	0.85(0.19)	0.091(0.004)	634.(50.)	944.(26.)
HOUSE-NRC4	PRE	E	10/08/87-05/26/88	32	231	691C	0.987	61.6(1.9)	0.57(0.12)	0.086(0.002)	614.(33.)	820.(15.)
HOUSE-NRC5*	PRE	E	11/06/87-06/21/88	24	215	925C	0.958	52.4(2.5)	1.27(0.25)	0.171(0.011)	864.(61.)	1329.(47.)
HOUSE-NRC6*	PRE	E	10/06/87-05/31/88	30	238	935C	0.982	56.0(1.6)	1.06(0.15)	0.126(0.004)	733.(37.)	1120.(24.)
HOUSE-NRC7*	PRE	E	01/24/88-06/30/88	16	151	489C	0.984	63.0(2.5)	0.91(0.13)	0.117(0.007)	882.(45.)	1214.(28.)
HOUSE-NRC8	PRE	E	10/08/87-06/30/88	36	259	706C	0.986	62.7(1.5)	0.28(0.09)	0.096(0.003)	718.(26.)	822.(14.)
HOUSE-NRC9	PRE	E	10/06/87-06/28/88	36	259	599C	0.985	60.3(1.4)	0.52(0.06)	0.076(0.002)	520.(18.)	710.(11.)
HOUSE-NRC10*	PRE	E	10/02/87-03/18/88	19	168	677C	0.961	50.4(9.1)	1.64(0.81)	0.101(0.006)	472.(165.)	1072.(132.)

Notes: Sample types I and E are for interior and exterior retrofit cases, respectively. Reference temperature units are Fahrenheit degrees, and the base level and heat slope units are therm/day and therm/^{o}F-day, respectively. PDS is number of meter readings in time period. NAC is normalized annual consumption in therm/year, and is a measure of the total amount of metered gas used annually. Houses marked with asterisk were deleted from final analysis.

Table 5.5. PRISM program results for post-retrofit data.

********************* PRISM-Heating Only (HO) ***

UNIT ID	PRE OR POST	SAMP TYPE	TIME PERIOD	# PDS	# DAYS	RAW CONS X	RXR	TREF	BASE LEVEL X PER DAY	HEAT SLOPE X PER HDD	HEATING PART X PER YEAR	NAC X PER YEAR
HOUSE-ME01	POST	I	10/02/88-06/25/89	36	259	1075C	0.975	58.9(2.3)	0.67(0.20)	0.145(0.006)	943.(54.)	1187.(28.)
HOUSE-ME02	POST	I	01/05/89-06/29/89	24	168	476C	0.982	62.1(2.5)	0.77(0.13)	0.084(0.003)	613.(40.)	894.(19.)
HOUSE-ME03	POST	E	10/09/88-06/25/89	32	234	705C	0.982	59.5(1.9)	0.66(0.11)	0.096(0.004)	637.(31.)	879.(17.)
HOUSE-ME04	POST	I	10/01/88-06/24/89	35	245	944C	0.992	58.6(1.4)	0.63(0.11)	0.135(0.003)	870.(30.)	1099.(15.)
HOUSE-ME05	POST	I	10/17/88-06/21/89	29	214	980C	0.975	56.9(2.2)	1.13(0.19)	0.140(0.006)	843.(49.)	1257.(30.)
HOUSE-ME06	POST	I	10/12/88-06/28/89	34	245	1008C	0.990	53.9(1.2)	1.02(0.10)	0.154(0.004)	829.(26.)	1202.(19.)
HOUSE-ME07	POST	I	10/04/88-06/27/89	35	251	989C	0.993	55.6(1.0)	0.61(0.10)	0.155(0.003)	891.(25.)	1112.(16.)
HOUSE-ME08	POST	E	10/10/88-06/26/89	35	245	776C	0.986	54.7(1.5)	0.83(0.09)	0.110(0.004)	612.(23.)	914.(15.)
HOUSE-ME09	POST	I	10/02/88-06/24/89	30	265	812C	0.962	61.7(3.6)	0.55(0.24)	0.093(0.005)	671.(65.)	870.(29.)
HOUSE-ME010	POST	I	10/02/88-06/25/89	36	252	1038C	0.969	58.7(2.6)	1.20(0.19)	0.120(0.006)	774.(52.)	1211.(27.)
HOUSE-NRC1	POST	I	09/29/88-06/29/89	33	273	638C	0.972	62.4(2.6)	0.62(0.11)	0.064(0.003)	470.(31.)	695.(14.)
HOUSE-NRC2FO*	POST	I	08/04/88-01/20/89	15	153	870C	0.968	56.2(3.1)	1.22(0.40)	0.230(0.019)	1352.(106.)	1799.(69.)
HOUSE-NRC2SO*	POST	I	02/10/89-06/29/89	19	132	403C	0.970	55.1(2.5)	1.03(0.18)	0.147(0.010)	829.(53.)	1207.(38.)
HOUSE-NRC3	POST	E	10/08/88-05/27/89	29	219	795C	0.960	58.1(3.5)	1.04(0.23)	0.092(0.005)	577.(59.)	958.(31.)
HOUSE-NRC4	POST	E	10/06/88-05/25/89	30	217	644C	0.938	59.0(3.9)	1.07(0.21)	0.067(0.004)	437.(53.)	829.(29.)
HOUSE-NRC5FO*	POST	E	09/07/88-01/27/89	12	135	550C	0.974	51.6(2.9)	0.91(0.22)	0.168(0.017)	826.(53.)	1158.(45.)
HOUSE-NRC5SO*	POST	E	01/27/89-05/27/89	13	113	446C	0.979	53.7(3.0)	0.74(0.25)	0.156(0.011)	831.(66.)	1103.(45.)
HOUSE-NRC6*	POST	E	10/04/88-05/30/89	23	224	869C	0.933	60.0(4.6)	0.70(0.42)	0.110(0.008)	745.(109.)	1000.(55.)
HOUSE-NRC7*	POST	E	01/05/89-06/29/89	15	162	627C	0.977	69.7(7.5)	0.65(0.63)	0.105(0.006)	987.(207.)	1223.(44.)
HOUSE-NRC8	POST	E	10/06/88-06/29/89	36	252	758C	0.991	67.0(1.8)	0.38(0.12)	0.084(0.002)	724.(36.)	861.(11.)
HOUSE-NRC9	POST	E	10/04/88-06/29/89	34	259	557C	0.978	56.5(2.0)	0.52(0.08)	0.070(0.003)	419.(22.)	608.(13.)
HOUSE-NRC10*	POST	E	10/01/88-03/18/89	12	147	456C	0.958	40.7(3.2)	1.98(0.13)	0.067(0.007)	199.(22.)	923.(28.)

Notes: Sample types I and E are for interior and exterior retrofit cases, respectively. Reference temperature units are Fahrenheit degrees, and the base level and heat slope units are therm/day and therm/°F-day, respectively. PDS is number of meter readings in time period. NAC is normalized annual consumption in therm/year, and is a measure of the total amount of metered gas used annually. Houses NRC2 and NRC5 each changed owners during the last week of January, 1989. Data for the first and second owners are shown by the suffixes FO and SO for the first owner and second owner, respectively. Houses marked with asterisk were deleted from final analysis.

Table 5.6. Pre- and post-retrofit measured load for 15 houses.

House Number	Normalized Thermal Load (therm/year)				Load Savings (therm/year)	Standard Error (therm/year)
	Pre-retrofit	Standard Error	Post-retrofit	Standard Error		
ME01	967	16	922	17	45	23
ME04	952	12	906	11	46	16
ME05	980	23	904	24	76	33
ME06	879	21	872	22	7	30
ME010	1076	23	938	22	138	32
ME02	656	19	571	20	85	28
ME07	851	9	856	10	-5	13
ME09	896	17	779	20	117	26
NRC1	606	10	498	12	108	16
ME03	825	26	767	18	58	32
ME08	478	6	447	10	31	12
NRC3	576	18	592	25	-16	31
NRC4	570	9	558	14	12	17
NRC8	620	10	638	10	-18	14
NRC9	557	7	511	10	46	12

Notes: The normalized thermal load is the total purchased energy, gas and electricity, that is thermalized within the house to maintain the house at its setpoint temperature. The first nine houses received interior retrofits, the last six received exterior retrofits. 1 therm = 10^5 Btu.

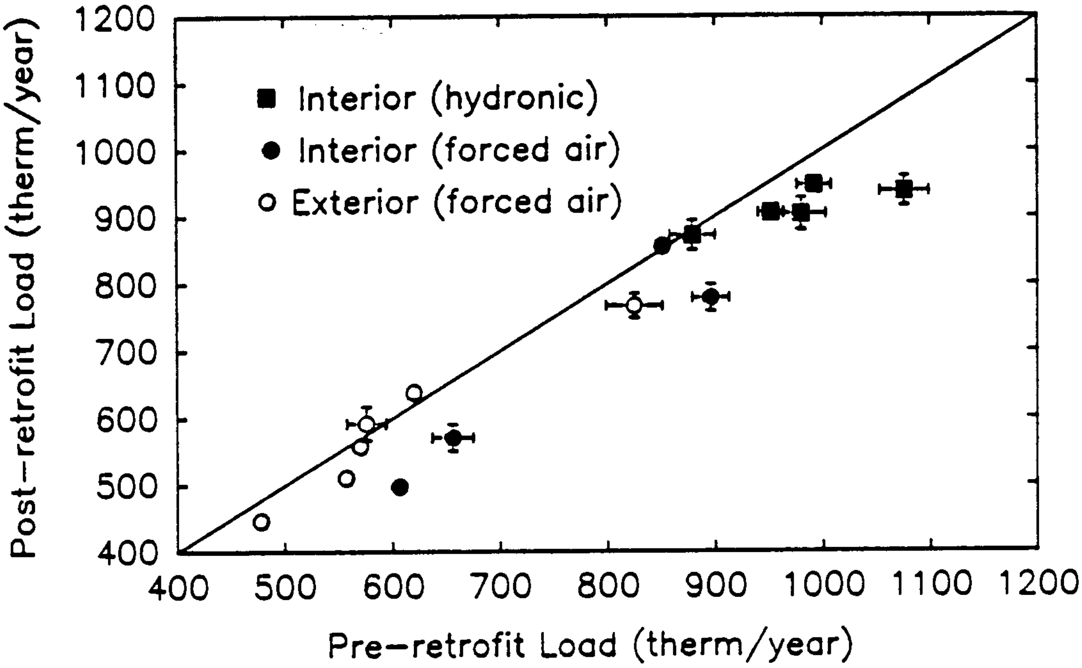

Fig. 5.1. Pre- and post-retrofit space heating loads.

Loads are calculated using the normalized thermal load method and expressed in therm per year (10^5 Btu/year). Standard errors are shown for each value for which they exceed the plotting symbol size.

Table 5.7. Average measured space heat energy savings.

Insulation Type	Pre-retrofit Space Heat Energy (therm/yr)	Post-retrofit Space Heat Energy (therm/yr)	Energy Savings (therm/yr)	Energy Savings (percent)	Energy Savings per Foot Insulated (therm/yr-ft)
Interior	1165	1073	92 (11)	7.9	0.79
Exterior	805	781	24 (12)	3.0	0.29
All Cases	1021	956	65 (8)	6.4	0.60

Notes: Average energy savings are based on loads shown in Table 5.6 divided by an estimated AFUE of 0.75. Standard error of energy savings is shown in parentheses.

Table 5.1. The AFUE value of 0.75 is somewhat larger than might be expected in existing housing. We assume here, however, that since a foundation retrofit is usually one of the last and most costly retrofits to be applied, that it is equally likely to be done either before or after an energy efficient furnace retrofit, and thus a higher average AFUE is justified.

Table 5.7 shows that the average energy savings for the interior and exterior retrofit cases were 92 therm/year and 24 therm/year, respectively. For all 15 houses the average savings were 65 therm/year. The interior and exterior retrofits saved 7.9 percent and 3.0 percent of the annual space heat energy, respectively.

5.4 DISCUSSION OF MEASURED SAVINGS

Quaid, in her study of foundation retrofits in 13 Minneapolis houses, found average space heat savings of 23.1 percent (197 therm/year) and 15.5 percent (111 therm/year) for eight interior and five exterior retrofits, respectively (Quaid, 1988). Quaid's study examined pre- and post-retrofit fuel bills for houses retrofit under the Minneapolis Energy Office's (now the Center for Energy and the Urban Environment) Operation Insulation program. These retrofits were performed without controlling for air sealing during retrofit, and houses that were reported by the owners to have had a change in the amount of heat added to the basement were removed from the study. Foundation insulation was not heavily promoted at the time the retrofits were done, so those receiving insulation were self-selected and may have had house or occupant characteristics that differed from those in the present study.

We can compare Quaid's findings to the present study for the interior retrofit cases by adding to the measured savings reported here, the savings that would have been provided by the measured pre-retrofit air sealing. We compare only interior cases, since for the present study the exterior cases received more extensive pre-retrofit work, and the reductions in air leakage measured here are not considered representative of those that would occur if only foundation insulation were applied. By estimating that an air leakage reduction of 1 AC/hour at 50 Pa reduces the annual infiltration rate by 1/17 AC/hour (Meier, 1986), we can calculate the energy savings to be expected due to the measured air leakage reduction. Applying this to the interior retrofits of the present study yields an average energy savings of about 0.40 therm/year per linear foot insulated. This additional savings equals 53 percent of the difference between the present study (0.79 therm/yr-ft) and Quaid's study (1.54 therm/yr-ft). In addition to this, Quaid's study reported that 35 percent of the households used their basements as living space before the retrofit, and that 65 percent used them as living space after. This indicates that many of the basements in Quaid's study may have been intentionally heated both before and after the retrofit, leading to the greater savings observed.

