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Energy Efficient House Research Project

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Part of
The National Program for
Building Thermal Envelope Systems
and Materials

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ENERGY EFFICIENT HOUSE RESEARCH PROJECT

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Part of
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Building Thermal Envelope Systems and Materials

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FOREWORD

The energy performance of whole buildings is a concern of the U.S. Department of Energy (DOE) as reflected in the National Program for Building Thermal Envelope Systems and Materials (BTESM) and as indicated in two previous National Program plans. Early interest of the DOE has focused on cold climate envelope and HVAC performance. This project was part of the BTESM National Program being conducted by Oak Ridge National Laboratory for DOE.

This project was made possible by a 1980 Energy Efficient Housing Demonstration Program of the Minnesota Housing Finance Agency which resulted in the construction of 144 new houses. The houses were constructed by 23 builders throughout Minnesota, and all had design thermal integrity factors of 3.0 Btu/ft^2-^{o}F day or less.

This research determined the actual, lived-in energy performance for these Minnesota houses and used instrumented inspection techniques to examine construction quality. An objective of the project was to see if certain designs had better energy performance than others. The Lawrence Berkeley Laboratory has detailed output from this study for inclusion in the Building Energy Data Base as part of their Building Energy Compilation and Analysis (BECA) Program.

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Lawrence Berkeley Laboratory

BTESM REPORTS

A. IMPLEMENTATION

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2. LBL-8925: *Thermal Performance of Buildings and Building Envelope Systems: An Annotated Bibliography* (March 1979).

3. STP-718: *Thermal Insulation Performance: A Symposium Sponsored by ASTM Committee C-16 on Thermal and Cryogenic Insulating Materials. American Society for Testing and Materials, Tampa, Fla., 22–25 Oct. 1978* (December 1980.)

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6. ORNL/Sub/7973/1: *The National Program Plan for the Thermal Performance of Building Envelope Systems and Materials* (March 1982).

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12. "1983 Daylighting Conference, Phoenix, Arizona, U.S.A., February 16–18, 1983, Part 1," *Energy and Buildings,* Vol. 6, No. 2 (1984).

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ENERGY EFFICIENT HOUSE RESEARCH PROJECT

B.D.Nelson, D.A.Robinson, G.D.Nelson, M.Hutchinson

ABSTRACT

This document is the final report for the Energy Efficient House Research Project.

The basis for this project was a set of energy efficient houses built in 1980 by the Energy Efficient Housing Demonstration Program of the Minnesota Housing Finance Agency. Under this program, 144 detached and attached housing units were constructed throughout the State of Minnesota by 23 different builders.

The research project utilized a simple data collection method involving homeowners in the field and utility data reports to establish a performance data base for the houses in the study. Data have been provided for addition to the BECA-A (new residential) data base on file at Lawrence Berkeley Laboratory, establishing a comprehensive data base for further analyses.

The 112 houses for which there were good quality energy data performed very well, but analysis of these data showed few significant correlations between energy performance and design features. The effectiveness of increased solar aperture or the use of night window insulation in reducing space heat energy consumption could not be proved or disproved statistically. One result, however, that did prove to be consistently significant was the loss of space heating energy due to the presence of below slab forced air distribution systems.

Detailed field investigation of 25 houses revealed many commonly practiced housing design and construction methods that degrade the energy performance of solar and other features of potentially energy efficient houses. Several figures in this report and a set of slides accompanying this report illustrate these practices.

Indoor air quality was investigated in 12 energy efficient houses and in an equal number of control houses. Air quality in the energy efficient houses was found to be as good as in houses of conventional construction. Radon mitigation using subfloor ventilation was investigated and found to be successful in reducing the concentration of this indoor air contaminate. Attempts to seal out radon in two control houses were not successful.

An evaluation of the HOTCAN and CIRA computer programs for predicting space heat energy consumption showed these tools to be comparable.

A computer model based investigation of cost effectiveness of various energy efficient designs showed that tight and well insulated houses of simple design are most cost effective.

Three general builder guidelines for designing and constructing energy efficient houses are proposed.

ENERGY EFFICIENT HOUSE RESEARCH PROJECT FINAL REPORT
EXECUTIVE SUMMARY

This research project was conducted from October 1983 to June 1985 to identify factors affecting the energy performance of energy efficient houses in Minnesota. The houses used for this study were built in 1980 under an Energy Efficient Housing Demonstration Program (EEHDP) conducted by the Minnesota Housing Finance Agency. This program provided 144 detached and attached housing units throughout the State of Minnesota that were constructed by 23 different builders.

Overall, the houses were found to be very energy efficient. Better attention to detail, following builder guidelines suggested in this report, may have improved energy performance even more. Based on economic evaluation, simple designs appear to be most cost effective.

The specific accomplishments achieved by this project were:

1) Evaluation of the energy performance of 108 houses.
2) Correlation of energy performance with design variables.
3) Creation of a data base for further investigations.
4) Completion of an instrumented field examination of 25 houses.
5) Investigation of the indoor air quality in 24 houses.
6) Completion of a radon mitigation experiment in four houses.
7) Evaluation of two energy performance simulation computer programs.
8) Evaluation of the life-cycle cost of four house designs.
9) Development of general builder guidelines.

1) Evaluation of energy performance.

The average total thermal integrity factor (based on net space heat plus internal gains) for 25 groups of houses was 3.10 Btu/ft^2-^{o}F day. This value ranged from 2.3 to 4.2. The total annual thermal load for the houses ranged from 26.1 to 54.7 million Btu/year, with an average of 41.3 million Btu/year. While not directly calculated, the net heating energy for these houses is estimated to be about 70 percent of these values, with the remaining 30 percent provided by internal gains. A typical Minnesota new house is estimated to require about 100 million Btu/year net heating energy (1).

2) Correlation of energy performance with design variables.

Analysis of energy consumption data for 112 houses showed few significant correlations between energy performance and design features. The effectiveness of increased solar aperture or the use of night window insulation in reducing space heat energy consumption could not be proved or disproved statistically. One result, however, that did prove to be consistently significant was the loss of space heating energy due to the presence of below slab forced air distribution systems. In this case, the statistical analysis showed that these houses had an average loss of 5 to 10 million Btu/year due to the presence of below slab warm air distribution systems.

3) Data base created.

Energy consumption data for 12 months on 127 houses are included in computer files provided to Lawrence Berkeley Laboratory. These files contain the energy consumption and average weather data for each meter reading period for all houses, and include domestic supply and hot water temperatures for 47 submetered houses. Other available data are interior temperatures and information on the occupants and their operation of the houses.

4) Instrumented field examination of houses.

Detailed investigation of 25 houses revealed many commonly practiced housing design and construction methods that degrade the energy performance of potentially energy efficient houses. Slides and figures in this report illustrate these findings.

5) Investigation of indoor air quality.

Indoor air quality was investigated in 12 experimental EEHDP houses and in an equal number of control houses. Formaldehyde, nitrogen dioxide and radon were monitored. No significant differences in air quality were found between the energy efficient houses and the conventionally constructed control houses.

6) Radon mitigation experiment.

Radon mitigation using subfloor ventilation was found to be successful in reducing the concentration of this indoor air contaminate. Attempts to seal out radon in two control houses were not successful.

7) Evaluation of energy performance computer programs.

An evaluation of two computer programs for predicting space heat energy consumption (HOTCAN and CIRA) showed these tools to be comparable. Comparison of the measured and predicted total annual energy use yielded mixed results with measured energy uses falling within plus or minus five to ten million Btu per year of their predicted values.

8) Life-cycle cost effectiveness of four designs.

A model based investigation of cost effectiveness compared four levels of energy efficient design for four EEHDP houses chosen to represent a range of design approaches. This theoretical approach was necessary because in actual houses the comparison of cost effectiveness using measured data would be lost in the noise created by variations in occupant lifestyle and construction quality. For each of the four designs evaluated, the level based on the current Minnesota Energy Code was the most cost effective for a 25 year analysis period.

9) Builder guidelines for energy-efficient housing.

Three general builder guidelines are recommended based on the findings of this research. These general guidelines could be used to develop specific guidelines for the education of designers, builders and remodelers. The guidelines address: 1) the application and use of thermal insulation, 2) the reduction of air leakage, and 3) the design and installation of forced air heat distribution systems. These guidelines would apply to all housing, regardless of cost or complexity.

1. INTRODUCTION

The basis for this project was a set of energy efficient houses built in 1980 by the Energy Efficient Housing Demonstration Program (EEHDP) of the Minnesota Housing Finance Agency (MHFA). The EEHDP was based on a maximum energy design criterion for the space heating load of 3 Btu/ft^2-^{o}F day. Winning designs were selected on the basis of simplicity of design, cost effectiveness, and marketability.

Data on the MHFA-EEHDP houses were presented at the second conference of the American Council for an Energy Efficient Economy held in Santa Cruz, California in August 1982 (2). The mixed performance of the preliminary data for these houses demonstrated the need for further research into performance of energy efficient house design.

The purpose of this research was to identify factors affecting the energy performance of energy efficient houses in Minnesota. This purpose was achieved by designing a study to develop a data base for energy performance and variables affecting it, performing field inspections of the houses to identify additional factors affecting performance, and insofar as possible, statistically correlating these variables to energy performance.

The approach used in this research was to observe houses in the real world, as they were actually built and functioning. This led to some unanticipated results. That is, some things that in theory should reduce energy consumption may in fact not.

Because few design features correlated with actual house performance, a computer model based life-cycle analysis was used to evaluate the cost effectiveness of several selected levels of energy efficient construction.

2. EXPERIMENTAL APPROACH AND DATA HANDLING

2.1 DESCRIPTION OF HOUSES AND MEASUREMENTS IN DATA BASE.

The Energy Efficient Housing Demonstration Program resulted in the construction of 144 houses by 23 builders that created a unique laboratory for examining the energy use in groups of identical houses (3). Houses were built in groups with two to twelve identical (except for mirror image) single family detached or attached houses in each group. The research goal to collect performance data on all houses in the program resulted in high quality consumption data for 112 houses, with homeowner survey data for 93 houses.

The basic objective of the research was to evaluate the thermal performance of the envelopes of these houses and to relate this performance to characteristics of the houses. Because internal gains are a significant source of space heat in energy efficient houses, a principal goal of the research was to obtain simultaneous gas and electric meter readings for as many houses as possible.

As described below, the houses were divided into submetered and non-submetered groups for the purposes of data collection, with a data reading period for all houses of one calendar year starting in December 1983.

Based on the preliminary performance estimates of the first research project (4), a subgroup of 47 houses representing seven different designs was chosen for detailed study. These houses were chosen based on their superior performance as measured in the first study, and as a representative cross-section of the energy saving strategies used in the EEHDP. The general characteristics of the seven types of houses in this subgroup are shown in Table 2.1. As can be seen in Table 2.1, a variety of building types and a large range in solar aperture areas are represented by this subgroup of houses. The energy sources used to provide space heat and domestic hot water are shown in this table and include electricity, gas, and solar energy.

Energy to provide domestic hot water was measured either directly or indirectly, depending on whether the house was equipped with an electric or gas water heater. Electric water heater energy consumption was determined by using an hour meter to measure the total on-time of the upper and lower elements. A single hour meter was used to record the total on-time of both elements by wiring the meter across the switched side of each element as shown in Figure 2.1. These meters were installed by a licensed electrical contractor experienced in installing building monitoring and control equipment. As a part of this field installation, the electrician also measured and recorded the voltage and current supplied to several heater elements in each development so that the typical water heater consumption would be known. Because water heaters of identical manufacturer and model number were used within each development, a single power consumption factor was used for each house design. The product of this power consumption and the recorded on-time was then used as a measure of the electrical energy required to provide domestic hot water.

For houses equipped with gas water heaters, the gas consumption

TABLE 2.1 Characteristics of seven house designs selected for submetering.

BUILDER OR TYPE	TYPE OR POSITION	UNIT NUMBER(S)	SPACE HEAT ENERGY SOURCE	HOT WATER ENERGY SOURCE	SOLAR TYPE	FLOOR AREA (sqft)	SOUTH WINDOW AREA (sqft)	THERMAL INTEGRITY FACTOR (Btu/sqft-DD)
BUILDER A SLAB	MIDDLE	2,3,6,7	GAS	ELECTRIC	DIRECT GAIN	1290	129	2.28
	END	1,4,5,8				1290	129	3.62
BUILDER D	SPLIT/DET	27-28	GAS	SOLAR/GAS	DIRECT GAIN	1913	120	3.22
BUILDER G	SPLIT/DET	41-48	GAS	SOLAR/ELECT	DIRECT GAIN	1920	180	2.49
BUILDER N DETACHED	SPLIT	94-95	GAS	GAS	NONE	1632	19	2.85
	RAMBLER/WLK	96-97				2180	53	2.33
BUILDER Q	SPLIT/DET	120-127	GAS	GAS	DRCT GAIN/MASS FLR	1320	285	3.52
BUILDER R WALKOUT	GREEN HSE	129	ELECTRIC	ELECTRIC	GREEN HOUSE	1327	224	3.07
	END UNIT	128	ELECTRIC	ELECTRIC	GREEN HOUSE	1327	224	
	DOUBLE ENV	130	ELECTRIC	ELECTRIC	DOUBLE ENVELOPE	1235	224	2.85
	END UNIT	131	ELECTRIC	ELECTRIC	DOUBLE ENVELOPE	1235	224	
BUILDER S SLAB	MIDDLE 13	5,6,9,142	GAS	SOLAR/ELECT	DIRECT GAIN	1265	68	2.64
	END 133,	7,8,140,1,3				1265	68	2.8
	SPECIAL	134				1265	0	

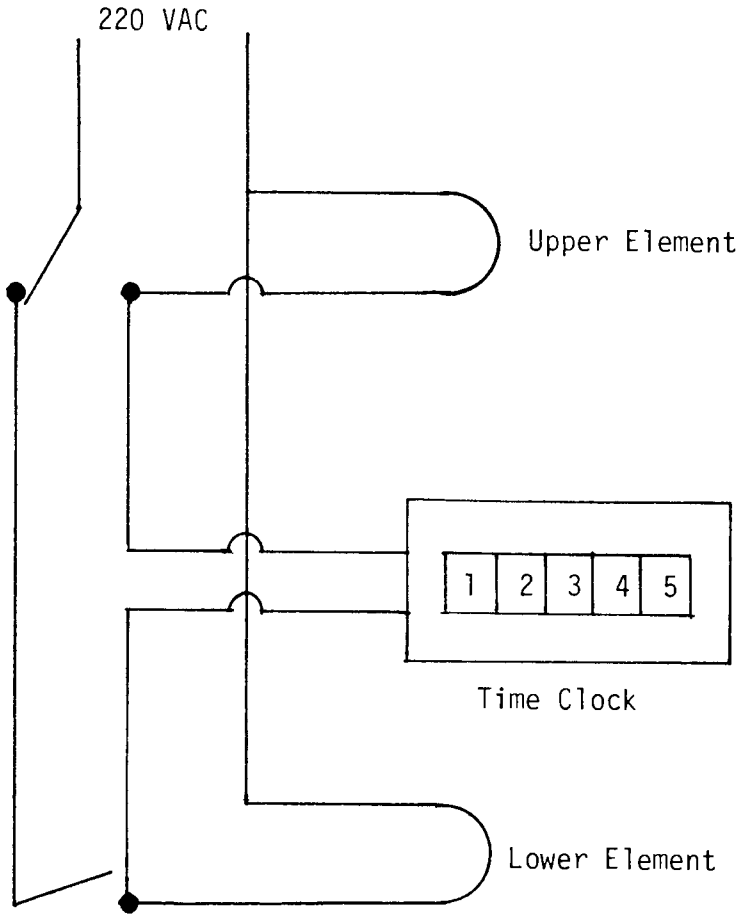

FIG. 2.1 Time clock wiring diagram for measuring the total on-time of two electric water heater elements.

for domestic hot water was determined indirectly by measuring the gas consumption of the space heating furnace. This was necessary since the residential water heaters used in these houses were equipped with typical passive thermal controls, and could not be easily metered. Furnace gas consumption was determined by using an hour meter to measure the on-time of the gas valve. As a part of the installation procedure, the electrical contractor ran each furnace and measured the gas consumption for a period of ten minutes so that the gas consumption rate would be known. Because of the variability among even nominally identical furnaces, this calibration was done for each submetered furnace. The calibration factor for each submetered house appears in the disc file for that house, and typical numbers for these constants appear in the file listings shown in Appendix C.

In addition to this energy submetering, a mercury in glass thermometer was used to measure the supply water and hot water temperatures in these houses at the same time that the submeters were read.

Indoor temperatures for the submetered houses were recorded on battery driven 90-day strip chart recorders. All but one of these 47 houses had a recorder placed in the vicinity of the thermostat. Of these houses, 22 had below grade living areas that were similarly monitored for indoor temperature.

Beyond the above submetering activity, the gas and electric utility meters for all houses in the project, both submetered and non-submetered, were read on a regular basis as described in section 2.2.

2.2 THE DATA COLLECTION SYSTEM.

Energy consumption data for the houses in the research program were collected through the use of paid and volunteer meter readers or from utility data records. Because of the need to obtain consistent and complete data records for the seven groups of submetered houses, the decision was made to select one home owner from each development to be a paid meter reader. For the non-submetered houses, each home owner was asked to become a volunteer meter reader for his or her own house, as well as for a neighboring house or two.

2.2.1 Paid readers.

Paid readers were selected based on their return rate for the weekly meter reading postcards that were used to collect energy use data for the first research project. Those showing the highest return rate were sent a letter explaining the research program to be conducted, and asking them to participate as a paid meter reader. Nearly all homeowners who were asked accepted this opportunity; and in only one case was it necessary to ask a second person to perform this task. The meter reading agreement is shown in Figure A-1.

So that data could be more compactly recorded and mailed, a self-mailing form was developed (see Figure B-1) that allowed for recording and mailing all data on a weekly basis. Each reader received a pack of pre-stamped forms for the entire program. These forms were filed by the principal investigator on the day they were

received, and the completeness of each file was checked on a regular basis. Readers with missing reporting forms were contacted by telephone to find out why their data had not been received. While some readers would mail their forms every week and others would mail several weeks of data at one time, all readers but one returned 100 percent of their meter reading forms on a regular basis.

Since the houses in the research project were all newly constructed, they all had their utility meters located outside the house. Because of this, these meters could be easily read on a weekly basis. However, cold and hot water temperatures and submeters for domestic hot water energy consumption were read only once each month, since access to the house was required.

In addition to these duties, each paid reader maintained the recording thermometers for his or her development. This involved changing the paper tape three times and replacing the battery once during the twelve-month monitoring period. Preloaded paper tape transport cartridges were sent to each reader, along with postage for returning the used data tapes. In only a few cases did improper instrument servicing result in the loss of data; of 280 expected data tapes, only five failed to record because of servicing errors. Three of these resulted from the transport being loose in the drive mechanism, and the remaining two could not be explained. Sixteen data tapes were not recorded either because the reader failed to put them in place on a timely basis (six tapes), the owner refused to have them in the house (eight tapes), or the owner turned off the recorder (two tapes). These numbers yield a mechanical failure rate of 1.89 percent for the recording thermometers used in this study. More careful installation of the paper tape transports in the three cases cited could have reduced the failure rate to less than 1 percent. These data have been cited in detail, since the principal investigator believes that they could be of value to other researchers setting up housing monitoring programs involving homeowners in the operation and maintenance of simple recording instruments.

2.2.2 Volunteer readers.

All owners of non-submetered houses were sent letters explaining the research program and asking them to participate as a volunteer meter reader for their own house, as well as for a neighboring house, if possible. Of the 96 remaining owners, 34 agreed to read meters. Three owners indicated a willingness to read one house besides their own, so commitments to read the meters of 37 houses were obtained. As was done for the paid meter readers, a special self-mailing form was prepared for returning the data on a regular basis. Because each reader had only one or two houses to report on, a monthly data reporting form was used. Again, each reader was sent enough pre-stamped reporting forms for one full year of data.

In order to improve the data reporting rate, phone calls were made during the early part of the research to inquire about missing data forms, but many readers remained irregular in returning their meter reading data sheets. Some data remained difficult to interpret, despite written instructions on two occasions as to the correct procedure for reading and recording the electric and gas meter

readings. Readers were also sent fast-food gift certificates valued at $10 as a special incentive early in the summer to encourage them to continue their meter reading activity, and to remind them of the importance of submitting complete data records for the summer months. However, at the end of the program only 18 of the original 37 volunteer reader houses had acceptable data files. The quality of these data is comparable to that of the data returned by the paid readers. For the entire project, good quality, simultaneous weekly gas and electric meter readings were obtained for 65 houses.

2.2.3 Utility data.

Data on the remaining houses were obtained directly from utility records. As a part of the original EEHDP building program, each buyer was required to sign an agreement giving the MHFA access to utility billing information, and these agreements were used to obtain the required utility data. Because utility meters were located outside the houses, the number of estimated readings was minimal, and the quality of the data was excellent. In a few areas served by the same utility for both gas and electric service, simultaneous gas and electric readings were also available (12 houses). With these data, simultaneous weekly or monthly gas and electric readings were available for a total of 77 houses in the program.

2.3 DESCRIPTION OF DATA BASE FILES.

The data base files for the research program were set up and maintained using dBASEII software running under a CP/M operating system. The data file flow used for the program is shown in Figure 2.2. The principle product file for the program is called the "LBL" analysis file. This file is described in detail in section 2.3.2.

2.3.1 Use of dBASEII.

Meter reading data received by mail was entered on a regular basis using the dBASEII command files called DATAENTR for submetered data and VOLDATA for volunteer data. A formatted screen was used for data input and checking. As each meter reading was entered, the consumption for the current meter reading period was calculated and displayed, along with the consumption for the previous meter reading period as a check for consistency and reasonableness in the current meter reading. Readings that appeared faulty due to common meter reading errors were corrected and reentered. Data sets that were consistently erratic were discarded from the data base. Holidays proved most troublesome in this respect; during these periods, the energy consumption of any single household could vary by a factor of two or more and still represent an accurate meter reading.

The quality of the meter readings provided by the paid readers remained consistently high after an initial start-up period. This required further telephone instructions to about one-half of the readers on what was required for accurate meter reading. The quality of data from all but one of the volunteer readers who reported for the entire period was also consistently good. For volunteer readers, telephone calls and letters appeared less effective in correcting

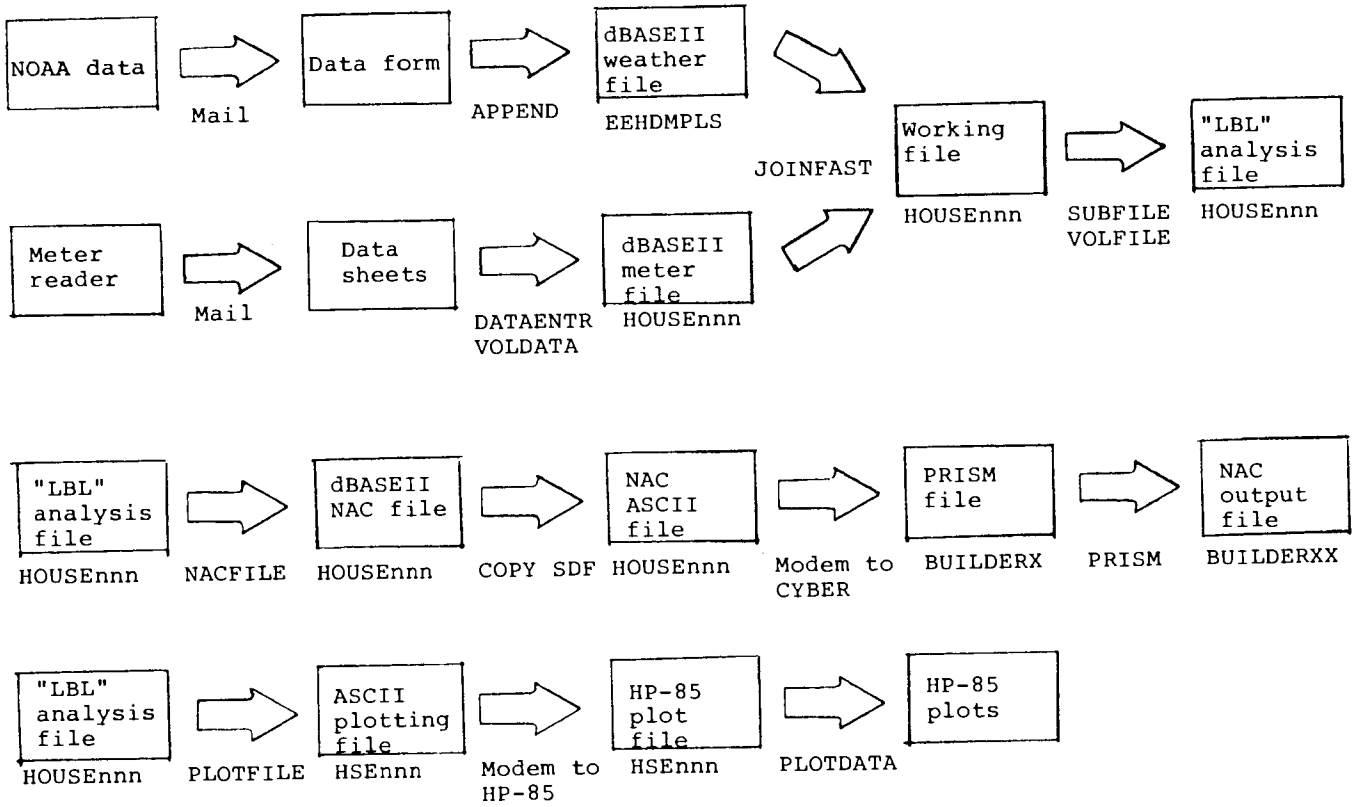

FIG. 2.2. Data file flow chart. Description of data is shown inside rectangular box; generalized file name is shown below box. Data handling programs or techniques are described below each arrow.

problems. Readers who were having problems were more likely to stop reading and drop out of the program altogether than to improve their meter reading skills.

Utility data were entered into dBASEII files directly using the dBASE II APPEND command. Because utility meters were located outside the houses in the research program, very few estimated readings were encountered. In those cases where estimated readings did appear, that meter reading period was skipped and a total value for the actual meter reading period was manually calculated and then entered into the data file. Houses that had changed owners were eliminated, since utility companies would not release the required meter readings based on an agreement signed by the previous owner.

2.3.2 Description of data files.

Lists of data files prepared for the three types of house groups (submetered, volunteer read, and utility read) appear in Appendix C, Tables C-1, C-6 and C-8. In these tables the number at the end of the house file name is the number assigned to that house during the EEHDP, and the #RCDS is the number of data readings for that particular house. For the submetered houses, the ENERGY USE column gives the type of fuel used for space heating and for heating domestic hot water. For the remaining houses, this column gives the space heat fuel use. For utility read houses where the gas and electric meters were read on the same day, both fuel types are shown.

For most houses there are few missing data. Exceptions are submetered houses 94 to 97 where about 10 readings are missing. Since most of these are summer readings, heating performance could still be determined.

Tables in Appendix C show typical file listings and structures for the primary product files produced by this research. The files show the consumption for the period of time between the reading dates given for each value. Also included in these files are weather data for the same periods of time. The average temperature and the average percent of sunshine are the average of these values for the periods shown, based on daily data provided by the National Climatic Data Center. Fargo weather data were used for houses 1-8, 34, 49-51, and 162-164, with Minneapolis-St. Paul weather data being used for the remainder of the houses. The last column, or field, in each file is a running index of the number of days from the beginning of the weather file used to create these data files. The actual value of this number is arbitrary, but it is useful since it can be subtracted from any other number in the same column to give the total number of days between meter readings. This might prove useful for further study using this data base.

The file structures shown describe the contents of each field and give the unit of measure to be applied. These files are called the "LBL" analysis file in Figure 2.2 and they formed the basis for the performance analysis of the houses in the research program.

3. FIELD RESEARCH

Field research was conducted in two primary areas: construction quality and indoor air quality. Field examination of construction was done for 25 houses using an instrumented inspection approach developed at Princeton University. In this process, a house is examined with an infrared scanning camera while it is pressurized or depressurized by means of a fan placed in an exterior door of the house. Fan pressurization enhances the infrared detection of air leaks, and if the air pressure and flow rates are also measured, a leakage area factor for the house may be calculated. During these inspections, furnace efficiencies were also measured, and wood moisture measurements were made in accessible framing areas.

Using passive monitoring techniques, indoor air quality measurements were made to examine the concentrations of nitrogen dioxide, radon, and formaldehyde in 12 selected EEHDP houses and in 12 control houses. As a follow up to this work, radon mitigation strategies were applied to four of these houses.

Each of these activities, because they involved contractor work on the homeowner's property, was carried out only after a signed agreement had been received from each homeowner. These agreements, along with letters explaining the work to be done and the benefits for the homeowner, were mailed out about four to six weeks before the work was to begin. Nearly all homeowners responded favorably to these requests and returned them promptly, except for a very few that required a follow-up telephone call to further explain the research program.

3.1 INSTRUMENTED EXAMINATION OF HOUSES.

House examination visits were made over two heating seasons during the winters of 1983-84 and 1984-85, with about half of the houses visited during each season. Houses examined during the first season were selected based on previous research work (5). The selection was based on poor performance either in terms of excessive leakage area or energy use, or on the basis of unusual design, particularly regarding solar energy features of the house.

Houses for the second season of visits were selected from the submetered house group based on a preliminary analysis of the meter reading data for these houses. For this selection, the sum of 70 percent of the gas consumption and 100 percent of the electric consumption, each converted to MBtu, was calculated for each house for the first two months of 1984. Houses showing the highest and lowest energy consumptions were then selected to receive a field inspection. In retrospect, this selection would have been better made using a full season's data to calculate the energy performance, but at the time these data were not yet available.

House inspection visits were documented by completing prepared forms and taking slides of both visible and infrared observations of interest. Infrared images were photographed from the scanning screen of the infrared scanning camera. Attempts were made to keep the infrared and visible views as similar as possible to facilitate

comparison of the two images. Because similar construction problems were found among the 25 houses examined, the results of this work are presented by individual building component, with the best examples of each type of problem selected from all of the houses examined. This report presents a narrative of the best 111 slides selected from the 1200 slides taken as a part of this work. Due to space and cost considerations, only five of the slides are presented as figures in the text of this report. A complete set of slides, accompanied by a copy of this section as narrative, is available as indicated on the inside front cover page of this report.

3.1.1 Attics.

In most of the 25 units inspected, the attics appeared to be the leakiest locations. In general, this group of houses seemed to have about the same number and kind of air leaks into the attic as observed in conventional houses. Most of the attic recommendations on the "Infiltration Reduction Checklist" (Figure B-8) included in the EEHDP Request for Proposal were not followed.

3.1.1.1 Furnace vents.

Slides 1 through 4 were taken in unit number 2. Slide 1 shows the chaseway for the furnace and water heater vent where it passes through a closet just below the attic. Slide 2 is a thermogram of the same chaseway taken with the house depressurized. It indicates that cold air is being drawn into the chaseway from the attic. Slide 3, taken from the attic before the insulation around the vent was disturbed, shows that water has been running down the vent and also dripping from the roof. The staining on the vent pipe and insulation appears to be due to water leaking around the roof penetration, although condensation could also be involved. Slide 4 was taken after the cellulose insulation was removed for inspection. The plastic sheeting was found just as it is shown here. A large gap is shown between the vent and the sheetrock. The insulation around the vent was quite damp, and the wet looking wood shown just to the left of the vent was tested and found to have a moisture content of 21 percent at a depth of 3/8-inch and 18.5 percent at 3/4-inch. Also, the vent is apparently beginning to corrode where the wet cellulose was in contact with it.

Slides 5, 6, and 7 were taken in units 116, 134, and 151, respectively. Slide 5 shows the furnace vent plus two other ducts, apparently a bath vent and a dryer vent, going through the same hole. There was no firestop sealing this chaseway, and even though it appeared as an air leak during the infrared inspection, the insulation was not wet and the vent did not appear to be corroding. The vent in slide 6 appears to be badly corroded and the insulation was wet around it. Although there is a gap between the firestop and the vent (where the knife is pointing), the firestop seemed to be doing a good job at stopping air leakage. The vent in slide 7 also appeared badly corroded, and the insulation was wet. The ceiling joist next to the vent measured 21 percent moisture at 3/8-inch depth and 15 percent at 3/4-inch. Although a metal firestop was installed in this case, it was not effective in stopping air leakage. The firestop is about 16-inches square, while the chaseway is at least 16-inches by

30-inches. An attempt was made to seal the rest of the opening with plastic sheeting, but it was not attached to the firestop and was only stapled into position. The infrared inspection showed a large leak here. These situations in which cellulose insulation is installed in contact with the furnace flue are potential fire hazards, since cellulose insulation, even though treated with fire retardants, is considered to be flammable. These vents could corrode through, exposing the insulation directly to the furnace flue gasses, causing a fire. Also, if insulation fell into it, a corroded flue could become blocked, causing flue gasses to spill into the house.

Slides 8, 9, 10, and 11 were taken in the attics of units 28, 32, 159, and 51, respectively, and all show large air leaks. In slide 8, the metal firestop is shown attached to the tops of the ceiling joists, leaving a gap between the gypsum board and the firestop. Slides 12, 13, and 14 were taken in unit 124. In slide 12, a chaseway for a furnace and water heater flue is shown built into a stairway with a cathedral ceiling. Slide 13 is a thermogram of the same chaseway, taken with the house depressurized. Slide 14 was taken from the accessible part of the attic, looking down at the flue in the narrow space above the cathedral ceiling. The flue was apparently wrapped with fiberglass before the cellulose was blown, however, there could still be cellulose in contact with the flue. The frost shown on the sheathing occurred mostly between the two trusses shown, with very small amounts of frost observed one or two trusses to either side. Note that the sheathing just above the chaseway was staying warm enough so that no frost was forming. These slides were taken when the outside temperature was about +5 degrees Fahrenheit.

3.1.1.2 Attic access hatches.

All houses but one that had attic access hatches, had hatches that were very leaky. Of these, only two attic accesses were weatherstripped at all, and this work was poorly done. The one unleaky attic access observed had been sprayed over with textured ceiling material. Slides 15 and 16 were taken in unit 118. Slide 16 is a thermogram of the same attic hatch shown in slide 15. Slides 17, 18 and 19 were taken of the attic access in unit 124. The frost in slide 19 is from moist air leaking through the hatch into the attic.

3.1.1.3 Attics in split-level houses.

The wall that separates the upper two levels of a split-level house appeared to be a large air leakage site in all houses with this feature. The lower half of this wall has heated space on both sides, while the upper half has heated space on only one side and attic space on the other. Normal practice is to use full length pre-cut studs to frame these walls just like any other partition wall. Unless the space between studs is carefully sealed where the ceiling of the lower level intersects this wall, the stud cavities form chaseways connecting heated space to the attic. Since these walls generally contain major plumbing, wiring, and duct runs, it is usually easy for heated air to get into the stud spaces of these walls.

Slides 20 through 25 were taken in unit 160. Slides 21 and 23 are shown in Figures 3.1 and 3.2, respectively. Slide 20 is taken from

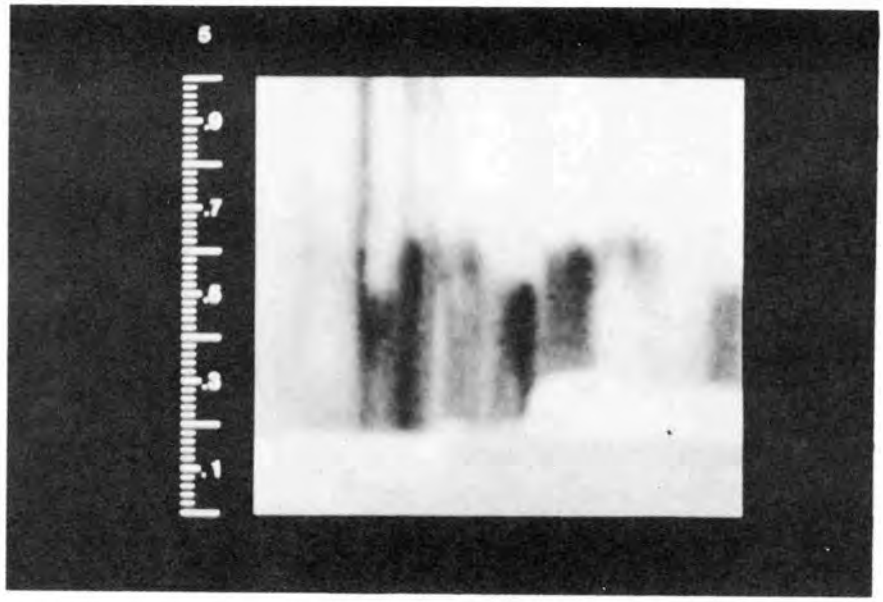

Figure 3.1
Wall thermogram in a split level house with the house depressurized. The bottom part of the wall, with heated space on the back side, is the coldest part due to cold air being drawn into the wall from the attic.

Figure 3.2
An attic view of the upper portion of the wall shown in Fig. 3.1, with the attic insulation removed for inspection. The open top of the fiberglass filled heated wall cavity is shown.

the living room on the third level of this split level house, and shows the wall that separates the second and third levels. The ceiling of the second level intersects this wall at about mid-height on the back side, so that there is an attic on the back side of the top half of the wall, and heated space on the back side of the bottom of the wall. Slide 21 is a thermogram of the same wall, taken with the house depressurized. The bottom part of the wall, with heated space on the back side, is the cold part of the wall due to cold air being drawn into the wall from the attic. Slide 22 was taken from the attic on the back side of the wall. The 2 by 4's in the top of the slide are continuations of the ceiling joists for the third level; the insulation at the bottom of the slide is above the ceiling of the second level. Slide 23 is a closer view of the bottom of the wall shown in slide 22, with the blown fiberglass removed for inspection. The polyethylene shown is the vapor barrier in the ceiling of the second level. The open top of the heated wall cavity shows between the pink fiberglass batts. The interior wall cavity is also exposed just to the left of the black plumbing vent. Water staining is shown on the gypsum board above and to the left of the plumbing vent. This staining is at the level of the top of the blown fiberglass, and was probably caused by condensation from warm, moist air leaking out of the house through the fiberglass insulation. There was also evidence of water staining on some of the wood in this area. Slide 24 shows the same wall, from the inside again, to the right of slide 20. The thermostat on the left in slide 24 appeared on the far right of slide 20. At the upper right is a return air grille that connects to two stud spaces that serve as a return duct. Slide 25 is a thermogram of this part of the wall, taken with the house depressurized. Cold air is apparently being drawn down the return, as well as through the grille, and a large stream of cold air was felt coming through the grille during depressurization. This return was designed to collect warm, solar heated air that is blown through a rock-bed under the first level floor. A thermostat turns on a fan whenever the living room temperature goes above the set point. Unfortunately, this fan not only moves warm air out of the living room, but because of the above air leak, appears to pull cold air from the attic as well.

A very similar situation was found in units 1 and 2. Slides 26 through 29 were taken in unit 1. Slide 26 shows another return air grille that serves the same purpose as the one in unit 160, discussed above. This slide was taken from the living room on the second level of this split level house. The ceiling in this area is the same height as the ceiling on the third level, while the ceiling height for the rest of the second level is lower. The slide shows the location where the ceiling height of the second level changes. There is attic space above the lower and upper ceilings, and behind the short wall between them. A fiberglass bath/shower stall is located behind the wall with the grille in it. Slide 27 is a thermogram of the same area taken with the house depressurized; note the framed picture in both slides for reference. The entire area of the wall that is covered by the shower stall on the other side appears cold.

Slides 28 and 29, taken from the attic, show the largest leak in this area. Slide 28 shows the attic as it was found, with the piece

of fiberglass shown behind the tape measure very loosely installed. Slide 29 shows the large leak that was visible when the fiberglass was removed. It was easy to put a hand into the hole just below and to the right of the tape measure and to touch the grille on the left and the shower stall on the right. Where the ceiling heights of the second and third level were different, this house had the same problem as observed in unit 160 above. Several additional houses included in this investigation had similar problems.

3.1.1.4 Kitchen soffit air leaks.

Slides 30 through 33 were taken in units 27 and 28. Slide 30 shows a soffit that was constructed above the kitchen cabinets. Slide 31 is a thermogram of the same area taken with the house depressurized. The soffit is cold due to attic air leaking into it. The soffit continues around an inside corner to the right of these slides and is connected to an interior partition wall. Much of the air leaking into the soffit appeared to be getting into the partition wall. Slide 32 shows the attic just above the soffit shown in the previous two slides. Water stains are apparent on the wood, and the cellulose insulation appears slightly discolored and has settled just above the soffit area. Slide 33 shows the same area with some of the insulation removed. The insulation was damp. The pencil in the photograph is sticking in a gap between a 2 x 4 and a piece of plywood. It appears that the gypsum board on the front face of the soffit is attached to this 2 x 4. The pocket knife is shown sticking into a gap between the plywood and the top plate of the exterior wall. There was apparently no attempt to seal these gaps.

3.1.1.5 Plumbing vents.

Air leaks were detected at penetrations for plumbing vents in most of the houses that were inspected. Slides 34 through 36, taken in unit 28, illustrate very typical plumbing vent leaks. Slide 34 was taken in the bathroom, and the main plumbing vent is located in the wall to the left of the hanging light fixture. Slide 35 is a thermogram of this wall, taken with the house depressurized. The top of the mirror is in the lower left corner and the light fixture chain is the vertical light line on the right. The cold streak to the left of this chain is due to cold air leaking from the attic around the vent. Slide 36 shows the vent from the attic after some of the insulation had been removed for inspection.

3.1.1.6 Partition walls and ceiling light fixtures.

All houses inspected had at least a few small leaks between the attic and the tops of the partition walls. Slides 37 through 39, taken in unit 85, illustrate two very common leaks. Slide 37 shows a partition wall between a bedroom and upstairs bathroom. Slide 38 is a thermogram of the intersection of the wall and ceiling just to the left of the doorway, taken with the house depressurized. Slide 39 shows what this area looked like from the attic when the insulation was removed. The hole where the wiring goes through the top plate is a common source of air leakage. A pocket knife blade is shown sticking into a crack approximately 1/32-inch wide between the top plate and

the gypsum board of the wall. The dark streak on the fiberglass batt that was covering up the leaks is indication of dirt that was filtered out of all the air that leaked from the house.