A summary of the PRISM results shown in Tables 5.4 and 5.5 is shown in Table 5.8 for the fifteen houses in the final analysis. Assuming that one CCF of gas is equal to one therm of energy, a comparison of the Tables 5.7 and 5.8 shows that the pre- and post-retrofit energy uses are nearly the same for all cases. The gas use values in Table 5.8 include space heating, plus a base use of water heating, cooking and clothes drying. The energy values in Table 5.7 include the above space heating value, plus the internal gains added by the normalized thermal load calculation. From this

Table 5.8. Average gas consumption based on PRISM analysis of measured data.

Insulation Type	Pre-retrofit Gas Use (CCF/yr)	Post-retrofit Gas Use (CCF/yr)	Gas Savings (CCF/yr)	Space Heat Gas Savings (percent)	Gas Saved per Foot Insulated (CCF/yr-ft)
Interior	1123	1058	65 (11)	8.3	0.59
Exterior	866	842	24 (11)	4.0	0.31
All Cases	1020	971	49 (8)	6.9	0.48

Notes: Values are calculated from data shown in Tables 5.4 and 5.5 for fifteen houses in final analysis. Percent space heat gas savings is calculated by assuming that 70 percent of pre-retrofit gas consumption is used for space heating (Hewett, 1986). Standard error of gas savings is shown in parentheses.

observation, and the near equality of the energy and gas use values, we conclude that for the houses in this study the base use is roughly equal to the space heat provided by internal gains. Overall, the normalized thermal load model yielded greater energy savings than the PRISM model. This may be the result of explicitly including internal gains in the calculation of the normalized thermal load. However, the PRISM model yielded greater percent savings, since in this case internal gains are not explicitly included as a part of the space heat.

Finally, the measured savings as a function of the area of insulation applied is shown in Figure 5.2. Both the interior and exterior cases show a weak correlation (R-squared values of 0.10 and 0.48, respectively) between the area insulated and the measured reduction in building load. Adding a single additional loss parameter to the savings regression model increased the R-squared value to 0.80 or greater for both the interior and exterior case. This analysis is presented in Section 8.2 of the report.

5.5 PREDICTED SAVINGS

Two different models were used to calculate the savings to be expected from the retrofits described in this report. The first was a detailed finite difference computer model that used the average measured pre- and post-retrofit basement temperatures, and the weather data from each measurement period to calculate the annual pre- and post-retrofit basement space heating loads. The load savings due to retrofit were then found from the calculated pre-and post-retrofit loads by subtraction. The second method used the Minnesota RCS energy audit calculation (MECS model). This model used only the average measured pre-retrofit basement temperature, and calculated the reduction in load to be expected from an increased basement wall R-value.

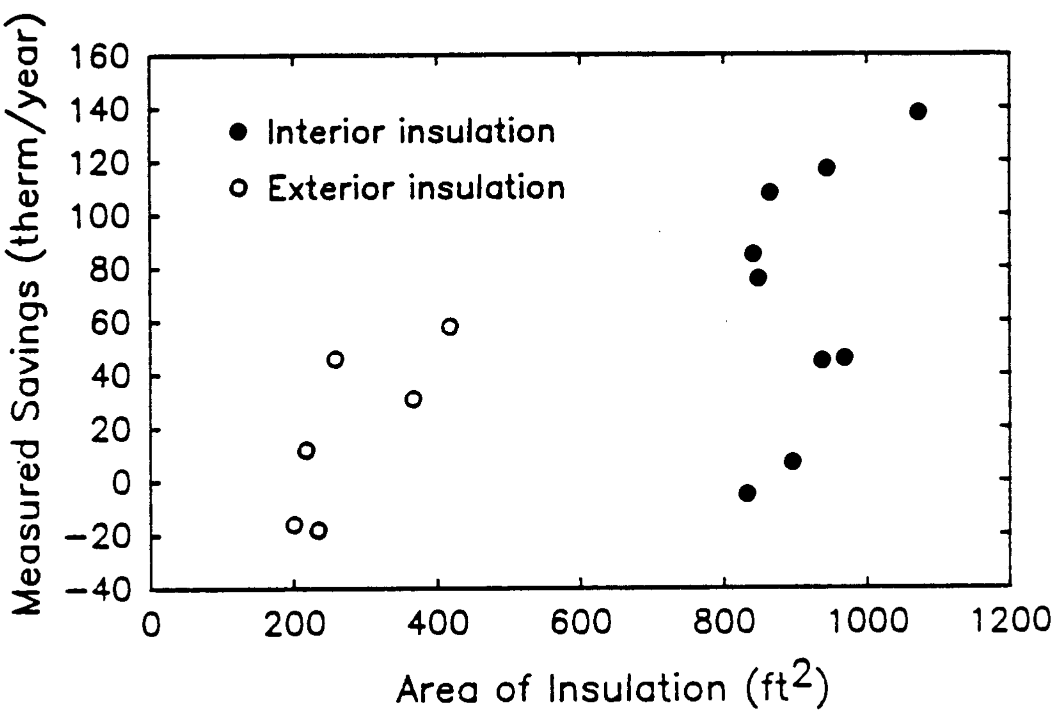

Fig. 5.2. Measured load savings versus insulated foundation area.

The finite difference program models a two-dimensional cross-section of the building foundation and generates average heat fluxes for the foundation wall and floor for each time step (Shen, 1988). These results are then scaled to model the three-dimensional footprint of each house (Labs, 1988). For the present study, a daily time step was used, and a uniform and constant basement air temperature was assumed as the interior boundary condition. Snow cover was assumed to be zero for both the pre-and post-retrofit season, and solar effects were not modelled. Soil thermal properties were assumed to be the same at each site, and were modelled using a moist, sandy soil with a thermal conductivity of 1.0 Btu/hr-ft-^{o}F. Before the start of the pre-retrofit period an average soil thermal conductivity of 1.1 Btu/hr-ft-^{o}F was found for soil samples obtained at the two sites where hourly data were collected. Because the Minneapolis-St. Paul area experienced a drought that extended for the duration of the study (Baker, 1990), the model value of 1.0 Btu/hr-ft-^{o}F is believed to be realistic, since dryer soil is less thermally conductive.

Figure 5.3 compares the measured savings found in this study with the savings predicted by the above two-dimensional finite difference model. The slope of 0.31 and the near-zero intercept of the regression line in this figure shows that on the average the houses in the study achieved about one-third of the savings predicted. A discussion of these lower than expected savings will be presented in Section 8 of this report.

Figures 5.4 and 5.5 compare the savings predicted by the RCS audit method with those predicted by the finite difference computer model. The predicted values in Figure 5.4 were calculated for pre- and post-retrofit temperatures set to 68 ^{o}F for both models. A linear regression analysis of the data shown in Figure 5.4

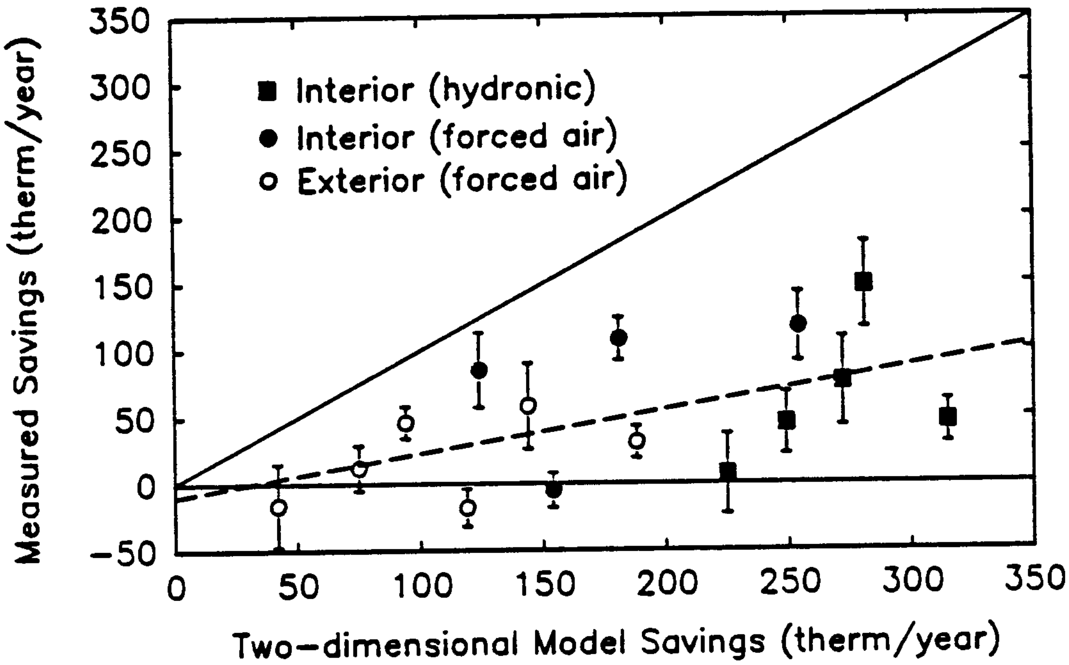

Fig. 5.3. Comparison of measured and predicted savings.

Standard error for each savings value is shown. Model calculation used measured pre- and post-retrofit basement temperatures, and six years actual weather data (five years for pre calculation and one for post). Running the program beyond first post-retrofit year did not significantly change the annual savings compared to the first year value. Intercept and slope of dashed regression line are -7.7 therm/year and 0.31, respectively. R-squared value is 0.27.

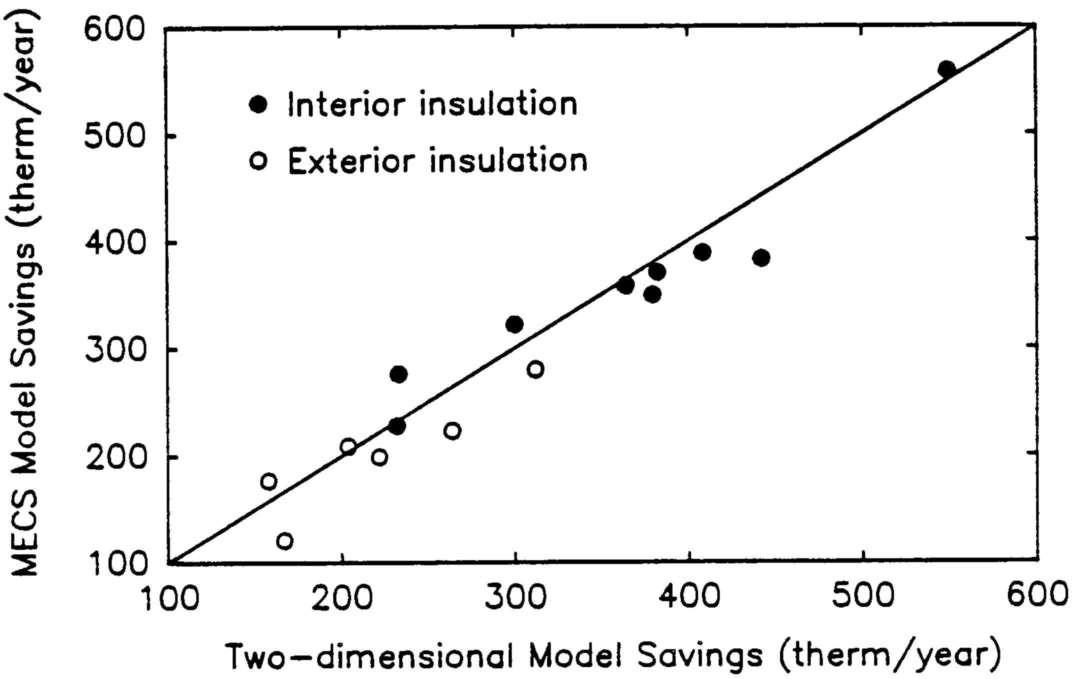

Fig. 5.4. Comparison of savings predicted by Minnesota RCS audit calculation (MECS model) and two-dimensional finite difference model for 68 °F basement temperature.

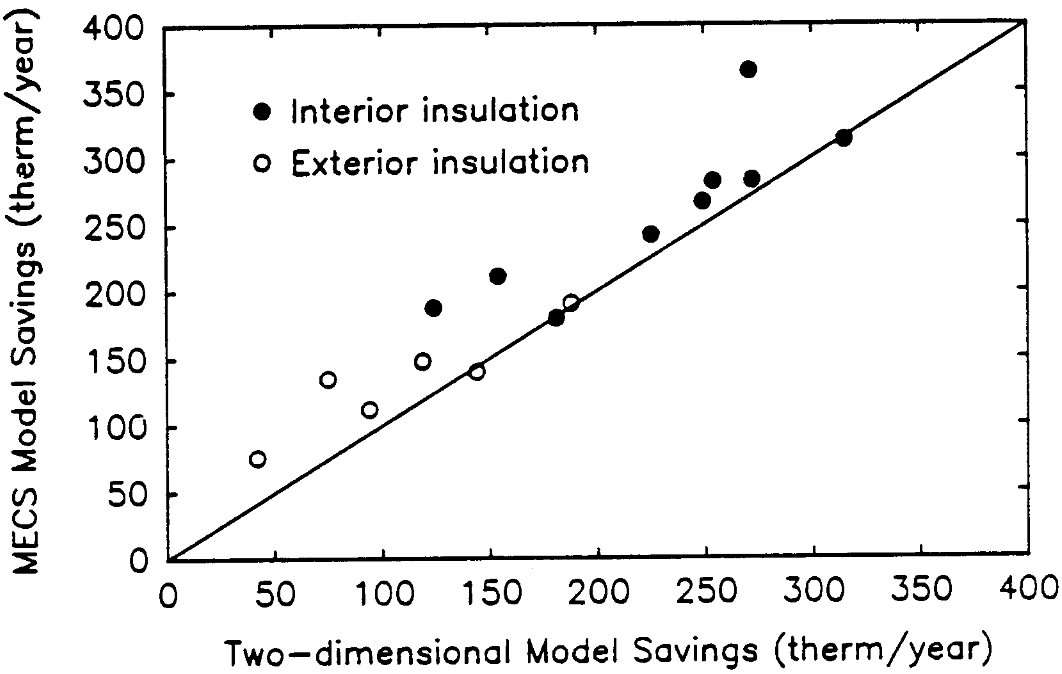

Fig. 5.5. Comparison of savings predicted by Minnesota RCS audit calculation (MECS model) and two-dimensional finite difference model for measured basement temperatures.

(regression line not shown) yielded a slope coefficient of 0.96, an intercept of 1.3 therm/year, and an R-squared value of 0.94. The standard error of the estimate for the savings predicted by the RCS audit as a function of the two-dimensional model prediction was 29 therm/year. This is on the same order as the average standard error for the savings measured using the normalized thermal load method, 22 therm/year. Thus, if we assume that the two-dimensional model predicts the true value for the savings, then the savings as predicted by the simplified RCS audit appears to be of sufficient precision for predicting audit performance. However, as shown by the results in Figure 5.3, the two-dimensional model appears to have little actual accuracy in predicting retrofit performance.

The interior boundary condition for the two-dimensional model assumes that the basement temperature is uniform and constant. Because it is unlikely that this boundary condition is met by the temperatures that occur in real basements, it is not surprising that the measured savings are so poorly predicted as shown in Figure 5.3. As will be discussed in Section 8, it appears that mechanisms other than basement wall conduction may affect the measured whole-house energy consumption.

Figure 5.5 is similar to Figure 5.4, however, in this figure the predicted values were calculated using the annual averages of the measured basement temperatures (average of fall and spring values in Table 4.1) for the pre-and post-retrofit period. As state earlier, the finite difference model used both the pre-and post-retrofit basement temperatures, and calculated a total consumption for each period. The RCS method used only the pre-retrofit temperature to calculate the change in energy use to be expected from increasing the basement wall R-value. Since the MECS model does not account for the increased post-retrofit temperature, the savings predicted by this model are greater than those predicted by the two-dimensional model. This is shown in Figure 5.5 where most of the points lie above the line of perfect correlation. A linear regression analysis (regression line not shown) yielded an R-squared value of 0.88, a slope coefficient of 0.94, and an intercept of 40.0 therm/year. The standard error of the estimate in this case is also 29 therm/year, but here the MECS model value is biased upward, as indicated by the regression intercept of 40 therm/year.

5.6 DATA AND ANALYSIS CHECKS

A variety of checks were made to examine the data base and analysis methodology for systematic errors. The heat content of the natural gas supplied to the study houses, and the house gas meter constants were obtained from utility company records. During the period of measurement for the study all gas meter constants were equal to 1.0, so the meter readings reported by the homeowners were used as received. During the period of the study, the heat content of the gas decreased by about 0.4 percent for both of the utilities companies involved. Compared to the total gas use, the post-retrofit gas use would have increased about 0.4 percent due to reduced heat content. Thus, the savings measured here are about 0.4 percentage points too small, and could be adjusted upward by that amount, if desired.

The amount of winter sunshine represents an unmetered internal gain that could affect retrofit savings. The annual percent of sunshine was the same for both the pre- and post-retrofit periods, 68 percent. The percent sunshine for the pre- and post-retrofit heating seasons (October to May) was 63 percent and 66 percent, respectively. While it is difficult to quantify the effect of this difference, the greater sunshine for the post-retrofit period would have acted to reduce energy use and to increase measured savings.

The average annual snow fall for the study area is about 49 inches. The amount of snowfall for the pre- and post-retrofit seasons was 42 and 70 inches, respectively. Again, while is it difficult to quantify the affect of snow cover, the greater snow cover in the post-retrofit season should have maintained a warmer ground temperature that would have added to the measured savings.

Ground temperatures 25 feet from the foundation and one and three feet below grade were measured at each of the two sites where hourly data were collected. At both sites the ground temperatures were colder in the post-period than in the pre-period, conflicting with what would be expected from the differences in snow cover described above. Ground temperature data were averaged for each site for the three months before (December to February) and three months after (March to May) the occurrence of the minimum ground temperature measured at a depth of three feet. The average of the ground temperatures measured at depths of one and three feet at both sites was 40.9 ^{o}F and 37.5 ^{o}F for the pre-and post-retrofit periods, respectively. Using a simple linear steady state model, it is estimated that this colder measured ground temperature would have decreased the expected retrofit savings by three to four percent. This estimate is based on a model that assumes: the temperature difference between the basement and the ground is between 20 to 30 ^{o}F; that one-third of the whole-house space heat energy goes to basement heating; and that the retrofit saves 25 percent of the energy lost below grade.

As stated earlier, the Minneapolis-St. Paul area experienced drought conditions throughout the period of the study (Baker, 1990). Thus, it is likely that during the study the soil at most sites was becoming more dry and less thermally conductive. Again, this drying should have acted to increase retrofit savings by reducing basement heat losses during the post-retrofit period. A telephone survey showed that only two homeowners (ME05 and ME010) may have increased the soil moisture around their houses due to lawn watering. However both of these houses had greater than average savings, reducing the apparent importance of soil moisture content.

Finally, as a check on the implementation of the PRISM program at Robinson Technical Services, duplicate runs were performed independently at the Center for Energy and Urban Environment. These checks were done beginning with raw data from duplicate homeowner reading sheets, and produced results nearly identical (differences less than one-half of the standard error of the NAC) to those obtained by the principal investigator. Differences in the normalized annual consumptions obtained by each analyst were due to the use of different data adjustment methods.

6. HOMEOWNER OBSERVATIONS

All 20 homeowners in the study reported that their basements were more comfortable after their foundations were insulated. As discussed earlier, the average basement temperature increased by 4.3 °F. Most likely this increase in air temperature, plus a decrease in radiative coupling due to warmer wall temperatures, led to the reported increase in comfort. Beyond increased basement comfort, 13 out of 20 homeowners reported greater comfort throughout the rest of their house as well. This enhanced comfort is most likely due to a warmer floor between the basement and the mainfloor. Based only on their own judgment and without additional information from the study, all homeowners said, if given the choice, they would insulate their foundations again. One homeowner that was very pleased with the increased level of comfort in her home said that, even with no cost savings, she would have had her foundation insulated just to enhance comfort.

When asked why they decided to have their basements insulated, the owners responded as shown in Figure 6.1. The figure shows results for 17 of the 20 homeowners in the study, and illustrates several differences in priority for the two sets of homeowners. The data show that the NRC homeowners were more motivated by saving money, while the MEO homeowners were more motivated by saving energy. While this is a somewhat expected difference between lower and middle income homeowners, it is probably an important difference to note when retrofit programs are promoted to different groups of homeowners. Fewer MEO homeowners cited the recommendation of the agency representative as being important. In this case, the homeowners are making a decision to purchase the retrofit with their own money, and seem to act more independently. Because the above data set is small, the above observations may not generally apply. However, they do shed some light on the owner attitudes encountered in this particular study.

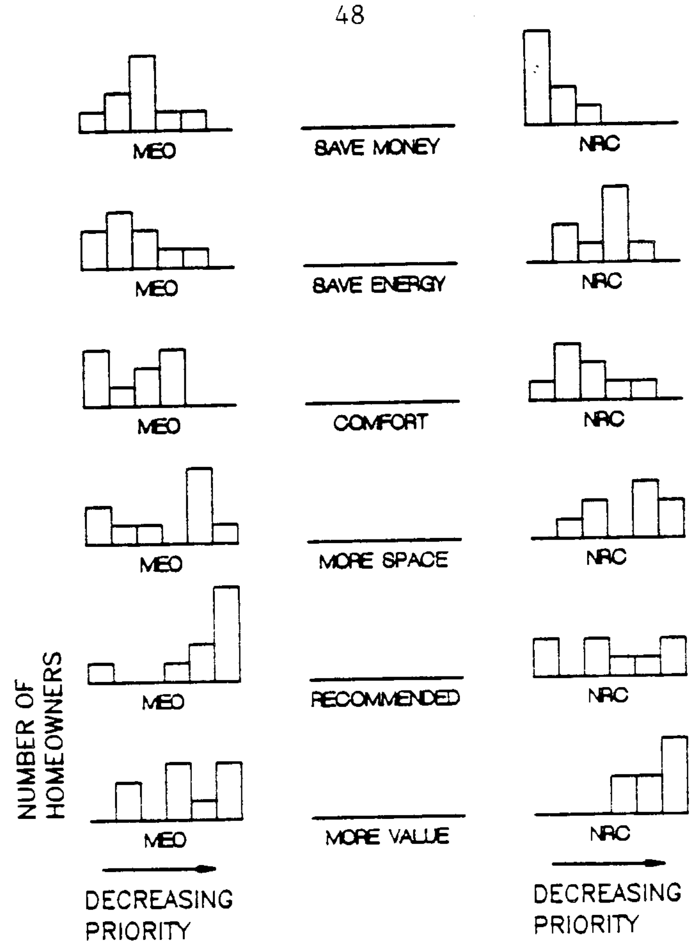

Fig. 6.1. Owner's priority for installing foundation insulation.

Results for nine CEUE and eight NRC homeowners are shown. Data for houses NRC1, NRC2 and ME03 were deleted because of incomplete responses to question. Owners were asked to order by priority their reasons for insulating their foundation. Six responses were offered: reduce energy bills, save energy, increase comfort level in house, create more living space, consultant recommendation, increase market value of house. Priority ranking in each graph is shown from left to right, with the bar on the left representing the number of owners choosing the response shown as their first priority. The baseline represents a homeowner count of zero. The tallest bars represent a homeowner count of five.

7. ECONOMIC ANALYSIS

7.1 RETROFIT COSTS AND SAVINGS

The total cost to retrofit each of the 20 houses in the study is shown in Appendix H. The total cost includes the labor and material to insulate the perimeter shown in Table H.1, plus the cost of the miscellaneous other insulation shown in Tables E.1 and E.2 of appendix E. Cost with finish includes gypsum board wall covering with taped joints ready for light sanding and painting. Cost without finish does not include cost of gypsum board covering or taping.

Table 7.1 shows the cost and first year savings for each retrofit in the final analysis. First year cost savings are calculated by dividing the load savings by an AFUE of 0.75, and multiplying by an energy cost of $0.55/therm. The average cost and savings for the 15 houses in Table 7.1 are shown in Table 7.2. The average interior retrofit, including a gypsum wall board finish, cost $2130, and has a first year savings of $51. The aggregate cost of conserved energy (based on a discount rate of 5.0 percent, and a time period of 30 years) and payback period for this retrofit are $1.51/therm and 42 years, with minimum measured values of $0.84/therm and 23 years (Houses ME010 and ME09). Not including the cost of the gypsum wall board finish, the minimum values would be $0.44/therm and 12 years, respectively. The cost of conserved energy is the per unit cost of the energy saved. For a retrofit to be economically competitive, the cost of conserved energy needs to be less than the cost of purchased energy, $0.55/therm.

Table 7.1. Economic analysis based on first year savings and cost of retrofit for 15 houses.

House Number	Load Savings (therm/ year)	First Year Savings ($/year)	Cost of Retrofit ($)		Cost of Conserved Energy ($/therm)		Simple Payback (years)		Benefit-to-Cost Ratio (unitless)	
			With Finish	Without Finish	With Finish	Without Finish	With Finish	Without Finish	With Finish	Without Finish
ME01	45	33.00	2006	1062	2.17	1.15	61	32	.25	.48
ME04	46	33.73	2622	1550	2.78	1.64	78	46	.20	.33
ME05	76	55.73	1784	984	1.15	0.63	32	18	.48	.87
ME06	7	5.13	2118	1358	14.76	9.46	413	265	.04	.06
ME010	138	101.20	2375	1335	0.84	0.47	23	13	.66	1.17
ME02	85	62.33	2035	1139	1.17	0.65	33	18	.47	.84
ME07	-5	---	1670	912	---	---	---	---	---	---
ME09	117	85.80	2020	1044	0.84	0.44	24	12	.65	1.26
NRC1	108	79.20	2540		1.15		32		.48	
ME03	58	42.53	1570		1.32		37		.42	
ME08	31	22.73	1669		2.63		73		.21	
NRC3	-16	---	1740		---		---		---	
NRC4	12	8.80	1150		4.68		131		.12	
NRC8	-18	---	1890		---		---		---	
NRC9	46	33.73	2035		2.16		60		.25	

Notes: The first nine houses received interior retrofits, the last six houses received exterior retrofits. All basements were unconditioned before and after retrofit. First year savings is equal to load savings divided by an estimated AFUE of 0.75 times an energy cost of $0.55/therm. Benefit-to-cost ratio is calculated as the ratio of the present value of the savings to the cost of the retrofit. Calculation used a present value factor of 15.4, based on a discount rate of 5.0 percent, and a time period of 30 years. The cost of conserved energy is equal to the energy cost of $0.55/therm divided by the benefit-to-cost ratio. An unfinished cost is not shown for the interior polystyrene retrofit in house NRC1, since code requires in this case that the insulation be covered with a fire-rated material.

TABLE 7.2. Summary of economic results shown in Table 7.1.

Type Ins	First Year Savings ($/year)	Cost of Retrofit ($)		Cost of Conserved Energy ($/therm)		Simple Payback (years)		Benefit-to-Cost Ratio (unitless)	
		With Finish	Without Finish	With Finish	Without Finish	With Finish	Without Finish	With Finish	Without Finish
Int	51	2130	1173	1.51	0.83	42	23	0.36	0.66
Ext	13	1675	---	4.54	---	129	---	0.12	---
All	36	1948	---	1.95	---	54	---	0.28	---

Notes: First year savings and cost of retrofit are average values from Table 7.1. Aggregate values of the benefit-to-cost ratio and of the cost of conserved energy were calculated using the same present value and energy cost as used in Table 7.1 (15.4 and $0.55/therm, respectively). Benefit-to-cost ratio is calculated as the ratio of the present value of the savings to the cost of the retrofit. The cost of conserved energy is equal to the energy cost of $0.55/therm divided by the benefit-to-cost ratio.