In houses that had cellulose attic insulation, small leaks like these seemed much less noticeable. It was surprising in one house to find almost no partition wall leaks, indicating that the builder had been careful, and had possibly even used techniques learned at an energy efficient building seminar. However, when the cellulose insulation was removed, the same kinds of holes and cracks were found as those shown in slide 39. This apparent ability of cellulose to reduce air leakage has been discussed in other research (6).

The plastic sheeting shown in slide 39 ends at the top plate and was not sealed to it. Because this plastic sheeting has gaps at precisely the same locations that the gypsum board has gaps, it is doubtful that it is contributing much to the airtightness of this house. If there were no plastic, but the cracks between the gypsum board and the top plates were sealed, as well as gaps around penetrations, the house could possibly be significantly tighter than it was with the plastic sheeting in place. Polyethylene vapor diffusion barriers, unless properly sealed, do not appear to significantly reduce air leakage.

Slides 40 through 42 were taken in unit 67. Slides 41 and 42 are shown in Figures 3.3 and 3.4, respectively. Slide 40 shows the walls of a closet that has been built out over a stairway. In slide 41, a thermogram taken with the house depressurized shows a cold streak coming down from the cathedral ceiling into the partition wall between the closet and the room where the slides were taken. Slide 42 was taken from the attic. A hand could be inserted into the top of the cold wall cavity that appeared in the middle of the thermogram. Two walls, a flat closet ceiling, and the cathedral ceiling all meet at this location, creating some complicated framing details. The cathedral ceiling structure also changes from trusses to solid wood rafters at this point. The plans showed no details for sealing the air-vapor barrier at this location.

Slides 43 and 44 were taken in unit 78. In slide 43 a vestibule is shown to the left of the windows. Slide 44 is a thermogram of the top of the vestibule where it intersects the cathedral ceiling, taken with the house depressurized. The leaky ceiling light fixture is apparent in both slides. Cold air from the cathedral ceiling is being drawn into the vestibule walls. This area appeared warm on the thermogram before the house was depressurized. Thermograms of other partition walls in this house did not show this problem.

Slides 45 and 46 were taken in unit 125, with the house depressurized. They illustrate air leakage around ceiling light fixtures. Most houses in this study were found to contain similar leaks.

3.1.1.7 Cold air returns.

Slides 47 through 49 were taken in unit 134, with the house depressurized. Slide 47 shows a cold air return grille in the upstairs bathroom. This grille is mounted on a chaseway that serves as a cold air return for the forced air furnace. Another return

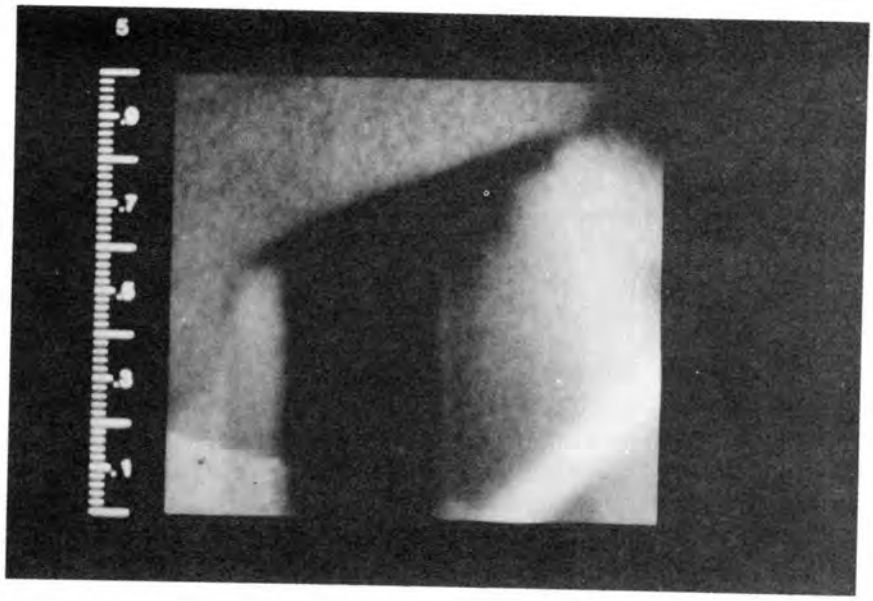

Figure 3.3
A thermogram taken with unit 67 depressurized showing a cold streak coming down from the cathedral ceiling into the partition wall between the closet and the room where this picture was taken.

Figure 3.4
A photograph taken from the attic located in back of the top part of the room shown in Figure 3.3. A hand could be inserted into the top of the cold wall cavity that showed up in the middle of the thermogram.

grille also feeds this chaseway, and the chaseway is also used for plumbing. There was a very large flow of air coming out of this register, probably the single largest leak found among the 25 houses that were inspected. Slide 48 is a thermogram of the grille, which is cold due to the flow of cold air from the attic. Slide 49 shows the attic directly above the chaseway. Plastic sheeting, attached to the framing at the top of the chaseway with nothing except staples, had been used to hold up the insulation. The insulation directly below the white deposits had a crusty texture to a depth of about an inch or so below the surface, indicating that it had been wet. The darker insulation around the edge of the hole was also crusted, although this crust was thinner. The rest of the insulation in the attic had no such crust, and all the insulation was dry at the time of inspection during March 1985. The weather at this time was warm with no recent cold spells. An inspection of the chaseway showed that the insulation in the exterior wall was covered only by plastic sheeting stapled to the studs. This plastic had unsealed joints and could have been leaking before the large hole appeared. The owners of the house reported that in previous winters they had experienced a lot of condensation on their windows, but that this past winter there was much less. It is conjectured that this hole appeared between the last two winters, increasing the infiltration rate of the house enough to make a noticeable change in the amount of window condensation.

3.1.1.8 Other attic insulation problems.

Slide 50 is a thermogram of a ceiling area in unit 129 taken without the pressurization fan operating. The ceiling in this house had several similar areas. Slide 51 was taken in the attic just above the thermal leak shown in slide 50. The top layer of batt insulation has been folded back for this slide showing a poorly fitted bottom layer of batts running in the same direction. Such large gaps were found on both the ends and edges of the batts in this attic.

Slides 52 and 53 were also taken in unit 129, and illustrate a different problem. Slide 52 shows the upstairs ceiling on the south side of the house. Just outside and above the windows is an overhang with a continuous soffit vent for attic ventilation. The attic insulation was installed to extend past the top plates of the exterior walls, and in some cases covered the soffit vents. Slide 53 is a thermogram taken of the same ceiling. The wind blowing against the side of the house is evidently forcing outside air under the batts of insulation. The air flow seems to follow the gap between the ceiling joists and the batts of insulation.

Slide 54 and slide 55 (shown in Figure 3.5) were taken in unit 68 with no depressurization. Slide 54 shows the cathedral ceiling above the kitchen area. The ceiling is built with trusses which allow a ventilated air space above the insulation. Slide 55 is a thermogram of the same ceiling area. The entire cathedral ceiling in this room consisted of cold streaks, as shown in this small area. Most of these streaks began at the bottom of the ceiling and extended various distances up the ceiling with the coldest part of each streak appearing at the bottom. The appearance of the ceiling with the infrared camera did not change appreciatively when the house was

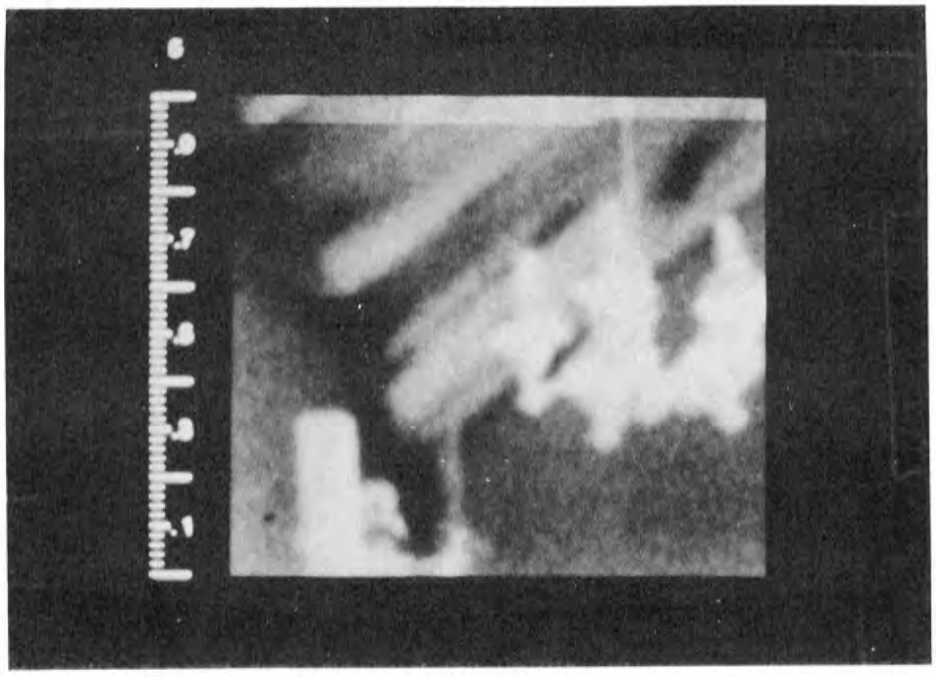

Figure 3.5
A thermogram of the cathedral ceiling above the kitchen area in unit 68. The ceiling is built with trusses that allow a ventilated air space above the insulation. Apparently, these cold streaks are caused by outside air entering the lower soffit vents and getting underneath the insulation batts.

either pressurized or depressurized. Apparently, these cold streaks are caused by outside air entering the lower soffit vents and getting underneath the insulation batts where it then flows upward between the gypsum board ceiling and the insulation. Streaks beginning farther up on the ceiling might be due to air getting under the insulation between gaps in the batts.

3.1.2 Walls - air leakage.

3.1.2.1 Wall - floor intersections.

The largest and most common exterior wall air leaks were found where floors intersect the walls. This should not be surprising considering the difficulty of making an interior air/vapor barrier continuous in this area. Slides 56 through 59, taken at unit 97, show a condition common in the 25 houses inspected. Although this unit had a wood foundation, houses with masonry foundations looked about the same. Slide 56 shows the basement wall just above the washer and dryer. Slide 57 is a thermogram of this same area, taken with the house depressurized. Slide 58 shows dirt found on the insulation when it was removed. The dirtiest area of this batt was where the insulation rested on the bottom of the rim joist, indicating the greatest amount of air leakage. There was also some air leakage around the pipe that goes to the outside water faucet. Slide 59 shows the outside of this same area. Icicles appear on the exterior due to water running out from behind the siding and then freezing. This moisture might have come from a leaky connection in the dryer vent; or from higher up on the wall, although no evidence of this was found.

3.1.2.2 Cantilevered floors.

Locations where floors were cantilevered out beyond the foundation were usually found to have more air leaks than other floor - wall intersections in the same house. Slides 60 and 61 were taken of a cantilevered section of floor in unit 27. A large air leak, visible in slide 60, is responsible for the line of dirt on the insulation shown in slide 61. This leak is caused by the gap between the sill plate and the foam sheathing attached to the underside of the cantilevered joists.

Slides 62 and 63 were taken of the dining room ceiling on the first floor of unit 134, a two story house. Slide 63, a thermogram taken with the house depressurized, reveals cold streaks coming across the ceiling, starting at the exterior wall on the left. The first cold ceiling joist space at the top of the slide marks the beginning of a cantilevered floor that extends out past the exterior wall on the left.

Slides 64 through 69 were taken at unit 125. Slide 64 was taken in a corner of the lower level which is mostly below grade. The ceiling is made of precast concrete planks with hollow cores that are used as part of the forced air heating and solar storage system. The hollow cores are connected on both ends by gypsum board plenums built under the ends of the planks, as shown here above the windows. Slide 65 is a thermogram of this area, which indicates that cold air was leaking into the right end of the plenum when the house was

depressurized. Slide 66 was taken of this same location from the outside. The hole in the snow was made by warm air leaking out just above the exterior foundation insulation. This air leak is shown in slide 67, taken after some of the snow was removed. Slides 68 and 69 were taken at another location where an air leak was melting the snow. These slides also show polystyrene foundation insulation without a protective coating above grade.

3.1.2.3 Other wall air leaks.

Slides 70 and 71 were taken in unit 97 with the house depressurized. Slide 70 of the north basement wall shows a light switch to the right of the door and a combustion air intake vent to the right and above the door. Slide 71 is a thermogram of the same area which shows cold areas around the light switch and the combustion air intake due to cold air leakage at these locations. Air leaking around the combustion air intake also appears to be flowing down inside the wall and into the basement at the bottom of the wall.

Slides 72 and 73 were taken in unit 30 with the house depressurized. Slide 72 shows a large gap in the plastic sheeting under the electric service box. During depressurization, much cold air entered in this area, as shown in the thermogram on slide 73. Slide 74 shows a damaged vapor barrier in unit 30. Apparently this damage to the vapor barrier was done by the plumbing contractor. Slide 75 shows a large gap between the vapor barrier and an electrical outlet box.

3.1.3. Walls - conduction.

3.1.3.1 Batt insulation.

Every house in this project that was inspected using the infrared camera had areas of batt insulated walls that appeared non-uniform in temperature. This appearance may be generically described as "blotchy looking," and has been observed to be common to houses insulated with batt type insulation. By comparison, based on other field work experience, wall cavities properly filled with blown insulation appear to be very uniform in temperature. The studs in these walls also appear as very straight, distinct dark lines that are uniform in both width and temperature. However, for the houses in this study, some of the insulated cavities appeared to vary randomly in temperature, and in some cases looked as cold as the studs. And some studs looked colder or wider in areas, or were difficult to see at all. In most cases these areas looked about the same whether the house was pressurized, depressurized, or not pressurized at all.

Slides 76 and 77 were taken of an exterior wall in unit 27. A picture on the wall is shown in the upper left corner of the thermogram, slide 77. The studs are very difficult to distinguish from the insulated cavities. In other areas on the same wall, the studs were easily distinguishable.

Slides 78 and 79 were taken in unit 97. In the thermogram, slide 79, the studs appear to get both colder and wider at the bottom of the wall. Also, no two studs look the same, and the bottoms of the insulated cavities look colder, and non-uniform. This is hypothesized

to be the result of convection cells within the walls. Cold air may be flowing down between the insulation and the exterior sheathing, passing through the insulation (or through gaps due to poor installation) at the bottom of the wall cavity, and then flowing up between the gypsum board and the insulation.

Slides 80 through 82 were taken in unit 78. Both walls shown in slide 80 are exterior walls. Slide 81 is a thermogram of the area above the window. Slide 82 is a thermogram of the wall to the left of the corner, with the corner showing up on the far right of the slide.

Slides 83 and 84 are from unit 28 and show the above ground part of a basement wall. In slide 84, a thermogram, colder areas appear at the top of the wall because insulation inside the wall is folded in order to make it fit the cavity. A cold area also appears next to one of the studs, possibly due to a small gap between the stud and the insulation. Slides 85 and 86 were taken in unit 44 showing an above grade basement wall. The area shown in the thermogram of slide 86 would possibly become a "blotchy looking" area if gypsum board were installed on the wall.

3.1.3.2 Thermal bridges.

Slides 87 through 89 were taken in unit 151. Slide 87 shows the front of the house. The cement block retaining wall is connected to the cement block foundation wall, which is insulated on the exterior, except where connected to the retaining wall. Slide 88 was taken of a closet just behind the wall from where the retaining wall connects. The top half of the back closet wall shown is a stud wall, while the bottom half is the cement block foundation wall. Slide 89 is a thermogram of the left edge of the rear closet wall. The bottom half of this wall appears to be cold for several feet to the right of where it connects to the retaining wall. Slide 90 shows a similar situation in unit 124. In this case, it appeared that a concrete garage floor was in contact with the foundation, which was otherwise insulated on the outside.

3.1.3.3 Exterior foundation insulation.

Several houses used trowel-on coatings to protect extruded polystyrene foundation insulation. In each case observed, problems were found with the coating cracking or coming off. Slides 91 and 92 were taken at units 51 and 150, respectively. Pressure treated plywood which was used to cover insulation appeared to be holding up well. Many units had some exposed polystyrene insulation. Slide 93 taken at unit 97 is typical, but many units had more exposed insulation than this.

3.1.4 Heating and ventilation system inspections.

3.1.4.1 Air-to-air heat exchangers.

Of the 25 houses inspected, 13 had air-to-air heat exchangers. Three houses had through-the-wall, non-ducted units, while the remainder had centrally-ducted units. All of the ducted units were found to be poorly installed, and none had provisions for air flow balancing. In most cases, the sizes and lengths of connected ductwork

were such that the units, as installed, were probably very poorly balanced. Only two of the units had filters, and of these each had only one filter located in the outgoing air duct just before the heat exchange core. Some of the control systems were complicated, did not operate properly, or were not understood by homeowners. None of the ducted systems came with an owner's manual, and none of the owners had heard anything about possibly having to occasionally clean the heat exchanger. Many owners reported using them infrequently.

Slide 94 shows a heat exchanger in the basement of unit 44. The duct just above the middle of the slide (with the open tee pointing down) is the duct through which stale house air is drawn into the heat exchanger. The house air enters this duct at two locations. One is the 4-inch opening in the bottom of the tee shown in this slide, and the other is from the bathroom. The bathroom exhaust is drawn through a long piece of 3-inch flexible metal duct which connects to a 3-inch duct that joins the left side of the tee in the slide. The owners of this unit (and one other like it) complained about the bathroom exhaust not working. When the heat exchanger was operating, much air was removed from the basement, but almost no air could be detected leaving the bathroom. In addition, the controls for this system were complicated and appeared to be incorrectly wired. A dehumidistat control in the upstairs hall should have controlled the heat exchanger. However, it only turned on the furnace fan. There is also an adjustable timer in the basement that turns on both the furnace fan and the heat exchanger. In addition, there is a switch in the bathroom that only turns on the heat exchanger, for use as the bathroom exhaust fan. There is a regular bathroom exhaust fan that is only used as a grille for the duct to the heat exchanger. The builder told the owner that "it was only there for looks and wasn't needed."

Slide 95 shows an ineffective air-to-air heat exchanger installation in unit 125. The heat exchange core was a high quality commercial heat pipe unit installed in a locally fabricated, poorly constructed housing. There is a large amount of internal leakage at the location of the pen in the middle of the slide. When the access panel is in place, there is a similar gap between the access panel and the internal baffles. In the two units like this that were inspected, there was not enough pressure in the exhaust air stream to open the back-draft damper. One of the back-draft dampers had been painted shut since the house was built. The fresh air duct from the outside has a tee located near the heat exchanger to provide combustion air for the furnace and water heater. Because of this design, when the heat exchanger is on, it is drawing more air from the furnace room than from outside. This is because there is less resistance between the exchanger and the furnace room than between the exchanger and the outside air intake grille.

Slide 96 was taken in unit 118 and shows a through-the-wall heat exchanger installed in a bedroom. Slide 97 is a thermogram of the heat exchanger with the house at natural pressure. The exchanger and the area around are shown to be cold because of the cold air that is leaking in. The homeowner complained of cold drafts blowing in through the exchanger, especially when it was turned off. She said that some of her neighbors have sealed their heat exchangers shut and do not use them at all.

3.1.4.2 Heating systems.

Table 3.1 presents the results of steady-state furnace efficiency tests performed on all of the gas furnaces, and explains how combustion air requirements were met in each case. Steady state efficiency testing was performed using a Bacharach wet chemical CO2 analyzer and an electronic digital thermometer. The flue gas sample was taken upstream of the draft diverter. Measuring a flue gas temperature at this point was difficult because of the 100°F temperature difference sometimes observed between different locations in the outlet of the heat exchanger. The measurement was made in the middle of the outlet whenever possible. The number of low efficiencies measured is surprising.

Slide 98 was taken of the furnace in unit 48. This furnace was the second induced draft, recuperative furnace to be installed in this house, and it replaced the original furnace that had failed due to corrosion. The homeowner said the heating contractor replaced it at cost. The furnace was installed with no filter in the cold air return, and as shown in slide 98, the filter was simply left under the blower motor with no place to install it. Slide 99 shows a filter that was added by the homeowner; however, most of the return air will bypass this installation.

Slides 100 and 101 were taken of the furnace in unit 134. Slide 100 shows some corrosion in the flue outlet of the furnace. The flashlight in slide 101 is shining on an opening apparently designed to provide cooling air for the induced draft fan motor. This air intake was clogged with lint.

Slide 102 was taken in unit 97. The furnace room shown was in the middle of the basement, had insulated walls and a weatherstripped door. Yet, the room was very leaky, since insulation batts were used to seal the air leakage paths between the floor joists, and these batts were either loosely placed or even missing. There is a large gap between the bottom of the door and the floor, and a permanent warm air supply is installed in the warm air plenum so that heated air flows into the furnace room. Air-tight furnace room designs are supposed to treat the furnace room as an unheated space. All the ductwork in the furnace room is insulated and sealed and an outside air supply is ducted to the room. In unit 97 the outside air supply is ducted to the cold air return. Blower door tests performed both with and without the furnace room door shut showed no difference in the tightness of the house.

Slide 103 shows the crawlspace in unit 32. The exterior crawlspace walls are insulated, as is the floor above it. However, there is a warm air supply register in the middle of the floor that was open, supplying hot air to the crawlspace (just above the center of the slide).

3.1.4.3 Rock storage.

Slide 104 shows the circulation fan and ductwork for the rock bed storage that is under the basement floor of unit 160. A thermostat in the living room turns on this fan when the temperature in the living room goes above the setpoint. The intake side of the circulation fan is connected to a register high on the wall in the living room (this

TABLE 3.1 Measured furnace efficiencies and observed combustion air supplies in 21 houses.

Unit #	Steady State Efficiency, %	Vent Damper Installed Yes	Vent Damper Installed No	Method Used For Combustion air	Comments
1	76.5		x	1	
2	72		x	1	Combustion air duct stuffed with rag
27	74		x	2	
28	69		x	2	
30	75.5	x		3	
32	74.5	x		3	
44	86.5	induced draft		1	Original furnace rusted out/replaced
48	86.5	induced draft		1	Original furnace rusted out/replaced
51	74.5	x		4	
67	73		x	1	
68	72	x		1	Vent damper added by owner
97	75.5	x		2	Vent damper looks like retrofit
116	73		x	1	Induced draft furnace was specified, but not installed
118	79		x	1	Induced draft furnace was specified, but not installed
124	78	x		5	
125	77	x		5	
134	87	induced draft		1	
150	77.5		x	3	
151	74		x	3	
159	75		x	1	
160	68.5		x	1	

Methods for combustion air supply:

1.) Duct from outside to furnace room. Units 67 and 68 through roof, other through side walls.
2.) Duct from outside to cold air return.
3.) Fresh air supply from air to air heat exchanger ducted to cold air return on furnace.
4.) Duct from outside connected to furnace near burner--has electric damper
5.) Duct from outside to furnace room is also used as outside air intake for air-to-air heat exchanger. When heat exchanger is operating, it can draw air from furnace room and outside. There is less resistance in path from heat exchanger to furnace room than to outside.

register also has leaks into attic--see slides 24 and 25). Warm solar heated air is drawn from this register and then blown through the rock bed and out registers in the basement floor near the south wall. To prevent this warm air from flowing to the furnace ductwork, the plans specify a damper in the duct that goes to the furnace's cold air return. However, this damper was not installed. There are two thermostats in the hall on the second level, one that turns on the furnace fan only and another that turns on the entire furnace. Presumably, the thermostat that controls the fan should be set higher than the furnace thermostat. The homeowner sets the fan thermostat at 68°F and the furnace thermostat at 62°F. When the temperature of the second floor hall drops below 68°F, the furnace fan comes on and draws air in the reverse direction through the rock bed, even if the rockbed temperature is below room temperature. If the hall temperature drops below 62°F, the furnace burner comes on until the temperature warms to above 62°F. With this arrangement of set points, the furnace fan circulates air through the rock bed most of the winter. The furnace is a downflow furnace and all the air leaving the furnace first flows into the slab under the second level of this three level split level house. (See discussion in Section 3.1.4.4 below.)

The rock beds in unit 159 and 160 both fill with water in the spring, and the owner of 159 has had to install a sump pump. One of the owners of 159 also has had allergies for about two months each fall since moving into the house. The allergies, which had not been experienced previously, seem to begin when the heat is first turned on in the fall. It seems plausible that these allergies might be caused by biological activity in the wet rock beds.

3.1.4.4 Below slab ducts.

Eleven of the 25 inspected houses had forced air heating systems with warm air supply ducts beneath a concrete slab. The plans which were inspected for these houses all called for insulation either around or below ducts located close to the exterior edge of a slab. However, thermal bridges may be causing high heat loss in these ducts, especially where there is thermal bridging between the slab and the footings. Supply air temperature data on six houses was collected and data from one house are shown in Figure 3.6. This figure shows the differences between the cold air return temperature and the warm air supply temperatures measured at several locations through a one hour period in unit 1. After the furnace was on for more than an hour, the air coming out of the register farthest from the furnace was losing almost 2/3 of its energy to the ductwork under the slab. Of course, all of this heat is not totally lost since the house will lose less heat to a slab that is warmer. However, a large percentage of this energy is probably lost into the ground. In unit 1, after 100 minutes, the air coming out of the farthest registers had lost about 40 percent of its energy. In units 116 and 118, about 25 percent was being lost after 25 minutes. In unit 134, where all the supply air goes below the slab, about 50 percent of the heat was lost after 30 minutes.

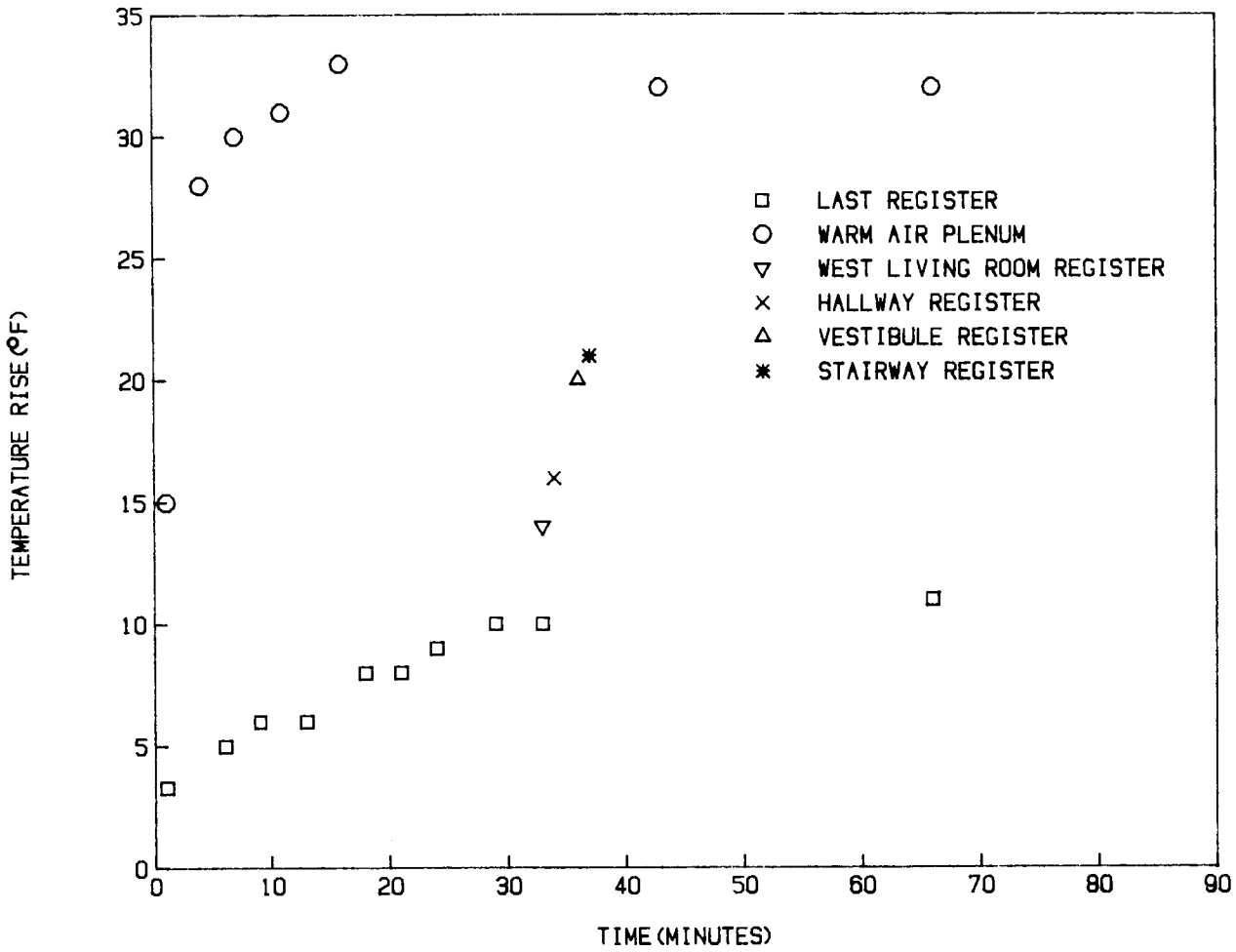

FIG. 3.6 Heat loss in below slab air distribution system.

3.1.5 Wood moisture measurements.

Wood moisture content was measured in most units with a Delmhorst hammer-probe type moisture detector. Whenever possible, a measurement was made in the attic at a location similar to the one shown in slide 105. Several attic locations were chosen where there was evidence of condensation or wet insulation. Several measurements were also made in basements, both in floor joists and rim joists. Most of the measurements were between 6 percent and 10 percent moisture. Two high readings were made in attics, and these were both made in wood that was in direct contact with wet cellulose insulation. Slides 4 and 7 show the approximate locations of these two readings. In both cases, the moisture content at a 3/8-inch depth was 21 percent. The wood was drier at a depth of 3/4-inch; 18 percent in one case and 15 percent in the other. Two measurements were made in rim joists at locations where the floor joists were cantilevered beyond the foundation. One of these locations is shown in slide 60. The two locations had moisture contents at a 3/8-inch depth of 15.5 percent and 13 percent. At a 3/4-inch depth the readings were slightly less.

3.1.6 Air tightness measurements.

Fan pressurization tests were performed to quantify air tightness on all 25 houses. Tables D-1, D-2 and D-3 give the results of these tests. The houses tested were both pressurized and depressurized, with and without intentional vents open, for a total of four tests on each house. Intentional vents include things such as furnace flues, combustion air supplies, dryer vents, air-to-air heat exchangers, and exhaust fans. The tests were performed according to standards for the Canadian R2000 program, and flows were measured for house pressures ranging from 15 to about 80 Pascals. Using these data, least squares fit Equation 3.1 was performed for each house. The resulting equation for each house was then used to calculate the various numbers reported in the Tables D-1 and D-2. The equation used for the least squares fit was:

$$Q=CxP^{n} \qquad (3.1)$$

where Q is the airflow into or out of the house in CFM, P is the pressure difference between the inside and outside of the house in Pascals, and C and n are fitting parameters.

In this study there were 11 detached houses with air-to-air heat exchangers and six houses without. The houses with heat exchangers averaged 4.07 AC/H at 50 Pa, with a standard deviation of 1.3 (depressurized, vents sealed). The houses without heat exchangers averaged 4.38 AC/H at 50 Pa, with a standard deviation of 1.5. The designers of the houses with heat exchangers were allowed to assume a natural infiltration rate of less than 0.5 AC/H by agreeing to do an additional checklist of infiltration reduction measures (Figure B-8). This process does not seem to have resulted in significantly tighter houses, and the additional items on the infiltration reduction checklist that were investigated during this research were mostly not done. Furthermore, even though the mandatory items on the infiltration reduction checklist were checked off on the Program Submission Forms, many were not completed. Builders may have done a

better job if they had known they would be required to pass a fan pressurization inspection.

3.1.7 Windows.

Very few problems were found with the air tightness of windows in these houses. Weatherstripping usually leaked a small amount in the corners, although a few windows leaked excessively due to damaged weatherstripping. Several windows fit so tightly that they had to be pushed shut from the outside to get them completely closed so that the latches would catch. Some small leaks between the window jambs or jamb extensions and the gypsum board wall material were also found.

The biggest problem observed with windows was condensation on the inside pane of glass. Slide 106 was taken in unit 124. This was a triple glazed window in the laundry room on the north side of the house. A roller type interior insulating shade is kept in place most of the time. Although the edge seals appeared good, the window was apparently tighter than the shade because condensation still formed on the window. In this house, the air-to-air heat exchanger was installed in such a manner that it tended to pressurize the house, contributing to the window condensation problem. If this house could be operated at a slightly negative pressure, this problem would possibly be solved.

Roller type sealed edge insulating shades were the most common window insulation found, and they were typically installed on double glazed south-facing windows. Triple glazed non-south facing windows usually were uninsulated. The shades appeared to be holding up very well and homeowners seemed quite satisfied with them. Many people reported ice forming on their windows when the shades were down, but on sunny days this would clear shortly after sunrise. All the south window sills in unit 124 were replaced due to damage from condensation, and the homeowner said that on very cold days the moisture did not ever disappear completely. She has learned, as have several others, to leave the shades down until a couple of hours after sunrise, which warms the windows and dries them faster. This, of course, would also reduce the solar gain.

Slide 107 was taken in unit 51. In this house, standard patio doors were used for south glazing, with very tight fitting insulated steel hinged doors used for night insulation. With the night insulation in place on a sunny day, it appeared that temperatures got hot enough to deform the plastic weatherstripping shown in the center of the slide. A greasy film was observed on the inside surface of this glass that may be due to high temperature outgassing of these weatherstripping materials. This greasy film was also observed in two other houses with very tight fitting interior insulating shutters on the south windows. Slide 108 shows the windows and insulating shades in unit 85. These large roll up insulating shades had no edge seals. The shades originally had four layers, but two layers were removed because there was too much weight for the roller mechanism. As is shown in this slide, the layers are stuck together, indicating that these shades are probably not performing the way they were designed.

One of the houses had sealed double glazed windows equipped with removable interior glazing panels fit into the window sash. Because

there was not a good enough seal between the sash and the removable glazing to prevent condensation on the double glazed window, mold was growing on the wood sash between the removable and fixed glazing layers.

Many of the houses had problems with fogging between panes of sealed edge multi-paned windows. This occurred in double glazed, triple glazed, south, and non-south windows. Several homeowners reported that nearly 50 percent of their windows had failed in this manner.

3.1.8 Solar water heaters.

Eleven of the 25 houses had solar domestic hot water heaters. Only one had thermometers installed so that the homeowner could see the temperature increase of the water as it flowed through the collector, and most homeowners did not know if their system was working properly or not. However, two homeowners did say they turn their backup water heaters off for the summer.

Slide 109 was taken in unit 27. For this installation the storage tank insulation was poorly done and is completely missing in some places as shown on this slide. Slide 110 was taken in unit 28. The large unsealed collector pipe penetration shown has created a large air leak in the wall between the garage and the house for this unit. Slide 111 was also taken in unit 28, and shows pipe insulation that has either shrunk or was not properly installed in the first place. Similar gaps were observed in the insulation installed over collector plumbing located on the roof of the house. Whether or not they had solar domestic hot water systems, most of the houses inspected had pipe insulation on the domestic hot water pipes inside the house.

3.1.9 Built vs. design comparison.

Whenever copies of the house plans or Submission Forms were available, the designs were compared with the actual construction that could be observed in accessible areas.

The R-values of building assemblies with parallel heat flow paths (such as walls where the R-value of the studs is less than the R-value of the cavity insulation) were calculated incorrectly on all of the Submission Forms that were inspected due to an incorrect example in the instructions supplied with the Submission Forms. These incorrectly calculated R-values were somewhat higher than the correctly calculated values, leading to an under prediction of the heat loss through these assemblies of up to 10 percent.

The actual south-facing glass area was measured, and was usually found to be less than that used in the solar calculations. In many cases, this was probably due to designers using rough opening sizes or nominal window sizes instead of glass area. For units 124 and 125 there was a very large difference; the Submission Form claimed 300 square feet for a measured area of 181 square feet. This could significantly affect the predicted performance of these units. These changes, however, may have been approved by Minnesota Housing Finance Agency and appeared on later plans.

In at least one unit, number 97, the R-values used for windows appeared to be much too high. It appears that the manufacturer's

specified U-value may have been used to calculate an R-value, and then the interior and exterior air film resistances were added to that. However, the manufacturer's specified U-value already properly accounts for air films.

The largest number of discrepancies between design and actual construction appear to be in the air tightening measures used in the houses. Designers checked nearly all the required measures on the Submission Form infiltration checklist. However, many of the measures, such as sealing penetrations in top plates, weatherstripping attic access hatches, and installing furnaces with vent dampers, were rarely completed.

3.2 INDOOR AIR QUALITY STUDY.

3.2.1 Selection of houses monitored.

Research houses were selected for indoor air quality monitoring based on the owner's response to the Indoor Air Quality Questionnaire shown in Figure B-3. This questionnaire was sent to homeowners along with the original letter describing the program. Homeowners were requested to complete and return the questionnaire if they wanted to participate in this part of the research. Questionnaires were returned for 49 of the 144 houses in the program, and of these, 42 homeowners said they would like their house to be included in this part of the study. Based on questionnaire responses, 12 houses were selected as a small sample of the types of houses that could be expected to have indoor air quality problems. Houses were selected if it appeared likely that any two of the three contaminants being examined (NO2, radon, or formaldehyde) would be present in the house. The houses selected and the basis for their selection appear in the memo to Bruce Nelson dated January 13, 1984 (see Figure A-4).

Control houses were selected by research house owners using instructions provided by the principal investigator. Research house owners were asked to complete the Indoor Air Quality House Survey shown in Figure B-4 for their own house. They were then asked to find a neighboring house built before 1978 that matched the characteristics of their own house as closely as possible. Neighboring houses were specified so that the effect of any local radon concentration in the soil could be examined, and pre-1978 houses were specified in an attempt to obtain control houses that would be less well sealed than the research houses. Even though most house owners were diligent about finding an appropriate control house, only about one-half of them were able to find control houses meeting a majority of these criteria. The remainder of the owners selected houses of friends or relatives as a last resort.

3.2.2 Air quality monitoring program.

The indoor air quality monitoring program was conducted entirely by mail through the use of simple passive monitors. Formaldehyde and NO2 were measured using diffusion tube monitors that were prepared and analyzed by Air Quality Research,Inc. and the Wisconsin State Laboratory of Hygiene, respectively. Radon concentrations were measured using Track Etch type SF detectors supplied and analyzed by

the Terradex Corporation.

Each home owner participating in the monitoring program was sent a complete kit for making the required measurements in his or her house. Two monitors of each type were sent to each homeowner along with instructions to place them in the areas of their houses where they spent most of their time, with the exception that one of the radon monitors was to be placed in the below grade area of the house. The diffusion monitors for formaldehyde and NO2 were open and kept in place for one week at each location. Because the end of the heating season was near, the monitoring period for the radon monitors was kept to a relatively short period of about six weeks. At the end of each monitoring period, postcards were sent to each home owner reminding them to return their detectors for analysis using pre-paid mailers provided for this purpose. Overall this process worked quite well, and in only a few cases were follow-up telephone calls necessary to have the exposed monitors returned.

During the first week of the monitoring period, each homeowner was asked to keep a daily activity log by completing the Daily Activity Form shown in Figure B-6. Beyond this form, the owners of the control houses were asked to complete the Housing Structure Survey form (Figure B-7) to identify the physical characteristics of their houses.

3.2.3 Results of indoor air quality measurements.

The results of the indoor air quality measurements are shown by the histograms in Figures 3.7 through 3.11. Each histogram represents a total of 48 measurements made in 12 experimental and 12 control houses. The relative errors for the formaldehyde and NO2 measurements are reported by the analysis laboratories to be plus or minus 15 percent and 10 percent respectively. The percent standard deviation for the radon measurements depends on the activity level measured. A few typical values are shown below.

Typical percent standard deviations for radon concentrations measured using Track Etch detectors.

Radon concentration(pCi/l)	Standard Deviation(%)
.29	101.5
.75	52.1
1.29	38.9
2.30	28.3
3.47	22.7
5.15	18.4

Since the relative precisions of all three monitor types are either smaller than or on the same order as their respective histogram cell size, the shape of the distributions shown in these histograms would change little if the precision of the measurements were improved. Because of this, these data represent an accurate picture of the indoor contaminants for the houses examined in this study.

The histogram for NO2 separating control and experimental houses, Figure 3.7, shows a generally lower concentration of NO2 in the

experimental houses. The reason for this is shown in the next histogram, Figure 3.8, separating houses equipped with gas versus electric kitchen ranges. The houses using gas cooking have higher concentrations of NO2, indicating that most of the higher concentrations are due to gas cooking and that most of the gas ranges are installed in the control houses. Conversely, in the first histogram, the experimental houses appear to have lower concentrations mainly because they have electric ranges for cooking. As can be seen from these data, all but three of the 48 measurements made fell within the national ambient air quality standard for NO2 of 100 ug/m^3.

The distribution of formaldehyde is more uniform between the experimental and control houses, as shown in Figure 3.9. The means and standard deviations for all the distributions shown are given in Table 3.2 below. The deviation of the mean is shown in parenthesis, and is calculated as the standard deviation divided by the square root of the number of observations.

Table 3.2.
Statistics for Indoor Air Quality Measurement Results

Measurement	Contaminant		
	NO2 (ug/m^3)	Formaldehyde (ppm)	Radon (pCi/l)
Experimental	14+/-18(4)	.058+/-.034(.007)	2.3+/-1.4(.3)
Control	41+/-38(8)	.042+/-.025(.005)	2.3+/-1.6(.3)
Above grade	-----	-----	2.0+/-1.2(.3)
Below grade	-----	-----	2.6+/-1.7(.4)

Although the standard deviations for the formaldehyde measurements overlap considerably, the deviations of the means show that the control houses might have a slightly lower formaldehyde concentration than the experimental houses which were built more recently. This could be an indication of an aging process taking place with the formaldehyde materials used in these houses. All but three of the 48 formaldehyde measurements made were within the .1 ppm guideline of the ASHRAE 62-1981 ventilation standard, and the three cases that did exceed this guideline were in houses that contained new formaldehyde bearing household goods.