For exterior insulation cases, Table 7.2 shows that the average cost is $1675, and that average the first year savings is $13, with an aggregate cost of conserved energy of $4.54, and an aggregate payback of 129 years. Minimum values for the cost of conserved energy and the payback in this case are $1.32/therm and 37 years, respectively (House ME03).

7.2 MODELED SAVINGS FOR HEATED BASEMENTS

The cost effectiveness of foundation retrofits applied to intentionally heated, or habitable, basements was estimated using the two-dimensional finite difference model cited earlier to calculate pre- and post-retrofit energy use for basements controlled at 68 ^{o}F. The results of this analysis for the final 15 houses are shown in Table 7.3. This table shows the average first year savings to be $272 and $162 for the interior and exterior cases, respectively. For the interior case the cost of conserved energy is $0.28/therm and $0.15/therm, with and without finish. The simple payback is 7.8 years and 4.3 years, with and without finish. For exterior insulation the cost of conserved energy is $0.37/therm and the simple payback is 10.3 years.

The modeled savings here are likely to be more realistic than in the unheated retrofit case, since we are assuming an intentionally heated space that is maintained at a uniform temperature. That is, in this case the model boundary condition of a uniform interior air temperature is more likely to be met. As a preliminary examination of this assertion, thermal fluxes measured at the University of Minnesota Foundation Test Facility were compared with those calculated using the two-dimensional finite difference model. For this comparison, the interior air of the basement test module was well mixed and maintained at a temperature

TABLE 7.3. Economic analysis of average first year savings based on modeled performance of heated basements.

Type Ins	First Year Savings ($/year)	Cost of Retrofit ($)		Cost of Conserved Energy ($/therm)		Simple Payback (years)		Benefit-to-Cost Ratio (unitless)	
		With Finish	Without Finish	With Finish	Without Finish	With Finish	Without Finish	With Finish	Without Finish
Int	272	2130	1173	0.28	0.15	7.8	4.3	1.96	3.67
Ext	162	1675	---	0.37	---	10.3	---	1.49	---
All	228	1948	---	0.31	---	8.5	---	1.77	---

Notes: Values are based on modeled performance of 15 houses in final analysis. Savings were calculated using the two-dimensional finite difference model cited in the text and pre-and post-retrofit basement temperatures of 68 ^{o}F.

of 68 ^{o}F. The measured and calculated total wall fluxes were then compared for a two month period from February to March 1990. The measured and calculated total wall fluxes for this two month period differed by three percent, supporting the assertion that the above modeled savings are realistic.

8. EXAMINATION OF MISSING SAVINGS

For each house in the study the basement was an uncontrolled zone without a thermostat. For most of these houses the only sources of basement space heat were equipment losses or heat losses from the main floor to the basement. The current study shows that the application of retrofit insulation in such an uncontrolled zone produces savings that are highly variable and that, on the average, these savings are much lower than those predicted by the two-dimensional finite difference model that assumes a uniform and constant basement temperature. In this section of the report we speculate on mechanisms that might be causing the varied savings observed here.

8.1 BASEMENT CEILING THERMAL CONDUCTION

The pre- and post-retrofit basement and setpoint temperatures for each house are shown in Table 4.1 and Figure 4.1. The basements follow a general pattern of being cooler in the spring than the fall, and being warmer after the retrofit than before. The average increase in basement temperature was 4.3 ^{o}F.

No relation between basement warming and savings was observed. This is shown in Figure 8.1 where the savings, expressed as a basement ceiling energy flux, are plotted against the decrease in temperature difference between the main floor and the basement of the house. Because main floor temperatures changed very little, most of the temperature changes shown in Figure 8.1 are due to increased basement temperatures. No obvious correlation is observed in this figure, showing the independence of savings from the change in the basement temperature, and indicating that mechanisms other than ceiling conduction might play an important

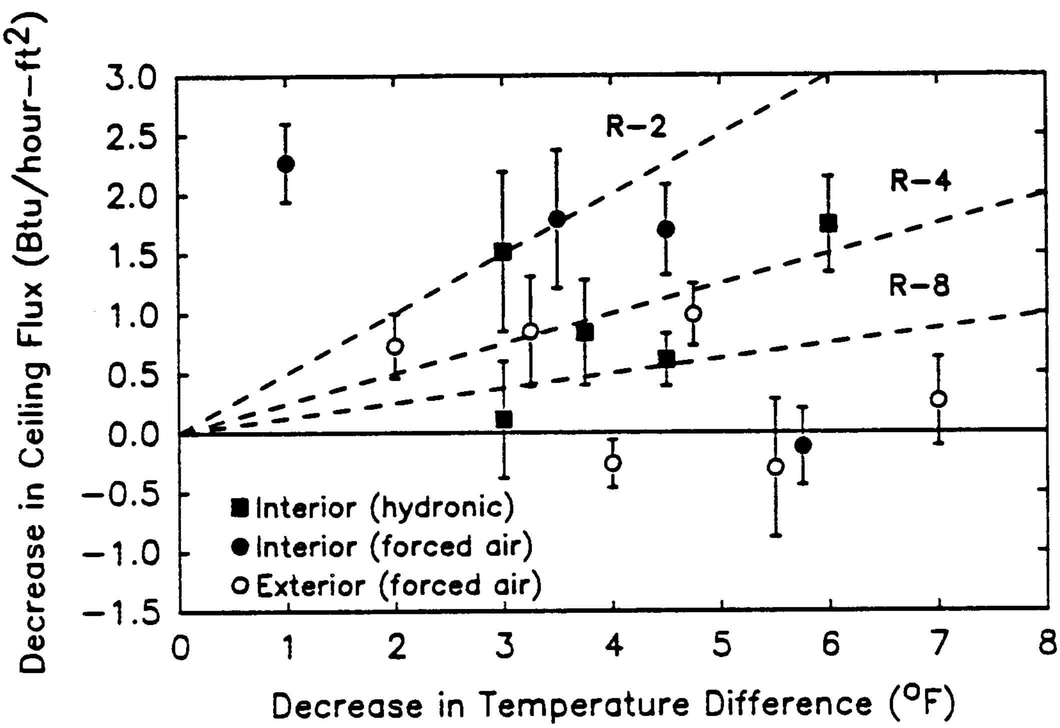

Fig. 8.1. Load savings expressed as a basement ceiling energy flux versus decrease in temperature difference between basement and first floor.

Savings in load is shown expressed as a decrease in the average annual energy flux through the basement ceiling. The x-axis is the decrease in the temperature difference between the basement and the first floor of the house between the pre- and post-retrofit seasons. The slope of a line on this plot represents an effective ceiling U-factor. Lines are shown for U-factors of 0.125 (lowest slope line), 0.25, and 0.50 (R-values of 8, 4, and 2, respectively).

role in the savings observed. It needs to be remembered here, however, that the temperatures shown in Figure 8.1 were measured at mid-distance between the basement ceiling and the floor, and, due to stratification, they may not be representative of the basement ceiling temperature responsible for driving the basement ceiling heat flow shown. Finally, the air movement next to the basement ceiling is complex and site specific, so that the actual ceiling U-factors are highly variable and unknown.

The dashed lines in Figure 8.1 show ceiling U-factors of 0.125, 0.25, and 0.5. These factors show that for some houses the ceiling conductance may be setting an upper bound on the savings that can be achieved by reduced thermal flow between the main floor control zone and the basement of the house. The outlier in Figure 8.1 (upper left corner) was an unusual house that had no basement stairway inside the house. The basement in this case was entered from a stairway located outside the house in an attached garage. The basement was also filled with a large amount of household goods that could have assisted in maintaining air stratification. In this case, the air temperature near the basement ceiling may have changed more than the one Fahrenheit degree shown in Figure 8.1.

8.2 REGRESSION MODEL

Figure 5.2 shows the measured load savings as a function of the area of insulation applied to the foundation. As discussed in Section 5.4, both the interior and exterior cases show only a weak correlation (R-squared values of 0.10 and 0.48, respectively) between the area insulated and the reduction in building load.

The behavior in Figure 5.2 was examined using multiple linear regression to examine the possibility that some unsuspected mechanism was reducing the predicted savings. The most successful model for both the interior and exterior cases took the following form:

$$\text{MEASURED SAVINGS} = a_1 * (\text{AREA INSULATED}) + a_2 * (\text{LOSS PARAMETER})$$

where the capitalized quantities are regression variables, and the a_n's are the regression coefficients. A zero-intercept model was chosen since the measured savings can be expected to be zero if no insulation is installed. The loss parameters for the best models were found to be the height of the house for the interior retrofit data, and the reciprocal of the insulation depth for the exterior retrofit data. The height of the house was expressed as the number of stories, and was found by dividing the total floor area of the house by the area of the basement ceiling. For this study then, the number of stories is defined as a dimensionless measure of the house height.

Regression analysis was performed using a commercial statistical package. R-squared values were calculated with the sum of squares of the dependent variable centered either on the origin or on the mean value of the dependent variable (Kvalseth, 1985), and were adjusted downward for sample size (Weisberg, 1980). Care is required here, since zero-intercept models will typically overestimate the R-squared value by using sums of squares centered on the origin. Using these two methods of calculation, adjusted R-squared values for the above models were found to be 0.94 and 0.83 for the interior retrofit data, and 0.86 and 0.80 for the exterior retrofit data. As expected, R-squared values based on centered data (second value for each case) yield a more conservative estimate of the goodness of fit. For both the interior and exterior models, the p-values of the a_1 coefficients were less than 0.005, and the p-values of the a_2 coefficients were less than 0.02. Examination of the leverage, Cook's distance, and Studentized residuals for each model showed that no single house in either model was unusually influential. We conclude that the a_n's in the above models are statistically significant (p-value less than .05), and that both models explain 80 percent or more of the measured savings.

Figures 8.2 and 8.3 show the fraction of savings missing versus the loss parameters identified by the analysis. The fraction of savings missing was calculated by dividing the difference between the predicted savings and the measured savings by the predicted savings, where the predicted savings was calculated using the finite difference model. This was done to normalize for the different size houses in the study, since larger houses tended to have larger savings.

Both loss parameters identified above are physically reasonable. The height of the house is a measure of the driving force for air infiltration that, when combined with an increased basement temperature, would be expected to reduce savings due to an increase in stack driven infiltration. The dependence of exterior retrofit savings on the reciprocal of the depth below grade shows that the first foot of insulation below grade is more effective than the second, and that the agreement between the measured and predicted savings improves as the depth of the insulation below grade increases.

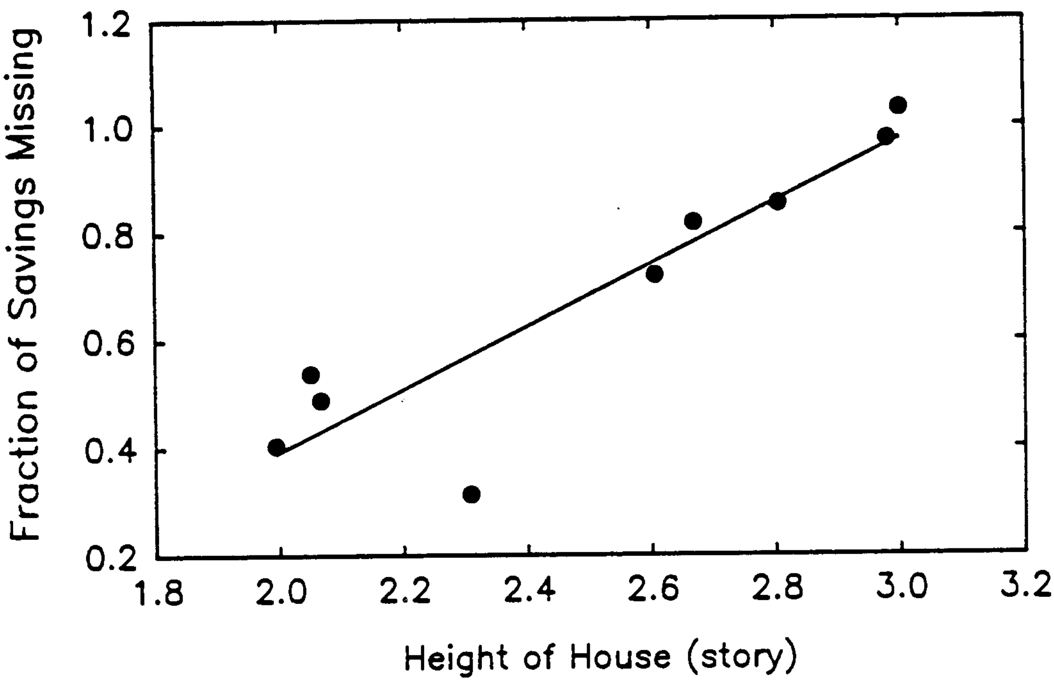

Fig. 8.2. Missing savings versus loss parameter for nine interior retrofits.

The height of the house is expressed in stories, a dimensionless number equal to the total floor area of the house divided by the ceiling area of the basement.

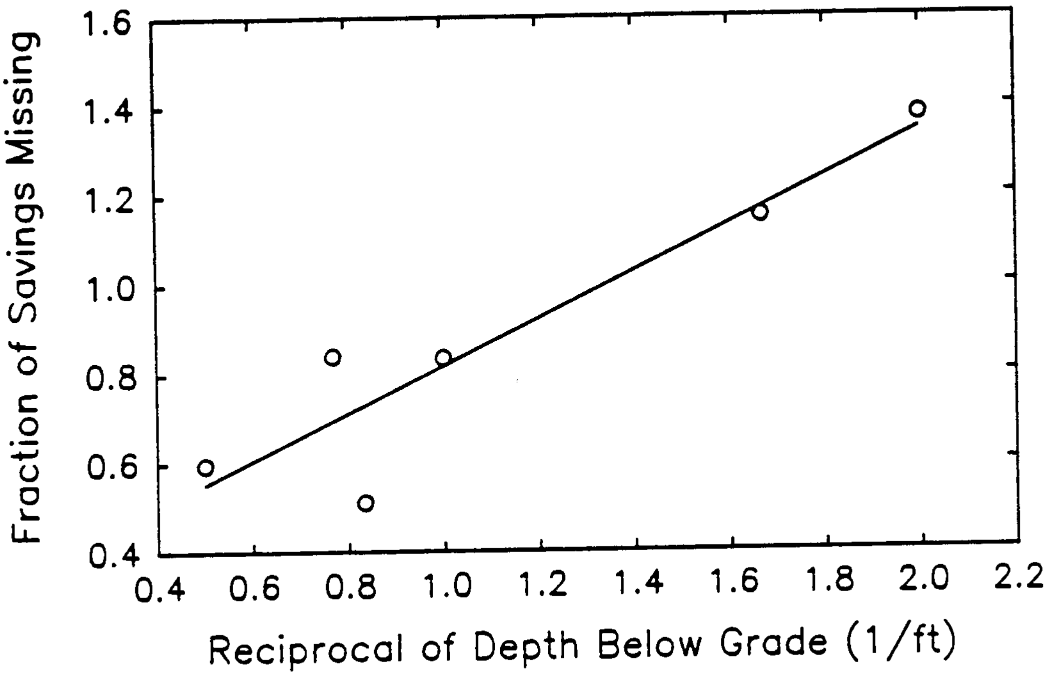

Fig. 8.3. Missing savings versus loss parameter for six exterior retrofits.

The reciprocal of the depth below grade is the reciprocal of the depth of the exterior insulation below the grade level of the house.

Neither the measured change in basement air temperature nor composite variables based on measured pre-and post-retrofit basement air temperature (for example, a composite variable for the stack driven air infiltration) was significant for either the interior or exterior retrofit cases. Furthermore, the height of the house was not significant for the exterior retrofit case.

The a_1 values (standard error in parentheses) described above were found to be as follows:

a_1 = 0.18 (0.03) therm/ft^2 for the exterior case, and

a_1 = 0.30 (0.04) therm/ft^2 for the interior case.

Using an average height of 2.8 feet for the exterior wall insulation and 7 feet for the interior wall yields savings of 0.50 and 2.1 therm per linear foot of insulation, respectively. The interior value is in good agreement with the value of 2.0 therm/ft calculated by the two-dimensional model, indicating that the interior insulation may be performing as predicted. The exterior value is one-half of the predicted value of 1.0 therm/ft, indicating that the insulation might be changing the coupling of the house to the foundation as well as the coupling of the foundation to the ground. Or, alternatively, this result may indicate that the model assumption of a uniform basement temperature may be better met for the interior insulation case than for the exterior insulation case.

8.3 OBSERVATIONS AND SPECULATIONS

The above results could certainly be fortuitous. It is noteworthy, however, that in addition to the above statistical results, both models also demonstrate appropriate physical superposition. That is, the under-performing (as measured by a_1) exterior retrofits are compromised by a factor relating to the geometry of the insulation, while the properly performing (again as measured by a_1) interior retrofits are compromised by a factor relating to the geometry of the house.

Based on these results, we speculate that air movement within the basement, and air movement between the basement and the remainder of the house, are key to understanding the performance of these retrofits. Air movement within the basement, as well as radiative effects, may be increasing the coupling of the house to foundation for the exterior retrofit case, and reducing the expected savings. Whole house air movement driven by stack infiltration may be reducing the expected savings for the interior retrofit houses.

Since little is known about the actual details of the coupling between a house and its foundation, the above speculations are offered as a starting point for the examination of this important, but poorly understood, problem. One practical recommendation is that the practice of placing exterior insulation at least 2 feet below grade is a good one, and should be used in all cases where possible (see Figure 8.3).

9. CONCLUSIONS AND RECOMMENDATIONS

On the average, the houses in the study achieved only about one-third of the whole-house energy savings that were predicted by the two-dimensional finite difference model used in the study. Savings may have been over predicted by the model, since it assumed a constant and uniform basement air temperature and did not include effects of basement air stratification on whole-house energy use.

While energy savings were highly variable, all basements were warmer after retrofit than before, and the average basement temperature increased by 4.3 ^{o}F. In spite of variable savings, all homeowners were very pleased with their retrofits, and, in addition to greater basement comfort levels, most reported a greater level of comfort throughout the rest of their house as well.

The average energy savings for the interior and exterior retrofits were 92 and 24 therm/yr, respectively. These savings were 7.9 and 3.0 percent of the pre-retrofit space heat energy use.

The aggregate payback periods for the interior retrofits with and without a finished wall were 42 and 23 years, respectively, with minimum values of 23 and 12 years. The average costs for these retrofits were $2130 and $1173 with and without a finished wall, respectively. The aggregate payback period for the exterior retrofits was 129 years, with a minimum of 37 years. The average exterior retrofit cost was $1675.

Even though the foundation retrofits examined here improved comfort in all cases, model calculations show that the application of retrofits to intentionally heated space is required to achieve payback periods of ten years or less.

In summary, we conclude that insulation applied in an uncontrolled zone produces highly variable results, and has the principal effect of increasing the temperature and comfort of the basement, rather than producing cost-effective whole-house energy savings.

Based on the savings observed in this study, and the current energy and retrofit costs used here, we recommend that cold climate foundation retrofits be applied to unconditioned basements if increased comfort is desired. Using these same energy and retrofit costs and based on modeled energy savings, we further recommend that conditioned basements be insulated to enhance comfort and to obtain cost-effective energy savings.

The examination of alternative strategies to reduce the energy use of unconditioned or uninhabited basements is recommended. In particular, duct sealing and insulating, basement wall and basement ceiling air sealing, and basement ceiling insulation are strategies that could be examined.

The effect of air stratification and internal air movement on the effectiveness of foundation insulation needs further examination. Detailed basement temperature monitoring and enhanced modeling of boundary conditions that include non-uniform basement air temperatures appear to be required for the accurate prediction of foundation retrofit savings.

Interzone coupling and retrofit induced losses appear to be very important, but are poorly understood. In particular, the effect of basement air movement on losses due to the presence of a basement needs to be assessed. The distinction between basement heat loss - that is, soil conduction loss - and heat loss due to the presence of a basement - that is, whole house losses due to all other mechanisms - appears to be very important and in need of further clarification.

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APPENDIX A

Candidate House Survey

JOINT FOUNDATION INSULATION PROJECT
CANDIDATE HOUSE SURVEY

Name of Owner: ______________________

Address: ______________________ Home Telephone: __________

______________________ Work Telephone: __________

Minneapolis Energy Office only:

Does the house presently have attic and wall insulation?

yes no

(If no) Are you willing to contract to have this work done before the beginning of the first heating season of the study, (before September, 1987)?

yes no

(If yes to either question) Are you willing to contract to have your foundation insulated?

yes no (comments) ______________________

____

CHARACTERISTICS OF HOUSE:

Below Grade Floor Area ______ ft^2

Main Floor Area ______ ft^2 Number of floors above grade ______

General Condition: excellent good fair poor

Year Built ______

Heating System Type ______________________

Is house representative of the community's housing stock?

yes no (explain) ______________________

____

Are heating ducts accessible for sealing air leaks or applying insulation without removing parts of the building structure? yes no (comments - note if suspended ceiling is present) ______________________

____

FOUNDATION:

Type: concrete block   poured concrete   stone

Exterior Surface: smooth   rough

Existing Insulation: none   (or describe) ______________________________

____

Is foundation wall structurally sound (free of large cracks, no sign of buckling or crumbling):   yes   no (explain) ______________________

____

Is basement dry and free of signs of periodic flooding (such as water marking):   yes   no (explain) ______________________________

____

Does soil next to foundation slope away from house: yes   no   level mixed (comments) ______________________________

Does house have gutters: yes   no

Are gutters clean and in good working order: yes   no

How far away from the house is rainwater directed before it reaches soil or pavement? ________ ft.

Does the water reaching soil or pavement drain away from house?

yes   no (comments) ______________________________

Is rim joist accessible for sealing air leaks without removing either interior or exterior parts of building structure?

yes   no   (comments - please note if suspended ceiling present)

____

What fraction of the foundation perimeter is accessible for the application of insulation if: only exterior insulation is used _______, only interior insulation is used _______, a combination of exterior and interior insulation is used _______?

Total height of the foundation wall _______ft. Height of foundation wall above grade _______ ft.

Would you recommend exterior, interior or combination insulation? Why?

____

____

(MEO only) Would the owner prefer exterior, interior or a combination of insulation? Why? ______________________________

____

OWNER AND HOUSEHOLD INFORMATION:

Are you willing to have foundation insulation work delayed until about one year from now? yes no

In the next two years (through the summer of 1989):

do you have any plans of moving? yes no

or of making major changes in the house envelope, such as building an addition or finishing unfinished areas? yes no

or making any major changes in your heating system? yes no

(describe any major changes planned for the house envelope or heating system)

____

____

Do you expect any major changes in household living patterns in the next two years? no yes (describe) __________________________

____

Are there any sources of unmetered energy that are used to provide space heat, such as kerosine, wood, oil or propane stoves? no yes

(If yes), what type of heater do you use? __________________

and roughly how often do you use it? _____________________

Are there uses of metered energy outside the primary envelope of the house, such as a heated garage, a heated swimming pool, or extensive security lighting? no yes (describe) __________________________________

____

What type of appliances are used in the house.

Clothes dryer: gas ____, electric ____, does not have dryer ____.

Kitchen range: gas ____, electric ____.

Water heater: gas ____, electric ____.

(MEO only) Beyond attic and wall insulation some additional retrofit work (mainly air sealing) may need to be done to your house before the project starts. This work will be paid for by program funds and be provided to you at no cost. Are you willing to have this work done on your house? no yes

Participants in this project will be paid $20 per month to read 3 meters per week (gas, electric and furnace time clock). Postage paid self-mailing reporting forms will be provided, and payment checks will be mailed monthly when reporting forms are received. Are you willing to read your meters and to sign an agreement to do this for the 21 month duration period of the project? yes no

Are you willing to allow researchers into your home as required by the study. This will include quarterly visits by Gary Nelson, one of the nation's foremost experts in this type of monitoring, and visits for the installation and inspection of insulation work? yes no

Two of the homes chosen for this study will have a computerized monitoring system for 21 months that would be set to answer your telephone for a ten minute period each week, so that data from temperature sensors and other equipment can be transferred to a computer. The time during the week when this could be done would be worked out between you and the researchers. Are you willing to have such a system installed in your home? yes no

Write any additional comments here, including perceptions of the homeowner's attitude and ability for participation in the study project: ________________

____

____

____

____

Based on the house selection criteria established, rate this house on a scale of 1 to 3 (1 highest to 3 lowest) for its suitability as a study project house ___.

Signature of Auditor: ________________________________

Date of Survey: ____________

APPENDIX B

House Selection Criteria

JOINT FOUNDATION INSULATION STUDY (JFIS) CRITERIA FOR SELECTION OF CANDIDATE HOUSES

Physical Structure - Necessary Attributes

1) House is representative of community's housing stock as determined by the auditor/consultant, including age, size, foundation type, heating system type.

2) Foundation is structurally sound. No unusually large or severe cracks, no major holes, buckling or crumbling of basement walls.

3) Basement does not have serious moisture problems.

4) Rim joist is accessible for sealing air leaks without removing permanent parts of the structure.

5) At least three-quarters of the foundation perimeter is accessible for insulation, assuming that a combination of interior and exterior insulation can be used.

Physical Structure - Desirable Attributes

1a) Houses provided by the Minneapolis Energy Office should all be in Minneapolis.

1b) Houses provided by Natural Resources Corporation should not be in the most distant suburbs.

2) Conditions contributing to basement moisture should not be present, e.g., soil slopes away from basement wall, gutters are present and clear of debris, and drain spouts extend well away from house.

Owner/Household - Necessary Attributes

1) For houses provided by the Minneapolis Energy Office: owners should want foundation insulation and be willing to pay for it.

2a) For houses provided by Minneapolis Energy Office: houses should have attic and wall insulation already or owners should be willing to add before beginning of study period.

2b) For houses provided by Natural Resources Corporation: houses should have attic and wall insulation already or this should be added as a part of the weatherization work.

3) Owner is willing to defer foundation insulation for one year after audit.

4) Owner has no plans to move or do other major work to house in next two years, including building any additions, changes in the heating system, or changes in the amount of heated space.

5) Household uses no unmetered space heat, such as propane, oil or woodburning stoves.

6) Owner is willing to read own meters (gas, electric, clock on furnace) once per week, in return for $20 per month, for 21 months.

7) Owner/household is willing to allow field researcher quarterly access to house.

Owner/Household - Desirable Attributes

1) Household is planning no major changes in occupancy or living patterns in next two years.

2) At least two of the final twenty houses must be willing to allow extensive computerized monitoring equipment in the house for the duration of the project.

APPENDIX C

Homeowner Agreement with Robinson Technical Services

RTS
ROBINSON TECHNICAL SERVICES

Griggs-Midway Building
1821 University Avenue, Suite 151S
St. Paul, Minnesota 55104
(612) 646-1695

Foundation Research Homeowner Agreement

This is an agreement between ______________________________ (referred to as the "homeowner") and Robinson Technical Services (RTS) for the following:

1) The homeowner agrees to read the following meters at about the same time and on the same day each week for a period of 21 months:

a) The electric utility meter
b) The gas utility meter
c) A furnace run time meter
d) A water heater run time meter, if the house has a gas water heater and a gas kitchen range.

The above meter reading will be done on a "best effort" basis to read the meters at the same time and on the same day each week. It is understood that long weekends or vacations may require an occasional change of reading day. If the meters cannot be read for a period of two weeks by the homeowner, then the homeowner will find a substitute to read the meters.

2) In exchange for the above meter reading activity, RTS will pay the homeowner $20 per month. Checks will be mailed within three days after meter readings have been received. RTS will provide the homeowner with meter reading instructions and stamped self-mailing meter reading forms.

3) The homeowner agrees to have two temperature recording meters placed in his or her home for the 21 month meter reading period.