Radon concentration is shown in Figures 3.10 and 3.11. As can be seen in Figure 3.10 and Table 3.2 the control and experimental houses have about the same distributions and mean values for radon concentration. Separating the radon data between above and below grade measurements shows that the below grade areas might have a somewhat greater radon concentration than the above grade areas. This would be expected, since soil gas is thought to be a primary source of radon in houses. However, as shown in Table 3.2, this difference does not appear to be statistically significant for this data set. As can

be seen from the histograms in Figures 3.10 and 3.11, six of the measurements made exceeded the 4 pCi/l level for which remedial action is recommended by the Environmental Protection Agency. These measurements represent excessive levels in five houses. Also, from these data, borderline concentrations of 2-4 pCi/l were found in a total of ten houses.

Each homeowner participating in this part of the research received a report on the measurement results for his or her house. This report (see Figure A-6) listed the recommended concentration limits discussed above and suggested that the homeowner take remedial action if the concentration for any contaminant in their house was shown to be excessive. Owners of houses with results that showed remedial action was recommended also received a postcard that they could return to the Energy Division to receive a personal telephone call discussing the results and suggesting possible remedial actions. Of the six homeowners receiving these cards, only one was returned requesting personal contact by an agency staff person.

3.3 RADON MITIGATION EXPERIMENT.

Based on the radon concentrations reported above, four houses, two experimental and two control, were selected to be retrofitted in an attempt to reduce their measured radon concentrations. Two strategies, subfloor ventilation and below grade sealing, were used to reduce the radon concentration in these houses. As with the other field work in this project, all participants received a project explanation and signed an agreement before any work was begun. After this retrofit work had been completed, the radon levels were remeasured using the same technique used for the first measurements.

3.3.1 Description of measures taken.

Subfloor ventilation was installed in two experimental houses equipped with foundation tile systems draining to a sump in the below grade area of the house. This was done by installing a ventilation system from the sump to the outside of the house using 4-inch diameter aluminum duct of the same type used for venting a clothes dryer. A positive flow of air from the sump to the outside was assured by using a continuously operating fractional horsepower fan that was placed entirely within the duct. The fan assembly included a 1/500 hp, 3000 rpm shaded pole Dayton brand motor equipped with a 2 1/2-inch diameter aluminum fan blade, costing a little over $5. Several larger prototypes were built, but they proved to be unacceptably noisy for continuous operation in a house. This work was guided by previous observations that a positive ventilation system was required to prevent back flow into the sump from the outside, but that only a small fan was required for successful ventilation.

Below grade sealing was carried out in the two control houses chosen. The sealing work was done by the homeowner working under instructions provided by the same field research contractor that had performed the inspections described in section 3.1. In order to obtain their participation, these homeowners were offered outright grants of $350 for materials and labor for sealing their below grade

areas according to instructions provided during the inspection visit by the field research contractor. After the homeowner reported that the work had been done, a second inspection was conducted to see if the prescribed work had been correctly completed. Most of the work consisted of caulking cracks in below grade walls and floors, and painting these areas with water sealing paint.

3.3.2 Results of mitigation measures.

The results of the above retrofit work are shown in Figures 3.12 and 3.13. In contrast to the first set of measurements, three, rather than two radon detectors were used in each house for the second evaluation. For these measurements, the homeowners were instructed to place two radon detectors side-by-side in the below grade area of their house in the same location used for the first measurement. The third detector was to be placed in the same location used for the above grade detector in the first measurement. The side-by-side detectors were used as a blind test of the precision of the Track Etch detector.

Figure 3.12 shows the results for the houses receiving subfloor ventilation. As can be seen, both houses show a significant reduction in radon concentration with all post ventilation values below 2 pCi/l. This reduction appears to be significant enough so that further mitigation work would not be recommended.

Figure 3.13 shows the results for the houses receiving below grade sealing. For house 74C, the radon concentration was not significantly changed from the previous measurement indicating that the sealing effort was not effective. House 78C shows about a 50 percent increase in radon concentration. Because it seems improbable that sealing would produce this increase, it is reasonable to expect that some other circumstances, such as a seasonal change in radon concentration, may have produced this result. A large crack remaining under the forced air furnace could also have produced this effect, but based on site inspections, this is not likely. Another visit to this house with equipment for making real time radon measurements is recommended as a first step in discovering why the radon concentration increased in this house.

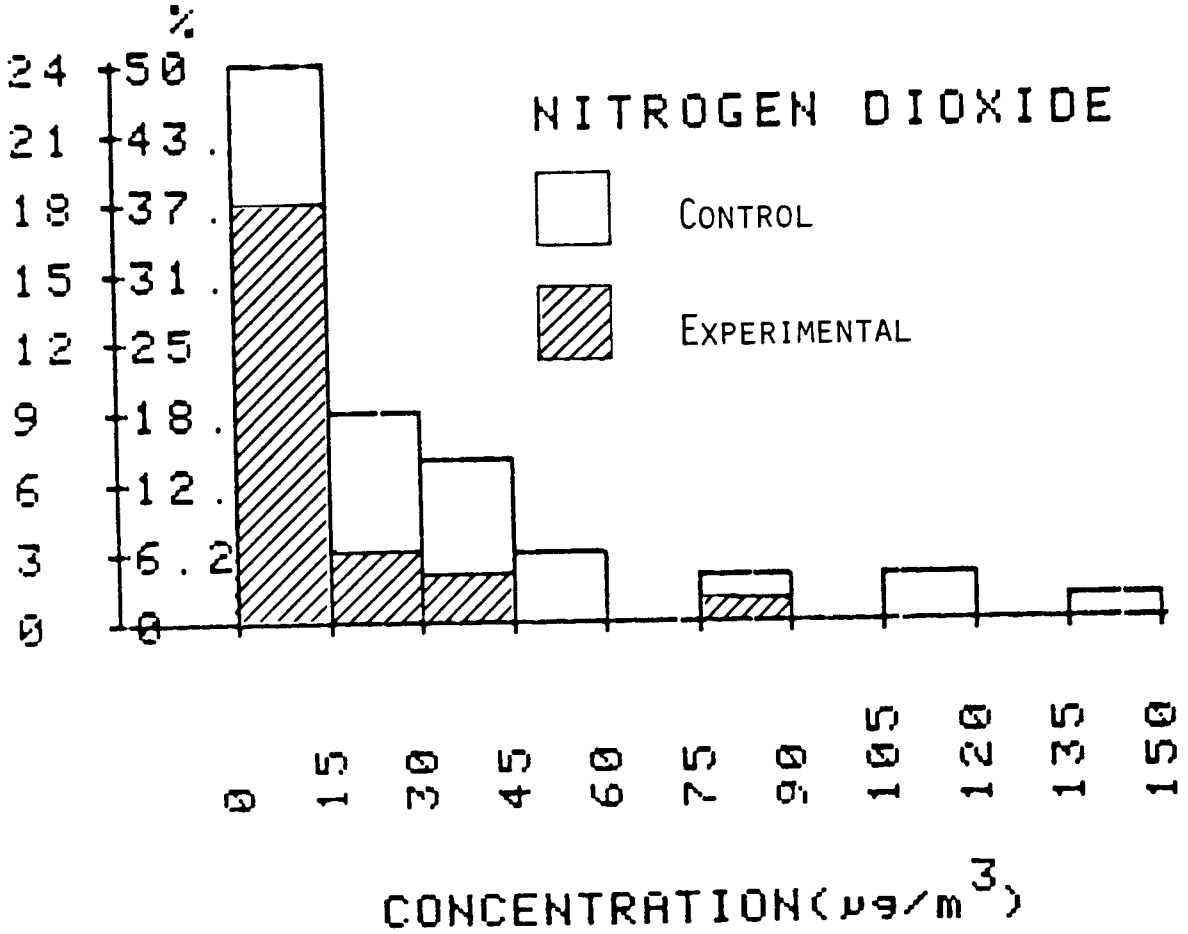

FIG. 3.7 Nitrogen dioxide concentration in 12 experimental and 12 control houses measured at two locations in each house.

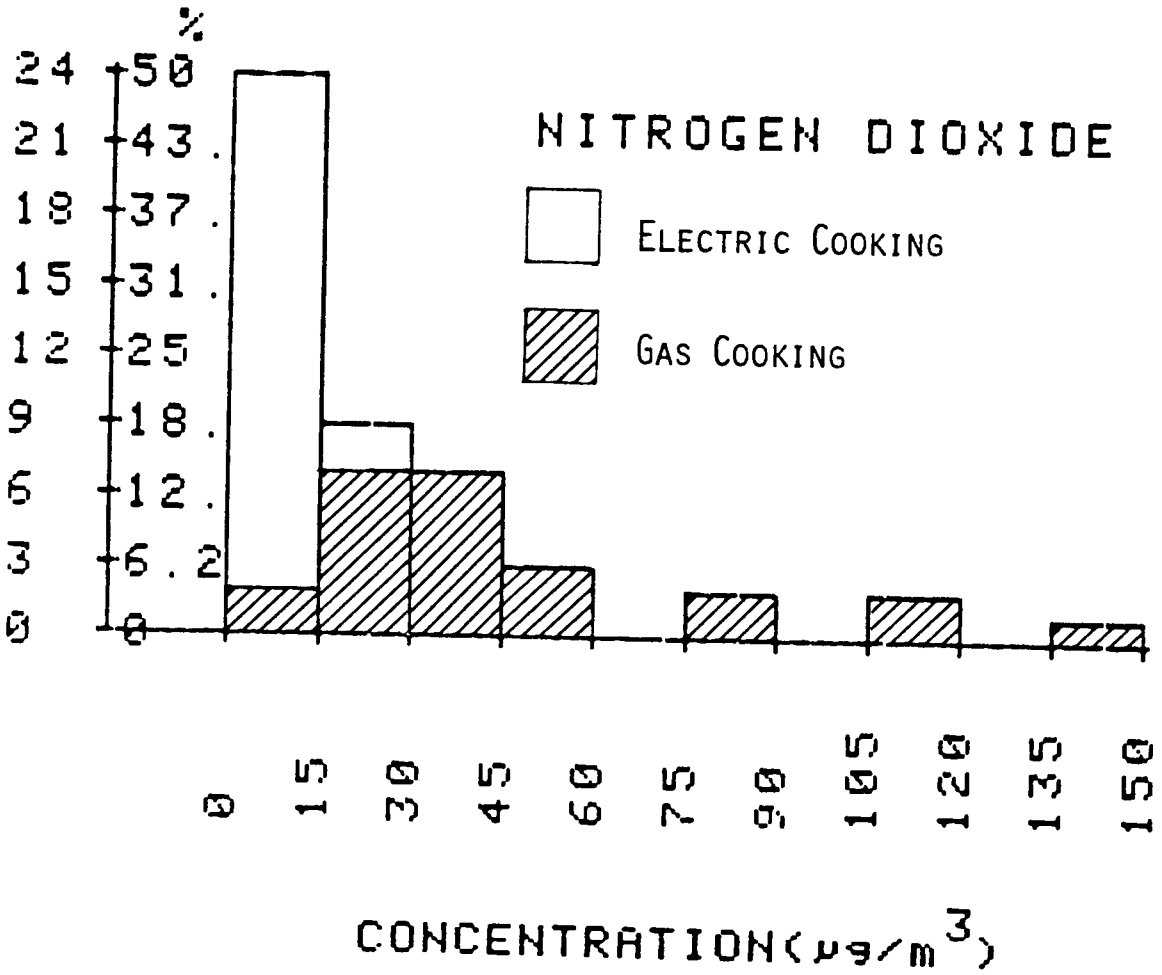

Fig. 3.8 Nitrogen dioxide concentration in 12 houses with and 12 houses without gas cooking. Nitrogen dioxide concentration was measured at two locations in each house.

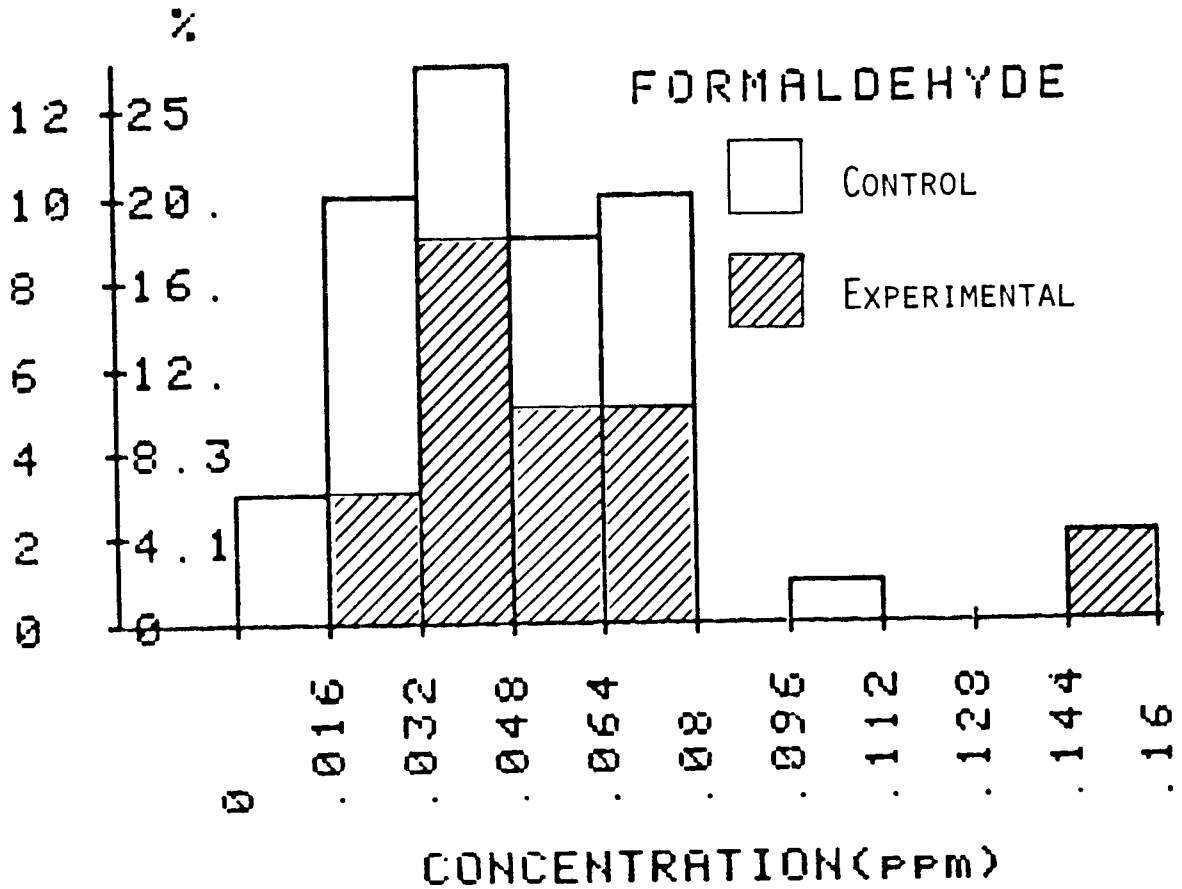

FIG. 3.9 Formaldehyde concentration in 12 experimental and 12 control houses measured at two locations in each house.

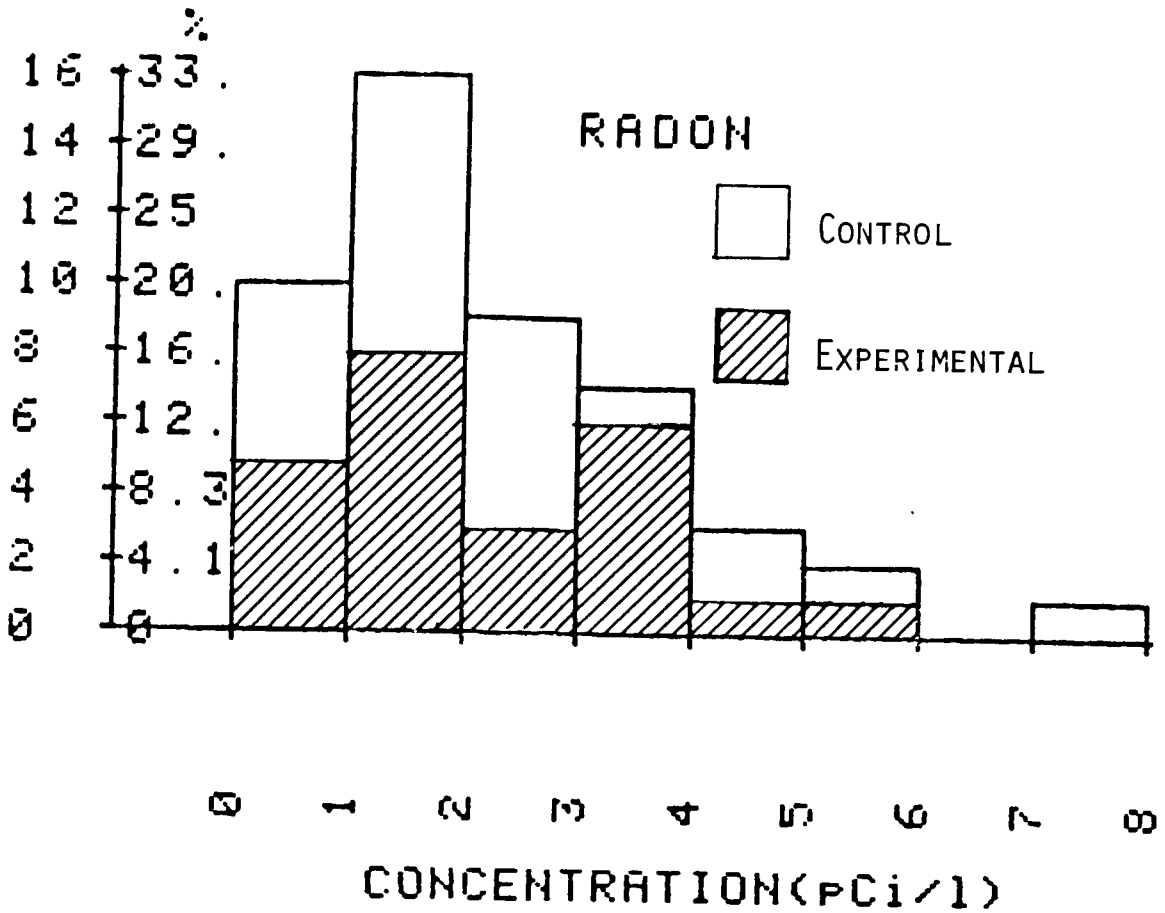

FIG. 3.10 Radon concentration in 12 experimental and 12 control houses. Radon concentration was measured at two locations in each house, one below grade, and one above grade.

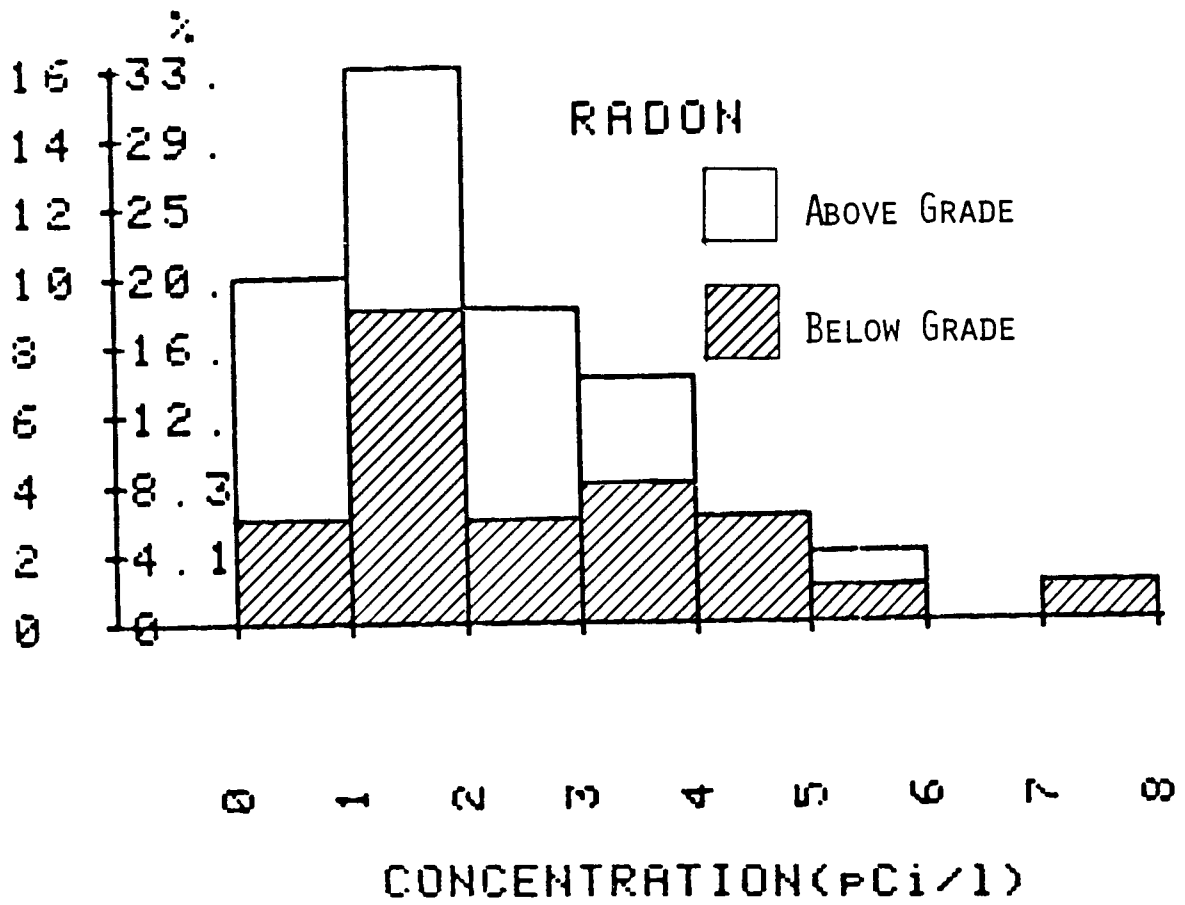

FIG. 3.11 Above grade and below grade radon concentration in 12 experimental and 12 control houses.

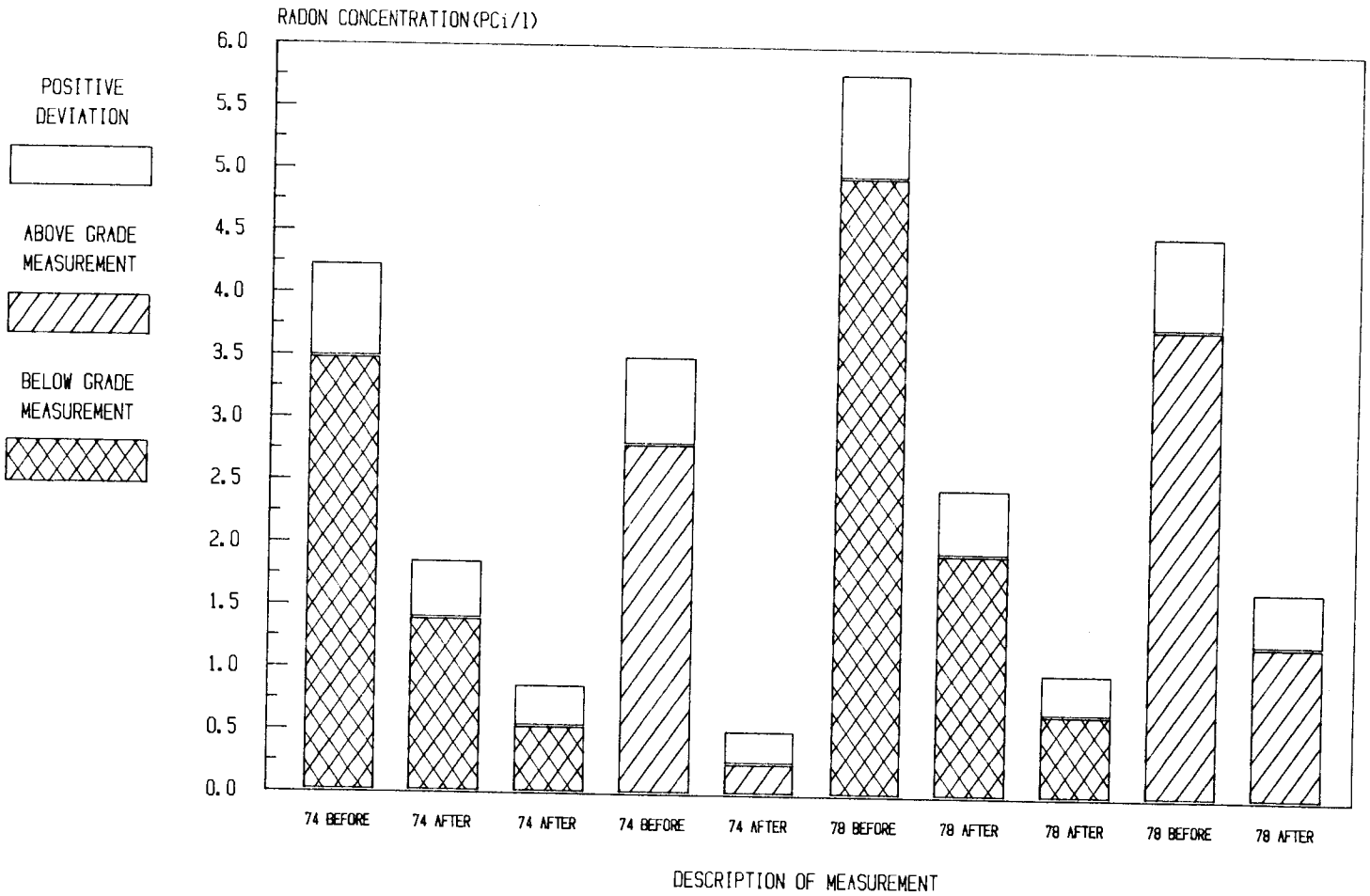

FIG. 3.12 Radon levels in units 74 and 78 before and after subfloor ventilation.

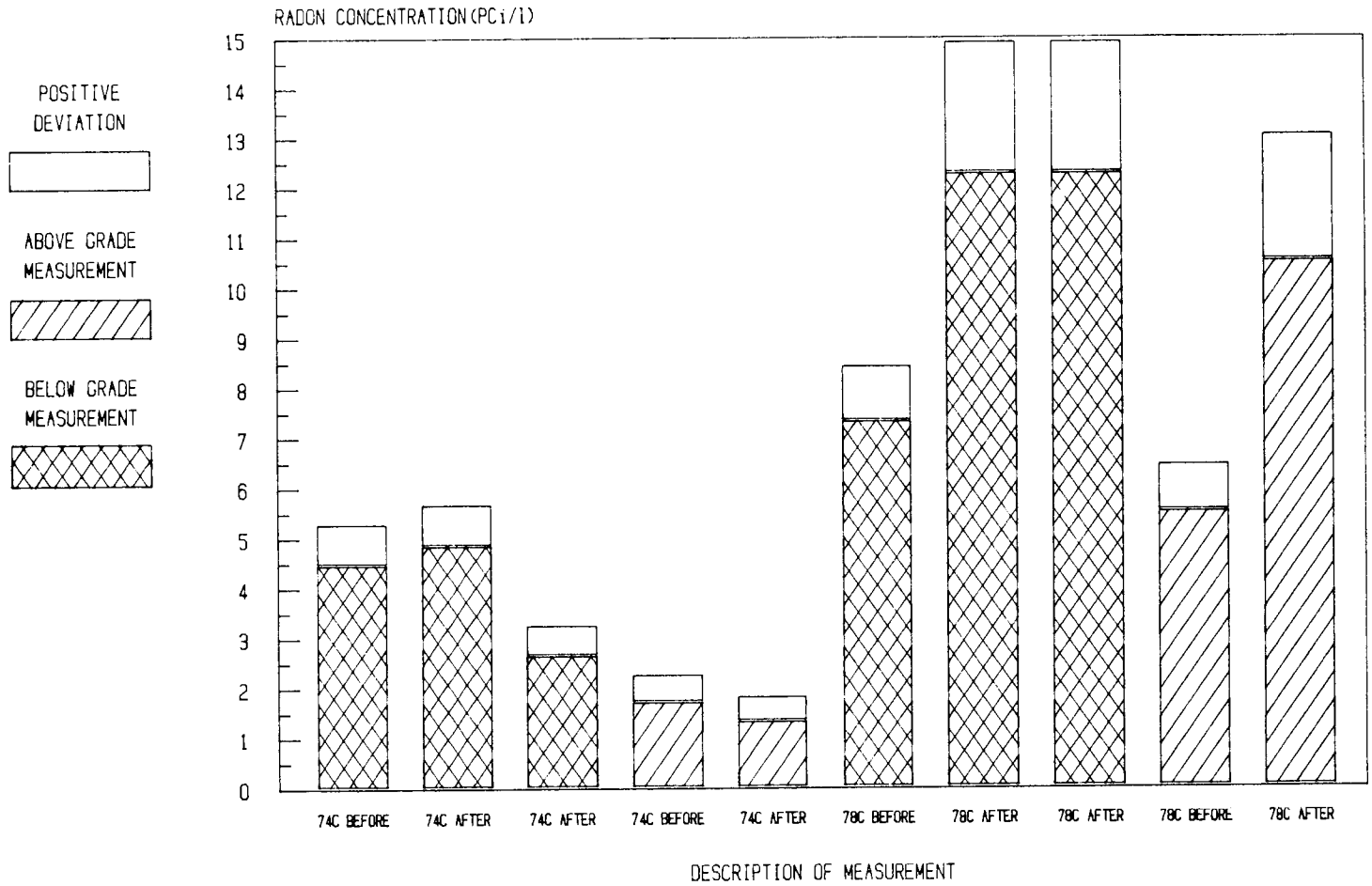

FIG. 3.13 Radon levels in units 74C and 78C before and after basement sealing.

4.0 ANALYSIS OF HOUSE PERFORMANCE

4.1 METERED ENERGY USE ANALYSIS.

As explained in Section 2.3.2, the energy consumption data file prepared for the Lawrence Berkeley Laboratory was used as the starting point for the analysis of all metered energy use. The principal goal of this analysis was to determine the total annual building envelope space heat load for the houses in the study. This load is defined to equal the annual sum of all metered energy thermalized within the house that is utilized for space heating. This load is exclusive of the solar energy collected by the house itself, but includes corrections for the gains and losses due to occupancy. Compared to three building performance models in use today, the Princeton Scorekeeping Method (PRISM) normalized annual consumption (7), the Lawrence Berkeley Laboratory BECA-A performance indicators (8), and the Iowa home heating requirement (9), the methodology used in this analysis is most closely related to the Iowa home heating requirement. Also included in this part of the study is an examination of the energy used for heating domestic hot water.

4.1.1 Analysis of house energy requirement.

4.1.1.1 Development of model for the total thermal energy requirement.

The analytical method developed for the evaluation of the houses in this research project was designed to yield indices that would be performance measures of the building envelope. This was done by analyzing the total thermal load of a house based on the total of all metered energy thermalized within the house envelope. Houses using unmetered sources of external energy such as wood or kerosene were eliminated from the study. So that the precise energy would be known for each reading period, simultaneous meter readings were obtained for as many houses as possible using the methodology described in Section 2.2.

The model used to analyze these data is shown in Figure 4.1 and consists of a single load line described by a slope β and an x-axis intercept of T'. The intercept temperature, T', is physically interpreted as the ambient temperature below which the house requires heat from some source of energy. The house heating system usually does not come on at this temperature, since enough thermal energy is usually provided by internal gains or by solar gains to furnish the heat required. As the ambient temperature falls, the amount of thermal energy required to keep the interior of the house at a comfortable temperature increases as shown by the upward slope of the load line with decreasing temperature. While this load line is all that needs to be known about an individual house, if houses are to be compared, more information about the use of the house needs to be included.

The most direct and important user effect on household energy consumption is the setpoint of the thermostat, shown by Tset in Figure 4.1. The temperature Tset is the interior temperature (not ambient temperature) at which the household heating system turns

on to supply space heat. For most houses, the internal sources of energy plus solar gains provide enough heat so that the ambient temperature can fall below the thermostat setpoint temperature before the furnace is required to provide additional heat. The ambient temperature at which these gains just match the building thermal load, and below which heat from the furnace is required is called the reference temperature shown by Tref in Figure 4.1. In summary, Tset is an interior setpoint temperature selected by the homeowner, Tref is an ambient temperature that depends on the building envelope, the internal and solar gains, and the setpoint temperature, and T' is an ambient temperature that depends on the building envelope, solar gains, and the setpoint temperature.

The two data fitting parameters, β and T', may be linearly transformed into other pairs of numbers that may be used to describe the performance of a house. For this study the thermal load of the house envelope as modeled in Figure 4.1 was divided into two portions, one dependent on ambient temperature, and the other independent of ambient temperature. This was done starting with the concept that space comfort is the driving mechanism for household thermal use. Based on this, the model calculation proceeds with the assertion that the ambient temperature (not interior temperature) at which thermal energy is required from somewhere for space comfort is equal to Tset.

In order to continue our model development, it needs to be noted that an apparent inconsistency has just been introduced in that Tset has just received nearly the same definition as that given to T'. The difference is that T' is defined as the ambient temperature that marks the onset of envelope thermal load, while Tset is defined as the ambient temperature that marks the onset of the comfort thermal load. This inconsistency arises from the assumption that space comfort is uniform during the heating season. As will be seen from data to be presented later, the temperature T' is commonly greater than Tset. This has the physical interpretation that for these houses, thermal energy is required for space heat at ambient temperatures above the thermostat set point. Thus, T' can be interpreted as the ambient temperature required to maintain the inside temperature at Tset in the absence of any metered thermal inputs. In this case, the house is unventilated and heated by conduction through the exterior envelope, a situation unlikely to be found in practice, since in this situation most people would simply open a window and ventilate their houses.

It is proposed by the principal investigator that for temperatures between Tset and T', thermal input is required due to losses to the cooler, below grade portions of the building. This requirement for space heat above the thermostat setpoint could explain in part the anecdotal observations that houses seem cold in the fall and spring. This effect was dubbed "The mental-thermal lag effect" at the 1984 ACEEE, Santa Cruz meeting where it was a lively source of spontaneous speculation.

The above temperature ranges for ventilation apply if internal and solar gains are small. For larger internal and solar gains,

the ambient temperature for which ventilation is required for cooling may be less than either Tset or T', but greater than Tref. While T' may be either greater or less than Tset, we will continue our model development using the case for which T' is greater than Tset, as shown in Figure 4.1

The inconsistency between the definitions of Tset and T' can be removed by assuming that the house is ventilated for ambient temperatures above Tset and heated by some source for ambient temperatures below Tset. This assumption that some source of heat is required below Tset allows us to separate the thermal load of the house into the two parts desired. The temperature dependent part is just equal to the number of degree days below the setpoint temperature times the slope β. The temperature independent part is equal to the part of the load that is left over, namely the value ε as shown in Figure 4.1 times the number of days for which the ambient temperature is below Tset. The total thermal load of the building is then taken as the sum of these two values. Because this thermal load may be normalized to any setpoint temperature using long term average weather data, it will be called the Normalized Thermal Load (NTL) for the purposes of this study. Analytically, for a normalized setpoint temperature of 68°F the NTL may be written as follows:

$$\text{Normalized Thermal Load} = H_0\ (68°F)\beta + D_0\ (68°F)\varepsilon \qquad (4.1)$$

where H_0 (68°F) is the long term average number of degree days for a base temperature of 68°F, and D_0 (68°F) is the number of days for which the average temperature is below 68°F. The 68°F temperature that appears in Eq. 4.1 is used to normalize houses to the same set point temperature so that the space heat energy consumption may be compared across houses.

The two terms in Equation 4.1 have the following physical interpretation. The first term is the thermal load due to all ambient temperature dependent losses from the envelope of the house, and is equal to the sum of the conductive envelope losses and losses due to air infiltration. The second term in Equation 4.1 is equal to the sum of the ambient temperature independent losses, and gains within the envelope. This ambient temperature independent load is physically equal to the below grade and gray water losses minus the solar and metabolic gains within the house envelope. Because the energy use being modeled consists of the sum of all metered energy thermalized within the house envelope, internal gains do not appear explicitly in this analysis, and thermal gains provided by either a furnace or by internal sources are considered to be indistinguishable. Corrections for the occupancy related gray water losses and metabolic gains are described in Section 4.2.2.

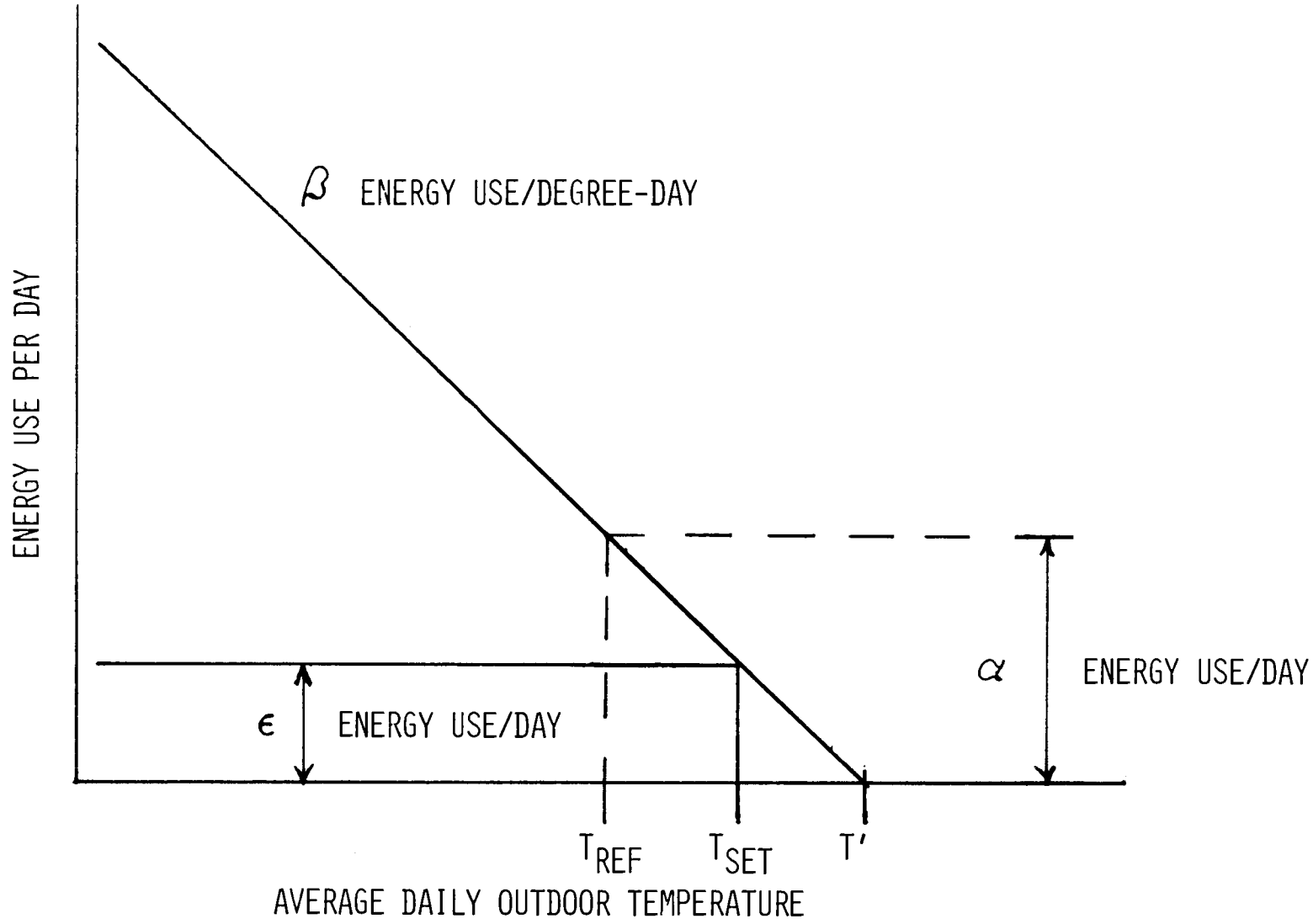

FIG. 4.1. Heating only model used to calculate the normalized thermal load(NTL) from PRISM output parameters. The total energy use per day consists of all metered energy thermalized within the building envelope.

4.1.1.2 Application of PRISM program to the calculation of normalized thermal load.

The original proposal for this project outlined the analysis just presented and stated that a least squares technique would be used to find the relevant parameters. At that time, the principal investigator assumed a special computer program would be written to address this task. However, during the period of the research project, the Princeton Scorekeeping Method (PRISM) program became available and appeared to be well suited for the required analysis. Because this program was well documented and also available to other researchers, if additional analysis on the data base were desired, the decision was made to use the PRISM program to find the parameters required for the model given in Equation 4.1.

The PRISM program directly yields the α, β, and Tref parameters shown in Figure 4.1. As discussed before, Tref is the temperature below which the house requires space heat from the furnace. The α parameter is physically interpreted as a measure of the average metered energy for those months during which heat is not required from the furnace. Because α largely depends on summer consumption that could include non-winter uses such as air conditioning, it is not a good measure of the internal gain energy available for heating during the winter. Furthermore, because of the dependence of Tref on α, Tref may also be a poor estimate for the true reference temperature. Nevertheless, α and Tref are useful intermediate parameters for this analysis, since together with β, they complete the point-slope specification required for the determination of the performance load line shown in Figure 4.1.

The PRISM analysis directly provides the beta parameter required for the calculation of the first term in Equation 4.1. The second term in Equation 4.1 requires a value for ε that may be found by geometry from Figure 4.1. By inspection of Figure 4.1, and from the definition of the slope β, T' and ε may be written as follows:

$$\varepsilon = \beta\,(T' - T_{set}) \tag{4.2}$$

$$T' = T_{ref} + \alpha/\beta \tag{4.3}$$

The use of ε as given by Eq. 4.2 to calculate the normalized thermal load is based on the approximation that ε is independent of the normalization temperature used in Eq. 4.1.

The normalized thermal load was then calculated by applying Equations 4.1-4.3 to the PRISM parameters for each house. The reliability of this normalization procedure is demonstrated in Appendix F.

4.1.1.3 Calculation of the normalized thermal load.

Based on the definition of the normalized thermal load, the input energy consumptions required for the desired analysis need to be set equal to the sum of all metered input energy thermalized within the building envelope. This was done by assuming that 100 percent of the electric and 70 percent of the gas consumptions were

thermalized within each house. Within these assumptions are other assumptions or approximations that merit further study. For example, if a house has extensive outdoor lighting or the homeowner uses an electric heater to preheat an automobile engine, the electric consumption thermalized within the house itself would be less than 100 percent. The gas conversion factor of 70 percent depends not only on the annual efficiency of the furnace, but also on the ventilation of other gas combustion devices such as clothes dryers and kitchen ranges. Beyond this, if the analysis is to reflect only building envelope performance, the four terms of the ambient temperature independent load also need to be addressed. The below grade losses and solar gains are by definition a part of the envelope performance model, and are thus automatically included in the analysis where they are quantified by the temperature independent building load. However, the gray water losses and metabolic gains are user dependent and need to be dealt with as a part of the input data if the analysis is to represent envelope performance only. These numbers are difficult to estimate, and for the purposes of this discussion they are assumed to cancel exactly, since they are similar in magnitude, as well as correlated, because increased occupancy levels increase both hot water consumption and metabolic gain (10). This assumption is examined in detail in Section 4.2.2 of this report.

The dBASEII program, NACFILE, shown on the flow chart in Figure 2.2 was used to prepare the input files required for the PRISM program using the above assumptions and data from the LBL analysis files. For houses where simultaneous gas and electric metered data were available (65 houses), the input energy consumptions were converted to a common thermal equivalent (therms or 10^5 BTU) and then added as described above. Data from all electric houses (12 houses) and houses with gas consumption data only (42 houses) were also converted to a common thermal equivalent using the above efficiency factors. One PRISM input file was created for each group of houses built by a single contractor, and the PRISM short summary output for each of these house groups is shown in Appendix E. The use of weekly or monthly data for these calculations is readily determined by observing the number of readings listed. Houses showing about 50 readings were read weekly, while those showing about 12 readings were read monthly. For groups of houses that were submetered and read by paid readers, each house in the group shows a weekly reading rate. Other separate weekly reading rates were provided by the volunteer meter readers in the program.

The quality of fit provided by the PRISM program to the metered data is given by the standard error of the normalized annual consumption (NAC) that is shown in the last column of the PRISM output. For the 127 PRISM runs shown in Appendix E, the majority, 97 (76 percent of the total), have a standard error for the NAC less than 5 percent, with only four having standard errors greater than 10 percent. The standard errors calculated for the normalized thermal loads (NTL) of the 119 houses listed in Appendix F are not quite as good, with the majority, 67 (56 percent of the total), having a standard error of 5 to 10 percent. Of the remaining houses, 27 (23 percent of the total) have a standard error of less than 5 percent,

and 25 (21 percent of the total) have a standard error of greater than 10 percent. In general, for any given house, the percent standard error of the NTL appears to be at least twice as large as the percent standard error of the NAC, but less than the percent standard error of the slope, β. Because the NAC is larger than the NTL, the absolute errors of the NTL are actually better than this, and range from one and one-half to two times greater than the absolute errors of the NAC.

Again, it should be carefully noted that the PRISM program application used in this work differs from that developed by the program authors, and that the analysis presented here needs to be evaluated on its own merits (see Appendix F).

The results of the analysis of applying Equations 4.1-4.3 to the PRISM output parameters are shown in Tables 4.1 and 4.2. Table 4.1 shows results for houses that are either all electric, or for which simultaneous gas and electric readings were available. For Table 4.2, gas readings only were available for most of the houses shown, and in these cases the average daily electric consumption for the period January to March 1984 was added to the PRISM baseload result for each house before T' and ε were calculated. For those cases where simultaneous readings were available from volunteer meter reading data, the average electric energy value is described by the notation "IN BASE."

Tables 4.1 and 4.2 present many rich results that require research beyond the scope of the present work. Units 1-8 by builder A as listed in Table 4.1 are an interesting example. The temperature independent load varies over a large range for these houses (-16 to 232 ccf/yr), yet the total normalized thermal load is well behaved and clearly shows the end, middle, middle, end locations of units 1-4 and 5-8 in these two quadplexes. It would be interesting to return to these houses to see why their energy consumption signatures are so varied.

The houses by builder M in Table 4.1 had the largest solar apertures of all the houses in the research study. From survey data, all the homeowners in this development used night insulation except the owner of unit 84. Does the large negative temperature independent energy balanced by a large temperature dependent energy indicate the presence of an uncontrolled thermal flux due to solar energy input during the day and large aperture losses at night? Finally, an example related to the effect of below grade losses is shown in the results for houses by builder G. These houses were split entry houses with lower level areas below grade. Table 4.1 shows that the houses with the three smallest temperature independent loads are also the three houses with the lowest measured lower level temperatures. While these are selected cases and the noise level is high, it appears that the normalized thermal load and its temperature independent and temperature dependent subcomponents may reveal information about energy use in houses that is not available using other techniques.

TABLE 4.1 PRISM program results and normalized thermal load (NTL) values for houses with simultaneous gas and electric meter readings. Standard errors of the NTL are calculated in Appendix F.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	SETUP TEMP (F)	SETBACK TEMP (F)	SETPOINT TEMP (F)	BASEMENT TEMP (F)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)
BUILDER A											
1	58.01	.794	.0413			70		77.24	86	367	453
2	41.46	1.006	.0346			67		70.54	35	308	343
3	47.12	.548	.0338			65		63.33	-16	300	284
4	52.01	1.103	.0365			68		82.23	149	324	473
5	57.68	.638	.0423			66		72.76	82	376	458
6	42.61	.909	.0349			68		68.66	7	310	317
7	61.07	.767	.0266			72		89.90	137	236	373
8	70.01	.809	.0292			70		97.72	232	260	492
BUILDER D											
26	54.01	1.157	.0436			70	64	80.55	132	388	519
27	55.97	.746	.0546			65	60	69.63	73	485	558
28	60.2	1.411	.0596			74	70	83.87	169	530	699
BUILDER G											
41	60.71	.689	.0366			65	65	79.54	153	325	478
42	63.2	.746	.0391			70	62	82.28	138	348	485
43	54.38	1.152	.0573			70	64	74.48	74	509	583
44	58.38	.421	.0426			68	60	68.26	3	379	382
45	61.01	.582	.0407			70	60	75.31	62	362	424
46	58.2	.699	.0466			68	60	73.20	70	414	484
47	59.01	.981	.036			69		86.26	178	320	498
48	57.97	1.346	.0483			75	68	85.84	150	429	580

TABLE 4.1 Continued.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	SETUP TEMP (F)	SETBACK TEMP (F)	SETPOINT TEMP (F)	BASEMENT TEMP (F)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)
BUILDER M											
84	51.06	1.035	.0864	70	67	70.27		63.04	-179	768	589
82	47.57	.359	.04	60	50	59.15		56.55	-30	356	326
83	55.8	.864	.0516	70	65	69.35		72.54	47	459	506
85	60.74	.459	.0534	70	66	69.81		69.34	-7	475	467
BUILDER N											
94	45.29	1.332	.05			67	60	71.93	71	444	515
95	48.89	.871	.0461			67	60	67.78	10	410	420
96	59.01	1.082	.0347			68	55	90.19	221	308	529
97	54.22	1.197	.0418			68	57	82.86	178	372	550
BUILDER P											
110	52.95	.512	.0484	68	68	70.07		63.53	-91	430	339
111	61.29	.645	.0309	68	61	66.85		82.16	136	275	410
112	49.04	.912	.032	70	59	66.59		77.54	101	284	385
113	40.01	1.513	.0486			67.78		71.14	47	432	479
114	43.91	1.028	.0708	70	70	71.65		58.43	-269	629	361
115	48.63	.988	.0404	70	68	70.73		73.09	27	359	386
117	44.01	1.258	.0553	70	63	68.43		66.76	-27	492	465
119	64.95	.069	.0619			67.78		66.06	-30	550	520
108	49.87	1.176	.0569	69	64	68.56		70.54	32	506	538
109	49.8	1.032	.0435	70	60	67.05		73.52	81	387	467
116	57.01	.546	.0285	68	58	65.47		76.17	88	253	341
BUILDER Q											
120	56.67	1.028	.036			68	66	85.23	178	320	498
121	69.53	.912	.0306			70	68	99.33	258	272	530

TABLE 4.1 Continued.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	SETUP TEMP (F)	SETBACK TEMP (F)	SETPOINT TEMP (F)	BASEMENT TEMP (F)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)
122	64.01	.794	.0325			72	68	88.44	153	289	442
123	64.48	.588	.0341			68	65	81.72	134	303	437
124	62.16	.625	.0217			65	62	90.96	162	193	355
125	62.97	1.504	.0299			70	70	113.27	371	266	637
126	41.01	.952	.0374			63	60	66.46	37	332	370
127	63.01	1.264	.0221			65	60	120.20	350	196	547
BUILDER R											
128	53.12	.424	.0588			66		60.33	-96	523	427
129	42.6	.835	.0582			62		56.95	-84	517	433
130	49.15	.673	.0234			68		77.91	67	208	275
131	58.01	.99	.037			70		84.77	157	329	486
BUILDER S											
132	58.36	.603	.0074			52		139.85	187	66	252
133	63.1	.296	.0381			67		70.87	42	339	381
134	64.57	.608	.0363			67		81.32	149	323	472
135	68.01	.681	.0248			70		95.47	181	220	402
136	65.27	.404	.0323			70		77.78	72	287	359
137	68.01	.499	.0246			67		88.29	150	219	369
138	60.09	.311	.0361			68		68.70	7	321	328
139	62.53	.444	.0327			65		76.11	104	291	395
140	43.16	.894	.0497			67		61.15	-83	442	358
141	55.51	.512	.037			65		69.35	46	329	375
142	55.39	.559	.0386			72		69.87	-24	343	320
143	55.85	.358	.0334			66		66.57	5	297	302

TABLE 4.1 Continued.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	SETUP TEMP (F)	SETBACK TEMP (F)	SETPOINT TEMP (F)	BASEMENT TEMP (F)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)
BUILDER V											
160	57.2	.924	.077	65	61	65.86		69.20	74	684	758
158	58.19	.544	.046	67	60	66.06		70.02	52	409	461
159	65.49	.363	.0436	64	62	65.99		73.82	98	388	485
BUILDER W											
162	56	.614	.0329	65	60	65.4		74.66	87	292	380
163	82	.365	.0259	72	72	73.23		96.09	170	230	400
165	73	.686	.0307	70	68	70.73		95.35	217	273	490
164	59.17	.307	.0448	65	63	66.78		66.02	-10	398	388

AVERAGE FOR ALL HOUSES ABOVE 67.78

TABLE 4.2 PRISM program results and normalized thermal load (NTL) consumption values for houses with separate gas and electric meter reading dates. Cases labeled "IN BASE" are for simultaneous meter readings provided by volunteer meter readers. Standard errors of the NTL are calculated in Appendix F.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	SETUP TEMP (F)	SETBACK TEMP (F)	SETPOINT TEMP (F)	AVERAGE ELECTRIC ENERGY (CCF/DAY)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)
BUILDER B											
9	60.28	.166	.044			68.73	.46	74.51	73	391	464
10	58.06	.185	.0448	68	64	68.23	.39	70.89	34	398	432
11	51.39	.647	.0421	70	65	69.35	.77	85.05	190	374	564
12	61.21	.334	.0451	68	64	68.23	.67	83.47	197	401	598
13	61	.298	.04	68	64	68.23	.6	83.45	175	356	530
14	55.38	.317	.0375	68	62	67.31	.44	75.57	89	333	422
16	61.49	.352	.0374	68	68	70.07	.42	82.13	129	332	462
15	55.9	.616	.0441	67	65	68.36	IN BASE	69.87	19	392	411
BUILDER C											
17	57.32	.574	.0512			68.73	.57	79.66	161	455	616
19	54.34	.272	.0432	70	68	70.73	.58	74.06	41	384	425
20	60.14	.457	.0458	71	71	72.44	.41	79.07	87	407	494
21	55.93	.344	.0559	70	60	67.05	.42	69.60	41	497	538
24	59.6	.56	.0588	70	70	71.65	.6	79.33	130	523	652
BUILDER E											
29	56.14	.006	.036	68	60	66.39	.72	76.31	102	320	422
30	55.34	.034	.0439	68	64	68.23	.68	71.60	43	390	433
32	51	1.498	.0466	70	70	71.65	IN BASE	83.15	154	414	568

TABLE 4.2 Continued.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	SETUP TEMP (F)	SETBACK TEMP (F)	SETPOINT TEMP (F)	AVERAGE ELECTRIC ENERGY (CCF/DAY)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)
BUILDER H											
49	37.43	.041	.0446	66	62	66.65	1.19	65.03	-21	396	376
50	54.1	.023	.0504			68.73	1.09	76.18	108	448	556
52	55.12	.027	.0489	68	60	66.39	.71	70.19	53	435	488
51	44	.805	.0614	70	65	69.35	IN BASE	57.11	-216	546	330
BUILDER I											
53	55.43	.516	.05	64	64	66.91	.41	73.95	101	444	545
54	59.14	.526	.0446	70	63	68.43	.81	89.10	265	396	661
55	55	.332	.0467	60	54	60.99	.35	69.60	115	415	531
57	57.93	.512	.0572			68.73	.32	72.48	61	508	570
58	54.9	.487	.0616	68	64	68.23	.44	69.95	30	548	578
59	54.77	.519	.0568			68.73	.46	72.01	53	505	558
60	62.64	.293	.0559			68.73	.55	77.72	144	497	641
61	55.94	.492	.051	70	70	71.65	.29	71.27	-6	453	448
62	66.25	.247	.0452			68.73	.25	77.25	110	402	512
63	68.48	.136	.0455			68.73	.4	80.26	151	404	555
BUILDER J											
65	55	.035	.0531	68	68	70.07	1.09	76.19	93	472	565
66	49.45	.117	.0644			68.73	.75	62.91	-108	572	465
68	62	.01	.0487	67	64	67.9	.26	67.54	-5	433	428
70	54.65	.043	.0514	70	70	71.65	.84	71.83	3	457	459
71	63	.038	.0707	72	72	73.23	.57	71.60	-33	628	595
72	58.55	.124	.0416	72	68	71.39	.54	74.51	37	370	407
67	63	.251	.0569	70	64	68.89	IN BASE	67.41	-24	506	482
69	59.58	.88	.0531	70	66	69.81	IN BASE	76.15	97	472	569

TABLE 4.2 Continued.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	SETUP TEMP (F)	SETBACK TEMP (F)	SETPOINT TEMP (F)	AVERAGE ELECTRIC ENERGY (CCF/DAY)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)
BUILDER K											
75	56.22	.444	.0487	66	66	68.49	.27	70.88	33	433	466
73	63.8	.584	.0524	70	68	70.73	IN BASE	74.95	63	466	529
74	60.09	1.003	.0464	65	63	66.78	IN BASE	81.71	199	412	611
BUILDER T											
148	70.05	.233	.0397			68.73	.22	81.46	145	353	498
150	62.71	.273	.0456	70	60	67.05	.43	78.13	145	405	550
151	65.31	.404	.0454			68.73	.53	85.88	223	404	627
BUILDER U											
152	55.84	.027	.0519	68	68	70.07	.74	70.62	8	461	469
153	53.48	.007	.049			68.73	.68	67.50	-17	436	418
154	49.43	.113	.0421	62	60	64.41	.76	70.17	70	374	444
156	57.05	.042	.046	68	68	70.07	.95	78.62	113	409	522
157	56.45	.093	.0451	68	67	69.61	.74	74.92	69	401	470
155	48.66	.497	.0416	64	60	65.07	IN BASE	60.61	-53	370	316
			AVERAGE FOR ALL HOUSES ABOVE			68.73					

4.1.1.4 Setpoint temperature correlation.

The setpoint temperature required for the calculation of ε in Equation 4.2 was statistically estimated for each non-submetered house using self-reported survey data. The survey, to be discussed in detail later, asked the homeowner to report his or her setup and setback thermostat settings. In order to obtain a single average setpoint temperature from these data, a temperature correlation function was statistically derived based on the measured and self-reported temperature data obtained from the group of submetered houses. The correlation developed is based on data from 24 of the 47 submetered houses, with 23 houses removed because of very irregular measured temperature patterns or missing survey data. Most of the houses removed were those designs that included a large solar contribution to the daily energy flow within the structure. Using these data, the following correlation (r squared = .78) was found by multiple regression:

$$\text{Average setpoint temperature}(^{o}F) = 16.35 + .33\ T_{setup} + .46\ T_{setback} \qquad (4.4)$$

where T_{setup} and $T_{setback}$ are self-reported temperatures for each house, and the average setpoint temperature is an approximation of the average temperature in the house.

The results of this correlation are shown in Tables 4.1 and 4.2. Here it can be seen that Equation 4.4 predicts setpoint temperatures that are about $2^{o}F$ higher than the self-reported values for those cases where the setup and setback temperatures are the same. This agrees with other observations that self-reported temperatures have a tendency to be a few degrees Fahrenheit lower than actual thermostat settings.

4.1.2 Domestic hot water analysis.

Two types of analysis were done to examine the use of domestic hot water in the group of submetered houses. The first was an analysis of average energy consumption based on average submeter readings, and the second was an analysis of the average number of gallons of hot water consumed based on the seasonality of the energy required to provide domestic hot water.

The average energy required to supply domestic hot water for the three types of systems examined in this study is shown in Table 4.3 below.

TABLE 4.3

Average energy per week per person for providing domestic hot water using three types of water heating systems. The deviation of the mean is equal to the standard deviation of the average energy consumption divided by the square root of the number of observations.

Type of water heater	Therms/week-person	Deviation of mean
Electric	1.07 +/- .33	.12
Solar/electric	.87 +/- .22	.07
Gas	2.64 +/- .62	.23

If it is assumed that the electric water heaters are 100 percent efficient, and that the usage patterns for each group of each type of water heater belong to the same normal distribution, then the relative efficiencies of the solar/electric and gas water heaters may be calculated. Using the results in Table 4.3 the average efficiency of the gas water heaters in this study is found to be 41 $\pm$ 6 percent, while the contribution of solar to the solar/electric system is found to have an average value of 19 $\pm$ 13 percent.

Disaggregating the solar/electric systems into their original two groups yields solar contributions of 45 $\pm$13 percent, and 8 $\pm$12 percent for each group. The second group was located in an area of extremely hard water that might have produced the very poor performance observed.

The average hot water consumption and delivery temperature can be found by plotting the energy required to heat water for a given averaging period versus the average supply water temperature for that period. Because the amount of energy required to heat water to the fixed setpoint of the water heater depends on the inlet water temperature, the seasonal variation in the inlet water temperature provides a natural variable for determining the average mass of water heated during any averaging period. This is shown in Figure 4.2 where the average energy per week to heat water is plotted against the average supply water temperature. As the supply water temperature increases the average weekly energy to heat water decreases. If we assume that the average hot water use during each measurement period is constant and that the average system efficiencies are as given above, then the slope of the line shown is a measure of the average mass of water heated per measurement period. The mass of water obtained with this analysis is the average mass of water delivered at any temperature above the supply water temperature. Furthermore, the average temperature at which this mass of water is delivered is given by the x-axis intercept of the line plotted in Figure 4.2.

The above analysis was applied to each set of submetered data by writing a least-squares fitting routine in dBASEII that would directly perform the required calculations using the LBL data files. Of all the houses in the submetered data set, 33 yielded a least-squares fit at a significance level of .05 or better. Using these cases only, the average volume of hot water delivered was found to be 325 $\pm$ 108 gallons per person per week, at an average delivery temperature of 101 $\pm$ 14 ^{o}F.

These are valuable results since they are a measure of the true average demand for task hot water, and can serve as the basis for the design of more effective domestic hot water systems. The result that the average delivered water temperature is only a little above body temperature seems to indicate that most of the water delivered is probably used for washing or bathing activity. The modest average delivered water temperature found in this study also suggests that the use of simple batch solar water heaters together with point of use tankless heaters might be an optimum way to provide domestic hot water. Beyond this, these results can be used to quantify the average value for the thermal loss due to gray water leaving a house. By knowing the average measured supply water temperature for any period

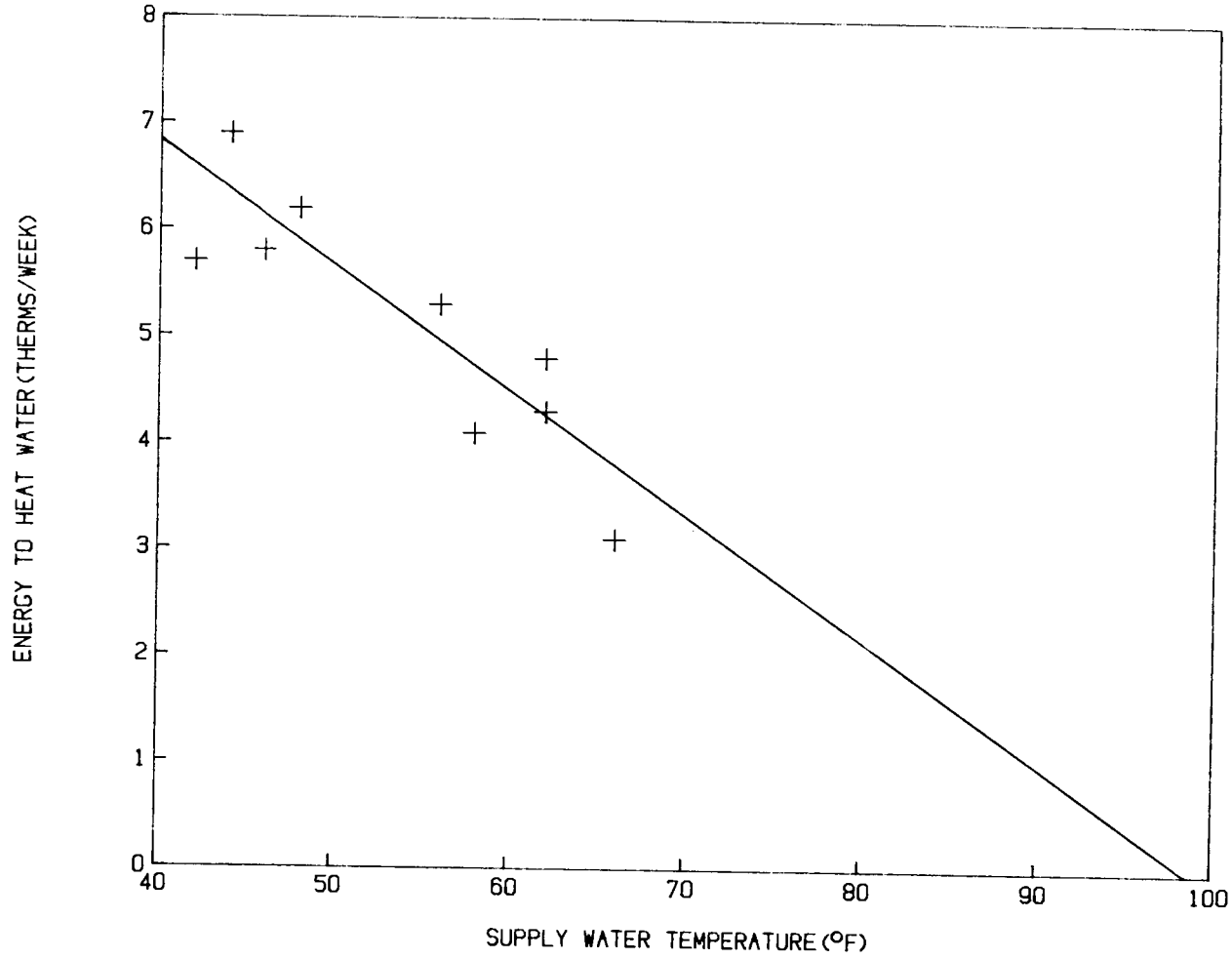

FIG. 4.2 Least squares fit of seasonal variation in the energy required to provide domestic hot water.

of time, and using the average delivery temperature and mass flow rate found in this study, the average gray water loss for the period of time being examined may be readily estimated.

4.2 PERFORMANCE ANALYSIS.

The overall performance of the research houses was evaluated using the measured performance data discussed above, plus survey data to be presented in this section. Of the 127 houses for which metered data were available, 15 were deleted for reasons listed below. With these 15 deletions, 112 houses remained for detail analysis.

NUMBER OF HOUSES	REASON FOR DELETION
7	Other fuel used (wood, kerosine)
4	No electric utility data
2	Poor prism fit (one house vacant)
2	Only one house by builder

4.2.1 Homeowner survey.

In order to evaluate the effect of occupant behavior on the measured energy use of the households in the research program, a survey was sent to each homeowner. Of the 144 surveys sent, five were returned as undeliverable, and of the remaining 139, 115 or 83 percent were completed and returned for analysis. In order to increase the rate of return, each homeowner was promised a $2.00 cash incentive for completing and mailing his or her questionnaire. Because of the cluster nature of the houses in the survey, these incentives were sent out the same day as the survey was received, so that the credibility of the offer among neighboring homeowners would remain high. Beyond this, reminder postcards were sent to all homeowners one week after the first mailing, and to homeowners with missing surveys two weeks after that. To further increase the likelihood that the survey would be completed and returned, it was designed to be just one page, and to be self-mailing.

4.2.1.1 Description of survey.

The survey form is shown in Figure G-1. Each question was designed to be answered with a single number or a "yes" or "no". This worked well, except for question 5 which was discarded from the analysis. This question, designed to evaluate homeowner attention to simple maintenance, received several "no" answers followed by the comment that the filter was changed "more often than once each year." Since the phrase "at least once a year" was required for clarity in the survey, this question was deleted. Because the houses were designed for first time home buyers, many were sold with unfinished living areas designed to be finished later by the homeowner. So that the extent of these changes would be known, question 19 asked the homeowner to describe any changes that had been made to the house since it was purchased.

4.2.1.2 Results of survey.

In the previous discussion, it was stated that of all the houses in the program, 112 had adequate metered data so that a detailed energy use analysis could be completed. Of these 112 houses, survey forms were returned by 94, or 84 percent of the homeowners. A summary of the survey data for 93 of these houses appears in Table 4.4. For this data set, one house was removed because a zero south glass area produced an unacceptable division by zero error during data normalization. These data are felt to be representative of the entire group of research houses, since the missing surveys were distributed rather evenly among different house groups in the data set.

TABLE 4.4
Survey results for 93 research houses

Question	Number of responses or average value
Number of people 12 years or older	1.91
Number of people less than 12 years old	.74
Number of people home during the day	.90
Burned wood or kerosine to help heat home	7
Builder still in business	57
Open windows to ventilate in winter	40
Solar domestic hot water system installed	33
Solar domestic hot water system works	24
Movable insulation in most windows	63
Movable insulation works	56
Movable insulation used daily	57
Number of loads of laundry a week	5.8
Air-to-air heat exchanger installed	49
Air-to-air heat exchanger works	34
Heat exchanger run on a regular basis	28
Number of hours per day heat exchanger is on	5.5
Houses with window air conditioners	8
Houses with central air conditioners	27
Lower level basement heated	78
Average finish of lower level ceiling	1.4
Average finish of lower level floor	1.4
Ducts below concrete floor	44
Change to house	11

Question 1 of the survey showed that of these households 71 were stable during the year, and that 23 experienced an increase or decrease in family size. From an examination of the three parts of question 1, most of these changes appeared to be new babies or new spouses.

Question 3 was not used, since all but seven homeowners responded "yes" to this question. Data from question 2 appear in Tables 4.1 and 4.2, and the data from question 12 concerning whether the house has gas or electric appliances, was used for the domestic hot water analysis, but was not tabulated for this report.

Question 17 on the finish of the lower level was evaluated using a scale of 0, 1, and 2, with 0 representing an unfinished lower level. This question was asked, since earlier work (11) had demonstrated that the coupling of heated upper areas of a house to colder ground coupled wall and floor areas was responsible for a significant portion of the overall heat loss of a structure. Question 18, on the presence of heating vents in slab floors, was based on the field observation presented earlier that 50 percent or more of the heat provided by a forced air furnace could be lost due to the presence of a below slab air distribution system.

Several observations may be made from the data presented in Table 4.4. Moveable window insulation is present in 63, or 68 percent of the houses, and of these 63 houses, 57 report that the insulation is used on a daily basis. Thus 90 percent of the people who have night insulation report using it on a regular basis. The importance of proper below grade insulation is emphasized by the fact that 78, or 84 percent, of the homeowners report that they heat a basement or lower level during the winter. Other results of the survey are more appropriately left to the statistical analysis that will be presented next.

4.2.2 Statistical analysis.

The statistical data analysis for the houses in the research program was done using the MULTREG program installed on the CYBER system at the University of Minnesota. MULTREG is a versatile interactive computer program for the analysis of data using multiple regression techniques, and was developed by the University of Minnesota Department of Applied Statistics. The regression variables used for this analysis are listed in Table 4.5 and are described in section 4.2.2.1.

Table 4.5
Regression variable list

MULTREG variable	Field Description (units)
1	House number
2	Ambient temperature independent load (therms/yr)
3	Ambient temperature dependent load (therms/yr)
4	Total floor area (sq ft)
5	UA above grade (Btu/hr-^{o}F)
6	UA below grade (Btu/hr-^{o}F)
7	South window area (sq ft)
8	Other window area (sq ft)
9	Infiltration load (Btu/hr-^{o}F)
10	Measured below grade or setpoint temperature (^{o}F)
11	Survey returned
12	Stable or unstable household during year
13	Number of people 12 years or older
14	Number of people less than 12 years old
15	Number of people home during the day
16	Builder still in business

17	Window ventilation in winter
18	Solar domestic hot water system installed
19	Solar domestic hot water system works
20	Moveable window insulation installed
21	Moveable window insulation works
22	Moveable window insulation used
23	Loads of laundry per week
24	Air-to-air heat exchanger installed
25	Air-to-air heat exchanger works
26	Heat exchanger operated on regular basis
27	Hours air-to-air heat exchanger runs each day
28	Lower level of house heated
29	Finish of lower level ceiling
30	Finish of lower level floor
31	Vents in cement floor
32	Changes to house

4.2.2.1 Description of regression variables.

Variables 2 and 3 are the temperature independent and temperature dependent components of the normalized thermal load that appear in Tables 4.1 and 4.2. The next five variables, 4 to 8, appear in Table 4.6 that describes the physical characteristics of the research houses. The UA values shown in Table 4.6 were calculated using a simple model that was set up on the same VISICALC worksheet as used to prepare this table. Each house was modeled as being a square box, having a certain number of floors, and placed in the ground to a given depth. This model greatly simplifies the calculations required, and, for house geometries within architectural interest, yields heat loss areas with an accuracy of about 10 percent. Using the heat loss areas provided by this model, the UA values for each house were found using standard ASHRAE calculation techniques. Floor area, window area, and R-value data were obtained from the previous study (12).

Variable 9, the infiltration load for each house, is shown in Table D-4. Measured values were obtained using standard air pressurization techniques, and were measured either as a part of the previous research (15), or as a part of the field inspection work done during this study. Houses not measured in either program were assigned the average value for their builder group if two or more houses were measured, or were assigned a default value equal to the average of all the houses if none of the houses in the group were measured. Two houses by builder R were simply assigned the same value as that of their single identical neighbors. The use of average values appears reasonable, since an examination of Table D-4 shows fairly consistent measured values for any single builder. The natural infiltration rate was calculated by dividing the measured air change rate at 50 Pa by a scaling factor of 17. The annual infiltration load was calculated based on a heating season of 8000 Fahrenheit degree-days.

To examine the effect of interior temperatures on below grade heat loss, the below grade temperatures measured in the submetered houses were entered as variable 10. For houses where this temperature was

TABLE 4.6 Physical characteristics and calculated UA values for EEHDP research houses.

BUILDER OR TYPE	TYPE OR POSITION	UNIT NUMBER(S)	SOLAR TYPE	U VALUES SOUTH WINDOWS	U VALUES OTHER WINDOWS	UA ABOVE GRADE (Btu/hr- F)	UA BELOW GRADE (Btu/hr- F)	ANNUAL CONDUCTIVE LOAD(THERMS) ABOVE GRADE	BELOW GRADE	TOTAL
BUILDER A	MIDDLE	2,3,6,7	DIRECT GAIN	.55	.35	122	11	234	20	255
SLAB	END	1,4,5,8		.55	.35	137	16	264	30	294
BUILDER B	DUPLEX	9-10	DIRECT GAIN	.55	.55	136	35	261	67	327
SPLIT	DETACHED	11-16		.55	.55	148	46	284	89	373
BUILDER C	SPLIT/DUP	17-24	DIRECT GAIN	.55	.35	248	51	476	99	575
BUILDER D	SPLIT/DET	27-28	DIRECT GAIN	.55	.35	158	60	303	115	418
BUILDER E	SPT/WLK/DET	29-32	GREEN HSE/DRCT GAIN	.55	.55	253	46	486	88	574
BUILDER G	SPLIT/DET	41-48	DIRECT GAIN	.55	.35	206	59	395	114	509
BUILDER H	2 STRY/BSMT	50-52	TROMBE	.55	.55	209	67	401	129	530
BUILDER I	SPLIT/DET	53-63	DIRECT GAIN	.55	.55	214	66	411	126	537
BUILDER J	SLAB/DUP	65-72	DIRECT GAIN	.55	.55	135	10	260	20	279
BUILDER K	SPLIT/DET	73-75	NONE	.35	.35	145	62	278	119	397
BUILDER M	2 STRY/CLSP	82-85	DRCT GAIN/ROCK BED	.35	.35	264	51	507	97	604
BUILDER N	SPLIT	94-95	NONE	.35	.35	114	46	219	88	307
DETACHED	RAMBLER/WLK	96-97		.35	.35	141	56	272	108	379
BUILDER P	MIDDLE	109-117	DIRECT GAIN	.55	.35	117	8	226	15	241
SLAB	END	108,119		.55	.35	135	12	259	23	281

TABLE 4.6 Continued.

BUILDER OR TYPE	TYPE OR POSITION	UNIT NUMBER(S)	SOLAR TYPE	U VALUES SOUTH WINDOWS	U VALUES OTHER WINDOWS	UA ABOVE GRADE (Btu/hr- F)	UA BELOW GRADE (Btu/hr- F)	ANNUAL CONDUCTIVE LOAD(THERMS) ABOVE GRADE	BELOW GRADE	TOTAL
BUILDER Q	SPLIT/DET	120-127	DRCT GAIN/MASS FLR	.55	.35	204	40	392	76	468
BUILDER R	GREEN HSE	129	GREEN HOUSE	.35	.35	115	17	221	33	254
WALKOUT	END UNIT	128	GREEN HOUSE	.35	.35	124	31	238	60	298
	DOUBLE ENV	130	DOUBLE ENVELOPE	.35	.35	111	14	214	26	240
	END UNIT	131	DOUBLE ENVELOPE	.35	.35	117	25	225	49	274
BUILDER S	MIDDLE	135,6,9,142	DIRECT GAIN	.55	.35	98	8	188	16	204
SLAB	END	133,7,8,140,1,3		.55	.35	113	12	218	24	241
	SPECIAL	134		.55	.35	107	12	206	24	230
BUILDER T	SPLIT/DET	148-151	DIRECT GAIN	.55	.35	150	46	288	88	376
BUILDER U	TYPE A	153	DRCT GAIN/WTR TUBES	.55	.55	177	47	340	91	432
SPLIT/DET	TYPE B	154-155	DRCT GAIN/WTR BED	.55	.55	179	49	344	94	439
	TYPE C	156-157	DRCT GAIN/WTR TUBES	.55	.55	163	50	314	95	409
BUILDER V	SPLIT/DET	158-160	DRCT GN/TRMB/RCK BD	.55	.35	248	52	476	99	575
BUILDER W	SPLIT	163	DIRECT GAIN	.55	.35	108	48	208	93	301
DETACHED	SPLIT	165	TROMBE	.55	.35	175	59	336	113	449
	RAMBLER	164	DIRECT GAIN	.55	.35	101	79	193	152	345

TABLE 4.6. Continued.

BUILDER OR TYPE	TYPE OR POSITION	UNIT NUMBER(S)	FLOOR AREA (sq ft)	NUMBER OF FLOORS (n)	DEPTH BELOW GRADE (ft)	SOUTH WINDOW AREA (sq ft)	OTHER WINDOW AREA (sq ft)	R VALUES CEILING	WALLS ABOVE GRADE	WALLS BELOW GRADE	BASEMENT FLOOR
BUILDER A	MIDDLE	2,3,6,7	1290	1.5	4	129	20	43	23	14	2
SLAB	END	1,4,5,8	1290	1.5	4	129	20	43	23	14	2
BUILDER B	DUPLEX	9-10	1198	2	4	143	23	41	24	17	2
SPLIT	DETACHED	11-16	1198	2	4	143	23	41	24	17	2
BUILDER C	SPLIT/DUP	17-24	1758	2	4	350	47	46	34	10	2
BUILDER D	SPLIT/DET	27-28	1913	2	4	120	69	49	27	16	2
BUILDER E	SPT/WLK/DET	29-32	1667	1.75	4	306	37	40	25	20	2
BUILDER G	SPLIT/DET	41-48	1920	2	4	180	108	57	23	11	8
BUILDER H	2 STRY/BSMT	50-52	1782	3	8	243	14	45	24	11	2
BUILDER I	SPLIT/DET	53-63	1849	2	4	196	45	39	21	12	2
BUILDER J	SLAB/DUP	65-72	1244	2	4	166	0	58	31	21	2
BUILDER K	SPLIT/DET	73-75	1968	2	4	76	144	49	27	15	2
BUILDER M	2 STRY/CLSP	82-85	1549	2	4	528	46	46	26	19	2
BUILDER N	SPLIT	94-95	1632	2	4	19	149	59	29	29	2
DETACHED	RAMBLER/WLK	96-97	2180	2	8	53	161	59	23	29	2
BUILDER P	MIDDLE	109-117	1240	2	4	121	38	56	24	14	5
SLAB	END	108,119	1260	2	4	121	38	56	24	14	5

TABLE 4.6. Continued.

BUILDER OR TYPE	TYPE OR POSITION	UNIT NUMBER(S)	FLOOR AREA (sq ft)	NUMBER OF FLOORS (n)	DEPTH BELOW GRADE (ft)	SOUTH WINDOW AREA (sq ft)	OTHER WINDOW AREA (sq ft)	R VALUES CEILING	WALLS ABOVE GRADE	WALLS BELOW GRADE	BASEMENT FLOOR
BUILDER Q	SPLIT/DET	120-127	1320	2	4	285	16	49	33	22	5
BUILDER R	GREEN HSE	129	1327	2	8	224	29	58	24	16	10
WALKOUT	END UNIT	128	1327	2	8	224	29	58	24	16	10
	DOUBLE ENV	130	1235	2	8	224	29	47	35	16	30
	END UNIT	131	1235	2	8	224	29	47	35	16	30
BUILDER S	MIDDLE	135,6,9,142	1265	2	4	68	64	52	26	16	2
SLAB	END	133,7,8,140,1,3	1265	2	4	68	64	52	26	16	2
	SPECIAL	134	1265	2	4	0	156	52	26	16	2
BUILDER T	SPLIT/DET	148-151	1501	1.5	4	144	23	45	24	16	5
BUILDER U	TYPE A	153	1582	2	4	215	9	57	28	24	2
SPLIT/DET	TYPE B	154-155	1638	1.5	4	173	56	57	28	20	2
	TYPE C	156-157	1629	2	4	178	17	57	28	22	2
BUILDER V	SPLIT/DET	158-160	1709	1.5	4	287	83	60	20	11	10
BUILDER W	SPLIT	163	1630	2	4	69	27	59	27	24	2
DETACHED	SPLIT	165	2080	2	4	171	40	59	27	19	2
	RAMBLER	164	2080	2	8	63	40	59	27	19	2

not available, the setpoint temperature as discussed previously was entered instead. Variables 11 and 12 were used to select subgroups of houses for analysis. For examining effects not related to survey data, the entire group of houses was available for analysis. However, for analysis requiring survey data, only the subset selected by variable 11 was used.

The remainder of the variables shown, numbers 13 to 32, are the survey data for each house as discussed previously.

4.2.2.2 Results of statistical analysis.

The MULTREG program was used in two principal ways for the analysis of the variables shown in Table 4.5. First it was used to calculate average values for the variables shown. These results appear in Tables 4.4 and 4.7. The second application of the MULTREG program was to carry out a statistical regression analysis using the variables listed in Table 4.5 to determine which of the variables shown would be the most effective for predicting the total energy consumption. The results of this analysis are presented at the end of this section.

The average values of the measured energy performance for 108 houses are listed in Table 4.7. This number includes 4 deletions beyond the 112 houses for which complete data were available. Unit 134 was deleted because it had a zero south glass area, and units 163 to 165 were deleted since there was only one house of each type by this particular builder. As can be seen, the 108 houses fall into 25 groups of various types as described in the column labeled "type or position." Shown in the last column of Table 4.7 is the average thermal integrity factor for each of these 25 groups, where the thermal integrity factor is defined as the normalized thermal load (NTL), or the sum of regression variables 2 and 3, divided by the floor area of the house and the average number of base 68°F heating degree-days for Minneapolis-St. Paul (8888°F-day).

The thermal integrity factors in Table 4.7 were calculated using normalized thermal loads corrected for gray water heat loss. Earlier it was assumed that the metabolic gains and gray water losses were equal and opposite. However, for the houses in this study, the gray water losses exceeded the metabolic gains and a correction was made. This was done by finding the difference between the gray water losses and metabolic gains for the heating season and then subtracting this number from the NTL, since this energy does not contribute to the thermal energy required to heat the house. Using the average hot water mass flow rate, supply temperature, and warm water discharge temperature found in this study, and assuming that 80 percent of the water heating energy left the house in gray water, an average thermal loss of 14,000 Btu/person-day was determined. Metabolic gains were estimated using the ASHRAE metabolic contribution of 360 Btu/hour per adult at rest and assuming an average occupation time of 14 hours per day. The sum of these yielded an annual net loss of 27 therms/person for the 287 day, base 68°F heating season used in this study. The total correction for each house was obtained by multiplying this value by a sum equal to the number of adults plus one-half the number of children in the house. For houses without survey data, a default

TABLE 4.7. Characteristics and thermal integrity factors for 25 groups of identical houses. Thermal integrity factor shown is a measure of the total building thermal load, and is equal to the normalized thermal load (NTL) divided by the heated floor area and the average number of heating degree-days. NTL has been corrected for gray water loss. See text.