4) The homeowner agrees to let a building research scientist into his or her home once every three months for servicing the above temperature meters, and to check on the operation of the run time meters.

If the research contract with Oak Ridge National Laboratory is canceled, or if the homeowner fails to read his or her meters on a regular basis, then this agreement is canceled.

______________________	________	______________________	________
Robinson Technical Services	Date	Homeowner	Date

Homeowner Name (please print): ______________________________

Name as preferred on check (please print): ______________________________

Address: ______________________________

____

Home Telephone: ______________________________

Other Telephone: ______________________________

APPENDIX D

Homeowner Agreement with Minneapolis Energy Office

MINNEAPOLIS
"The Resourceful City"

ENERGY OFFICE
Room 330, City Hall
Minneapolis, Minn. 55415
(612) 348-6829

Joint Foundation Insulation Study

Agreement between Minneapolis Energy Office and ______________________________

This is an agreement between ________________________________ (referred to as "homeowner") and the Minneapolis Energy Office (MEO) for the following:

1) The homeowner agrees to install foundation insulation during the summer of 1988, using the bid made by MEO in the summer of 1987. Unit prices of work will not change between 1987 and 1988. Unforeseen and specific changes may alter the original bid given to the homeowner, and will be subject to the homeowner's approval.

2) MEO will make available financing at below market interest rates for the foundation insulation work. (The current rate is 9 1/2%. Future rates should be similar.) Applicants will be evaluated using normal credit review and underwriting procedures. If financing is approved and dispensed before the foundation insulation is installed, the homeowner agrees to make scheduled payments to the loan source as per the loan agreement. MEO will make every effort to arrange timely financing to minimize the number of payments made by the homeowner before the work is completed.

3) MEO will manage the contractors installing the foundation insulation, supervise the work in the field, inspect the completed job and insure that all work is done to Operation Insulation standards.

______________________________ ______________________________
Minneapolis Energy Office Homeowner

______________________________ ______________________________
Date Date

APPENDIX E

Retrofit Insulation Parameters

Table E.1. MEO House Insulation Parameters.

House Number	Total Floor Area (ft^2)	Total Perimeter (ft)	Perimeter Insulated (ft)		Other Insulation		Insulation Added (R-value)			Exterior Parameters				Rim Joist Insulation Added[4]
			Interior	Exterior	Surface (units)	Amount	Interior	Exterior	Other	Average Height Above Grade[1] (ft)	Average Depth Below Grade[2] (ft)	Perimeter for Full Depth[3] (ft)	Rim Joist Covered	
MEO1	2210	124	117				13			2.1				Done
MEO2	1625	108	105				13			0.8				Done
MEO3	2584	146		90	Crawl(ft)	29		14	19	2.0	2.0	90	No	NA
MEO4	2990	134	121				13			2.6				Yes
MEO5	1970	110	106				15			2.2				Yes
MEO6	2730	127	99		Crawl(ft)	38	15		19	2.7				Yes
MEO7	2370	106	104				15			1.5				Yes
MEO8	1520	118		99	Ceil(ft^2)	80		10	13	2.3	1.0	99	Yes	Done
MEO9	1820	123	118				15			2.0				Done
MEO10	2125	138	134				15			3.0				Yes

1 - Average height from grade level to top of foundation.

2 - Average depth of exterior insulation below grade level for perimeter where below grade wall was accessible.

3 - Perimeter for application of below grade exterior insulation. Remainder of perimeter insulated to grade level.

4 - NA - not accessible.

Notes: Total floor area includes area of basement. Other insulation shows linear feet of crawl space or square feet of basement ceiling insulated.

Table E.2. NRC House Insulation Parameters.

House Number	Total Floor Area (ft^2)	Total Perimeter (ft)	Perimeter Insulated (ft)		Other Insulation		Insulation Added (R-value)			Exterior Parameters				Rim Joist Insulation Added[4]
			Interior	Exterior	Surface (units)	Amount	Interior	Exterior	Other	Average Height Above Grade[1] (ft)	Average Depth Below Grade[2] (ft)	Perimeter for Full Depth[3] (ft)	Rim Joist Covered	
NRC1	1340	110	108				8			0.8				Done
NRC2*	2620	144	139				8			3.2				Done
NRC3	1535	112	9	102	Wlrm(ft^2)	9		10	11	1.1	0.5	102	Yes	NA
NRC4	1200	106	9	92	Wlrm(ft^2)	9	11	10	11	0.7	1.3	92	No	Yes
NRC5*	2000	144	18	106	Wlrm(ft^2)	36	11	10	11	2.9	1.0	106	No	Done
NRC6*	1926	105		90				10		1.2	0.8	90	No	NA
slab		44		40				10		1.3	0.8	20		
NRC7*	2184	148	18	113	Wlrm(ft^2)	36	11	10	11	1.3	0.7	113	No	Yes
NRC8	1776	124		99				10		1.8	0.6	93	No	Yes
NRC9	1344	104		78	Crawl(ft)	13		10	11	2.3	1.2	41	No	Done
NRC10*	1440	120	12	87	Wlrm(ft^2)	16	11	10	11	0.9	0.3	61	Yes	NA

1 - Average height from grade level to top of foundation.

2 - Average depth of exterior insulation below grade level for perimeter where below grade wall was accessible.

3 - Perimeter for application of below grade exterior insulation. Remainder of perimeter insulated to grade level.

4 - NA - not accessible.

Notes: Total floor area includes area of basement. Other insulation shows linear feet of crawl space or square feet of wellroom ceiling insulated. Perimeter of wellroom insulated is shown under interior perimeter insulated. Houses marked with asterisk were deleted from final analysis.

APPENDIX F

Sample Weekly Data File

Table F.1. Sample dBASE weekly data file.

Record#	OWNER	DATE	DAYS	GAS	GASUSE	ELECTRIC	ELECTUSE	FURNACE	FURNUSE	WATERHTR	WATERUSE
1	BIXBY	10/04/87	999	725	999	17195	999	0.2	999.9	12.2	999.9
2	BIXBY	10/11/87	7	742	17	17332	137	8.5	8.3	15.3	3.1
3	BIXBY	10/18/87	7	753	11	17434	102	12.8	4.3	17.9	2.6
4	BIXBY	10/25/87	7	782	29	17565	131	29.5	16.7	21.0	3.1
5	BIXBY	11/01/87	7	799	17	17660	95	37.3	7.8	23.7	2.7
6	BIXBY	11/08/87	7	815	16	17729	69	44.7	7.4	25.6	1.9
7	BIXBY	11/15/87	7	839	24	17809	80	57.1	12.4	28.8	3.2
8	BIXBY	11/22/87	7	870	31	17885	76	74.0	16.9	31.6	2.8
9	BIXBY	11/29/87	7	907	37	17974	89	93.3	19.3	36.5	4.9
10	BIXBY	12/06/87	7	945	38	18052	78	114.7	21.4	40.0	3.5
11	BIXBY	12/13/87	7	983	999	18139	87	136.4	999.9	44.1	4.1
12	BIXBY	12/20/87	7	1025	42	18216	77	161.5	25.1	48.4	4.3
13	BIXBY	12/28/87	8	1071	46	18314	98	188.9	27.4	53.1	4.7
14	BIXBY	01/03/88	6	1121	999	18387	73	221.1	999.9	57.0	3.9
15	BIXBY	01/10/88	7	1197	76	18498	111	271.4	50.3	63.2	6.2
16	BIXBY	01/17/88	7	1245	48	18567	69	301.6	30.2	67.0	3.8
17	BIXBY	01/24/88	7	1295	50	18644	77	332.2	30.6	70.8	3.8
18	BIXBY	01/31/88	7	1351	56	18731	87	375.5	43.3	75.2	4.4
19	BIXBY	02/07/88	7	1416	65	18871	140	411.8	36.3	78.4	3.2
20	BIXBY	02/14/88	7	1479	63	18971	100	452.1	40.3	81.5	3.1
21	BIXBY	02/21/88	7	1524	45	19048	77	478.8	26.7	85.7	4.2
22	BIXBY	02/28/88	7	1563	39	19124	76	502.7	23.9	89.0	3.3
23	BIXBY	03/06/88	7	1596	33	19198	74	522.1	19.4	92.2	3.2
24	BIXBY	03/13/88	7	1629	999	19277	79	540.3	999.9	96.8	4.6
25	BIXBY	03/20/88	7	1671	42	19351	74	564.9	24.6	100.4	3.6
26	BIXBY	03/27/88	7	1701	30	19423	72	581.3	16.4	104.4	4.0
27	BIXBY	04/03/88	7	1727	26	19498	75	594.3	13.0	109.5	5.1
28	BIXBY	04/10/88	7	1742	15	19565	67	600.3	6.0	113.5	4.0
29	BIXBY	04/17/88	7	1763	21	19618	53	612.3	12.0	115.4	1.9
30	BIXBY	04/24/88	7	1787	24	19688	70	624.6	12.3	119.8	4.4
31	BIXBY	05/01/88	7	1801	14	19756	68	631.5	6.9	122.7	2.9
32	BIXBY	05/08/88	7	1806	5	19821	65	631.6	0.1	125.9	3.2
33	BIXBY	05/15/88	7	1814	8	19887	66	633.0	1.4	128.2	2.3
34	BIXBY	05/22/88	7	1821	7	19955	68	634.7	1.7	130.8	2.6
35	BIXBY	05/30/88	8	1827	6	20034	79	634.7	0.0	133.7	2.9
36	BIXBY	06/05/88	6	1831	4	20126	92	634.7	0.0	135.7	2.0
37	BIXBY	06/12/88	7	1837	6	20224	98	635.2	0.5	138.1	2.4
38	BIXBY	06/19/88	7	1841	4	20319	95	635.2	0.0	138.6	0.5
39	BIXBY	06/26/88	7	1845	4	20426	107	635.2	0.0	140.2	1.6
40	BIXBY	07/01/88	5	1847	2	20473	47	635.2	999.9	140.5	999.9
41	BIXBY	07/10/88	9	1853	6	20651	178	635.2	999.9	140.5	999.9
42	BIXBY	07/17/88	7	1858	5	20749	98	635.2	999.9	140.5	999.9
43	BIXBY	07/25/88	8	1864	6	20868	119	635.2	999.9	142.0	999.9
44	BIXBY	07/31/88	6	1867	3	20946	78	635.2	0.0	142.9	0.9

Notes: Gas and electric meters, and furnace and water heater run-time meters were read weekly by each homeowner. GAS and GASUSE are in units of CCF, ELECTRIC and ELECTUSE are in units of kWh, and FURNACE, FURNUSE, WATERHTR, and WATERUSE are in units of hours. Variable names ending in USE are uses for periods shown. Missing values are shown by 999 and 999.9.

APPENDIX G

Hourly Data Files

Table G.1. Hourly data monitored at two sites.

HOUSE NUMBER	DATA ACQUISITION SYSTEM CHANNEL NUMBER AND dBASE FIELD NAME													
	1	2 ELECTUSE	3 FURNUSE	4 WATERUSE	5 FLUX1	6 FLUX2	7 TEMP1	8 TEMP2	9 TEMP3	10 TEMP4	11 TEMP5	12 TEMP6	13 TEMP7	14 TEMP8
MEO2	Time from Midnight CST (hrs)	Electric Use (W-hours)	Furnace On-time (percent)	Wtr Htr On-time (percent)	Heat Flux Cntr Flr (W/m^2)	Heat Flux Crnr Flr (W/m^2)	Grnd Temp 1 ft deep (°F)	Grnd Temp 3 ft deep (°F)	Outside Air Temp (°F)	Air Temp at T'stat (°F)	Air Temp 2nd Floor (°F)	Air Temp Basement (°F)	Srfc Temp Crnr Wall (°F)	Srfc Temp Cntr Wall (°F)
NRC7	Time from Midnight CST (hrs)	Electric Use (W-hours)	Furnace On-time (percent)	Wtr Htr On-time (percent)	Heat Flux Cntr Wall (W/m^2)	Heat Flux Crnr Wall (W/m^2)	Grnd Temp 1 ft deep (°F)	Grnd Temp 3 ft deep (°F)	Outside Air Temp (°F)	Air Temp at T'stat (°F)	Air Temp NW Bedrm (°F)	Air Temp Basement (°F)	Srfc Temp Crnr Flr (°F)	Srfc Temp Cntr Flr (°F)

Notes: Data were monitored using a Fowlkes data acquisition system. Electric use was monitored using a pulse initieting kWh meter. Furnace and water heater on-times were measured by monitoring sets of dry contacts controlled by the operation of the furnace (relay across gas valve) and water heater (pressure switch connected to gas valve pressure tap). Fluxes were measured with flux plates bonded to the basement wall or floor and covered with plaster. Temperatures were measured using AD-590 temperature sensors. Heat flux plates were placed in the center (Cntr) and corner (Crnr) of either the floor (MEO2), or the wall (NRC7). Corner placement was about 18 inches from each surface, and the center wall placement was 18 inches above the floor. Surface temperature sensors were similarly placed. Ground temperatures were measured 25 feet from each house at depths of one and three feet. Units shown are for hourly data collected by Fowlkes system.

Table G.2. Weekly summary of hourly pre-retrofit data for house ME02.