BUILDER OR TYPE	TYPE OR POSITION	UNIT NUMBER(S)	SOLAR TYPE	GROUP NUMBER	NUMBER OF HOUSES IN GROUP	FLOOR AREA (sqft)	SOUTH WINDOW AREA (sqft)	THERMAL INTEGRITY FACTOR (Btu/sqft-DD)
BUILDER A	MIDDLE	2,3,6,7	DIRECT GAIN	2	4	1290	129	2.28
SLAB	END	1,4,5,8		1	4	1290	129	3.62
BUILDER B	DUPLEX	9-10	DIRECT GAIN	3	2	1198	143	3.79
SPLIT	DETACHED	11-16		4	6	1198	143	4.06
BUILDER C	SPLIT/DUP	17-24	DIRECT GAIN	5	5	1758	350	3.03
BUILDER D	SPLIT/DET	27-28	DIRECT GAIN	6	2	1913	120	3.22
BUILDER E	SPT/WLK/DET	29-32	GREEN HSE/DRCT GAIN	7	3	1667	306	2.74
BUILDER G	SPLIT/DET	41-48	DIRECT GAIN	8	7	1920	180	2.49
BUILDER H	2 STRY/BSMT	50-52	TROMBE	9	3	1782	243	2.59
BUILDER I	SPLIT/DET	53-63	DIRECT GAIN	10	9	1849	196	2.96
BUILDER J	SLAB/DUP	65-72	DIRECT GAIN	11	8	1244	166	4.01
BUILDER K	SPLIT/DET	73-75	NONE	12	3	1968	76	2.65
BUILDER M	2 STRY/CLSP	82-85	DRCT GAIN/ROCK BED	13	4	1549	528	2.99
BUILDER N	SPLIT	94-95	NONE	14	2	1632	19	2.85
DETACHED	RAMBLER/WLK	96-97		15	2	2180	53	2.33

TABLE 4.7. Continued.

BUILDER OR TYPE	TYPE OR POSITION	UNIT NUMBER(S)	SOLAR TYPE	GROUP NUMBER	NUMBER OF HOUSES IN GROUP	FLOOR AREA (sqft)	SOUTH WINDOW AREA (sqft)	THERMAL INTEGRITY FACTOR (Btu/sqft-DD)
BUILDER P	MIDDLE	109-117	DIRECT GAIN	17	9	1240	121	3.21
SLAB	END	108,119		16	2	1260	121	4.21
BUILDER Q	SPLIT/DET	120-127	DRCT GAIN/MASS FLR	18	8	1320	285	3.52
BUILDER R	GREEN HSE	129	GREEN HOUSE	19	2	1327	224	3.07
WALKOUT	END UNIT	128	GREEN HOUSE			1327	224	
	DOUBLE ENV	130	DOUBLE ENVELOPE	20	2	1235	224	2.85
	END UNIT	131	DOUBLE ENVELOPE			1235	224	
BUILDER S	MIDDLE 13	5,6,9,142	DIRECT GAIN	22	6	1265	68	2.64
SLAB	END 133,	7,8,140,1,3		21	4	1265	68	2.8
	SPECIAL	134				1265	0	
BUILDER T	SPLIT/DET	148-151	DIRECT GAIN	23	3	1501	144	3.74
BUILDER U	TYPE A	153	DRCT GAIN/WTR TUBES	24	5	1582	215	2.55
SPLIT/DET	TYPE B	154-155	DRCT GAIN/WTR BED			1638	173	
	TYPE C	156-157	DRCT GAIN/WTR TUBES			1629	178	
BUILDER V	SPLIT/DET	158-160	DRCT GN/TRMB/RCK BD	25	3	1709	287	3.24
BUILDER W	SPLIT	163	DIRECT GAIN			1630	69	
DETACHED	SPLIT	165	TROMBE			2080	171	
	RAMBLER	164	DIRECT GAIN			2080	63	

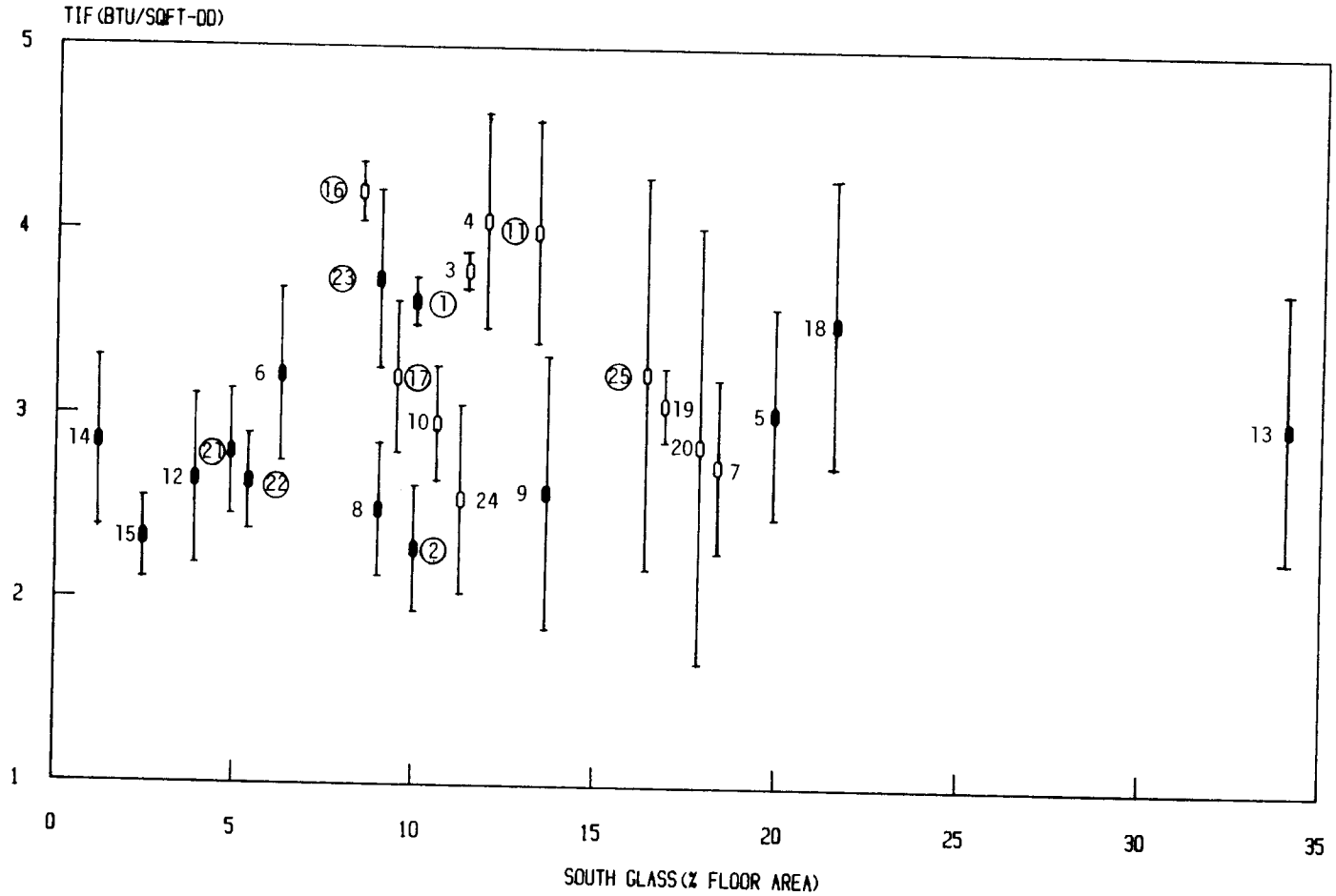

FIG. 4.3. Thermal integrity factor for 25 groups of houses. Thermal integrity factor includes all metered energy thermalized within the house envelope, corrected for gray water loss and metabolic gain. Mean and standard deviation of energy performance is shown for each house group. Closed and open circles represent air change rates less than or greater than the group average of 5.3 AC/H @ 50 pa. House groups with below slab air distribution systems are shown by circled group numbers.

occupancy based on the average value for all surveyed houses was used. This correction reduced the standard deviations of the thermal integrity factors for all but 4 of the 25 house groups shown in Table 4.7.

These thermal integrity factors are also shown in Figure 4.3, where they are plotted against the south glass area for each house group. In Figure 4.3 the south glass area is expressed as a percent of house floor area, and the standard deviation in the measured energy use for each group is shown by the bars attached to the average value point. As can be seen, there appears to be no direct correlation between the amount of south glass area and thermal integrity factor for these houses. This conclusion is also supported by the more detailed regression analysis to be presented later in this section.

In Figure 4.3 the house groups having the five largest standard deviations (groups 9, 13, 18, 20, and 25), are either high mass structures (9, 13, 18, and 25), or of double envelope design (20). The high mass structures with the largest deviations in performance (13, 18, and 25) all have their mass coupled to the house by forced convection. While the average performance of these structures can be quite satisfactory, the ability to control or predict energy consumption seems to be diminished by the presence of additional mass. The remainder of the houses, except for group 24, do not contain large amounts of additional mass.

Figure 4.3 shows a wide range in the average performance of the twenty-five house groups. Based on the measured air leakage rates shown in Table D-4 the house groups shown in Figure 4.3 were divided into those with leakage rates less than and greater than the overall average leakage rate of 5.3 AC/H @ 50 Pa. The low and high leakage rate house groups are shown by the closed and open circles respectively in Figure 4.3. As can be seen the best performing houses had below average leakage rates while the worst performing houses had above average leakage rates. In addition to air leakage rates, Figure 4.3 shows the presence of a below slab warm air distribution system by a circle around the group number. With the addition of these data, all of the groups that have thermal integrity factors exceeding 3.2 Btu/sq.ft.-^{o}F Day, except for groups 6 and 18, have either a high air leakage rate, a below slab air distribution system, or both of these characteristics.

Because these two factors are also the only ones that are consistently significant based on the regression analysis to be discussed later, it appears that they may be the principal variables for explaining the difference in energy performance of the houses in this research program. Since the air leakage rate could also be an excellent proxy for the overall quality of construction, the principal investigator believes that it should be used with caution in the prediction of performance of the houses in this research program. That is, a poorly sealed house may also be poorly insulated because of the improper application of insulating materials.

The difference in energy performance between house groups with varying numbers of common walls is shown in Figure 4.3 by the four pairs of house groups numbered 1 and 2, 3 and 4, 16 and 17, 21 and 22. House groups 1,16, and 21 are all end units in a row of four or

more houses, while groups 2, 17, 22 are the respective, and nearly identical, middle units for these same developments. While groups 21 and 22 have nearly the same performance with the end unit using slightly more energy than the middle unit, the end unit groups 11 and 16 use from 25 to 50 percent more energy than their middle unit counterparts. The large difference in performance between the end and middle units for groups 1 and 2, and 16 and 17 might result from the presence of below slab air ducts in these units. Groups 3 and 4 represent duplex and detached houses of otherwise similar design with the detached design using about 10 percent more energy than the duplex units.

The presence and use of night insulation in the research houses is shown in Figure 4.4, where the houses are divided into three groups having small, medium, and large south window areas. Small, medium, and large are defined here as less than 10 percent, between 11 and 20 percent, and greater than 20 percent of the floor area of the house as the south aperture area. It can be seen from these data that night insulation is installed in nearly half or more of the houses in each group, and that in each group the majority of this insulation is used. It is interesting to note that as the south window area increases, the percentage of houses that have and use night insulation also increases.

The effectiveness of night insulation was evaluated by examining the average performance values of the above houses, and the results of this analysis are shown in Figure 4.5. This figure shows the average thermal integrity factor for houses that use night insulation compared to those that do not use night insulation, for each of the groups defined above. As can be seen, the houses in this research program appear to perform about the same whether or not night insulation is used, independent of the south glazing area of the house. This conclusion is supported by detailed statistical t-tests between the mean consumptions with and without night insulation that showed no significant difference in energy use. The average performance of all houses is shown by the last set of bars in Figure 4.5. These results are very similar to those found in the SERI Class B monitoring program (15) and seem to demonstrate the difficulty of predicting the long term field performance of night insulation.

A number of MULTREG regression calculations were done using the regression variables described earlier, and the results of three of these calculations are shown in Appendix G. The MULTREG results shown are for the full sample of houses for which survey data were available, plus subsamples of data for the small and medium aperture houses. These calculations were done using the SCREEN command of MULTREG which yields the best regression for the given data based on Mallows' C_p statistic (16). The regression variables that appear in Appendix G are the same as those listed in Table 4.5.

An examination of these results shows that they are mixed with regard to what would be intuitively expected. For example, variable 9, the infiltration load, adds to the total energy use for each group of houses shown. That is, the coefficient of this UA term is positive for all three groups. Note, however, that the coefficient of the UA values for the above grade and below grade losses are both positive

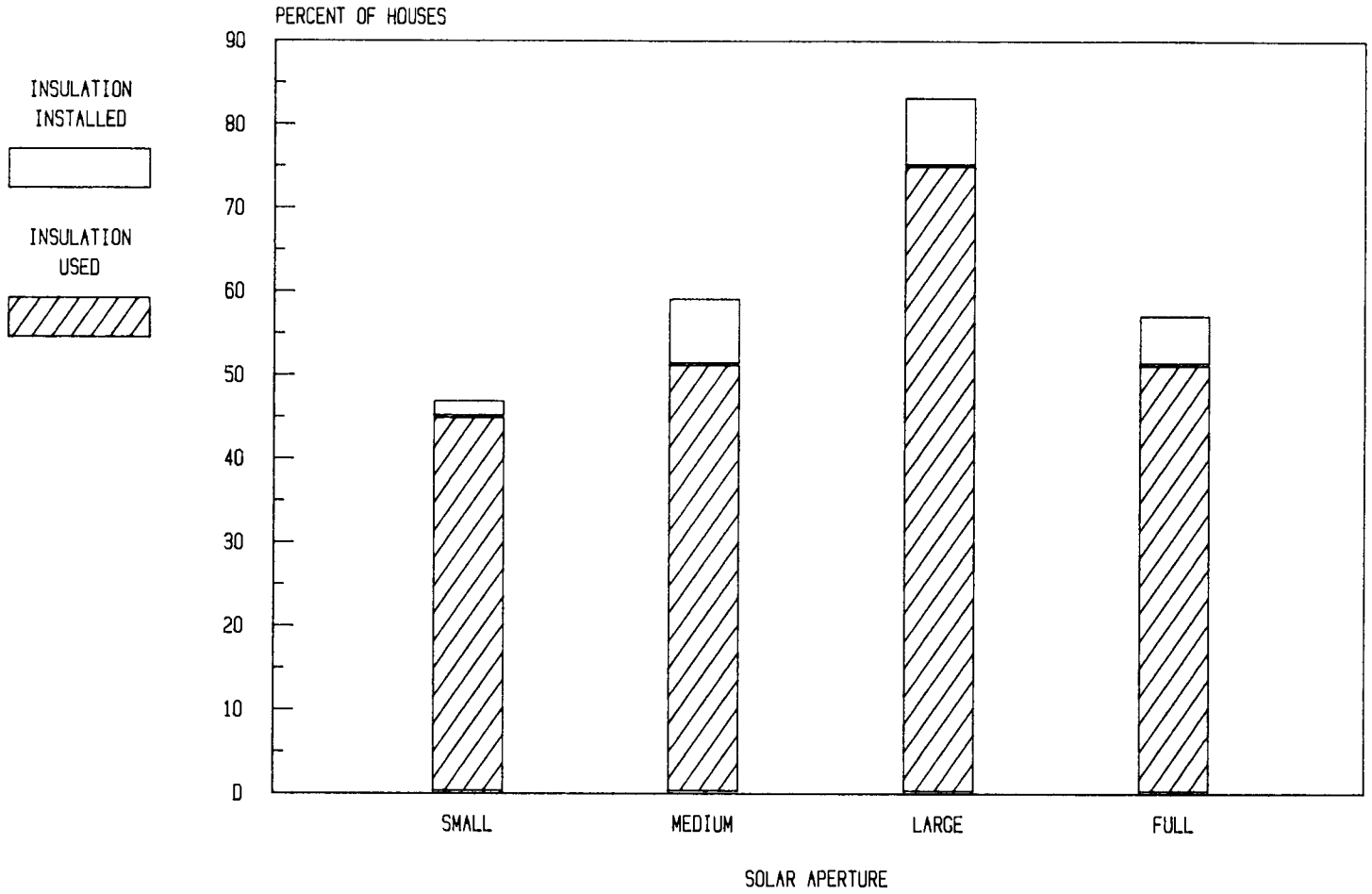

FIG. 4.4 Percentage of night time window insulation installed and used for three ranges of south window area.

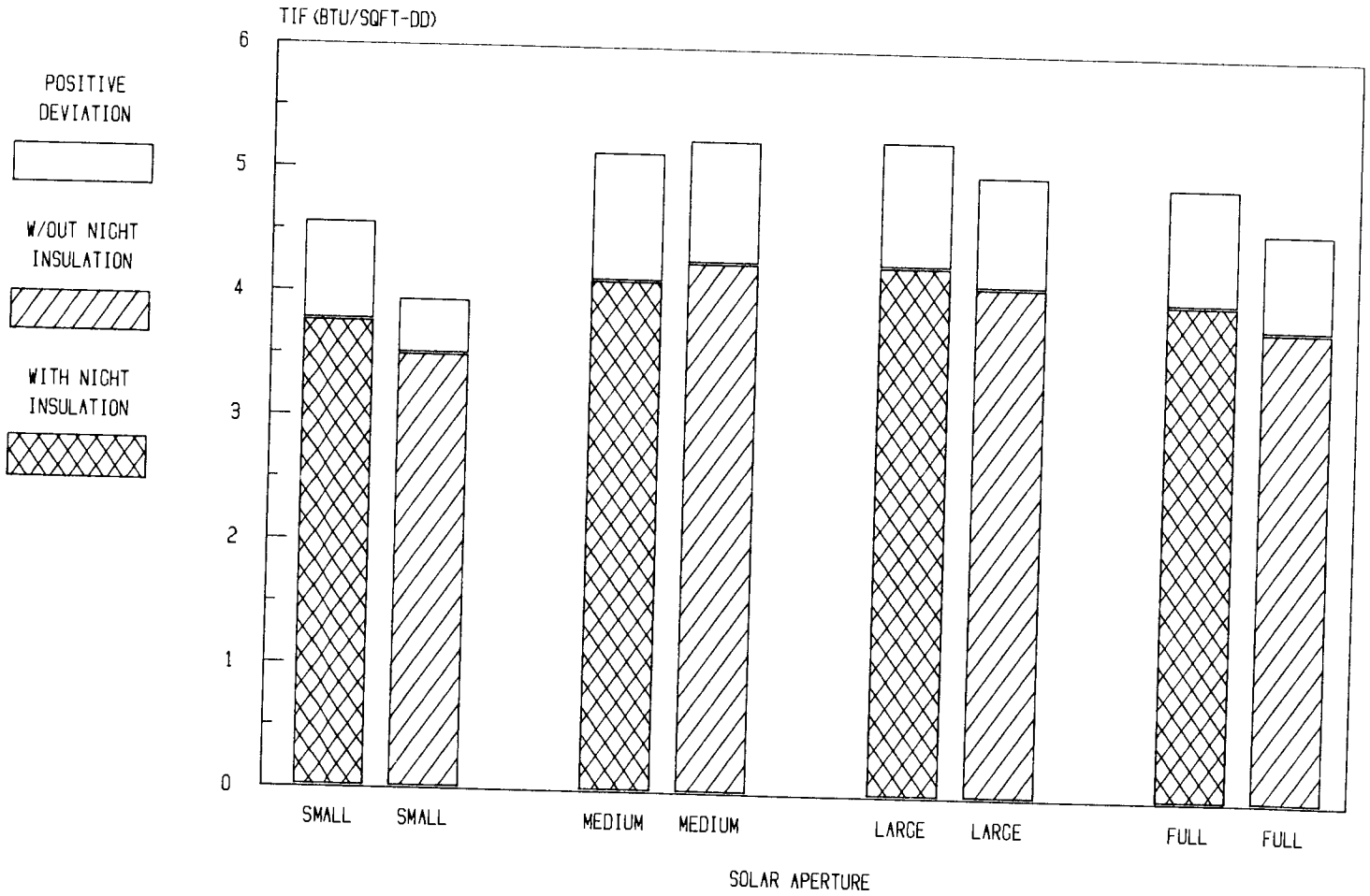

FIG. 4.5. Average thermal integrity factor (TIF) for small, medium, and large aperture houses with and without night insulation use. Insulation use was based on self-reported data. TIF has not been corrected for gray water loss and metabolic gain.

for only the full sample of houses, and that the below grade coefficient is negative for the small aperture houses while the above grade coefficient is negative for the medium aperture houses. The coefficients for the solar aperture, variable 7, are also mixed, with the coefficient for the small aperture houses showing a net gain of 1.54 therms/year per sq.ft. of solar aperture, while the medium aperture houses show a loss of .52 therms/year per sq.ft. of solar aperture. The coefficient for the full sample of houses shows a decrease of .01 therms/year for each sq. ft. of solar apeture, in agreement with earlier observations that the performance of the entire group of houses appears to be independent of south glazing area.

The most significant correlation (t-value = 4.67) occurs in the medium aperture house group for variable 31, the presence of below slab ducts for warm air distribution. The correlation coefficient in this case shows that, on the average, houses of this type have below slab distribution losses of 110 therms/year. Depending on the annual heating energy required, this loss could amount to 20 to 25 percent of the total heat loss from the house. This is in general agreement with the field observation that more than 50 percent of the energy entering the below slab portion of a heat distribution system may be lost before it reaches the supply register.

Another aspect of this part of the study that was briefly examined included regression runs using only one of the components of the total heating energy as the dependent variable. When this was done using the subgroup of stable households, a significant correlation (t-value = 6.1) of 39 therms/year per person was found between the temperature independent energy and the number of people living in the house. Earlier, based on submetered data and the assumption that 80 percent of the water heating energy leaves in the grey water flow, a loss of 27 therms/year per person was calculated as the average net annual value of the metabolic gain and gray water loss for the houses in this study. If a gray water loss equal to 100 percent of the water leaving the house is assumed, rather than 80 percent, the average net heat loss becomes 37 therms/year per person, in good agreement with the above value. While these numbers need to be confirmed by other studies, it seems reasonable to conclude that a good approximate number for the incremental net energy requirement per person for the households in this study is between 30 and 40 therms/year per person.

5. CALCULATED ENERGY PERFORMANCE USING CIRA AND HOTCAN

5.1 DESCRIPTION OF ANALYSIS.

The energy use for each of the seven submetered house designs was calculated using the CIRA and HOTCAN programs developed by the Lawrence Berkeley Laboratory and the National Research Council Canada, respectively.

Prepared forms were used to set up the input data for each program. To help maintain objectivity and uniformity in this analysis, these forms were independently completed by a registered architect working under a special subcontract with the principal investigator. The information given to the architect consisted of the original program submission materials, including blueprints, plus the field inspection information obtained during the current research study.

Because the CIRA and HOTCAN programs use different methods for defining the below grade areas of a house, an input technique was needed that would represent the houses equally well for either program. To accomplish this, an adjustment was made in the CIRA input method. The CIRA program defines below grade areas in terms of a fixed height basement that has a given part of this height exposed above grade. In order to have the correct wall areas, both above and below grade, the CIRA input for the height of the basement above grade was adjusted to give the correct below grade wall area. Then the R-value of the above grade area was set to a value of R-300, so that the above grade portion of the basement wall would not contribute to the heat loss of the house. The above grade portion of the basement wall was then entered as a separate wall component. It could be anticipated that this technique would introduce errors by transferring a heat loss component from the intermediate temperature basement "zone" to the temperature regulated above grade zone used in the program. However, large changes in the subfloor insulation between these zones, changes that would be expected to affect the basement zone temperature, produced little or no change in overall energy use. From this, the principal investigator concluded that moving a heat loss area from the basement component to an above grade wall component did not produce large errors in the predicted annual energy use. This probably results from the fact that for these houses the below grade walls are so well insulated that the addition of insulation in series between the temperature regulated zone and the basement does not appreciably affect the basement temperature.

Infiltration calculations were done using the leakage area method as provided by each program. The air change rate at 50 Pascal and the appropriate leakage area (required for HOTCAN, but not CIRA) for each house design were taken from fan pressurization measurements on the single house that appeared to be most representative of the entire design group. In addition to data on the house envelope, average occupancy and thermostat setpoint temperatures were also required by each program. The average values of these data for each group of submetered houses were obtained from the homeowner survey and the measured interior temperatures discussed earlier.

5.2 COMMENTS ON PROGRAMS.

Both programs were menu driven and relatively easy to use. The CIRA program operating under CP/M was somewhat faster than the Apple II HOTCAN version used for this study. This version of HOTCAN was written to operate with only 48k of memory, requiring frequent and time consuming disc access. The most time consuming part of running HOTCAN appeared to be in setting up the solar calculation factors for a specific weather file. However, once this was done and the location name for the weather file was not changed, succeeding runs were much quicker. Entering and editing data for each program was easy and required about the same effort for either program.

The programs probably differed the most in their output formats. HOTCAN output includes energy use by component which is very useful for developing economically optimum designs. While not as complete as HOTCAN, the CIRA output could be formatted in several different ways to enhance its value. The CIRA program includes a clever calculator mode that allows the user to manipulate data into different formats for presentation either as a printed or plotted output.

Examples of CIRA and HOTCAN output are shown in Appendix H. These examples show the second primary difference between the programs, the amount of input data listed by each. As can be seen, HOTCAN lists the area and R-value of each component, while CIRA lists only the total values for most of these components. This makes the HOTCAN input somewhat easier to check, since input values can be checked without using the program. This input listing is probably needed more for HOTCAN than for CIRA, since using the program menu to check input values is somewhat faster for CIRA than HOTCAN.

5.3 RESULTS OF ANALYSIS.

The results of applying the CIRA and HOTCAN programs to the submetered house designs examined are shown in Figures 5.1 through 5.3. In each of these figures, the diagonal line shows where the plotted values would need to be for perfect agreement between the predicted results or measured data being compared.

The first two figures compare the predicted net and total energies for each of the seven houses as calculated by CIRA and HOTCAN. The net energy shown in Figure 5.1 is the energy consumption that needs to be specifically supplied by space heating equipment, and represents the net amount of purchased energy for space heating for each house design. Except for builder G, the CIRA and HOTCAN results agree with each other to within 5 MBtu or less. Excluding builder G, and assuming a furnace efficiency of 75 percent and a cost of natural gas equal to $6.00/Mcf, the largest error in annual energy cost would be $40.00. The input data for builder G was reexamined by the same person that prepared the original input and no input errors could be found. Beyond an undiscovered error, it is unknown why this design shows such a large difference between the net energy values predicted by CIRA and HOTCAN.

The calculated total energy consumption for each design is shown in Figure 5.2. The total consumption is defined here as the net

consumption as defined above, plus internal gains supplied by the occupants' use of energy within the building envelope. The internal gains calculated by CIRA and HOTCAN for these houses roughly average about 15 MBtu, as can be seen by the shift in the origin of this plot compared to that of Figure 5.1. By adding internal gains, the agreement between the energy values predicted by CIRA and HOTCAN is improved for builders D,G,N, and S, but made somewhat worse for builders A, Q, and R. The difference between Figures 5.1 and 5.2 show the sensitivity of the analysis to the assumptions made regarding the utilization of internal gains within the building envelope. Beyond this, the HOTCAN output showed that the solar gains for these houses were also about the same size as the internal gains shown above. Very roughly, internal gains and solar gains each contributed about one-third of the overall space heat energy required by the designs examined. Because of the large contribution by these difficult to analyze energy sources to the net energy required, it is remarkable that the agreement in the net energies shown in Figure 5.1 is as good as it is.

Figure 5.3 shows the comparison of the total energy use predicted by CIRA and HOTCAN to the total energy use measured in this research program. The measured energy use shown is the average of the normalized thermal load values for all houses of the same type in each submetered group, uncorrected for gray water heat loss. In each case the measured energy use is greater than the predicted amount, indicating that perhaps too much of the metered energy is assumed to be thermalized within the house envelope. The offset of the dashed line shown represents the average gray water heat loss correction for these houses calculated using the thermal integrity factors listed in Table 4.7. While this average correction clearly reduces the average difference between the measured and predicted values, a more detailed analysis shows that individual corrections to measured data would do little to reduce the scatter remaining in Figure 5.3. Further analysis using these data show that the average difference between the predicted and gray water corrected measured values is about 6.8 MBtu per season, about the same as the average gray water correction shown in Figure 5.3 (7.2 MBtu per season). That is, the average corrected scatter in Figure 5.3 would be about equal to the offset of the gray water correction line. It is the conclusion of the principal investigator that until better techniques are developed for the analysis of the difficult to quantify aspects of residential energy use, such as gray water loss, that there will probably be little overall improvement in the analysis of energy use in houses.

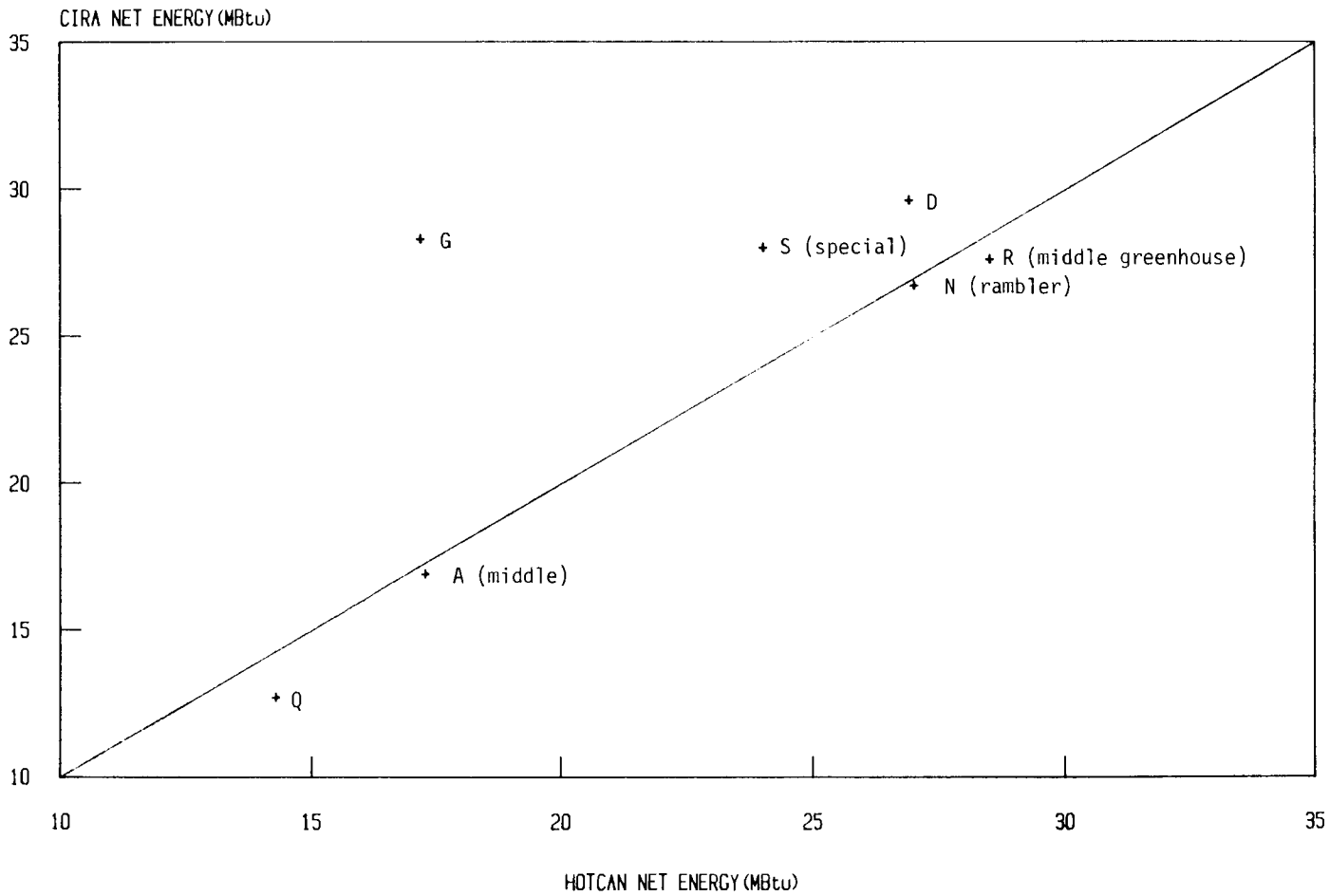

FIG. 5.1 Comparison of net energy required by seven different house designs as calculated using the CIRA and HOTCAN computer programs. Net energy is defined as the energy provided by space heating equipment. Each design is labled by the builder letter. House type and position are specified as required.

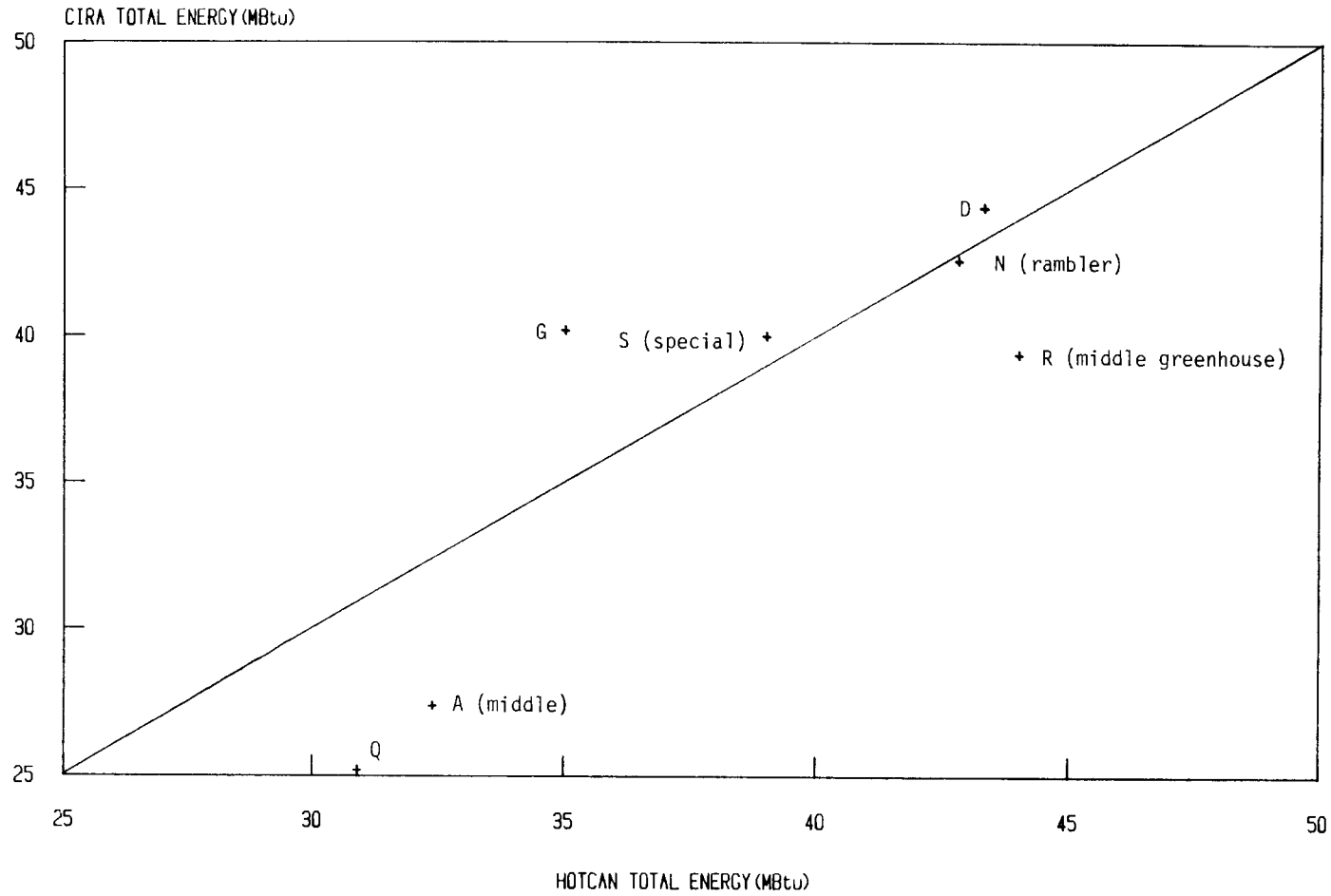

FIG. 5.2 Camparison of the total energy required by seven different house designs as calculated using the CIRA and HOTCAN computer programs. Total energy is defined as the energy provided by space heating equipment plus internal gains. Each design is labled by the builder letter. House type and position are specified as required.

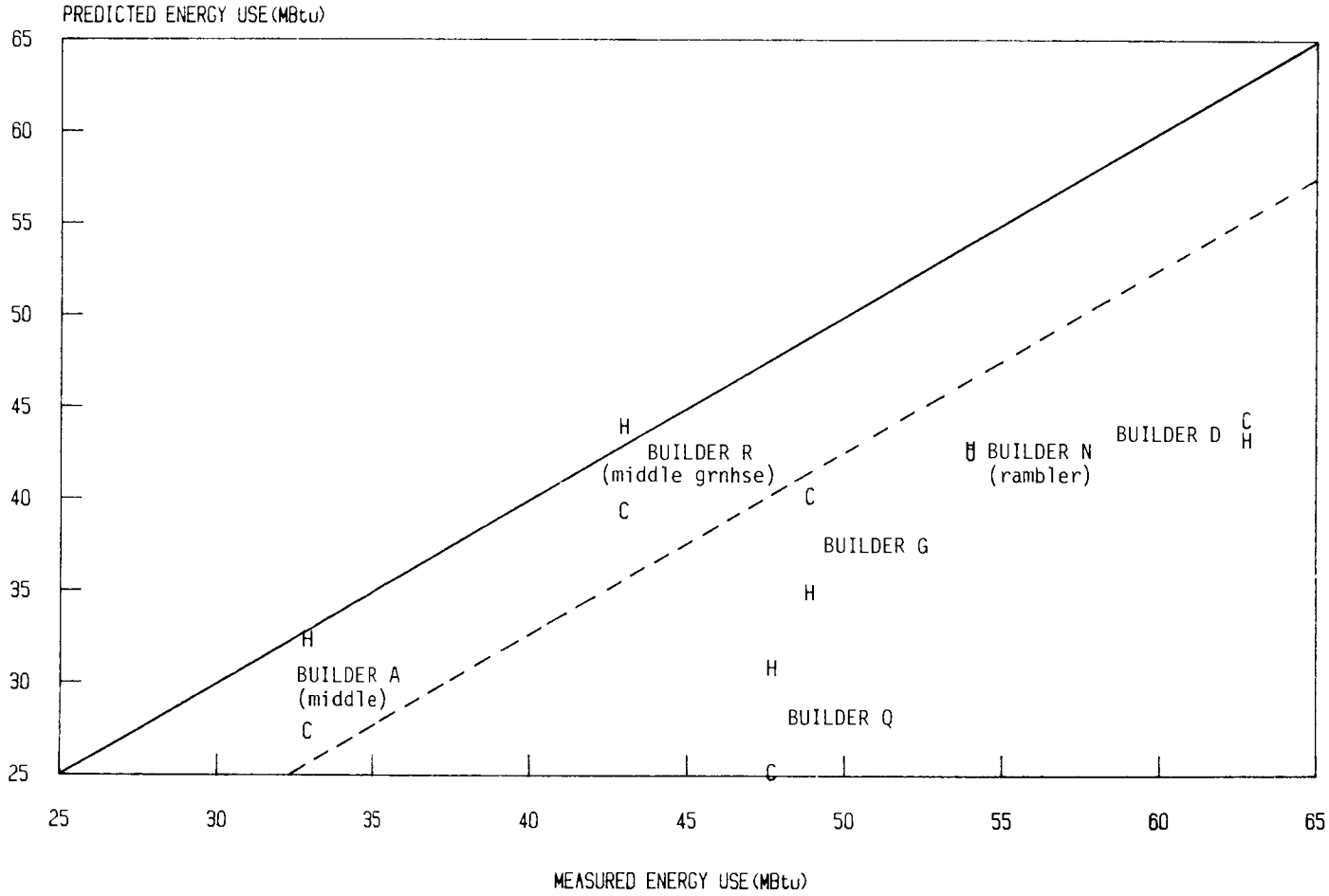

FIG. 5.3 Comparison of predicted and measured total energy required by six different house designs. The CIRA and HOTCAN predicted values are denoted by C and H, respectively. The measured energy use is the average measured energy use for similar units by the same builder. A single special unit by builder S has been removed since there was only one unit of this type. The dashed line shows the average gray water correction for the six designs shown.

6. LIFE-CYCLE ANALYSIS FOR FOUR DESIGNS

The cost effectiveness of the houses built under the MHFA Energy Efficient Housing Demonstration Program was examined by calculating the life-cycle cost of four levels of energy saving features applied to four selected house designs. The four designs were chosen to be representative of the over twenty different designs built in the EEHDP, and included attached and detached houses ranging from slab-on-grade to full basement construction. Houses were also chosen to represent a variety of solar features, and included large aperture houses with added mass to houses with little or no south glazing and no added mass.

The analysis involved two steps: a cost analysis provided by the Minnesota Housing Finance Agency, and a series of HOTCAN calculations to evaluate the energy performance of each house design. Using this information, a life-cycle cost analysis was carried out.

This theoretical approach was necessary because, if actual house cost and performance data were used, the comparison of cost effectiveness across house designs would not be meaningful due to variations in construction quality and occupant lifestyle. This is a fundamental property of life-cycle analysis and cannot be avoided (17).

6.1 COST ANALYSIS.

6.1.1 Component values.

The component values used in this analysis for each level of energy saving features for each of the four selected houses is shown in Appendix I, Table I-1. Design #1 is taken as the base case for this comparison study, and shows component values as required by the the Minnesota Energy Code that was in effect in 1980. Design #2 closely resembles the current HUD-Mininum Property Standards, and is based on the more stringent Minnesota Energy Code that became effective in January 1984. Design #3 represents a slightly higher energy efficiency standard chosen by the authors. The fourth level in this comparison is the EEHD house as designed.

In addition to these code based component values, Table I-1 also shows the values assigned to each design for window insulation, storage mass, furnace efficiency, and air infiltration rate. As can be seen, window insulation is used only in EEHDP units 44 and 124. The added storage mass in these two houses is not quantified in Table I-1, but was accounted for in the energy analysis to be discussed in the next section. The 75 and 87 percent furnace efficiencies shown represent reasonable values for conventional and recuperative furnaces, respectively. The air infiltration rates shown represent several levels of envelope sealing both with and without mechanical ventilation as described in the narrative to Appendix I.

6.1.2 Incremental and total costs.

The basis for the incremental costs used in this analysis is presented in Appendix I. These costs were assembled from a survey of a dozen or more resources, including builders,

in Tables I-2 through I-5. The last column in each of these tables shows the incremental cost to build the EEHDP unit as designed for the EEHD program. In each case, the first column shows the component area of the EEHDP design being examined. This area is used to scale the total costs for each of the energy efficiency design levels shown. Total costs are then calculated by multiplying the incremental costs per square foot by the design area shown in the first column. The incremente representative of current practice.

Designs #1 and #2 were assumed to be built with 25/32-inch fiber board sheathing that was then replaced with rigid insulation for the remainder of the designs examined. Because most rigid insulating materials appear to be competitive on a cost per unit R-value per square foot basis, a generic material was assumed for this portion of the analysis.

The costs to build each EEHDP design to the three levels of energy efficiency shown in Table I-1 are shown in Tables I-2 through I-5. The last column in each of these tables shows the incremental cost to build the EEHDP unit as designed for the EEHD program. In each case, the first column shows the component area of the EEHDP design being examined. This area is used to scale the total costs for each of the energy efficiency design levels shown. Total costs are then calculated by multiplying the incremental costs per square foot by the design area shown in the first column. The incremental cost for the base case is taken as zero except for the addition of south glazing in units 44 and 124.

6.2 ENERGY USE ANALYSIS.

The energy use for each of the 16 designs described above was calculated using the HOTCAN program described in Chapter 5. For this analysis, the natural air change rate was set at zero, and a forced air change rate equal to that shown in Table I-1 was used. For those cases where heat recovery ventilation was specified, a heat recovery effectiveness of 60 percent was used to calculate the ventilation portion of the heating load. All structures were assumed to have light-weight thermal mass levels except for the EEHDP "as designed" cases of units 44 and 124. These two cases were also the only designs assumed to be equipped with window insulation. The results of these calculations are shown in the second column of Table 6.1. The next two columns in this table show the annual fuel use and the annual fuel cost. The fuel use has been calculated based on the furnace efficiencies shown in Table I-1, and the fuel cost is based on an average natural gas cost of $6.03/Mcf for 1985, estimated by the Minnesota Department of Energy and Economic Development (17).

6.3 LIFE-CYCLE ANALYSIS.

Based on the above analysis, the total life-cycle cost to construct and heat each of the 16 designs discussed above was calculated as shown in Table 6.1. The present values for the fuel costs and savings shown were calculated using a real discount rate of 3 percent, yielding present worth factors of 17.41 and 25.73 for the

25- and 50-year time periods, respectively. The additional cost to build was taken from Tables I-2 through I-5. The last two columns of Table 6.1 show the total life-cycle costs for each design for the 25- and 50-year time periods examined.

These results are also shown graphically in Figures 6.1 through 6.4. Here the total life-cycle cost for each house design is shown as a bar consisting of the sum of the cost to build, plus the present value of the cost of fuel. Two sets of bars are shown for each house, one set for each time period analyzed. As can be seen, the same general pattern is shown by each type of house. That is, design 2 has the lowest life-cycle cost for the 25 year time period, while design 3 has the lowest life-cycle cost for the 50 year time period for each of the houses examined. Design 3 seems to be cost effective because of the low U-value windows and higher efficiency furnace used, while the "as designed" option appears to be too expensive due to the addition of wall insulation, window insulation, or thermal mass.

6.4 COST EFFECTIVENESS OF QUALITY CONTROL.

From the analysis in section 4.2.2, it appears that the principal predictors of performance are the air leakage rate and the presence of below slab air distribution systems. If these variables are taken as proxies for general building quality control, it can concluded that much of the variability among the house groups shown in Figure 4.3 is due to varying levels of quality control in the construction of the houses in this study. This broad assumption may not be entirely true, but by asserting it, the present value of energy savings that might be obtained through quality control of residential construction can be estimated. If the scatter of average values for the groups of houses shown in Figure 4.3 is indeed due to variation in construction quality, then it appears from this figure that 1-2 Btu/sq.ft.-^{o}F day could be saved through quality control in building. That is, from Figure 4.3 it appears that the worst performing houses could have their thermal integrity factors reduced by 1-2 Btu/sq.ft.-^{o}F day through the application of quality control. The present value of the savings due to such a reduction in energy use is shown for some typical design and cost values in Table 6.2. The present value of the savings shown in the last column of this table ranges from $1,575 to $9,048, depending on the specific assumption made. Since the smallest of these values could pay for one to two weeks of work by one person, quality control in building would appear to be very cost effective.

TABLE 6.1. Life-cycle economic analysis of three levels of energy efficiency based on four different EEHDP house designs.

UNIT OR DESIGN TYPE	ANNUAL ENERGY USE (MBtu)	ANNUAL FUEL USE (MBtu)	ANNUAL FUEL COST ($)	NET PRESENT FUEL COST ($)		NET PRESENT FUEL SAVINGS ($)		ADDITIONAL COST TO BUILD ($)	TOTAL LIFE-CYCLE COST ($)	
				25 YEARS	50 YEARS	25 YEARS	50 YEARS		25 YEARS	50 YEARS
UNIT 44										
AS DESIGNED	20	23	139	2413	3567	7945	11742	9576	11989	13143
DESIGN 3	37	43	256	4465	6598	5893	8710	5405	9870	12003
DESIGN 2	53	71	426	7419	10964	2940	4344	2461	9880	13425
DESIGN 1	74	99	595	10358	15308	0	0	1530	11888	16838
UNIT 97										
AS DESIGNED	36	48	289	5039	7447	4759	7034	4167	9206	11614
DESIGN 3	38	44	263	4585	6777	5213	7704	3177	7762	9954
DESIGN 2	46	61	370	6439	9516	3359	4965	900	7339	10416
DESIGN 1	70	93	563	9798	14481	0	0	0	9798	14481

TABLE 6.1. Continued.

UNIT OR DESIGN TYPE	ANNUAL ENERGY USE (MBtu)	ANNUAL FUEL USE (MBtu)	ANNUAL FUEL COST ($)	NET PRESENT FUEL COST ($)		NET PRESENT FUEL SAVINGS ($)		ADDITIONAL COST TO BUILD ($)	TOTAL LIFE-CYCLE COST ($)	
				25 YEARS	50 YEARS	25 YEARS	50 YEARS		25 YEARS	50 YEARS
UNIT 124										
AS DESIGNED	12	16	96	1680	2482	6439	9516	8418	10098	10900
DESIGN 3	23	26	159	2775	4102	5343	7897	4408	7183	8510
DESIGN 2	35	47	281	4899	7240	3219	4758	1970	6869	9210
DESIGN 1	58	77	466	8119	11998	0	0	870	8989	12868
UNIT 134										
AS DESIGNED	23	26	159	2775	4102	2964	4380	2800	5575	6902
DESIGN 3	19	22	132	2293	3388	3446	5093	2411	4704	5799
DESIGN 2	28	37	225	3919	5792	1820	2689	565	4484	6357
DESIGN 1	41	55	330	5739	8482	0	0	0	5739	8482

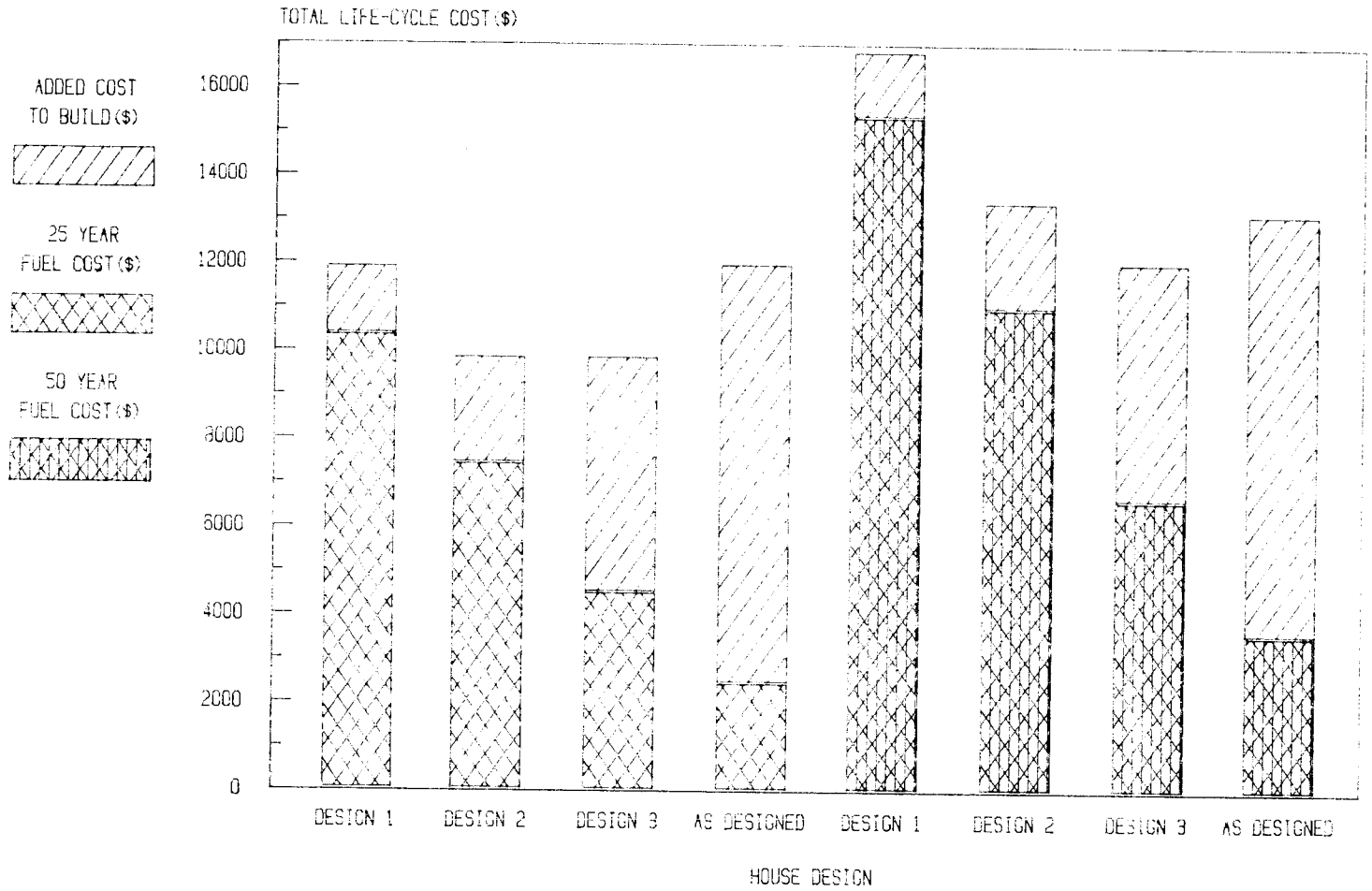

FIG. 6.1 Life-cycle cost economic analysis of four levels of energy efficiency based on EEHDP house 44.

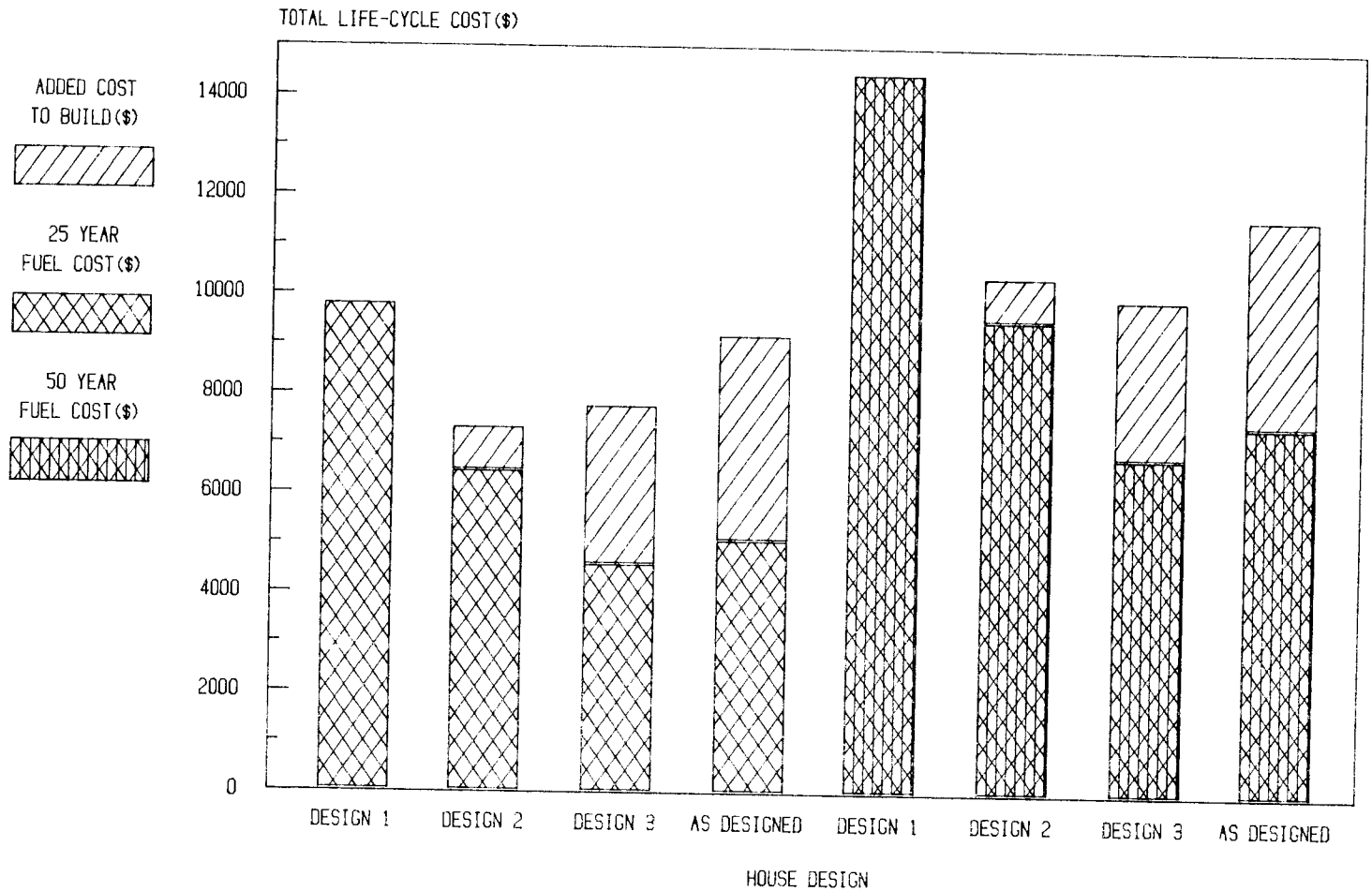

FIG. 6.2 Life-cycle cost economic analysis of four levels of energy efficiency based on EEHDP house 97.

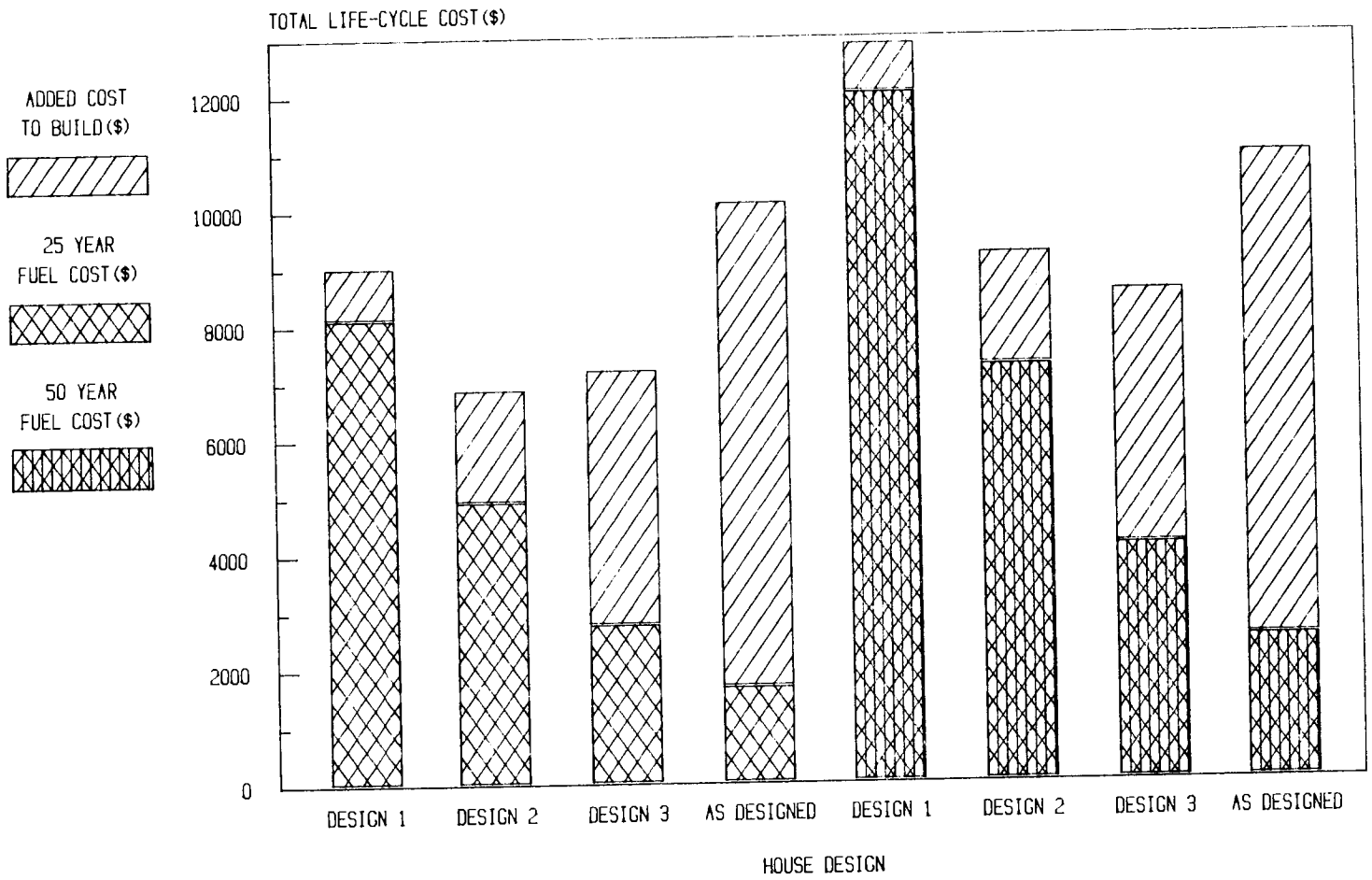

FIG. 6.3 Life-cycle cost economic analysis of four levels of energy efficiency based on EEHDP house 124.

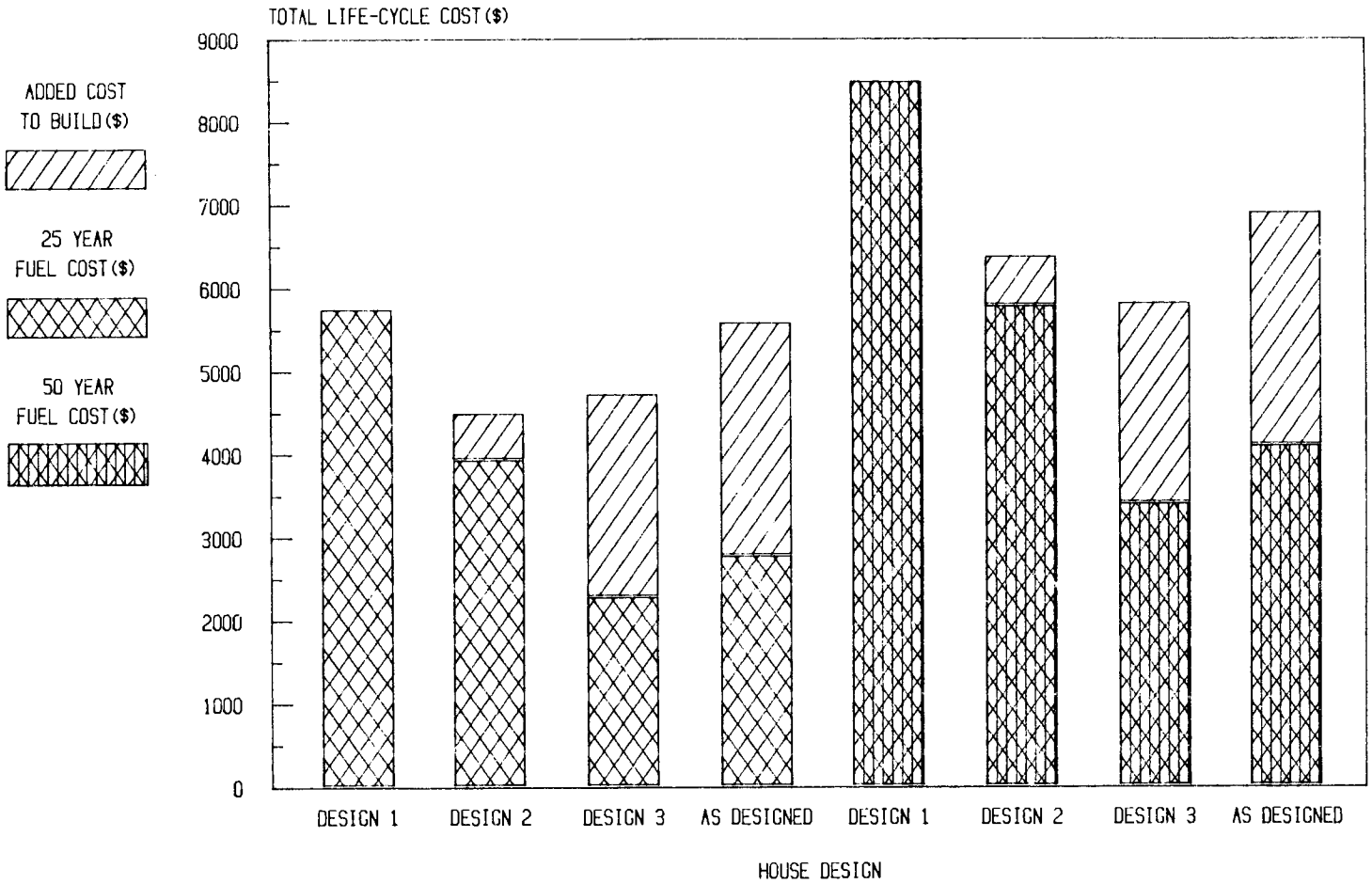

FIG. 6.4 Life-cycle cost economic analysis of four levels of energy efficiency based on EEHDP house 134.

TABLE 6.2. Present value of savings that could be achieved through building quality control for two levels of energy use reduction. Annual energy savings are for a 1500 ft^2 house in an 8000 heating degree day climate. Annual cost savings are for fuel costing $6.03/MBtu and a furnace efficiency of 80 percent.

REDUCTION IN TIF (BTU/SQFT-DD)	ANNUAL ENERGY SAVINGS (MBTU)	ANNUAL COST SAVINGS ($)	TIME PERIOD (YEARS)	DISCOUNT RATE (%)	PRESENT VALUE OF SAVINGS($)
1	12	90	25	3	1575
			50	3	2328
2	24	181	25	3	3151
			50	3	4656
1	12	90	25	0	2262
			50	0	4524
2	24	181	25	0	4524
			50	0	9048

7. SUMMARY, BUILDER GUIDELINES AND RECOMMENDATIONS

This study is based on information ranging from quantitative computer analysis to qualitative field examination to anecdotal observations, and thus represents a range of facts, judgments and speculations about the energy consumption in real houses. While this creates a challenging agenda for the researcher, it also presents to the reader a range of interpretations as to the meaning and value of the results presented. Furthermore, many findings need to remain general since the houses investigated in this study are "first generation" energy efficient houses, and many improvements in energy efficient design and construction have taken place in the five years since they were built. Because of this, a critical examination and use of these results is encouraged.

A primary objective of this project was to identify "what works" in energy-efficient housing. Basic findings were that low air leakage houses performed better than high air leakage houses, and that houses with below-slab air ducts used more energy than those without this feature. A tentative finding of this research is that construction quality, rather than any particular set of design features, is the key to superior energy performance. Future research should control construction quality to quantify the impact and cost of this variable.

7.1 ANALYTICAL FINDINGS.

The overall performance of the houses in the research program was excellent. The average measured thermal integrity factor for the entire group of 108 houses was 3.1 Btu/ft.^{2} ^{o}F day, with a range of 2.3 to 4.2. Because these values are a measure of the total building envelope performance exclusive of internal gains, the actual heat provided by the heating systems in these houses was even less. This average performance may be compared with two other studies in which the thermal performance of groups of houses was measured on the same basis. The SERI Class B monitoring program (18) found an average thermal integrity factor of 3.49 Btu/ft.^{2}-^{o}F day for the 54 houses studied. A larger sample of 262 newly constructed houses in Iowa (19) was evaluated using a survey based on utility billing data. The houses in this study were found to have an average Home Heating Index (equivalent to the Thermal Integrity Factor as defined in this study) of 4.73 Btu/ft.^{2}-^{o}F day.

A detailed statistical analysis performed on the metered data for the houses in the research project led to results that did not prove or disprove the effectiveness of the solar features incorporated in the houses examined. An analysis of the thermal integrity factors for the houses examined showed that there was no statistically significant change in the total energy used by the houses as the area of the solar aperture was increased. These results are based on an aggregate analysis of the houses in the study, and for any particular design, the range of performance may be large (as shown in Figure 4.3). In addition, much variability has been introduced into these results due to varied attention to construction detail as observed during the field investigation of these houses (see discussion under Field Observations).

An examination using self-reported survey data for the presence and use of window insulation showed that the reported use of window insulation had no significant effect in reducing the total energy consumption of the houses examined. While common sense dictates that some houses must be using less energy than they would without the use of window insulation, these results point to the difficulty of applying an energy saving feature so that aggregate savings are achieved.

Analysis of domestic hot water use in the submetered set of houses was aided by the observation that the seasonal variation in the supply water temperature provided a natural variable for examining hot water consumption. This led to the conclusion that the occupants of these houses used an average of 325 gallons of water per person per week, and that the average delivery temperature of this water was 101°F. These volumes and temperatures indicate that the use of low temperature solar batch water heaters followed by point-of-use single pass water heaters might be an optimal way of providing domestic hot water. Comparing the average performance of the electric water heaters to the submetered gas and solar/electric water heaters in the project, an average efficiency of 41 percent was found for the gas water heaters, and an average solar contribution of 19 percent was found for the solar/electric systems. Disaggregating the solar/electric systems into their original two groups yielded solar contributions of 45 $\pm$ 13 percent and 8 $\pm$ 12 percent for each group. The second group was located in an area of extremely hard water that might have produced the very poor performance observed. Using the above values for the average gray water volume and temperature, plus ASHRAE metabolic data, a net average loss due to occupancy of 27 therms/year per person was found for the houses in this study.

Applying a detailed statistical regression analysis using building design data plus self-reported survey data to the problem of predicting measured energy consumption produced mixed results. One result, however, that did prove to be consistently significant was the loss of space heating energy due to the presence of below slab forced air distribution systems. In this case, the statistical analysis showed that these houses had an average loss of 50 to 100 therms/year due to the below slab distribution system. This analysis also showed a very significant correlation of 39 therms/year per person increase in the ambient temperature independent load per added household occupant, in reasonable agreement with the net metabolic and gray water load obtained using submetered data (27 therms/year per person).

In order to evaluate the total building envelope thermal load, a normalized thermal load (NTL) value was defined and evaluated as part of this study. The NTL was determined by fitting a linear load line to the total metered energy thermalized within the building envelope as a function of the ambient temperature. By assuming that space heating was required for ambient temperatures below the thermostat setpoint temperature, the total thermal load of the building was divided into two parts, one dependent on ambient temperature and the other independent of ambient temperature. The load line required for the calculation of these values was determined for the metered data on each house using the Princeton Scorekeeping Method (PRISM) program.

The suitability of the PRISM program for this analysis is examined in detail in an appendix to this report. Based on the data and analysis in this report, the above model for the normalized thermal load yields information about the energy use of houses that is not available using other techniques.

The net and total energy consumptions of seven house designs were calculated using the CIRA and HOTCAN micro-computer programs. The calculated net energies ranged from 15 to 30 MBtu/year, with the calculated total energies being about 15 MBtu/year more than these. While the percentage variation between the results of these programs was somewhat large, the absolute differences were only about 5 MBtu/year. Comparison of the predicted and measured total energies yielded mixed results with measured energies deviating from the predicted values by an average of 11 MBtu/year. Correcting the measured energies for gray water heat loss reduced this average deviation to about 7 MBtu/year.

Four house designs were selected for cost analysis. In order to examine the cost effectiveness of the energy saving strategies demonstrated by these houses, four levels of energy efficiency were defined and applied to each design for life-cycle cost comparison. The cost of each of the sixteen houses defined in this manner (four designs times four levels of efficiency) was calculated using cost data obtained from the local building community. The net energy use for each design was found using the HOTCAN computer program. The total life-cycle cost was then calculated for 25- and 50-year time periods, using present fuel costs and a real discount rate of 3 percent. In each case, the building option based on the current Minnesota Energy Code (closely resembles current HUD-MPS) was the most cost effective for the 25 year time period.

7.2 FIELD OBSERVATIONS.

Instrumented field inspections of 25 houses were made using an infrared scanning camera and a precision blower door, plus a variety of other instruments for measuring temperature, humidity, wood moisture content, and furnace efficiency. While some measurements, such as air change rates and furnace efficiencies, could be readily quantified, the effects on energy use of other more complex phenomena, such as air movement through insulation, remain subjective. In addition to these field inspections, the indoor air quality was evaluated in 12 experimental and 12 control houses, with radon mitigation action and remeasurement carried out in two experimental and two control houses.

Infrared observations showed many examples of insulation that was not performing as intended. Many of these examples resulted from improperly fitting batt type insulation in wall or ceiling cavities that allowed for convective looping and thermal short circuits within the cavity. In some roof situations, the effectiveness of the insulation was compromised by the movement of ventilation air through rather than over, the insulation material. In several cases ceiling insulation was not performing properly because it had become wet due to condensation formed by warm moist house air leaking into the

attic. These examples point to the importance of properly installed air-vapor barriers for maintaining the integrity of insulating materials.

Most of the below grade insulation used in the houses examined was rigid board insulation applied to the exterior of foundation walls. Many of the above grade protective coverings required for the preservation of this insulating material had deteriorated, and had not been replaced or repaired. Also observed were thermal bridges formed by retaining walls and horizontal slabs that were butted against, but not insulated from exterior masonry walls. In this case, cold areas created on the exterior walls were easily seen with the infrared camera.

The most ubiquitous construction problem was air leakage. Air leakage into attics was found in nearly all houses; one of the most common sources of leakage was the attic access hatch. Even though the program submission forms for nearly all of the houses in the project indicated that the attic hatch had been sealed, the observations made in this study showed that only two houses actually had some kind of weather stripping in this area. Of greater concern were some of the air leaks found around furnace flues that may have wetted the insulation surrounding the flue pipe due to condensation. In several houses that had damp blown cellulose in contact with the flue pipe, the flue pipe had started to corrode, indicating that remedial action is probably required.

Dropped ceilings, such as soffit areas in kitchens and bathrooms, were another source of air leaks. In most of these areas, the air-vapor barrier was broken at the edge of the soffit so air could leak from the soffit into the attic. Complex framing areas that are hard to seal, such as the rim joist area, were also observed to be the origin of many air leaks. In addition to these primary sources of air leakage, many other smaller sources, such as plumbing and electrical openings, were observed to leak air. Overall, the average air change rate for the 17 detached houses examined in this study was found to be 4.18 air changes per hour at a pressure of 50 Pascals with the houses depressurized and with the intentional vents sealed.

Many types of mechanical systems were installed in the houses inspected, but because of various design and installation problems their performance was mixed. The average steady state efficiency for the 18 conventional gas furnaces measured was found to be 74 percent, with the lowest two units being just below 70 percent. The three induced draft recuperative furnaces measured all had efficiencies of about 87 percent. One of the recuperative furnaces examined was a replacement model for the original furnace that had failed after three years due to corrosion.

About 50 percent of the houses examined were equipped with air-to-air heat exchangers for heat recovery ventilation. All of these units were found to be poorly installed, and none had been provided with any means for balancing the air flows into and out of the house. Some of these heat exchangers had complex and difficult to operate control systems that were not understood by the homeowners. In most cases, the homeowners had received no instructions on the use and maintenance of these devices.

As discussed in the analytical findings section above, houses with below slab ducts were found to use more energy than houses without this type of warm air distribution system. About 50 percent of the houses examined had below slab air distribution systems. By measuring the entry and exit temperatures of the air moving through these systems, it was found that from 25 to 65 percent of the distributed energy was being lost to the duct work buried beneath the slab.

Many of the solar features incorporated in these designs were probably hampered from performing as expected because of frequently noted inattention to important details in both design and construction. Ducts intended to transport solar-warmed air often drew in cold outdoor air due to missed details. Solar domestic water heating systems were sometimes constructed without adequate controls or monitoring devices to assure their proper operation.

Improperly designed rockbeds for solar thermal storage also appeared to be a problem area for these houses. Although the performance of these rockbeds was not evaluated in detail, some observations were made. In several cases, because of the air circulation control system design or the design of the air duct system itself, warm, furnace heated, house air was allowed to pass through a rockbed that was below the setpoint temperature of the furnace thermostat. Other problems reported by homeowners were the presence of water in the rockbed in the spring, and the experience of allergic reactions at the start of the heating season.

A key finding of this research is that attention to detail in the design and construction of energy efficient housing, as well as all housing, would be richly rewarded by consistently improved energy performance. Correcting many small air leaks or misfitted insulation after a house is completed is very costly and unlikely to be returned in energy savings. But, avoiding these problems during construction would be very cost effective.

Yet, this attention to detail is apparently difficult to achieve. Perhaps the builders in the Energy Efficient Housing Demonstration Program did not expect that these details would affect energy performance. If this is the case, tools should be developed to show builders the importance of quality control.

The indoor air quality was evaluated in 12 experimental and 12 control houses using simple passive monitoring techniques to measure the nitrogen dioxide, formaldehyde, and radon levels in each house. No significant differences were found between the experimental and control groups, except for elevated levels of nitrogen dioxide in houses with gas cooking ranges.

Radon measurements showed that five of the above houses had radon concentrations that exceeded the 4 pCi/l level for which remedial action is recommended by the Environmental Protection Agency. Radon mitigation techniques applied to four of these houses resulted in significant reductions for two houses that were equipped with subfloor ventilation systems. The radon concentration in two houses that received below grade sealing and caulking was somewhat increased for one house, and not significantly affected for the other.

7.3 BUILDER GUIDELINES.

Three general builder guidelines can be derived from this research. Within the framework of these general guidelines, specific guidelines and methods for implementing them can be developed for different climatological regions and building practices.

GUIDELINE # 1

Envelope design and construction should be more sensitive to the application and use of thermal insulation. Insulation should be installed to prevent air movement within insulated cavities.

The rationale for this guideline is based on several observations of insulation being in place, but not performing effectively because of areas of higher conductivity or convective air movement within the insulation cavity. Numerous illustrations of these observations are given in sections 3.1.1 and 3.2.3.

GUIDELINE # 2

The design of exterior envelopes should specify details for air leakage reduction. In construction, these details should be followed and other possible sources of air leakage should be sealed.

Uncontrolled air leakage can seriously compromise an otherwise good design. In particular, if an extra investment in time and resources is being made to provide an energy efficient house, a relatively small additional investment to assure quality control to avoid air leakage would be most cost effective. These observations are discussed in Sections 3.1.1 and 3.1.2.

GUIDELINE # 3

Design and install the heat distribution system so as to insure effective operation.

Leakage of outdoor air into cold air returns or leakage of warm air from supply ducts into unheated spaces will reduce the effectiveness of the heating system. The potential for leakage is enhanced due to the fan driven pressure differentials in the distribution system, and the potential for heat loss is increased because of the high temperature differences between the ducts and the surrounding space. Examples that illustrate this guideline are given in section 3.1.4.

7.4 RECOMMENDATIONS.

7.4.1 Education of builders and designers.

From the general builder guidelines and results of the instrumented examinations provided in this report, specific builder guidelines could be assembled for particular climatic and construction industry conditions. Training designers and builders of new and remodeled homes to avoid the problems cited in this report would result in improved energy performance for the nation's housing stock.

A means of readily accomplishing this recommendation would be to provide copies of this report and its accompanying slides to people who are involved in educating the building community.

7.4.2. Extension of current research.

The data base established by this research effort has been only partially examined. Based on the results achieved to date, it appears that further analysis would continue to yield valuable insights into the ways in which houses and their occupants use energy. The following areas of investigation appear worthy of further analysis:

- Regression analysis using subsets of houses to examine more closely the effects of varying solar aperture area and below grade construction.
- New regression analysis of sunshine data (compiled, but never examined, as a part of the original study) to further understand the apparent independence of building performance on solar aperture area.
- Further examination of the reliability of the Normalized Thermal Load (NTL) method developed in this study. While this method yielded reliable results for the current study, its general applicability and reliability need to be established.
- Exploratory analysis based on field observations and submetered data. These observations and data formed the basis of the general results of the current study, but further house by house examination of correlations between these data sets is required to more completely understand the effects of specific construction problems and occupant behavior.
- Repair major defects in selected houses, monitor performance after work has been completed, and calculate the cost-effectiveness of retrofitting new houses.

7.4.3 Future research.

This research effort suggests ways to improve building practices for the construction of energy efficient houses. However, the question still remains, "What would it cost to build houses right in the first place, and how much better can we expect such houses to perform?" To answer this question would require a program to build a group of quality controlled houses that could be compared on a cost and performance basis with an equal set of houses built without the benefit of quality control. Such an experiment would yield valuable data on the cost-effectiveness of quality control in new construction that could be used as the basis for more effective building codes and housing policy.

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APPENDIX A

Program Documents

Meter Reading Agreement

As a paid meter reader for my development I will perform the following tasks on a timely and regular basis for a twelve month period starting October 8, 1983.

1) Read the gas and electric meters for each house in my development on the same day once each week.

2) Complete the data recording form to be provided and mail it to Robinson Technical Services the next day.

3) Read the time clocks located on either the electric water heater or the gas furnace once each month.

4) Record the cold water temperature in my house and the hot water temperatures in all the houses once each month.

5) Put recording temperature meters in place at the beginning of the program , and remove them at the end of the program.

6) Put a new paper tape and batteries in each temperature recorder once every three months.

For this service I will be paid a flat monthly rate of $25.00, plus $4.00 for each house in my development. Since my development has ____ houses I will be paid a total of $____ per month for this service.

I understand that I will be paid every three months, and that I will be paid only if my data reporting has been 100% complete. If I fail to report data for two consecutive weeks this agreement will be considered null and void.

Printed name:_____

Signature:_____

Address:_____

_____

Home Telephone:_____

Other Telephone:_____

FIG. A-1. Meter reading agreement for paid meter readers.

Meter Reading Agreement

Please check each statement to indicate your willingness to read meters in your development.

____I do not want to read any meters at all. I'm tired of meter reading.

____I would not mind if a neighbor read my meters.

____I would object to having my meters read by a neighbor.

____I will read my own meter only on a weekly basis and return the meter reading postcards sent to me.

____ I will read my own meter, plus those of my neighbors as listed below and return a recording form each week.

List of Houses to be Read

Address	Owner's name	Owner's signature

By signing and retuning this agreement I understand that I will perform the tasks checked above to the best of my ability for a period of one year starting October 8, 1983.

Printed name:_____

Signature:_____

Address:_____

_____

Home Telephone:_____

Other Telephone:_____

FIG. A-2. Meter reading agreement for volunteer meter readers.

RTS
ROBINSON TECHNICAL SERVICES

Griggs-Midway Building
1821 University Avenue, Suite 151S
St. Paul, Minnesota 55104

(612) 646-1695

November 6, 1984

Dear

As you know from the meter reading activity in your home the Minnesota Department of Energy and Economic Development is conducting a year long intensive research project involving those houses built under the Energy Efficient Housing Demonstration Program conducted by the Minnesota Housing Finance Agency. As a part of this research a detailed field study is being conducted on 25 of the 144 houses built under this program.

Based on preliminary analysis of the performance data of your house and other houses in your development your house has been selected for detailed field study. This study will involve a two-day site visit by one person (or alternatively a one-day visit by two persons). During this visit your home will receive a fan pressurization test to measure its air leakage rate, a thermal infrared scan both inside and out to detect air and heat leakage, and some on the spot correction of problems in those areas that are accessible for repair. This method of analyzing the performance of a house and performing on the spot repairs was first developed at Princeton University, and is called the "House Doctor" method of energy use analysis. This service will be performed for you free of any cost for labor or materials.

During the House Doctor visit sophisticated equipment will be used to measure and view the air and energy leakage from your home in a manner that will not affect either the appearance or cleanliness of your home. Your house will be pressurized to a small pressure using a blower that is installed in one door of your house. The air pressure and air flow rate through the blower serve as a measure of the air leakage rate for your house. During the time the blower is running the infrared scanning camera will be used to view the house and to detect any warm air that might be leaking out. The blower is then reversed and the infrared camera used to view cold air leaking into the house. Based on these infrared pictures of your house, materials will be applied to seal any leaks discovered. The infrared camera will also be used to look for missing insulation, and, where accessible, insulation will be added.