Record#	LASTDAY	DATE	ELECTUSE	FURNUSE	WATERUSE	FLUX1	FLUX2	TEMP1	TEMP2	TEMP3	TEMP4	TEMP5	TEMP6	TEMP7	TEMP8
1	6316	11/12/87	80.53	6.58	10.74	0.2	-0.1	45.5	50.0	38.0	64.3	59.5	60.4	57.6	59.5
2	6323	11/19/87	79.99	7.08	11.73	1.1	0.6	44.7	48.0	40.8	65.5	61.3	60.8	57.5	59.4
3	6330	11/26/87	82.40	12.88	12.60	0.6	-0.2	39.8	45.9	30.7	64.0	57.2	59.5	55.8	58.1
4	6337	12/03/87	92.59	15.25	12.41	0.6	0.0	38.3	43.4	29.5	64.2	58.3	59.2	55.1	57.3
5	6344	12/10/87	114.77	17.37	13.70	0.6	0.2	37.1	41.8	31.9	65.7	61.5	58.9	54.1	57.1
6	6351	12/17/87	91.22	17.94	13.24	0.1	0.0	36.7	41.0	24.6	64.9	60.2	58.1	53.4	56.5
7	6358	12/24/87	93.10	17.31	11.36	0.9	0.7	35.2	39.8	28.2	65.5	61.0	58.1	53.0	56.1
8	6365	12/31/87	87.73	22.22	11.80	0.3	0.4	35.1	39.2	19.9	65.1	60.3	57.5	52.3	55.6
9	6007	01/07/88	108.72	32.79	15.73	-1.8	-1.3	34.2	38.5	-1.1	64.1	58.2	55.0	49.9	53.6
10	6014	01/14/88	89.68	29.05	13.46	-1.2	-0.9	32.5	37.3	7.5	62.9	57.8	53.6	48.2	51.7
11	6021	01/21/88	81.36	17.78	13.24	1.0	0.9	32.4	36.5	26.9	64.5	60.1	55.4	49.7	52.8
12	6028	01/28/88	111.17	26.71	16.52	0.5	1.0	32.7	36.4	8.6	64.9	60.0	55.5	49.9	53.1
13	6035	02/04/88	101.74	25.77	13.29	0.8	0.8	32.8	36.2	13.5	64.3	59.5	55.3	49.8	53.0
14	6042	02/11/88	85.86	31.48	11.34	-0.6	-0.2	32.8	36.1	1.5	63.4	57.9	53.4	48.1	51.6
15	6049	02/18/88	76.75	19.52	10.40	-0.1	0.4	32.7	35.9	20.9	63.5	58.9	53.4	48.0	51.1
16	6056	02/25/88	72.14	20.61	11.68	0.9	1.1	32.9	35.9	20.6	63.9	59.2	54.2	48.8	52.0
17	6063	03/03/88	52.13	13.60	12.67	1.5	2.0	32.9	35.8	32.1	65.6	62.0	55.8	49.9	53.1
18	6070	03/10/88	47.30	12.77	10.25	2.2	2.5	33.6	35.8	37.2	66.1	62.9	56.5	50.7	53.8
19	6077	03/17/88	48.17	17.39	10.28	1.3	2.0	36.0	37.2	28.1	65.1	61.0	56.4	51.0	54.0
20	6084	03/24/88	34.45	14.65	6.61	1.6	2.1	36.1	37.3	34.1	64.9	61.7	56.1	50.8	53.6
21	6091	03/31/88	40.90	12.31	6.39	2.3	2.7	39.2	38.9	38.2	65.2	62.4	56.9	51.7	54.4
22	6098	04/07/88	34.16	6.01	6.04	2.6	3.4	43.6	41.2	50.3	66.6	65.3	57.9	53.0	55.4
23	6105	04/14/88	33.23	4.69	7.71	2.8	3.8	47.9	44.7	49.1	67.2	66.8	59.0	54.7	56.9
24	6112	04/21/88	36.07	8.05	7.56	2.9	3.7	47.3	45.9	44.0	67.3	65.6	59.1	55.3	57.8
25	6119	04/28/88	39.64	7.49	6.74	2.8	3.3	47.0	46.2	46.2	67.2	65.6	59.3	55.3	57.9
26	6126	05/05/88	35.53	0.22	10.08	4.7	4.9	51.6	47.7	66.0	72.2	76.3	61.9	57.1	59.6
27	6133	05/12/88	36.43	0.00	8.23	4.2	5.3	54.9	51.0	64.1	70.6	74.3	63.6	59.7	61.4
28	6140	05/19/88	41.00	0.00	8.48	2.6	3.7	54.4	52.3	60.0	67.5	71.0	61.9	59.3	60.8
29	6147	05/26/88	40.82	0.00	7.63	5.0	5.3	58.0	54.0	70.9	73.7	81.0	64.5	61.1	62.6
30	6154	06/02/88	55.37	0.00	7.80	8.1	8.2	62.8	57.0	79.0	81.0	88.2	69.0	64.7	66.1
31	6161	06/09/88	90.68	0.00	5.44	6.0	8.3	65.2	60.3	74.6	75.1	80.4	70.6	69.9	68.2
32	6168	06/16/88	44.53	0.00	5.28	5.8	5.2	65.3	61.2	76.5	76.9	81.6	69.6	67.3	67.9
33	6175	06/23/88	156.74	0.00	5.85	4.9	5.6	68.3	63.0	80.3	75.9	83.5	69.4	67.4	68.1
34	6189	07/07/88	149.15	0.00	5.43	6.5	6.5	69.4	65.1	82.3	80.2	88.6	71.7	68.2	69.3
35	6196	07/14/88	88.34	0.00	6.20	5.5	5.6	71.6	67.0	78.2	78.5	86.6	71.1	69.2	70.2
36	6203	07/21/88	80.71	0.00	4.95	5.9	5.9	71.4	67.8	76.4	80.1	86.7	72.8	70.1	70.9
37	6210	07/28/88	88.16	0.00	5.09	5.6	5.4	69.7	67.1	80.5	80.0	86.3	72.5	69.8	70.5

Notes: Units of measurement are as follows: ELECTUSE (kWh), FURNUSE (hours), WATERUSE (hours), FLUXn (W/m^2), and TEMPn (^oF). Electric, furnace, and water use are totals for period. Flux and temperature values are average for period. First digit of LASTDAY value designates the measurement site; the remaining digits are the Julian date number used by the Fowlkes data acquisition system.

Table G.3. Weekly summary of hourly post-retrofit data for house ME02.

Record#	LASTDAY	DATE	ELECTUSE	FURNUSE	WATERUSE	FLUX1	FLUX2	TEMP1	TEMP2	TEMP3	TEMP4	TEMP5	TEMP6	TEMP7	TEMP8
1	6231	08/18/88	143.46	0.00	6.16	6.4	6.6	73.3	69.9	80.5	80.7	87.0	76.7	72.7	72.4
2	6238	08/25/88	39.24	0.00	5.66	2.7	3.1	71.4	70.1	71.0	74.8	76.4	72.6	71.7	72.1
3	6245	09/01/88	35.06	0.00	5.64	0.4	1.9	66.8	67.3	66.4	71.8	74.1	70.1	69.5	70.2
4	6252	09/08/88	34.09	0.00	6.42	1.0	1.2	65.0	65.3	63.7	69.5	70.9	68.8	67.6	68.5
5	6259	09/15/88	37.58	0.00	5.97	2.2	1.8	63.3	63.5	65.0	70.5	71.7	68.4	66.3	67.1
6	6266	09/22/88	38.88	0.00	5.95	1.9	1.8	62.8	62.9	63.0	69.2	69.7	68.0	65.3	66.1
7	6273	09/29/88	39.35	0.00	6.80	1.0	0.9	61.0	61.7	58.9	67.2	66.9	66.1	63.5	64.4
8	6280	10/06/88	40.25	1.83	7.93	0.1	0.6	57.4	59.9	49.9	64.9	60.7	65.0	61.5	62.6
9	6294	10/20/88	45.83	3.61	8.84	0.6	2.0	52.2	54.6	50.4	68.0	61.1	66.7	59.1	60.7
10	6301	10/27/88	43.24	8.46	9.07	0.0	1.9	47.5	52.3	38.5	66.4	53.2	65.8	56.5	58.5
11	6315	11/10/88	47.27	9.18	9.07	2.1	4.6	42.4	46.4	37.6	65.1	51.6	64.3	53.2	55.2
12	6322	11/17/88	51.37	10.39	8.95	1.5	4.7	40.6	45.1	32.8	64.0	48.3	63.4	50.6	53.8
13	6329	11/24/88	45.86	12.58	10.69	1.4	5.4	37.7	42.8	30.0	63.7	45.8	62.7	48.3	51.6
14	6336	12/01/88	51.52	12.23	11.64	0.8	4.9	37.4	41.2	26.1	62.7	45.9	61.7	48.1	50.8
15	6343	12/08/88	51.70	10.63	10.49	1.0	5.3	36.0	40.1	28.8	62.7	45.3	61.2	47.2	49.9
16	6350	12/15/88	51.08	19.67	10.51	0.9	4.7	33.7	38.6	15.0	61.4	41.1	59.5	45.0	47.6
17	6357	12/22/88	57.35	19.31	9.62	3.3	7.1	32.3	37.0	25.9	65.6	59.5	61.1	44.2	46.6
18	6364	12/29/88	54.18	26.34	10.38	3.4	8.3	31.6	36.3	14.4	65.8	59.5	61.5	44.2	46.5
19	6006	01/05/89	75.56	23.48	13.37	2.9	8.1	30.6	35.4	15.5	65.7	59.5	60.9	43.5	45.6
20	6013	01/12/89	59.22	25.32	10.97	2.0	7.5	31.0	34.9	12.3	64.5	58.5	59.9	43.2	45.3
21	6020	01/19/89	52.63	18.83	9.65	3.1	8.8	31.1	34.7	26.0	65.9	60.1	60.8	43.3	45.3
22	6027	01/26/89	58.43	16.49	10.51	3.2	8.9	31.4	34.6	27.3	65.6	59.9	61.0	43.9	46.2
23	6034	02/02/89	51.80	19.81	10.33	2.5	8.5	31.6	34.5	24.1	65.8	59.8	60.8	43.9	46.6
24	6041	02/09/89	73.12	35.27	11.72	1.9	7.6	30.7	34.3	0.0	65.3	58.6	59.1	41.5	43.9
25	6048	02/16/89	49.97	21.55	9.92	2.3	8.6	30.8	34.1	19.2	65.5	59.2	59.8	41.3	44.4
26	6055	02/23/89	56.12	27.09	10.11	2.0	8.8	30.7	34.0	9.5	65.6	59.1	59.5	40.8	43.7
27	6069	03/09/89	59.22	21.98	11.34	2.8	10.0	30.6	33.6	21.1	65.6	59.6	60.3	40.4	43.6
28	6076	03/16/89	51.73	15.07	10.98	2.7	10.1	31.8	33.7	30.8	66.4	61.2	60.4	41.3	44.9
29	6083	03/23/89	51.41	19.29	12.19	2.7	10.3	32.2	34.0	23.7	66.2	60.7	60.4	41.2	44.9
30	6090	03/30/89	48.02	6.88	11.85	3.3	10.6	32.3	33.9	44.5	67.9	64.6	61.0	42.4	46.9
31	6097	04/06/89	45.97	10.55	9.40	3.7	10.6	32.8	34.1	40.1	67.0	63.3	61.4	44.0	48.6
32	6104	04/13/89	41.87	12.15	7.23	3.0	9.9	36.0	35.4	35.6	66.9	63.0	61.4	45.1	49.6
33	6118	04/27/89	48.10	1.33	10.20	3.8	10.0	49.2	44.0	57.5	70.2	69.6	63.1	49.7	54.0
34	6125	05/04/89	52.27	7.06	12.35	3.5	9.1	48.5	46.7	46.8	68.2	65.5	63.2	51.4	54.9
35	6132	05/11/89	56.02	5.67	13.33	3.5	8.6	49.2	47.2	50.8	69.1	68.3	63.2	51.7	55.0
36	6139	05/18/89	61.02	0.00	14.69	5.9	10.5	56.1	50.3	67.3	75.0	76.6	66.1	53.9	57.4
37	6146	05/25/89	62.96	1.89	13.86	3.6	8.4	60.0	54.5	67.2	71.9	74.6	65.2	57.2	60.1
38	6153	06/01/89	59.26	0.00	13.30	1.2	5.5	59.4	56.6	59.0	66.6	67.8	63.1	58.3	60.8
39	6160	06/08/89	68.08	0.00	13.38	4.1	6.6	60.6	57.0	65.7	70.8	74.4	64.6	58.5	61.0
40	6167	06/15/89	39.46	0.00	8.25	2.0	4.7	60.1	58.0	60.7	67.2	69.2	63.3	59.3	61.7
41	6174	06/22/89	43.13	0.00	7.48	4.6	8.3	62.6	58.6	73.6	76.8	81.3	67.0	60.0	62.2
42	6181	06/29/89	39.78	0.00	6.60	3.6	8.2	66.0	61.4	73.2	77.8	81.9	69.0	62.4	64.3

Notes: Units of measurement are as follows: ELECTUSE (kWh), FURNUSE (hours), WATERUSE (hours), FLUXn (W/m^2), and TEMPn (^oF). Electric, furnace, and water use are totals for period. Flux and temperature values are average for period. First digit of LASTDAY value designates the measurement site; the remaining digits are the Julian date number used by the Fowlkes data acquisition system.

Table G.4. Weekly summary of hourly pre-retrofit data for house NRC7.