FIG. A-3. Letter to homeowners describing field work to be done.

Since we would like to complete this part of our research by January 1985, your prompt reply to this letter would be most appreciated. If possible, we would like a reply within one week, so that we may start scheduling visits. You will be called and an appointment will be set up to conduct this work sometime between now and January.

If you would like to participate in this part of our research project please complete and sign the enclosed information form, and return it to Robinson Technical Services in the enclosed envelope. If you do not wish to have a House Doctor visit to your home please check the box at the bottom of this letter and return it to Robinson Technical Services.

Sincerely yours,

David A. Robinson

/_/ I am not interested in participating in this aspect of the housing research project.

Copy: May Hutchinson, Minnesota Housing Finance Agency

FIG. A-3. Continued.

RTS
ROBINSON TECHNICAL SERVICES

Griggs-Midway Building
1821 University Avenue, Suite 151S
St. Paul, Minnesota 55104

(612) 646-1695

To: Bruce Nelson

Date: January 13, 1984

From: David Robinson

Subject: Selection of houses for indoor air quality survey

Using the questionnaires returned by the EEHDP homeowners, I have selected the houses discussed below as candidates for the indoor air quality survey described in the research project work statement. To assist you in your evaluation of these survey sites I am attaching copies of the questionnaires returned by the owners of the selected houses. In general houses were selected on the basis of having potentially large concentrations of any of the three contaminants being surveyed. These contaminants are radon, nitrogen dioxide, and formaldehyde. It was attempted to pick houses in which at least two out of three of these contaminants would be present. However, this was not always possible, particularly for the case of houses with gas ranges. My selections are as follows.

Unit 18)
This house has a gas range, a heavy smoker, and a sump in the basement, and is a good candidate for radon and combustion products(NO2) analysis. With three adults in the house there could also be additional cooking activity using the gas range.

Unit 35)
This house also has a gas range, and in addition has a Trombe wall passive solar system. The absence of a basement sump avoids results that could be confounded with radon emission from the Trombe wall.

Unit 45)
This house has a basement sump, and a kerosine heater is used. The NO2 levels in this house should be particularly interesting.

Unit 74)
This house has a heavy smoker and a sump in the basement. The NO2 levels due to smoking are of interest in this house.

Unit 85)
This house has a rock bed and a basement sump, and is a good candidate for radon analysis.

Unit 96)
This house has a wood foundation and a basement sump, and should provide information about soil as a radon source.

FIG. A-4. Memo to Bruce Nelson describing houses selected for indoor air quality monitoring.

Bruce Nelson, Page 2

Unit 105)
This and the next house seem to have a formaldehyde problem. They also have a block wall used for passive solar storage. A possible radon source.

Unit 106)
See unit 105

Unit 108)
This house could have a formaldehyde problem.

Unit 111)
This house was selected because it had a gas range.

Unit 117)
This house was selected because it had a gas range.

Unit 124)
This house has a gas range and sump in the basement. A concrete floor between the upper and lower levels could be a possible source of radon.

About six other houses could also have been chosen, but they would have had nearly identical characteristics to the houses listed above. An exception to this would be the Moorhead houses(units 1 to 8) that might have excessive radon concentrations as shown by Art Rosenfeld at the BERC meeting.

FIG. A-4. Continued.

RTS
ROBINSON TECHNICAL SERVICES

Griggs-Midway Building
1821 University Avenue, Suite 151S
St. Paul, Minnesota 55104

(612) 646-1695

February 29, 1984

Dear

Based on your completed Indoor Air Quality Questionnaire that you returned to us several months ago, your home has been selected for further indoor air quality analysis. Provided you are still interested in this part of our research program, please read this letter, complete the enclosed house survey form, and return the form to Robinson Technical Services in the enclosed envelope. If you are not interested in this offer, please check the box at the bottom of this letter and return it to Robinson Technical Services.

The indoor air quality survey to be taken in your home will be done using passive monitors that consist of small (about the size of a pen), simple plastic or glass tubes that contain materials chosen to absorb or record several types of indoor air contaminants. The contaminants to be measured are nitrogen dioxide, formaldehyde, and radon. Nitrogen dioxide is one of many products produced by the combustion of materials, and will be used to test for the presence of the products of combustion. Formaldehyde is a common industrial chemical used in the production of many household materials such as carpet and certain wood products. Radon is a naturally occurring radioactive gas present in many soils and in ground water. The monitors to be sent to you for placement in your home have been specifically designed to measure the low levels of these contaminants that we expect to be present. These levels will be compared with suggested standards and the results reported to you.

Houses exhibiting unusually high concentrations of any contaminant may also be the subject of further field examination to find sources of contamination. This would only be done provided the homeowner would like this additional research activity in his or her home.

To participate in this research you will need to help us with several activities. Because the entire survey will be done by mail, you will need to place the monitors in your house, record where they were put and when, and finally to seal off the monitors and return them to Robinson Technical Services for analysis. You will receive two monitors of each type; so you will be responsible for putting in place and returning six monitors in all. Prepaid mailers will be furnished for returning the monitors to Robinson Technical Services.

FIG. A-5. Letter to homeowners describing participation required for indoor air quality monitoring program.

February 29, 1984
Page 2

So that we can compare the air quality in your home with that of a more conventional house, we also need your help in finding a neighboring house that is similar to yours but built before 1978. The house should have as many characteristics as possible in common with yours, and should be chosen so that the two columns on the Indoor Air Quality House Survey form are as much alike as reasonable. We ask that you find a neighbor who is willing to participate in having an indoor air quality survey done in his or her home and together fill out and sign the survey form. This letter can be used to explain the research program to your neighbor, and an extra copy is included for this purpose.

After we receive a completed and signed house survey form, a kit of six monitors and instructions for use will be sent to each homeowner and neighbor free of charge. The nitrogen dioxide and formaldehyde monitors will each be exposed one week and then returned. The radon monitor will be returned after an 8 week exposure.

Because of the late start of our program your prompt attention to this request would be much appreciated. If possible we would like to have a reply by February 1.

Each monitoring kit plus analysis is worth about $175, and has been designed to produce accurate survey data. We hope that you will feel that the availability of this detailed information about your house will be adequate compensation for the effort we are asking on your part. For our part we will provide you with complete results of this survey for your personal use.

Sincerely yours,

David A. Robinson

/_/ I am not interested in participating in this aspect of the housing research project.

Copy: May Hutchinson, Minnesota Housing Finance Agency

FIG. A-5. Continued.

RTS
ROBINSON TECHNICAL SERVICES

Griggs-Midway Building
1821 University Avenue, Suite 151S
St. Paul, Minnesota 55104

(612) 646-1695

June 15, 1984

Dear

This letter presents the results of the indoor air quality survey done this past winter for the State Energy Division by Robinson Technical Services. As you know, 24 houses were surveyed using six monitors each (two for each contaminant), so a total of 144 monitors were sent out, returned, and analyzed.

The results for your house are shown below along with two other numbers that can be used for comparison purposes. The average value shown is the average of all 48 monitors used for each contaminant. The recommended levels shown are based on standards and guidelines issued by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers and the Environmental Protection Agency.

Contaminant (units)	Location	Concentration	Average	Recommended
Radon (pCi/1)	_____	_____	2.3	4.0
	_____	_____		
Nitrogen Dioxide (ug/m^3)	_____	_____	27	100
	_____	_____		
Formal-dehyde (ppm)	_____	_____	.05	.1
	_____	_____		

In general remedial action is suggested in those locations where the concentration exceeds the recommended level. If you would like more information about controlling the air quality in your home you may contact the Energy Information Center at 296-5175 in the metro area, or call the statewide number 1-800-652-9747 and ask for the Energy Information Center.

Sincerely yours,

David A. Robinson

FIG. A-6. Letter to homeowners presenting results of indoor air quality measurements.

APPENDIX B

Field Work Documents

Meter Reader_____ Date_____ Cold Water Temperature____ °F

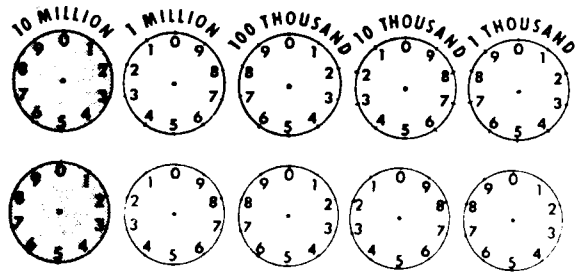
Owner_____

Address_____ Gas

Hour Meter_____

Hot Water Temperature_____

Comments_____ Elec



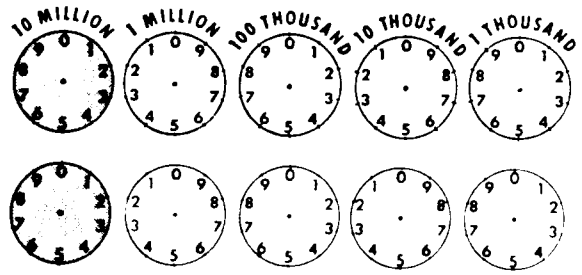
Owner_____

Address_____ Gas

Hour Meter_____

Hot Water Temperature_____

Comments_____ Elec



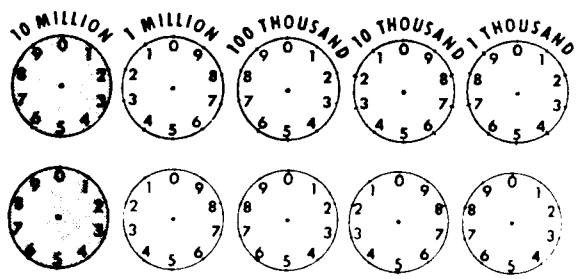
Owner_____

Address_____ Gas

Hour Meter_____

Hot Water Temperature_____

Comments_____ Elec



Owner_____

Address_____ Gas

Hour Meter_____

Hot Water Temperature_____

Comments_____ Elec

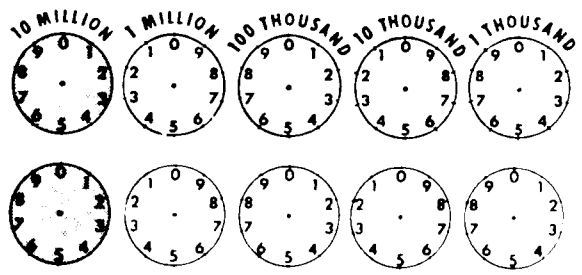


FIG. B-1. Data recording form for submetered houses. This self-mailing form was returned on a weekly basis by the paid meter readers in the research program.

Meter Reader_____Number_____

Owner_____Address_____

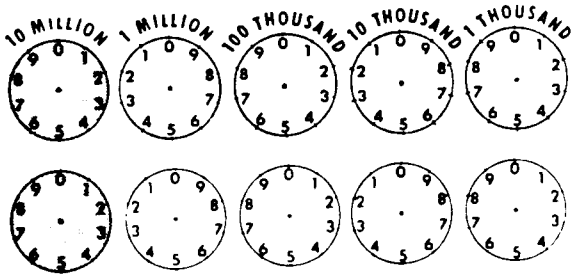
Month:_____

Day:_____SMTWTFS
(Enter date and circle day of week read)

Comments:

Gas

Elec



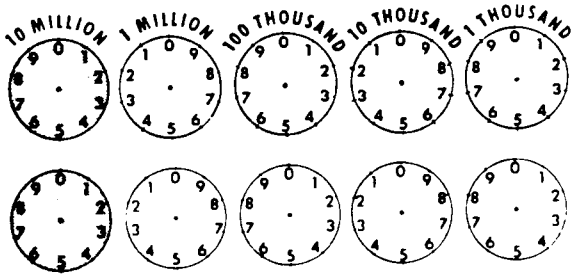
Month:_____

Day:_____SMTWTFS

Comments:

Gas

Elec



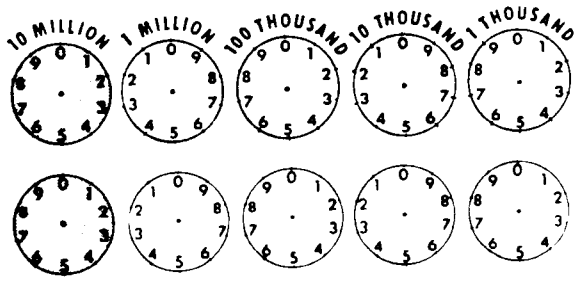
Month:_____

Day:_____SMTWTFS

Comments:

Gas

Elec



Month:_____

Day:_____SMTWTFS

Comments:

Gas

Elec

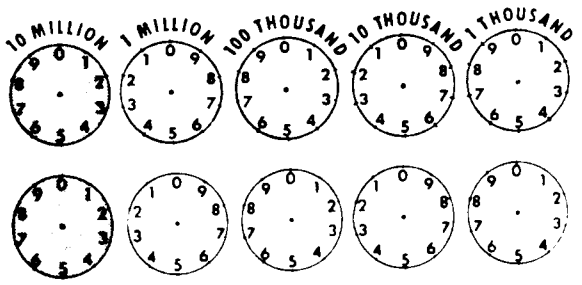


FIG. B-2. Data recording form for non-submetered houses. This self-mailing form was returned every four weeks by the volunteer meter readers in the research program.

Indoor Air Quality Questionnaire

In order to assist us in the selection of houses to be examined for indoor air quality please answer the following. In each case circle the best answer, or provide the number requested.

Name:_____

Address:_____

_____

1) Generally do you think that the quality of the air in your house is: excellent, very good, good, poor, unacceptable?

2) During the winter does the amount of humidity in your house make it: too dry, about right, too moist?

3) During the winter do you use a dehumidifier or humidifier to control moisture levels: yes or no? If so which device: dehumidifier or humidifier?

4) Does your house have an air-to-air heat exchanger: yes or no? If so, is it used to reduce moisture in the winter: yes or no?

5) Describe the approximate amount of water condensation on your windows during cold winter weather: windows are clear, some slight fogging in corners, fogged over entire area, some water droplets form, many droplets form and water runs off window.

6) Have you noticed any mold on your walls or ceilings: yes or no? Comment:
_____.

7) How many adults live in the house?_____ How many children 12 or under live in the house?_____

8) Are there smokers in the house: yes or no? If so, how many packs of cigarettes are smoked per week in the house?_____

9) Does your house have any unventilated combustion devices in it such as a kerosine heater or a gas range: yes or no? If so, list the devices here:
_____.

10) Do you burn wood to heat your home: yes or no? Comments:
_____.

11) Have you or members of your family experienced respiratory illnesses beyond the usual winter colds and coughs: yes or no? Comments:_____
_____.

12) Have you or members of your family experienced irritation of the eyes or nose resulting in tearing and painful eyes, or tingling sensations in the nose: yes or no? Comments_____.

13) Do you have an open sump in the basement used to collect water from drain tiles installed around the foundation of the house: yes, no, not sure?

14) Would you like your house to be included in the sample of houses to be examined for indoor air quality: yes, no, need more information ?

FIG. B-3. Indoor air quality questionnaire used to select houses for monitoring.

Indoor Air Quality House Survey

Your Name Name:_____

Address Address:_____

and _____

Phone Home Phone:_____ Other Phone:_____

Neighbor's Name:_____

Name Address:_____

Address and _____

Phone Home Phone:_____ Other Phone:_____

Please complete each question for each house, and place answer in the appropriate column. Please sign as indicated at end of form.

	Your House	Your Neighbor's House
1) Year in which house was built?		
2) Amount of humidity in the house during the winter if a humidifier is <u>not</u> used: too dry, OK, too moist.		
3) How many adults live in the house?		
4) How many children 12 or under live in the house(list all other people as adults)?		
5) Are there smokers in the house?		
If so, how many packs of cigarettes are smoked per week in the house?		
6) List any unventilated combustion devices used in the house, such as a gas range or kerosine heater.		
7) Is wood burned to heat the house?		
8) Does the house have any new(less than six months old) carpet, cabinets, or furniture?		
9) Depth of basement floor below the level of the outside ground: full(7-8 feet), half(3-4 feet), no basement(slab on grade).		

FIG. B-4. Indoor air quality house survey used as homeowner worksheet for the selection of control houses.

	Your House	Your Neighbor's House
10) Does the house have a foundation drain tile system leading to an open or loosely covered sump in the basement?		

Please indicate your willingness to participate in the research survey described in the accompanying letter by signing below.

Your signature: _____

Your neighbor's signature: _____

FIG. B-4. Continued.

MONITORING INSTRUCTIONS

STEP 1 Select locations for monitors. Place tube type monitors for formaldehyde and nitrogen dioxide in areas where you spend a lot of time such as a living room or bedroom. Do not place these tube type monitors directly in a kitchen, bathroom, or laundry area. Place one radon monitor in your basement and place the other monitor somewhere else in your house. The radon monitors are in the aluminum foil envelopes.

STEP 2 Open the tube type monitors and put them in place. Remove the caps from each tube type monitor and hang the monitors from your ceiling using the tacks provided(or they may be taped up or tied to a fixture). Save the caps, and the small formaldehyde monitor box. The monitors should be hung so that they are 2 feet away from any wall. Use the labels provided to record the location of the tubes, and the date and time the tubes were open to the air in your home. The formaldehyde monitors need to have their labels placed on the tubes.

These monitors are to be left open for one week. During this week please fill out the Daily Activity Form for each day. After one week the tubes should be recapped and sent to Robinson Technical Services(see mailing instructions).

STEP 3 Use a scissors to open the radon monitors by cutting open the aluminum envelopes along one edge. Save the envelopes. By unwinding the labels the radon monitors may be hung up as in step 2 or they may just be set on a shelf or table. **Do not remove the caps on these monitors!** Use the label to record the location of each monitor and the dates the monitors were put in place and removed.

These radon monitors should be left in place six weeks. They should then be folded up inside the aluminum envelopes and returned to Robinson Technical Services(see mailing instructions).

Note: All monitoring materials are non-toxic and may be put in the garbage if they should become broken.

MAILING INSTRUCTIONS

STEP 1 After one week cap the tube type detectors and record the stop time on each tube. Be sure the location is also shown on each. Place the formaldehyde monitors in their original box. Put this box, the nitrogen dioxide monitors, and the Daily Activity Form in the white prepaid envelope and return to Robinson Technical Services.

STEP 2 After six weeks record the stop time on each radon monitor and check to be sure the location has been recorded. Rewrap each monitor in its original foil envelope(use kitchen foil if it has become lost) and return both monitors to Robinson Technical Services in the prepaid manila envelope.

FIG. B-5. Instructions for the use of the passive indoor air quality monitors used in the research program.

DAILY ACTIVITIY FORM

Day After Start of Test	Number of People at Home*		Number of Cigarettes, Cigars, or Pipe Fills Smoked	Hours Use of Kerosine Space Heater or Gas Range (specify)	Number of Times Exhaust Fan Used+		Number of Windows Open
	Day	Night			Kitchen	Bath	
1							
2							
3							
4							
5							
6							
7							
8							

*Use A or C to indicate adults or children 12 and under respectively. For example, for two adults and two children 12 and under write, 2A and 2C.

+Only for fans that exhaust to the outside of the house.

Add any comments on special household activities affecting the indoor air quality in your home during this test period:_____

Name:_____

Address:_____

FIG. B-6. Daily activity form used for the first week of indoor air quality monitoring.

HOUSING STRUCTURE SURVEY

Family Name _____

Address _____

Telephone _____ Date _____

GENERAL STRUCTURE CHARACTERISTICS

House Type: ☐ detached ☐ attached ☐ apartment ☐ other (specify) _____

Size: Ground Level Area (include attached garage) _____ ft^2 Total Volume _____ ft^2 Age: _____

Structure Materials: ☐ wood ☐ concrete block ☐ poured concrete ☐ other (specify) _____

External Cladding: ☐ wood ☐ stucco ☐ brick ☐ metal ☐ vinyl ☐ concrete ☐ other (specify) _____

Number of floors above substructure: ☐ one ☐ two ☐ three ☐ split ☐ other (specify) _____

Attic: ☐ yes ☐ no Use: ☐ storage ☐ residence ☐ other (specify) _____

Vents: ☐ yes ☐ no Windows: ☐ yes ☐ no

Garage: ☐ detached ☐ attached—one wall borders living space ☐ attached—two walls border living space

Door to living space: ☐ yes ☐ no Area: _____ ft^2

INTERIOR SURFACE MATERIALS

Walls: _____ plaster board, _____ wood, _____ plaster, _____ brick, _____ other (specify) _____

Floors: _____ wood, _____ linoleum, _____ carpet, _____ other (specify) _____

Ceilings: _____ wood, _____ plaster board, _____ plaster, _____ other (specify) _____

ENERGY USE ASPECTS

Heating System: ☐ central forced air ☐ hot water/steam ☐ baseboard ☐ wall/space heater ☐ other (specify) _____

Energy: ☐ gas ☐ oil ☐ electric ☐ solar ☐ other (specify) _____

Heat Exchanger: ☐ central ☐ window _____ flow rate

Fire Places: _____ number in house _____ number with dampers _____ number with glass doors

Air Conditioning: ☐ central ☐ windows ☐ heat pump

Infiltration Characteristics: ☐ apparently tight ☐ apparently leaky ☐ uncertain

Weather Stripping: ☐ doors ☐ windows

Exhaust Fans: ☐ kitchen ☐ bathroom ☐ other (specify) _____

Kitchen Range: ☐ gas ☐ electric Unvented Space Heater: ☐ yes ☐ no Specify _____

SUBSTRUCTURE (Complete more than one section, if applicable.)

Basement: floor area _____ ft^2 depth below ground _____ ft. height above ground _____ ft.

Floor Material ☐ open ground ☐ concrete, thickness _____ in. (if known) ☐ other (specify) _____

Floor Finish: ☐ sealant ☐ paint ☐ linoleum ☐ carpet ☐ other (specify) _____

Wall Material: ☐ concrete block ☐ poured concrete ☐ stone ☐ wood ☐ other (specify) _____

Wall Finish: ☐ sealant ☐ paint ☐ plasterboard ☐ other (specify) _____

Doors: ☐ to exterior ☐ to living space ☐ windows _____ ft^2 (total window area)

Drainage: ☐ sump ☐ drain ☐ none ☐ other (specify) _____

Use: ☐ recreation ☐ storage ☐ residence ☐ other (specify): _____

Crawl Space: area _____ ft^2 depth below ground _____ ft. height above ground _____ ft.;

Floor Material: ☐ open ground ☐ concrete, thickness _____ in. (if known) ☐ other (specify) _____

Floor Finish: ☐ sealant ☐ paint ☐ none ☐ other (specify) _____

Wall Material: ☐ concrete block ☐ poured concrete, thickness _____ in. (if known) ☐ stone ☐ wood ☐ other (specify) _____

Vents: ☐ yes ☐ no Door (or other opening): ☐ to exterior ☐ to living space

Slab: area _____ ft^2 thickness _____ in. (if known)

Finish: ☐ sealant ☐ linoleum ☐ carpet ☐ wood ☐ other (specify) _____

Other Substructure Type: Describe. _____

FIG. B-7. Housing structure survey form used to collect information about control houses.

3.10 Builder Certification and Submission Checklist

The checklist in this Section is provided as a means for the submittor to check that all pertinent items have been submitted as required. All items must be checked "yes", "no", or "not applicable". The checklist will be used by the MHFA to determine the completeness of the submission.

Following the checklist is a description of the commitments the proposer agrees to enter into. The checklist and commitement form must be signed by an officer of the company whose signature binds the proposal.

3.10.1 Infiltration Reduction Checklist

Following is a list of items to reduce infiltration that are described in Section 2.3.1 and 2.3.2 Indicate in the appropriate box if the infiltration reduction measure will be incorporated in the building. Where appropriate these measures should be detailed in the drawings or listed in the specification.

Items from 2.3.1		Yes	No	Not Applicable
.1	Vestibules			
.2	Casement windows, swinging doors			
.3	Doors with magnetic weather-stripping			
.4	Recessed lights			
.5	Insulate and weatherstrip attic door			
.6	Vent dampers			
.7	Combustion air ducts			
.8	Seal cracks at windows, doors and framing			
.9	Independent continuous vapor barrier			
.10	Fireplace			
	a. damper on top of flue			
	b. glass doors			
	c. combustion air duct			
	d. masonry thermal break			

FIG. B-8. Infiltration reduction checklist. This checklist was a required part of each builder's program proposal.

3.10.1 Infiltration Reduction Checklist (Continued)

	Item from 2.3.1 (Continued)	Yes	No	Not Applicable
	e. air tight insulated partition around flues			
	f. insulated firebox			
	g. insulated masonry			
.11	Caulk holes in upper and lower wall plates			
.12	Gaskets for electrical outlets and switches			
.13	Airtight heating stove with combustion air duct			
.14	Seal joints in ducts			
.15	Ducts partially formed by joist spaces			
.16	Sill plate sealer and caulking			
.17	Vapor barriers at drop ceilings			

	Item from 2.3.2			
.18	Air/air heat exchange			
.19	Caulk joint at bottom of gypsum board walls			
.20	Exhaust fans to have motor dampers			
.21	Caulk around all pipes and conduits			
.22	Seal around vents and chimneys			

3.10.2 Submission Material

In order for the submission to be complete, the following material must be included in this submission.

Item	Included	Not Included
Solar access easement (not necessary)		
Two copies of Section 3.0 Submission Form		
Two copies of all drawings and specifications listed in Section 3.8		
Complete Sworn Construction Statement Section 3.9		

FIG. B-8. Continued.

APPENDIX C.

Sample Data Files

TABLE C-1. Data files for 47 submetered houses.

DATABASE	FILES	# RCDS	ENERGY USE(space heat, hot water)[a]
HOUSE1	DBF	00052	G,E
HOUSE2	DBF	00052	G,E
HOUSE3	DBF	00052	G,E
HOUSE4	DBF	00052	G,E
HOUSE5	DBF	00052	G,E
HOUSE6	DBF	00052	G,E
HOUSE7	DBF	00052	G,E
HOUSE8	DBF	00051	G,E
HOUSE26	DBF	00051	G,SG
HOUSE27	DBF	00051	G,SG
HOUSE28	DBF	00051	G,SG
HOUSE41	DBF	00051	G,SE
HOUSE42	DBF	00051	G,SE
HOUSE43	DBF	00051	G,SE
HOUSE44	DBF	00051	G,SE
HOUSE45	DBF	00051	G,SE
HOUSE46	DBF	00051	G,SE
HOUSE47	DBF	00051	G,SE
HOUSE48	DBF	00051	G,SE
HOUSE94	DBF	00042	G,G
HOUSE95	DBF	00042	G,G
HOUSE96	DBF	00042	G,G
HOUSE97	DBF	00042	G,G
HOUSE120	DBF	00053	G,G
HOUSE121	DBF	00053	G,G
HOUSE122	DBF	00053	G,G
HOUSE123	DBF	00053	G,G
HOUSE124	DBF	00053	G,G
HOUSE125	DBF	00053	G,G
HOUSE126	DBF	00053	G,G
HOUSE127	DBF	00053	G,G
HOUSE128	DBF	00052	E,E
HOUSE129	DBF	00052	E,E
HOUSE130	DBF	00052	E,E
HOUSE131	DBF	00052	E,E
HOUSE132	DBF	00053	G,SE
HOUSE133	DBF	00053	G,SE
HOUSE134	DBF	00053	G,SE
HOUSE135	DBF	00053	G,SE
HOUSE136	DBF	00053	G,SE
HOUSE137	DBF	00053	G,SE
HOUSE138	DBF	00053	G,SE
HOUSE139	DBF	00053	G,SE
HOUSE140	DBF	00053	G,SE
HOUSE141	DBF	00053	G,SE
HOUSE142	DBF	00053	G,SE
HOUSE143	DBF	00053	G,SE

[a]G-gas, E-electric, SE-solar with electric backup, SG-solar with gas backup.

TABLE C-2. Portions of a typical file for house with submetered electric water heater. File structure with description of fields is shown in Table C-3. Empty fields are filled with default values.

```
USE HOUSE1
LIST FOR #<=10.OR.#>=40
```

00001	DEC	18	83	0	0	DEC	18	0.0	3.84	53	999	999	999	0	0	201
00002	DEC	26	83	46	319	XXX	99	99999.9	3.84	99	999	999	999	-11	48	209
00003	JAN	2	84	2	229	XXX	99	99999.9	3.84	99	999	999	999	6	74	216
00004	JAN	9	84	11	241	JAN	9	85.4	3.84	53	143	999	999	23	27	223
00005	JAN	16	84	20	242	XXX	99	99999.9	3.84	99	999	999	999	0	50	230
00006	JAN	23	84	24	257	XXX	99	99999.9	3.84	99	999	999	999	-4	76	237
00007	JAN	30	84	13	163	XXX	99	99999.9	3.84	99	999	999	999	16	22	244
00008	FEB	7	84	16	137	XXX	99	99999.9	3.84	99	999	999	999	13	51	252
00009	FEB	14	84	14	227	XXX	99	99999.9	3.84	50	140	999	999	27	34	259
00010	FEB	21	84	9	197	XXX	99	99999.9	3.84	99	999	999	999	32	28	266
00040	SEP	20	84	0	163	SEP	23	57.1	3.84	64	142	999	999	61	82	478
00041	SEP	27	84	1	180	XXX	99	99999.9	3.84	99	999	999	999	47	41	485
00042	OCT	4	84	0	179	XXX	99	99999.9	3.84	99	999	999	999	51	82	492
00043	OCT	11	84	1	159	OCT	14	75.0	3.84	62	142	999	999	60	30	499
00044	OCT	19	84	2	224	XXX	99	99999.9	3.84	99	999	999	999	49	23	507
00045	OCT	26	84	5	220	XXX	99	99999.9	3.84	99	999	999	999	40	38	514
00046	NOV	2	84	11	203	XXX	99	99999.9	3.84	99	999	999	999	25	60	521
00047	NOV	9	84	6	198	NOV	11	67.8	3.84	62	142	999	999	34	54	528
00048	NOV	16	84	7	270	XXX	99	99999.9	3.84	99	999	999	999	29	59	535
00049	NOV	23	84	9	207	XXX	99	99999.9	3.84	99	999	999	999	27	75	542
00050	NOV	30	84	12	187	XXX	99	99999.9	3.84	99	999	999	999	33	23	549
00051	DEC	7	84	16	194	XXX	99	99999.9	3.84	99	999	999	999	10	54	556
00052	DEC	14	84	17	208	DEC	16	80.4	3.84	54	142	999	999	21	58	563

TABLE C-3 Typical file structure for house with submetered electric water heater.

```
 LIST STRUCTURE
STRUCTURE FOR FILE:  B:HOUSE1  .DBF
NUMBER OF RECORDS:   00052
DATE OF LAST UPDATE: 02/08/85
PRIMARY USE DATABASE
```

FLD	NAME	TYPE	WIDTH	DEC	Description(units)
001	MONTH	C	003		
002	DATE	N	002		Date gas and/or electric
003	YEAR	N	002		meter(s) read
004	GAS	N	004		Gas consumption(100 ft^3)
005	ELECT	N	005		Electric consumption(kWh)
006	MONTHS	C	003		Date submeter read
007	DATES	N	002		
008	SUBM	N	007	001	Water heater on-time(hours)
009	CONSTANT	N	004	002	Water heater power(kW)
010	COLD:TEMP	N	002		Supply water temperature(^oF)
011	HOT:TEMP	N	003		Hot water temperature(^oF)
012	IN1:TEMP	N	003		Fields reserved for inside
013	IN2:TEMP	N	003		temperatures
014	OUT:TEMP	N	003		Average outside temperature(^oF)
015	PERCENTSS	N	003		Average percent sunshine
016	RECORD:NO	N	004		Days from start of weather file
** TOTAL **			00054		

TABLE C-4. Portions of a typical file for house with submetered gas furnace. File structure with description of fields is shown in Table C-5. Empty fields are filled with default values.

```
USE HOUSE120
LIST FOR #<=10.OR.#>=40
```

00001	DEC	4	83	0	0	DEC	4	0.0	0.42	54	146	999	999	0	0	187
00002	DEC	11	83	17	138	XXX	99	99999.9	0.42	99	999	999	999	13	20	194
00003	DEC	18	83	22	141	XXX	99	99999.9	0.42	99	999	999	999	5	41	201
00004	DEC	26	83	33	167	XXX	99	99999.9	0.42	99	999	999	999	-10	57	209
00005	JAN	1	84	19	229	JAN	2	17.3	0.42	52	144	999	999	7	61	215
00006	JAN	8	84	10	16	XXX	99	99999.9	0.42	99	999	999	999	26	46	222
00007	JAN	15	84	22	123	XXX	99	99999.9	0.42	99	999	999	999	7	38	229
00008	JAN	22	84	24	144	XXX	99	99999.9	0.42	99	999	999	999	-6	67	236
00009	JAN	29	84	21	137	ZZZ	29	14.9	0.42	46	164	999	999	18	18	243
00010	FEB	5	84	17	103	XXX	99	99999.9	0.42	99	999	999	999	19	51	250
00040	SEP	2	84	4	120	SEP	4	0.0	0.42	66	136	999	999	68	72	460
00041	SEP	10	84	4	122	XXX	99	99999.9	0.42	99	999	999	999	60	74	468
00042	SEP	16	84	4	119	XXX	99	99999.9	0.42	99	999	999	999	57	71	474
00043	SEP	26	84	6	148	XXX	99	99999.9	0.42	99	999	999	999	58	62	484
00044	OCT	1	84	4	74	XXX	99	99999.9	0.42	99	999	999	999	47	78	489
00045	OCT	7	84	6	111	OCT	7	0.3	0.42	62	142	999	999	58	34	495
00046	OCT	15	84	5	137	XXX	99	99999.9	0.42	99	999	999	999	60	8	503
00047	OCT	21	84	4	100	XXX	99	99999.9	0.42	99	999	999	999	45	27	509
00048	OCT	30	84	10	153	XXX	99	99999.9	0.42	99	999	999	999	43	51	518
00049	NOV	4	84	11	84	NOV	4	2.8	0.42	58	136	999	999	33	17	523
00050	NOV	11	84	10	125	XXX	99	99999.9	0.42	99	999	999	999	37	46	530
00051	NOV	18	84	13	100	XXX	99	99999.9	0.42	99	999	999	999	32	47	537
00052	NOV	26	84	14	75	XXX	99	99999.9	0.42	99	999	999	999	33	58	545
00053	DEC	4	84	21	132	XXX	99	99999.9	0.42	50	154	999	999	21	40	553

TABLE C-5 Typical file structure for house with submetered gas furnace.

```
  LIST STRUCTURE
STRUCTURE FOR FILE:  B:HOUSE120.DBF
NUMBER OF RECORDS:   00053
DATE OF LAST UPDATE: 02/15/85
PRIMARY USE DATABASE
```

FLD	NAME	TYPE	WIDTH	DEC	Description(units)
001	MONTH	C	003		
002	DATE	N	002		Date gas and electric
003	YEAR	N	002		meters read
004	GAS	N	004		Gas consumption(100 ft^3)
005	ELECT	N	005		Electric consumption(kWh)
006	MONTHS	C	003		Date submeter read
007	DATES	N	002		
008	SUBM	N	007	001	Gas valve on-time(hours)
009	CONSTANT	N	004	002	Gas flow rate(100 ft^3/hour)
010	COLD:TEMP	N	002		Supply water temperature(^oF)
011	HOT:TEMP	N	003		Hot water temperature(^oF)
012	IN1:TEMP	N	003		Fields reserved for inside
013	IN2:TEMP	N	003		temperatures
014	OUT:TEMP	N	003		Average outside temperature(^oF)
015	PERCENTSS	N	003		Average percent sunshine
016	RECORD:NO	N	004		Days from start of weather file
** TOTAL **			00054		

TABLE C-6. Volunteer data files for 18 houses. Gas and electric meters read at the same time.

DATABASE	FILES	# RCDS	ENERGY USE[a]
HOUSE15	DBF	00068	G
HOUSE32	DBF	00048	G
HOUSE34	DBF	00052	Propane
HOUSE51	DBF	00047	G
HOUSE67	DBF	00047	G
HOUSE69	DBF	00053	G
HOUSE73	DBF	00052	G
HOUSE74	DBF	00052	G
HOUSE82	DBF	00055	E
HOUSE83	DBF	00052	E
HOUSE85	DBF	00052	E
HOUSE108	DBF	00053	G
HOUSE109	DBF	00053	G
HOUSE116	DBF	00043	G
HOUSE155	DBF	00049	G
HOUSE158	DBF	00052	G
HOUSE159	DBF	00053	G
HOUSE164	DBF	00051	E

[a]G-gas space heat, E-all electric.

TABLE C-7. File structure and portions of a typical file for a house with a volunteer meter reader reading gas and electric meters at the same time each week.

```
  USE HOUSE32
  LIST FOR #<=10.OR.#>=40
00001  JAN   1  84    0      0  999  999    0    0   215
00002  JAN   8  84   20    130  999  999   26   46   222
00003  JAN  15  84   30    120  999  999    7   38   229
00004  JAN  23  84   34    135  999  999   -2   59   237
00005  JAN  29  84   30    148  999  999   18   22   243
00006  FEB   5  84   24    150  999  999   19   51   250
00007  FEB  14  84   27    171  999  999   23   40   259
00008  FEB  19  84   13     98  999  999   36   16   264
00009  FEB  26  84   16    117  999  999   32   57   271
00010  MAR   4  84   17    146  999  999   25   64   278
00040  NOV   4  84   15    131  999  999   34   30   523
00041  NOV  11  84   14    138  999  999   37   46   530
00042  NOV  18  84   16    141  999  999   32   47   537
00043  NOV  25  84   13    149  999  999   31   65   544
00044  DEC   2  84   23    146  999  999   29   19   551
00045  DEC   9  84   24    144  999  999   17   76   558
00046  DEC  16  84   23    130  999  999   28   22   565
00047  DEC  30  84   59    258  999  999   13   46   579
00048  JAN   6  85   25    130  999  999   12   76   586
```

```
  LIST STRUCTURE
STRUCTURE FOR FILE:   B:HOUSE32 .DBF
NUMBER OF RECORDS:    00048
DATE OF LAST UPDATE: 02/19/85
PRIMARY USE DATABASE
FLD       NAME       TYPE WIDTH   DEC   Description(units)
001      MONTH        C    003          Date gas and/or electric
002      DATE         N    002          meter(s) read
003      YEAR         N    002
004      GAS          N    004          Gas consumption(100 ft^3)
005      ELECT        N    005          Electric consumption(kWh)
006      IN1:TEMP     N    003          Fields reserved for inside
007      IN2:TEMP     N    003          temperatures
008      OUT:TEMP     N    003          Average outside temperature(°F)
009      PERCENTSS    N    003          Average percent sunshine
010      RECORD:NO    N    004          Days from start of weather file
** TOTAL **               00033
```

TABLE C-8 Utility data files for 62 houses.

DATABASE	FILES	# RCDS	ENERGY USE[a]
HOUSE9	DBF	00015	G
HOUSE10	DBF	00015	G
HOUSE11	DBF	00015	G
HOUSE12	DBF	00012	G
HOUSE13	DBF	00015	G
HOUSE14	DBF	00015	G
HOUSE17	DBF	00015	G
HOUSE18	DBF	00012	G
HOUSE19	DBF	00015	G
HOUSE20	DBF	00014	G
HOUSE21	DBF	00015	G
HOUSE24	DBF	00015	G
HOUSE29	DBF	00014	G
HOUSE30	DBF	00014	G
HOUSE31	DBF	00013	G
HOUSE49	DBF	00019	G
HOUSE50	DBF	00018	G
HOUSE52	DBF	00019	G
HOUSE53	DBF	00013	G
HOUSE54	DBF	00012	G
HOUSE55	DBF	00013	G
HOUSE57	DBF	00013	G
HOUSE58	DBF	00013	G
HOUSE59	DBF	00013	G
HOUSE60	DBF	00013	G
HOUSE61	DBF	00013	G
HOUSE62	DBF	00013	G
HOUSE63	DBF	00012	G
HOUSE65	DBF	00010	G
HOUSE66	DBF	00011	G
HOUSE68	DBF	00012	G
HOUSE70	DBF	00013	G
HOUSE71	DBF	00014	G
HOUSE72	DBF	00015	G
HOUSE75	DBF	00015	G
HOUSE76	DBF	00013	G
HOUSE77	DBF	00014	G
HOUSE84	DBF	00019	E
HOUSE105	DBF	00012	E
HOUSE106	DBF	00012	E

DATABASE	FILES	# RCDS	ENERGY USE
HOUSE110	DBF	00013	G,E
HOUSE111	DBF	00012	G,E
HOUSE112	DBF	00013	G,E
HOUSE113	DBF	00013	G,E
HOUSE114	DBF	00013	G,E
HOUSE115	DBF	00013	G,E
HOUSE117	DBF	00013	G,E
HOUSE119	DBF	00011	G,E
HOUSE148	DBF	00015	G
HOUSE149	DBF	00015	G
HOUSE150	DBF	00015	G
HOUSE151	DBF	00015	G
HOUSE152	DBF	00015	G
HOUSE153	DBF	00015	G
HOUSE154	DBF	00014	G
HOUSE156	DBF	00014	G
HOUSE157	DBF	00013	G
HOUSE160	DBF	00017	G,E
HOUSE16	DBF	00015	G
HOUSE162	DBF	00017	E
HOUSE163	DBF	00017	E
HOUSE165	DBF	00017	E

[a]G-gas space heat, E-all electric, G,E-gas space heat with gas and electric meters read on same day.