Record#	LASTDAY	DATE	ELECTUSE	FURNUSE	WATERUSE	FLUX1	FLUX2	TEMP1	TEMP2	TEMP3	TEMP4	TEMP5	TEMP6	TEMP7	TEMP8
1	5312	11/08/87	55.91	12.57	6.29	5.8	5.2	50.9	54.2	47.0	71.6	70.9	65.7	61.8	65.8
2	5319	11/15/87	68.90	15.57	16.34	7.1	6.4	46.6	52.7	41.4	71.9	70.7	64.9	60.7	65.3
3	5326	11/22/87	68.00	21.17	9.83	7.5	6.6	45.8	51.4	34.6	71.8	71.0	64.2	60.0	64.7
4	5333	11/29/87	78.77	21.69	16.73	8.3	7.9	41.9	49.1	32.7	72.4	70.9	63.5	58.8	64.1
5	5340	12/06/87	87.12	23.14	14.65	8.8	8.2	41.5	47.6	28.2	72.2	71.2	62.0	57.2	62.9
6	5347	12/13/87	79.85	24.38	11.32	9.1	8.8	41.0	46.4	33.7	71.9	70.8	62.6	57.4	63.1
7	5354	12/20/87	66.31	30.17	6.86	10.1	9.5	39.1	45.3	23.9	71.7	70.6	61.3	55.9	62.2
8	5361	12/27/87	113.29	23.27	14.28	9.8	9.2	38.5	44.1	24.9	71.6	70.4	60.2	55.1	61.2
9	5003	01/03/88	74.77	35.50	11.95	11.7	10.4	38.2	43.3	16.0	71.4	70.2	59.7	54.0	60.7
10	5010	01/10/88	80.46	46.33	12.17	14.3	11.7	35.9	41.9	-2.8	71.0	68.2	56.2	50.3	57.9
11	5017	01/17/88	95.80	31.94	21.19	12.6	12.1	34.4	40.3	19.4	72.3	70.8	58.0	51.8	58.9
12	5024	01/24/88	89.68	32.46	11.06	11.7	11.3	34.5	39.7	19.5	72.3	70.9	58.9	53.1	59.6
13	5031	01/31/88	80.32	34.39	18.76	11.6	11.1	34.5	39.2	15.2	72.0	70.6	57.8	52.3	58.7
14	5038	02/07/88	93.10	42.99	13.91	12.5	11.5	34.6	39.0	2.8	72.1	70.2	56.3	50.7	57.5
15	5045	02/14/88	97.60	40.09	17.65	13.6	13.2	33.9	38.4	6.3	72.6	70.7	56.6	50.8	57.9
16	5052	02/21/88	86.47	28.03	17.55	11.3	12.2	33.7	37.9	24.7	71.9	70.4	58.0	52.3	58.5
17	5059	02/28/88	92.12	25.83	17.67	11.1	12.4	33.5	37.6	27.5	72.2	70.6	58.7	52.7	59.1
18	5066	03/06/88	90.36	23.96	19.29	11.0	13.2	33.6	37.4	32.5	72.1	70.9	60.8	54.3	60.3
19	5073	03/13/88	77.15	26.52	11.84	11.8	12.8	33.9	37.5	35.8	71.9	70.8	63.1	56.3	62.2
20	5080	03/20/88	86.18	24.91	15.72	11.2	12.2	34.2	37.4	28.1	72.3	70.7	61.5	55.7	61.7
21	5087	03/27/88	81.25	19.88	17.62	10.1	11.1	34.8	37.4	38.0	72.0	71.0	61.1	55.3	61.1
22	5094	04/03/88	107.68	18.18	20.00	9.3	10.2	37.5	37.9	41.6	71.8	71.0	61.0	55.3	60.8
23	5101	04/10/88	73.51	6.80	16.31	7.7	8.9	43.8	40.4	53.2	71.7	71.4	62.2	56.4	61.0
24	5108	04/17/88	66.38	9.09	13.19	6.7	8.1	45.5	43.0	48.0	71.1	70.6	62.1	56.7	61.1
25	5115	04/24/88	72.72	11.91	16.83	7.3	8.3	45.1	44.1	43.4	71.9	71.2	62.3	57.0	61.5
26	5122	05/01/88	73.04	6.21	16.76	7.1	8.1	47.4	44.9	54.1	71.7	71.4	63.4	57.6	61.8
27	5129	05/08/88	62.28	0.00	11.74	6.1	7.4	53.1	47.3	66.8	74.3	74.5	65.5	59.2	62.5
28	5136	05/15/88	62.78	2.05	12.24	3.7	5.1	55.6	50.2	59.3	72.1	72.5	64.4	58.5	62.0
29	5143	05/22/88	55.69	0.90	9.24	4.7	5.9	57.3	51.8	64.8	73.7	73.9	65.7	59.2	61.8
30	5150	05/29/88	62.10	0.00	13.64	6.0	6.9	61.5	54.0	72.3	77.6	77.7	69.4	61.5	62.8
31	5157	06/05/88	105.30	0.00	10.46	6.3	6.9	66.2	57.1	77.8	81.9	82.1	73.7	66.6	65.2
32	5164	06/12/88	138.78	0.00	10.96	3.5	4.3	67.4	59.5	73.1	77.8	78.3	71.5	66.0	65.4
33	5171	06/19/88	130.10	0.00	7.22	5.0	5.8	69.4	61.1	77.6	79.2	79.5	74.0	68.2	66.4
34	5178	06/26/88	149.11	0.00	10.22	4.5	5.1	71.8	63.1	79.5	81.0	81.6	75.8	70.0	67.5
35	5185	07/03/88	54.14	0.00	5.20	1.8	2.3	72.4	64.7	72.7	77.5	77.7	72.0	67.8	66.9
36	5192	07/10/88	166.57	0.00	6.49	5.1	5.5	75.2	66.1	82.9	82.2	83.3	77.4	71.7	68.6
37	5199	07/17/88	139.72	0.00	7.61	3.2	3.8	75.8	67.8	79.4	81.0	81.3	76.0	71.0	69.0
38	5206	07/24/88	80.53	0.00	8.59	2.4	3.1	74.2	68.5	73.2	80.4	80.3	75.1	70.7	69.5

Notes: Units of measurement are as follows: ELECTUSE (kWh), FURNUSE (hours), WATERUSE (hours), FLUXn (W/m^2), and TEMPn (^oF). Electric, furnace, and water use are totals for period. Flux and temperature values are average for period. First digit of LASTDAY value designates the measurement site; the remaining digits are the Julian date number used by the Fowlkes data acquisition system.

Table G.5. Weekly summary of hourly post-retrofit data for house NRC7.

Record#	LASTDAY	DATE	ELECTUSE	FURNUSE	WATERUSE	FLUX1	FLUX2	TEMP1	TEMP2	TEMP3	TEMP4	TEMP5	TEMP6	TEMP7	TEMP8
1	5220	08/07/88	135.14	0.00	4.33	2.6	3.3	76.7	70.2	79.2	81.3	81.9	76.7	72.1	70.0
2	5227	08/14/88	85.28	0.05	6.33	2.7	3.4	76.5	71.2	76.8	82.5	82.8	77.1	72.1	70.4
3	5234	08/21/88	129.67	0.00	5.85	1.9	2.2	76.8	71.8	76.9	78.7	79.7	75.7	71.7	70.3
4	5241	08/28/88	61.06	0.00	8.85	-0.2	0.1	72.6	71.0	66.4	74.7	74.7	72.3	69.5	68.7
5	5248	09/04/88	74.34	0.00	7.44	0.9	0.4	69.7	69.2	66.6	75.5	75.4	71.2	67.1	68.0
6	5255	09/11/88	85.10	0.00	11.64	0.5	-0.1	66.8	67.5	64.3	73.6	73.6	69.3	65.5	66.9
7	5262	09/18/88	91.55	0.90	11.07	3.4	2.5	66.0	66.1	64.4	75.0	74.7	71.2	66.4	67.5
8	5306	11/01/88	127.12	16.53	9.42	6.3	6.6	66.8	69.4	34.0	70.7	69.4	67.5	62.2	65.6
9	5313	11/08/88	126.29	16.45	14.63	7.6	8.1	67.8	71.1	38.3	72.3	70.9	68.6	62.3	66.0
10	5329	11/24/88	145.15	21.06	11.24	7.6	9.6	38.3	45.2	29.6	71.9	71.9	67.3	60.6	65.4
11	5336	12/01/88	144.50	24.12	13.03	7.5	9.7	38.1	43.6	25.2	71.6	71.4	67.3	60.5	65.0
12	5343	12/08/88	143.32	21.20	9.06	7.8	10.1	37.6	42.9	29.2	71.8	71.6	67.0	60.2	64.9
13	5350	12/15/88	165.56	31.76	13.11	8.7	11.3	34.7	41.2	14.9	72.0	73.8	67.0	59.7	64.5
14	5357	12/22/88	154.26	26.20	14.66	9.2	11.7	32.9	39.3	26.0	72.5	73.6	66.8	59.4	64.8
15	5364	12/29/88	182.23	32.18	14.99	9.1	12.0	32.3	38.3	13.8	71.8	73.5	66.7	59.0	64.4
16	5006	01/05/89	153.94	30.73	12.94	9.0	12.1	31.6	37.4	14.1	71.7	73.3	65.8	58.1	63.9
17	5013	01/12/89	165.46	36.32	11.95	10.2	13.2	31.3	36.7	11.0	72.6	71.8	67.5	58.7	63.8
18	5020	01/19/89	153.04	25.14	14.81	10.3	11.6	31.0	36.0	26.1	72.4	69.6	67.0	58.1	64.0
19	5027	01/26/89	153.54	21.83	14.20	9.7	10.7	31.4	35.7	26.8	72.0	69.0	66.1	57.5	63.7
20	5034	02/02/89	167.47	24.71	16.65	9.6	11.1	31.9	35.7	23.8	72.7	71.6	66.5	57.5	63.8
21	5041	02/09/89	202.46	40.50	18.47	9.6	11.4	29.9	35.3	-0.6	71.9	73.9	65.7	56.5	62.8
22	5048	02/16/89	162.00	26.40	11.02	9.6	11.2	30.2	34.6	18.4	72.2	70.5	65.1	56.2	63.0
23	5055	02/23/89	198.07	29.85	22.34	8.8	10.8	30.7	34.5	8.2	72.3	71.0	64.1	55.5	62.2
24	5062	03/02/89	198.86	29.41	19.87	9.0	11.5	30.7	34.3	14.1	72.5	71.1	64.7	55.4	62.3
25	5069	03/09/89	192.96	25.29	22.26	9.5	12.5	30.5	34.1	20.2	72.5	70.2	64.9	55.3	62.7
26	5076	03/16/89	138.24	22.25	12.51	9.5	12.0	31.7	34.0	29.9	72.4	69.7	65.2	55.4	62.6
27	5083	03/23/89	146.59	25.11	12.22	9.6	11.3	32.3	34.4	22.8	72.6	69.9	65.5	55.7	62.5
28	5090	03/30/89	130.75	16.55	14.41	9.7	11.9	32.5	34.5	43.6	72.3	68.0	67.2	56.2	62.9
29	5097	04/06/89	148.00	16.22	19.95	8.8	10.9	32.9	34.7	40.1	72.0	67.7	67.2	56.5	63.0
30	5104	04/13/89	128.20	23.14	11.65	8.3	10.1	35.5	35.5	35.2	72.1	69.1	67.5	56.6	62.8
31	5111	04/20/89	137.56	10.43	18.59	7.3	9.5	41.8	38.1	49.0	72.9	67.4	66.9	56.9	62.9
32	5118	04/27/89	116.75	6.60	14.76	6.9	8.8	47.9	42.1	56.6	72.7	68.2	67.7	57.7	63.3
33	5125	05/04/89	116.64	15.60	16.20	7.2	8.8	46.8	44.4	45.8	72.6	70.0	69.1	58.0	63.8
34	5132	05/11/89	127.01	11.24	15.87	6.4	8.1	48.4	45.3	50.2	72.8	68.7	68.1	57.8	63.7
35	5139	05/18/89	118.69	0.55	14.31	6.1	7.6	56.0	48.4	66.3	75.7	68.0	68.5	58.5	63.7
36	5146	05/25/89	133.24	1.59	14.26	5.0	6.2	60.4	52.5	66.5	75.2	69.5	69.9	60.1	64.5
37	5153	06/01/89	116.93	3.98	11.08	3.7	4.8	59.4	54.8	58.9	71.5	68.5	68.4	60.1	64.2
38	5167	06/15/89	82.55	0.99	7.91	3.1	4.1	62.2	57.4	61.7	72.7	68.7	68.9	61.3	64.6
39	5174	06/22/89	105.91	0.29	9.89	5.3	5.9	65.7	58.7	73.6	78.6	72.0	72.5	62.8	65.3
40	5181	06/29/89	88.27	0.00	9.03	3.7	4.3	68.5	61.2	72.5	78.2	72.3	72.8	64.1	66.4

Notes: Units of measurement are as follows: ELECTUSE (kWh), FURNUSE (hours), WATERUSE (hours), FLUXn (W/m^2), and TEMPn (^oF). Electric, furnace, and water use are totals for period. Flux and temperature values are average for period. First digit of LASTDAY value designates the measurement site; the remaining digits are the Julian date number used by the Fowlkes data acquisition system. This site received a severe lightning strike at the start of the post-retrofit period, and six weeks data were lost. Ground temperature sensors were not replaced until 11/17/88 accounting for the sharp decrease in TEMP1 and TEMP2 for the period ending 11/24/88. Also on 11/17/88 the temperature sensor in the northwest bedroom was moved to the southeast portion of the basement that had been finished into a recreation room.

APPENDIX H

Retrofit Costs

Table H.1. Total cost to retrofit.

Retrofit Type	House Number	Total Perimeter Insulated (ft)	Cost of Retrofit ($)	
			With Finish	Without Finish
Interior	ME01	117	2006	1062
Interior	ME04	121	2622	1550
Interior	ME05	106	1784	984
Interior	ME06	99	2118	1358
Interior	ME010	134	2375	1335
Interior	ME02	105	2035	1139
Interior	ME07	104	1670	912
Interior	ME09	118	2020	1044
Interior	NRC1	108	2540	
Exterior	ME03	90	1570	
Exterior	ME08	99	1669	
Exterior	NRC3	102	1740	
Exterior	NRC4	92	1150	
Exterior	NRC8	99	1890	
Exterior	NRC9	78	2035	
Interior	NRC2*	139	3240	
Exterior	NRC5*	106	1737	
Exterior	NRC6*	130	1900	
Exterior	NRC7*	113	2020	
Exterior	NRC10*	87	2010	

Notes: Cost includes material and labor to insulate the perimeter shown, plus the cost of the miscellaneous other insulation shown in Tables E.1 and E.2. Cost with finish includes gypsum board wall covering with taped joints ready for sanding and finishing. Cost without finish does not include cost of gypsum board finish. Unfinished costs are not shown for NRC1 and NRC2, since these were interior retrofits that used polystyrene insulation, and a fire rated covering is required by code. The last five houses marked with an asterisk were deleted from the final analysis.

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