TABLE C-9 Typical utility file and file structure for an all electric house.

```
  USE HOUSE84
  LIST
00001  JUN   1  83     0       0    0    0    0    0     1
00002  JUN  30  83     0    1009    0    0   68   66    30
00003  AUG   1  83     0     887    0    0   77   82    62
00004  AUG  30  83     0     717    0    0   77   78    91
00005  SEP  28  83     0     695    0    0   62   68   120
00006  OCT  27  83     0    1216    0    0   50   43   149
00007  NOV  29  83     0    2997    0    0   36   27   182
00008  JAN   3  84     0    4616    0    0    5   45   217
00009  FEB   1  84     0    3630    0    0   11   42   246
00010  MAR   1  84     0    2566    0    0   27   44   275
00011  MAR  30  84     0    3856    0    0   24   58   304
00012  MAY   1  84     0     737    0    0   46   65   336
00013  MAY  31  84     0     749    0    0   56   73   366
00014  JUN  29  84     0     783    0    0   69   69   395
00015  JUL  31  84     0    1169    0    0   72   81   427
00016  AUG  29  84     0    1406    0    0   74   80   456
00017  SEP  28  84     0    1004    0    0   58   65   486
00018  OCT  29  84     0     963    0    0   51   36   517
00019  NOV  29  84     0    1744    0    0   33   43   548
```

```
  LIST STRUCTURE
STRUCTURE FOR FILE:   B:HOUSE84 .DBF
NUMBER OF RECORDS:    00019
DATE OF LAST UPDATE:  02/19/85
PRIMARY USE DATABASE
FLD        NAME        TYPE WIDTH   DEC   Description(units)
001       MONTH         C    003
002       DATE          N    002          Date electric meter read
003       YEAR          N    002
004       GAS           N    004          NA
005       ELECT         N    005          Electric consumption(kWh)
006       IN1:TEMP      N    003          Fields reserved for inside
007       IN2:TEMP      N    003          temperatures
008       OUT:TEMP      N    003          Average outside temperature(°F)
009       PERCENTSS     N    003          Average percent sunshine
010       RECORD:NO     N    004          Days from start of weather file
** TOTAL **                00033
```

TABLE C-10 Typical utility file and file structure for a house with gas space heat.

```
  USE HOUSE9
  LIST
00001  OCT  12  83    0     0    0    0    0    0   134
00002  NOV  10  83   33     0    0    0   45   40   163
00003  DEC  12  83   83     0    0    0   23   22   195
00004  JAN  11  84  110     0    0    0    6   50   225
00005  FEB   9  84   99     0    0    0   10   49   254
00006  MAR  12  84   75     0    0    0   25   48   286
00007  APR  10  84   54     0    0    0   36   58   315
00008  MAY  10  84   34     0    0    0   49   63   345
00009  JUN  12  84   12     0    0    0   62   71   378
00010  JUL  11  84    8     0    0    0   70   75   407
00011  AUG   7  84    6     0    0    0   74   77   434
00012  SEP   7  84    8     0    0    0   69   80   465
00013  OCT   5  84   13     0    0    0   56   66   493
00014  NOV   6  84   37     0    0    0   46   29   525
00015  DEC   6  84   57     0    0    0   29   46   555
```

```
  LIST STRUCTURE
STRUCTURE FOR FILE:  B:HOUSE9  .DBF
NUMBER OF RECORDS:   00015
DATE OF LAST UPDATE: 02/19/85
PRIMARY USE DATABASE
FLD       NAME       TYPE WIDTH   DEC    Description(units)
001      MONTH        C    003
002      DATE         N    002           Date gas meter read
003      YEAR         N    002
004      GAS          N    004           Gas consumption(100 ft^3)
005      ELECT        N    005           NA
006      IN1:TEMP     N    003           Fields reserved for inside
007      IN2:TEMP     N    003           temperatures
008      OUT:TEMP     N    003           Average outside temperature(°F)
009      PERCENTSS    N    003           Average percent sunshine
010      RECORD:NO    N    004           Days from start of weather file
** TOTAL **              00033
```

TABLE C-11 Typical utility file and file structure for a house with gas and electric meters read on the same day.

```
USE HOUSE110
LIST
00001  DEC  26  83    0     0   0   0   0   0  209
00002  JAN  27  84   90   526   0   0  10  47  241
00003  FEB  23  84   57   472   0   0  26  39  268
00004  MAR  23  84   71   399   0   0  22  59  297
00005  APR  24  84   31   439   0   0  44  64  329
00006  MAY  23  84    7   292   0   0  54  70  358
00007  JUN  25  84    7   367   0   0  66  68  391
00008  JUL  24  84    5   312   0   0  72  82  420
00009  AUG  22  84    5   368   0   0  74  80  449
00010  SEP  21  84    6   419   0   0  64  77  479
00011  OCT  22  84   10   348   0   0  52  31  510
00012  NOV  20  84   27   346   0   0  36  46  539
00013  DEC  26  84   65   454   0   0  22  46  575
```

```
LIST STRUCTURE
STRUCTURE FOR FILE:  B:HOUSE110.DBF
NUMBER OF RECORDS:   00013
DATE OF LAST UPDATE: 02/19/85
PRIMARY USE DATABASE
FLD      NAME        TYPE WIDTH   DEC   Description(units)
001      MONTH        C    003          Date gas and electric
002      DATE         N    002          meters read
003      YEAR         N    002
004      GAS          N    004          Gas consumption(100 ft^3)
005      ELECT        N    005          Electric consumption(kWh)
006      IN1:TEMP     N    003          Fields reserved for inside
007      IN2:TEMP     N    003          temperature
008      OUT:TEMP     N    003          Average outside temperature(°F)
009      PERCENTSS    N    003          Average percent sunshine
010      RECORD:NO    N    004          Days from start of weather file
** TOTAL **                 00033
```

APPENDIX D.

Air Leakage Measurements

TABLE D-1. Air leakage rates and areas for intentional vents open.

AC/H at 50 Pa stands for air changes per hour at a pressure difference of 50 Pascals. ELA is the effective leakage area, in square inches, as defined by the Lawrence Berkeley Laboratory (20), and is calculated from the flow at a pressure difference of 4 Pa. EqLA is Equivalent Leakage Area, in square inches, as defined by the Canadian General Standards Board (21) and is calculated from the flow at a pressure difference of 10 Pa.

	PRESSURIZED					DEPRESSURIZED					
Unit #	AC/H at 50 Pa	C	n	ELA(4)	EqLA(10)	AC/H at 50 Pa	C	n	ELA(4)	EqLA(10)	Comments
1	10.60					3.77	47	.70	35	69	A, 1, 2
2	14.00	138	.75	117	241	4.67	58	.70	43	85	A, 3
27	4.46	45	.82	41	90	4.24	58	.74	46	94	D
28	4.85	59	.77	50	106	4.26	51	.78	42	88	D
44	3.35	50	.72	40	79	2.93	49	.69	36	70	D
48	3.47	58	.70	44	86	3.40	59	.68	42	82	D
97	5.07	123	.62	86	158	3.99	82	.66	58	110	D
124	3.48					3.59	34	.72	26	53	D, 4
125	4.77	76	.59	52	93	3.88	44	.67	32	62	D
129	10.82	219	.59	141	250	9.38	164	.62	109	200	A, 5
131	8.29	86	.72	66	132	6.98	56	.78	46	98	A, 5, 6
131						19.30	366	.56	223	387	7
134	7.10	101	.63	69	127	6.13	73	.67	52	100	A, 5
30	6.37	81	.77	68	142	5.08	46	.86	43	98	D
32	7.80	248	.54	150	254	6.73	100	.73	78	158	D
51	3.23	38	.76	28		2.97	29	.81	25	55	D, 8
51						3.46	27	.87	26	59	9
51	3.03	34	.77	25							10
67	7.50	129	.61	88	159	6.76	52	.81	46	100	A, 2
68	4.39	51	.71	40	79	3.99	38	.76	31	65	A, 2
78	3.36	23	.91	24	57	3.14	38	.76	31	64	D
85	5.44	82	.66	62	118	4.93	46	.79	39	83	D, 11
116	8.02	75	.76	61	127	7.34	81	.72	62	124	A, 12
116											13
118	7.18	82	.70	63	125	6.06	60	.74	48	98	A, 12
150	5.42	65	.73	54	110	4.86	49	.78	41	88	D
151	5.61	85	.67	64	123	5.07	51	.78	43	90	D
159	8.48	104	.72	82	164	7.23	96	.70	72	142	D
160	7.49	57	.85	53	119	6.92	114	.65	80	149	D

TABLE D-2. Air leakage rates and areas for intentional vents sealed.

AC/H at 50 Pa stands for air changes per hour at a pressure difference of 50 Pascals. ELA is the effective leakage area, in square inches, as defined by the Lawrence Berkeley Laboratory (20), and is calculated from the flow at a pressure difference of 4 Pa. EqLA is Equivalent Leakage Area, in square inches, as defined by the Canadian General Standards Board (21) and is calculated from the flow at a pressure difference of 10 Pa.

	PRESSURIZED					DEPRESSURIZED					
Unit #	AC/H at 50 Pa	C	n	ELA(4)	EqLA(10)	AC/H at 50 Pa	C	n	ELA(4)	EqLA(10)	Comments
1	4.93					2.80	25	.78	21	45	A, 1, 2
2	9.84	51	.92	54	130	3.66	32	.78	27	58	A, 3
27	3.26	22	.92	23	55	3.58	41	.78	35	74	D
28	3.61	37	.81	34	73	3.47	36	.81	31	68	D
44	2.46	39	.71	30	59	2.22	37	.70	27	53	D
48	2.70	40	.72	32	64	2.63	50	.66	35	66	D
97	4.43	84	.68	64	125	3.61	60	.72	45	91	D
124	2.02					2.70	37	.63	25	46	D, 4
125	3.77	64	.57	43	76	3.07	33	.68	25	48	D
129	10.08	203	.59	131	233	9.12	149	.64	101	189	A, 5
131	7.76	84	.71	63	126	*	*	*	*	*	A, 5, 6
131											7
134	6.79	87	.66	62	116	5.96	98	.59	62	111	A, 5
30	6.03	65	.81	58	126	4.74	44	.85	40	91	D
32	7.37	149	.65	105	199	6.09	78	.77	64	134	D
51	2.99	281	.82	25	56	2.75	30	.78	25	54	D, 8
51											9
51											10
67	6.91	85	.69	65	127	6.27	42	.85	39	87	A, 2
68	3.89	35	.77	30	63	3.66	30	.80	26	55	A, 2
78											D
85	4.64	65	.68	50	98	4.44	42	.78	36	76	D, 11
116	6.38	72	.71	55	109	6.27	65	.73	51	103	A, 12
116	5.82	53	.77	44	91						13
118	5.57	49	.78	41	86	5.09	49	.75	39	81	A, 12
150	4.74	59	.73	48	98	4.30	49	.75	40	81	D
151	5.04	74	.68	56	109	4.65	57	.73	44	90	D
159	7.09	60	.82	54	118	6.60	135	.59	86	154	D
160	6.06	72	.73	57	116	6.28	109	.63	75	139	D

TABLE D-3 Comments on air leakage measurements.

COMMENTS: A = attached, D = detached

1.) Missing items not reliable, due to a mistake made in referencing nozzle pressures to inside instead of outside.

2.) End unit--made no detectable difference if adjacent unit was also at same pressure.

3.) Middle unit--we only had access to unit on 1 side, pressurizing that unit had no noticable affect on leakage of this unit.

4.) Windy, low-flow insert not available; low pressure readings not taken; missing items not reliable.

5.) Attached, end unit. Adjacent unit wasn't acessible to pressurize.

6.) Double envelope. Values reported here are for tests done with all doors and windows in interior envelope closed. The blower door was connected between the interior volume and outside. The depressurized, vents sealed test indicated the house was slightly leakier with vents sealed, than with vents open, which is impossible. Possibly the crawlspace access door was ajar.

7.) Exterior envelope tested. Doors between envelopes open.

8.) Interior, tightly fitting shutters (for 2 large south-facing sliding glass doors) shut.

9.) Same as 8, but shutters open.

10.) Same as 8, but large leak around flue stuffed with fiberglass.

11.) Volume used doesn't include the heated crawlspace.

12.) Attached unit -- units on both sides not pressurized -- see 13.) below.

13.) Unit to east pressurized to same pressure, unit to west was inaccessible.

TABLE D-4. Air leakage rates measured in present and previous programs.

Rates shown are for depressurized measurements with intentional vents open. Data for unit 134 was not available when this table was prepared. Comparison of AC/H values for this unit in TABLES D-1 and D-2 shows that the air leakage rate has almost doubled due to the presence of a large leak created between the times of the measurements (see text). Small differences in air change rates between tables are due to slightly different house volume being used for each calculation.

BUILDER, UNIT NUMBER OR MEASUREMENT		VOLUME (cu ft)	MEASURED AC/H AT 50 PASCAL (1/hr)	CALCULATED INFILTRATION AC/H AT 4 PASCAL (1/hr)	LOAD (Btu/hr- F)	ANNUAL INFILTRATION LOAD (THERMS)
BUILDER A						
PRESENT	1	11089	3.84	0.23	45	87
PRESENT	2	11089	4.76	0.28	56	107
PREVIOUS	3	11089	5.51	0.32	65	124
AVERAGE	4	11089	4.35	0.26	51	98
PREVIOUS	5	11089	3.62	0.21	43	82
AVERAGE	6	11089	4.35	0.26	51	98
PREVIOUS	7	11089	4	0.24	47	90
AVERAGE	8	11089	4.35	0.26	51	98
BUILDER B						
PREVIOUS	9	10277	6.31	0.37	69	132
PREVIOUS	10	10277	6.82	0.40	74	142
AVERAGE	11	10277	6.57	0.39	71	137
AVERAGE	12	10277	6.57	0.39	71	137
AVERAGE	13	10277	6.57	0.39	71	137
AVERAGE	14	10277	6.57	0.39	71	137
AVERAGE	15	10277	6.57	0.39	71	137
AVERAGE	16	10277	6.57	0.39	71	137
BUILDER C						
PREVIOUS	17	13843	4.45	0.26	65	125
PREVIOUS	19	13843	3.61	0.21	53	102
PREVIOUS	20	13843	3.4	0.20	50	96
AVERAGE	21	13843	3.82	0.22	56	108
AVERAGE	24	13843	3.82	0.22	56	108

TABLE D-4. Continued.

BUILDER, UNIT NUMBER OR MEASUREMENT	VOLUME (cu ft)	MEASURED AC/H AT 50 PASCAL (1/hr)	CALCULATED AC/H AT 4 PASCAL (1/hr)	INFILTRATION LOAD (Btu/hr- F)	ANNUAL INFILTRATION LOAD (THERMS)
BUILDER D					
PREVIOUS 26	14020	4.44	0.26	66	127
PRESENT 27	14020	4.47	0.26	66	127
PRESENT 28	14020	4.49	0.26	67	128
BUILDER E					
AVERAGE 29	11230	8.16	0.48	97	186
PRESENT 30	11230	7.02	0.41	83	160
PRESENT 32	11230	9.29	0.55	110	212
BUILDER G					
PREVIOUS 41	15503	2.2	0.13	36	69
PREVIOUS 42	15503	3.18	0.19	52	100
PREVIOUS 43	15503	3.04	0.18	50	96
PRESENT 44	15503	2.84	0.17	47	90
PREVIOUS 45	15503	2.5	0.15	41	79
AVERAGE 46	15503	2.84	0.17	47	90
AVERAGE 47	15503	2.84	0.17	47	90
PRESENT 48	15503	3.3	0.19	54	104
BUILDER H					
PREVIOUS 49	14302	4.17	0.25	63	121
PREVIOUS 50	14302	4.29	0.25	65	125
PRESENT 51	14302	2.9	0.17	44	84
PREVIOUS 52	14302	3.81	0.22	58	111
BUILDER I					
AVERAGE 53	13561	5.78	0.34	83	159
AVERAGE 54	13561	5.78	0.34	83	159
PREVIOUS 55	13561	5.33	0.31	77	147
PREVIOUS 57	13561	5.93	0.35	85	163
PREVIOUS 58	13561	5.74	0.34	82	158
PREVIOUS 59	13561	5.64	0.33	81	155
PREVIOUS 60	13561	5.33	0.31	77	147
AVERAGE 61	13561	5.78	0.34	83	159
PREVIOUS 62	13561	6.71	0.39	96	185
AVERAGE 63	13561	5.78	0.34	83	159

TABLE D-4. Continued.

BUILDER, UNIT NUMBER OR MEASUREMENT	VOLUME (cu ft)	MEASURED AC/H AT 50 PASCAL (1/hr)	CALCULATED AC/H AT 4 PASCAL (1/hr)	INFILTRATION LOAD (Btu/hr- F)	ANNUAL INFILTRATION LOAD (THERMS)
BUILDER J					
PREVIOUS 65	11230	8.38	0.49	100	191
PREVIOUS 66	11230	7.8	0.46	93	178
PRESENT 67	11230	6.72	0.40	80	153
PRESENT 68	11230	3.97	0.23	47	91
PREVIOUS 69	11230	6.97	0.41	83	159
PREVIOUS 70	11230	8.9	0.52	106	203
PREVIOUS 71	11230	8.45	0.50	100	193
PREVIOUS 72	11230	8.48	0.50	101	194
BUILDER K					
PREVIOUS 73	14232	3.26	0.19	49	94
PREVIOUS 74	14232	3.16	0.19	48	91
PREVIOUS 75	14232	2.5	0.15	38	72
BUILDER M					
PREVIOUS 82	12572	3.16	0.19	42	81
PREVIOUS 83	12572	4.71	0.28	63	120
PREVIOUS 84	12572	4.67	0.27	62	119
PRESENT 85	12572	4.78	0.28	64	122
BUILDER N					
PREVIOUS 94	12819	2.55	0.15	35	66
PREVIOUS 95	12819	2.95	0.17	40	77
PREVIOUS 96	17128	3.79	0.22	69	132
PRESENT 97	17128	3.84	0.23	70	134

TABLE D-4. Continued.

BUILDER, UNIT NUMBER OR MEASUREMENT	VOLUME (cu ft)	MEASURED AC/H AT 50 PASCAL (1/hr)	CALCULATED AC/H AT 4 PASCAL (1/hr)	INFILTRATION LOAD (Btu/hr- F)	ANNUAL INFILTRATION LOAD (THERMS)
BUILDER P					
AVERAGE 108	11390	6.4	0.38	77	148
AVERAGE 109	11390	6.4	0.38	77	148
AVERAGE 110	11390	6.4	0.38	77	148
AVERAGE 111	11390	6.4	0.38	77	148
AVERAGE 112	11390	6.4	0.38	77	148
AVERAGE 113	11390	6.4	0.38	77	148
AVERAGE 114	11390	6.4	0.38	77	148
AVERAGE 115	11390	6.4	0.38	77	148
PRESENT 116	11390	7.02	0.41	85	163
AVERAGE 117	11390	6.4	0.38	77	148
PRESENT 118	11390	5.79	0.34	70	134
AVERAGE 119	11390	6.4	0.38	77	148
BUILDER Q					
PREVIOUS 120	9450	4.16	0.24	42	80
AVERAGE 121	9450	3.88	0.23	39	75
PREVIOUS 122	9450	3.84	0.23	38	74
PREVIOUS 123	9450	3.89	0.23	39	75
PRESENT 124	9450	3.62	0.21	36	70
PRESENT 125	9450	3.91	0.23	39	75
AVERAGE 126	9450	3.88	0.23	39	75
AVERAGE 127	9450	3.88	0.23	39	75
BUILDER R					
ESTIMATE 128	12120	9.38	0.55	120	231
PRESENT 129	12120	9.38	0.55	120	231
ESTIMATE 130	10300	6.98	0.41	76	146
PRESENT 131	10300	6.98	0.41	76	146

TABLE D-4. Continued.

BUILDER, UNIT NUMBER OR MEASUREMENT	VOLUME (cu ft)	MEASURED AC/H AT 50 PASCAL (1/hr)	CALCULATED AC/H AT 4 PASCAL (1/hr)	INFILTRATION LOAD (Btu/hr- F)	ANNUAL INFILTRATION LOAD (THERMS)
BUILDER S					
PREVIOUS 133	8970	5.41	0.32	51	99
PREVIOUS 134	9217	3.38	0.20	33	63
PREVIOUS 135	9429	4.41	0.26	44	85
PREVIOUS 136	8970	5.22	0.31	50	95
PREVIOUS 137	9429	3.35	0.20	33	64
PREVIOUS 138	9429	4.84	0.28	48	93
PREVIOUS 139	9217	4.86	0.29	47	91
AVERAGE 140	8970	4.5	0.26	43	82
AVERAGE 141	9217	4.5	0.26	44	84
AVERAGE 142	8970	4.5	0.26	43	82
AVERAGE 143	9429	4.5	0.26	45	86
BUILDER T					
PREVIOUS 148	12960	4.97	0.29	68	131
PRESENT 150	12960	4.76	0.28	65	125
PRESENT 151	12960	4.97	0.29	68	131
BUILDER U					
DEFAULT 153	11477	5	0.29	61	117
DEFAULT 154	13808	5	0.29	73	140
DEFAULT 155	13808	5	0.29	73	140
DEFAULT 156	12431	5	0.29	66	126
DEFAULT 157	12431	5	0.29	66	126
BUILDER V					
PREVIOUS 158	12607	6.33	0.37	84	162
PRESENT 159	12607	7.14	0.42	95	183
PRESENT 160	12607	6.83	0.40	91	175
BUILDER W					
DEFAULT 163	16704	5	0.29	88	170
DEFAULT 164	16704	5	0.29	88	170
DEFAULT 165	16704	5	0.29	88	170

APPENDIX E.

PRISM Short Summary Output

TABLE E-1 PRISM short summary output for 127 houses. Houses are identified by CASE ID number and are grouped by builder.

CASE ID		TIME PERIOD	N OF READS	DATASET LABEL	N OF ITS	R-SQ	TREF	SE OF TREF	BASELOAD PER DAY	SE OF BASE	SLOPE PER HDD	SE OF SLOPE	NAC, CCF PER YEAR	SE OF NAC
H	1	12/18/83 - 12/14/84	51		4	.8040	58.00	(4.84)	.794	(.113)	.0413	(.0042)	549.78	(21.21)
H	2	12/18/83 - 12/14/84	51		6	.8193	41.46	(3.13)	1.006	(.047)	.0346	(.0036)	474.73	(12.17)
H	3	12/18/83 - 12/14/84	51		4	.8261	47.12	(3.50)	.548	(.057)	.0338	(.0033)	337.30	(13.25)
H	4	12/18/83 - 12/14/84	51		4	.7918	52.00	(4.17)	1.103	(.082)	.0365	(.0038)	585.10	(17.65)
H	5	12/18/83 - 12/14/84	51		4	.8650	57.68	(3.73)	.638	(.089)	.0423	(.0034)	496.27	(17.33)
H	6	12/18/83 - 12/14/84	51		7	.8052	42.61	(3.30)	.909	(.052)	.0349	(.0037)	446.61	(13.22)
H	7	12/18/83 - 12/14/84	51		4	.8179	61.07	(4.86)	.767	(.079)	.0266	(.0025)	467.54	(13.67)
H	8	12/26/83 - 12/14/84	50		5	.7361	70.00	(9.52)	.809	(.206)	.0292	(.0033)	572.52	(19.81)
H	9	10/12/83 - 12/ 6/84	14		3	.9934	60.28	(1.71)	.166	(.041)	.0440	(.0016)	361.46	(7.12)
H	10	10/12/83 - 12/ 6/84	14		3	.9707	58.06	(3.41)	.185	(.082)	.0448	(.0036)	349.94	(14.94)
H	11	10/ 3/83 - 11/28/84	14		3	.9678	51.39	(3.19)	.647	(.064)	.0421	(.0036)	441.04	(13.10)
H	12	10/ 3/83 - 11/28/84	11		3	.9361	61.21	(4.62)	.334	(.108)	.0451	(.0063)	440.53	(24.04)
H	13	10/ 3/83 - 11/28/84	14		4	.9759	61.00	(3.15)	.298	(.074)	.0400	(.0027)	389.39	(12.64)
H	14	11/ 1/83 - 12/28/84	14		4	.9839	55.38	(2.58)	.317	(.048)	.0375	(.0024)	329.67	(9.11)
H	16	10/18/83 - 12/ 7/84	14		3	.9750	61.49	(3.54)	.352	(.073)	.0374	(.0027)	395.51	(12.15)
H	15	8/ 7/83 - 12/23/84	67		5	.9362	55.90	(1.84)	.616	(.042)	.0410	(.0019)	463.24	(8.70)
H	17	10/12/83 - 12/10/84	14		4	.9243	57.32	(5.54)	.574	(.150)	.0512	(.0068)	523.79	(27.78)
H	18	10/12/83 - 12/10/84	11		3	.4824	81.00	(*****)	.183	(5.801)	.0153	(.0062)	269.25	(46.41)
H	19	10/12/83 - 12/10/84	14		4	.9434	54.34	(4.29)	.272	(.097)	.0432	(.0048)	335.60	(19.13)
H	20	10/12/83 - 12/10/84	13		4	.9946	60.14	(1.55)	.457	(.038)	.0458	(.0016)	478.53	(6.74)
H	21	10/12/83 - 12/10/84	14		3	.9419	55.93	(4.54)	.344	(.134)	.0559	(.0064)	451.05	(25.84)
H	24	10/12/83 - 12/10/84	14		4	.9026	59.60	(6.69)	.560	(.216)	.0588	(.0088)	596.74	(38.06)
H	26	12/11/83 - 12/ 9/84	50		4	.8478	54.00	(3.47)	1.157	(.080)	.0436	(.0038)	658.22	(17.95)
H	27	12/11/83 - 12/ 9/84	50		3	.9371	55.97	(2.29)	.746	(.065)	.0546	(.0030)	590.66	(14.24)
H	28	12/11/83 - 12/ 9/84	50		4	.8844	60.20	(3.45)	1.411	(.116)	.0596	(.0044)	921.43	(23.31)

TABLE E-1 Continued.

CASE ID		TIME PERIOD	N OF READS	DATASET LABEL	N OF ITS	R-SQ	TREF	SE OF TREF	BASELOAD PER DAY	SE OF BASE	SLOPE PER HDD	SE OF SLOPE	NAC, CCF PER YEAR	SE OF NAC
H	29	6/ 9/83 - 7/13/84	13		4	.9208	56.14	(5.68)	.006	(.097)	.0360	(.0053)	213.27	(21.16)
H	30	6/ 9/83 - 7/13/84	13		3	.9898	55.34	(1.91)	.034	(.040)	.0439	(.0022)	262.55	(8.80)
H	31	6/15/83 - 6/19/84	12		4	.9692	72.08	(6.14)	.171	(.167)	.0436	(.0038)	504.36	(22.07)
H	32	1/ 1/84 - 1/ 6/85	47		5	.7888	51.00	(3.95)	1.498	(.089)	.0466	(.0056)	770.31	(20.09)
H	34	12/11/83 - 12/ 2/84	51		4	.7638	59.00	(5.72)	1.039	(.196)	.0591	(.0067)	765.59	(35.76)
H	41	12/19/83 - 12/21/84	50		3	.9214	60.71	(2.77)	.689	(.057)	.0366	(.0022)	505.99	(11.23)
H	42	12/19/83 - 12/21/84	50		3	.8983	63.20	(3.45)	.764	(.081)	.0391	(.0026)	575.13	(14.31)
H	43	12/19/83 - 12/21/84	50		4	.9190	54.38	(2.35)	1.152	(.072)	.0573	(.0035)	734.87	(16.03)
H	44	12/19/83 - 12/21/84	50		3	.9136	58.38	(2.86)	.421	(.064)	.0426	(.0028)	425.72	(13.24)
H	45	12/19/83 - 12/21/84	50		4	.9044	61.00	(3.06)	.582	(.072)	.0407	(.0027)	497.82	(13.95)
H	46	12/19/83 - 12/21/84	50		3	.9292	58.20	(2.55)	.699	(.063)	.0466	(.0027)	550.55	(12.95)
H	47	12/19/83 - 12/21/84	50		5	.8814	59.00	(3.32)	.981	(.066)	.0360	(.0027)	593.15	(13.48)
H	48	12/19/83 - 12/21/84	50		7	.8625	57.97	(3.67)	1.346	(.092)	.0483	(.0042)	795.39	(19.37)
H	49	6/ 9/83 - 12/ 7/84	18		6	.9648	37.43	(2.68)	.041	(.029)	.0446	(.0048)	125.97	(8.56)
H	50	6/ 9/83 - 12/ 7/84	17		3	.9942	54.10	(1.31)	.023	(.028)	.0504	(.0017)	281.88	(6.18)
H	52	6/ 9/83 - 12/ 7/84	18		3	.9949	55.12	(1.13)	.027	(.025)	.0489	(.0014)	286.12	(5.50)
H	51	12/18/83 - 12/16/84	46		5	.9312	44.00	(2.12)	.805	(.059)	.0614	(.0039)	509.47	(14.06)
H	53	9/20/83 - 11/16/84	12		4	.9063	55.43	(5.14)	.516	(.124)	.0500	(.0082)	474.07	(28.53)
H	54	9/20/83 - 11/16/84	11		5	.8811	59.14	(6.88)	.526	(.145)	.0446	(.0092)	484.84	(32.39)
H	55	9/20/83 - 11/16/84	12		4	.9156	55.00	(4.75)	.332	(.109)	.0467	(.0071)	383.57	(24.91)
H	57	9/20/83 - 11/16/84	12		4	.9036	57.93	(5.74)	.512	(.157)	.0572	(.0098)	546.23	(34.63)
H	58	9/20/83 - 11/16/84	12		3	.9435	54.90	(3.90)	.487	(.112)	.0616	(.0078)	522.46	(26.41)
H	59	9/20/83 - 11/16/84	12		3	.8856	54.77	(5.69)	.519	(.152)	.0568	(.0105)	505.89	(35.66)
H	60	9/20/83 - 11/16/84	12		2	.9588	62.64	(4.28)	.293	(.129)	.0559	(.0058)	522.26	(23.29)
H	61	9/20/83 - 11/16/84	12		4	.9250	55.94	(4.66)	.492	(.114)	.0510	(.0074)	476.45	(26.07)
H	62	9/20/83 - 11/16/84	12		4	.8584	66.25	(9.12)	.247	(.245)	.0452	(.0088)	469.98	(38.25)
H	63	9/20/83 - 11/16/84	11		5	.8226	68.48	(12.55)	.136	(.340)	.0455	(.0110)	461.28	(47.64)

TABLE E-1 Continued.

CASE ID		TIME PERIOD	N OF READS	DATASET LABEL	N OF ITS	R-SQ	TREF	SE OF TREF	BASELOAD PER DAY	SE OF BASE	SLOPE PER HDD	SE OF SLOPE	NAC, CCF PER YEAR	SE OF NAC
H	65	9/20/83 - 11/16/84	9		5	.9766	55.00	(3.92)	.035	(.127)	.0531	(.0048)	311.28	(21.12)
H	66	6/20/83 - 6/12/84	10		5	.9521	49.45	(4.66)	.117	(.123)	.0644	(.0094)	331.92	(27.98)
H	68	9/20/83 - 11/16/84	11		3	.8003	62.00	(12.50)	.010	(.336)	.0487	(.0131)	357.69	(53.90)
H	70	9/20/83 - 11/16/84	12		3	.8974	54.65	(6.14)	.043	(.160)	.0514	(.0088)	300.84	(32.46)
H	71	9/20/83 - 11/16/84	13		3	.9547	63.00	(4.82)	.038	(.195)	.0707	(.0071)	545.48	(30.85)
H	72	9/20/83 - 11/16/84	14		3	.9309	58.55	(5.41)	.124	(.119)	.0416	(.0052)	312.25	(21.61)
H	67	12/12/83 - 12/ 9/84	46		3	.8141	63.00	(5.46)	.251	(.171)	.0569	(.0062)	519.29	(31.23)
H	69	1/ 1/84 - 1/13/85	52		4	.8222	59.58	(4.20)	.880	(.123)	.0531	(.0052)	675.25	(23.64)
H	75	10/ 3/83 - 11/29/84	14		4	.9496	56.22	(4.21)	.444	(.110)	.0487	(.0050)	448.70	(20.82)
H	76	8/31/83 - 10/ 1/84	12		5	.9727	58.00	(3.73)	.332	(.124)	.0606	(.0050)	502.58	(22.59)
H	77	10/ 3/83 - 11/29/84	13		4	.9672	60.00	(3.44)	.377	(.106)	.0532	(.0044)	497.59	(19.45)
H	73	12/ 4/83 - 12/ 9/84	51		3	.8367	63.80	(4.91)	.584	(.160)	.0524	(.0046)	618.37	(25.94)
H	74	12/ 4/83 - 12/ 9/84	51		3	.9551	60.09	(2.08)	1.003	(.058)	.0464	(.0020)	681.10	(10.72)
H	84	6/ 1/83 - 11/29/84	18		4	.8739	51.06	(5.55)	1.035	(.182)	.0864	(.0145)	792.87	(45.02)
H	82	12/ 4/83 - 12/16/84	54		5	.8361	47.57	(3.25)	.359	(.059)	.0400	(.0039)	296.49	(14.14)
H	83	12/18/83 - 12/16/84	51		4	.8927	55.80	(2.92)	.846	(.078)	.0516	(.0038)	607.74	(16.93)
H	85	12/ 4/83 - 11/25/84	51		3	.9251	60.74	(2.71)	.459	(.082)	.0534	(.0031)	538.48	(16.31)
H	94	12/11/83 - 1/ 6/85	41		6	.7861	45.29	(4.19)	1.332	(.101)	.0500	(.0066)	673.08	(22.96)
H	95	12/11/83 - 1/ 6/85	41		5	.8497	48.89	(3.71)	.871	(.087)	.0461	(.0049)	520.45	(18.69)
H	96	12/11/83 - 1/ 6/85	41		2	.6819	59.00	(7.36)	1.082	(.159)	.0347	(.0053)	621.44	(27.28)
H	97	12/11/83 - 1/ 6/85	41		4	.7325	54.22	(5.79)	1.197	(.142)	.0418	(.0058)	664.90	(27.10)
H	105	1/16/84 - 12/10/84	11		3	.9803	86.00	(-9.90)	.306	(-9.900)	.0473	(.0022)	822.14	(16.18)
H	106	1/16/84 - 12/10/84	11		6	.8181	41.00	(8.14)	1.132	(.073)	.0361	(.0139)	522.53	(20.29)

TABLE E-1 Continued.

CASE ID		TIME PERIOD	N OF READS	DATASET LABEL	N OF ITS	R-SQ	TREF	SE OF TREF	BASELOAD PER DAY	SE OF BASE	SLOPE PER HDD	SE OF SLOPE	NAC, CCF PER YEAR	SE OF NAC
H	110	12/26/83 - 12/26/84	12		4	.9545	52.95	(4.56)	.512	(.089)	.0484	(.0065)	437.69	(19.04)
H	111	12/26/83 - 12/26/84	11		4	.9859	61.29	(3.15)	.654	(.047)	.0309	(.0022)	458.05	(8.45)
H	112	12/26/83 - 12/26/84	12		4	.8971	49.04	(6.82)	.912	(.076)	.0320	(.0073)	474.36	(17.49)
H	113	12/26/83 - 12/26/84	12		6	.9368	40.00	(4.52)	1.513	(.057)	.0486	(.0099)	691.95	(14.97)
H	114	12/26/83 - 12/26/84	12		5	.9346	43.91	(5.66)	1.028	(.105)	.0708	(.0154)	622.84	(25.74)
H	115	12/26/83 - 12/26/84	12		6	.9691	48.63	(3.52)	.988	(.049)	.0404	(.0048)	536.01	(11.54)
H	117	12/26/83 - 12/26/84	12		6	.9785	44.00	(2.99)	1.258	(.047)	.0553	(.0063)	653.40	(11.29)
H	119	12/26/83 - 12/26/84	10		4	.9419	64.95	(7.23)	.069	(.227)	.0619	(.0094)	522.55	(40.44)
H	108	1/23/84 - 1/28/85	52		5	.8982	49.87	(2.55)	1.176	(.061)	.0569	(.0047)	689.61	(14.33)
H	109	1/23/84 - 1/28/85	52		5	.9050	49.80	(2.45)	1.032	(.045)	.0435	(.0035)	575.28	(10.53)
H	116	12/12/83 - 12/10/84	42		5	.7535	57.00	(5.82)	.546	(.081)	.0285	(.0041)	372.16	(17.28)
H	120	12/ 4/83 - 12/ 4/84	52		3	.8702	56.67	(3.46)	1.028	(.065)	.0360	(.0029)	590.87	(13.65)
H	121	12/ 4/83 - 12/ 4/84	52		6	.8023	69.53	(6.51)	.912	(.138)	.0306	(.0028)	619.23	(17.74)
H	122	12/ 4/83 - 12/ 4/84	52		4	.7996	64.00	(5.11)	.794	(.106)	.0325	(.0031)	543.09	(17.87)
H	123	12/ 4/83 - 12/ 4/84	52		4	.8697	64.48	(4.00)	.588	(.087)	.0341	(.0025)	484.76	(14.57)
H	124	12/ 4/83 - 12/ 4/84	52		2	.8106	62.16	(4.87)	.625	(.064)	.0217	(.0021)	386.98	(11.25)
H	125	12/ 4/83 - 12/ 4/84	52		2	.8412	62.97	(4.47)	1.504	(.079)	.0299	(.0026)	773.56	(14.05)
H	126	12/ 4/83 - 12/ 4/84	52		4	.7798	41.00	(3.46)	.952	(.052)	.0374	(.0045)	460.83	(13.88)
H	127	12/ 4/83 - 12/ 4/84	52		3	.6614	63.00	(7.42)	1.264	(.097)	.0213	(.0030)	622.31	(16.54)
H	128	12/11/83 - 12/ 9/84	51		4	.9311	53.12	(2.09)	.424	(.066)	.0588	(.0033)	462.06	(14.55)
H	129	12/11/83 - 12/ 9/84	51		7	.9333	42.60	(1.80)	.835	(.041)	.0582	(.0036)	495.90	(11.04)
H	130	12/11/83 - 12/ 9/84	51		5	.7368	49.15	(4.58)	.673	(.048)	.0234	(.0031)	349.40	(11.65)
H	131	12/11/83 - 12/ 9/84	51		5	.8713	58.00	(3.43)	.990	(.068)	.0370	(.0030)	594.30	(14.07)

TABLE E-1 Continued.

CASE ID		TIME PERIOD	N OF READS	DATASET LABEL	N OF ITS	R-SQ	TREF	SE OF TREF	BASELOAD PER DAY	SE OF BASE	SLOPE PER HDD	SE OF SLOPE	NAC, CCF PER YEAR	SE OF NAC
H	132	12/11/83 - 12/10/84	52		5	.2058	58.36	(18.03)	.603	(.072)	.0074	(.0030)	267.52	(14.62)
H	133	12/11/83 - 12/10/84	52		3	.9428	63.10	(2.57)	.296	(.059)	.0381	(.0019)	395.76	(10.10)
H	134	12/11/83 - 12/10/84	52		4	.8750	64.57	(3.92)	.608	(.089)	.0363	(.0026)	510.14	(15.05)
H	135	12/11/83 - 12/10/84	52		4	.8711	68.00	(4.75)	.681	(.077)	.0248	(.0018)	469.49	(10.95)
H	136	12/11/83 - 12/10/84	52		3	.8409	65.27	(4.58)	.404	(.095)	.0323	(.0027)	410.04	(15.55)
H	137	12/11/83 - 12/10/84	52		5	.7902	68.00	(6.36)	.499	(.103)	.0246	(.0024)	401.35	(14.54)
H	138	12/11/83 - 12/10/84	52		3	.8816	60.09	(3.40)	.311	(.070)	.0361	(.0027)	358.77	(13.63)
H	139	12/11/83 - 12/10/84	52		2	.8158	62.53	(4.86)	.444	(.093)	.0327	(.0031)	403.79	(16.56)
H	140	12/11/83 - 12/10/84	52		5	.8087	43.16	(3.37)	.894	(.068)	.0497	(.0055)	493.94	(17.65)
H	141	12/11/83 - 12/10/84	52		4	.9027	55.51	(2.76)	.512	(.054)	.0370	(.0025)	399.12	(11.60)
H	142	12/11/83 - 12/10/84	52		5	.9341	55.39	(2.22)	.559	(.046)	.0386	(.0021)	424.46	(9.77)
H	143	12/11/83 - 12/10/84	52		4	.9225	55.85	(2.47)	.358	(.043)	.0334	(.0020)	324.56	(9.28)
H	148	10/12/83 - 12/10/84	14		5	.9183	70.50	(10.87)	.233	(.299)	.0397	(.0050)	467.64	(26.64)
H	149	10/12/83 - 12/10/84	14		3	.9877	67.30	(3.09)	.227	(.105)	.0557	(.0028)	566.92	(13.54)
H	150	10/12/83 - 12/10/84	14		2	.9629	62.71	(4.70)	.273	(.122)	.0456	(.0041)	438.92	(18.48)
H	151	10/12/83 - 12/10/84	14		4	.9749	65.31	(3.96)	.404	(.110)	.0454	(.0032)	517.40	(15.52)
H	152	11/16/83 - 1/14/85	14		3	.9770	55.84	(3.27)	.027	(.080)	.0519	(.0041)	310.68	(15.52)
H	153	11/16/83 - 1/14/85	14		3	.9874	53.48	(2.21)	.007	(.052)	.0490	(.0028)	262.29	(10.34)
H	154	11/16/83 - 1/14/85	13		5	.9897	49.43	(2.17)	.113	(.033)	.0421	(.0027)	230.15	(7.46)
H	156	11/16/83 - 1/14/85	13		3	.9819	57.05	(3.15)	.042	(.067)	.0460	(.0034)	294.78	(12.82)
H	157	11/16/83 - 12/11/84	12		3	.9934	56.45	(1.79)	.093	(.037)	.0451	(.0020)	301.88	(7.59)
H	155	1/ 9/84 - 1/28/85	48		5	.8828	48.66	(2.69)	.497	(.049)	.0416	(.0037)	361.84	(11.68)
H	160	6/23/83 - 11/16/84	16		4	.9714	57.20	(2.68)	.924	(.085)	.0770	(.0061)	808.17	(20.54)
H	158	12/19/83 - 12/17/84	51		3	.8770	58.19	(3.35)	.544	(.082)	.0460	(.0036)	489.86	(16.89)
H	159	12/18/83 - 12/16/84	52		3	.8484	65.49	(4.36)	.363	(.122)	.0436	(.0035)	489.98	(20.09)
H	162	6/29/83 - 10/30/84	16		4	.8808	56.00	(6.35)	.614	(.102)	.0329	(.0050)	416.24	(21.52)
H	163	6/20/83 - 10/19/84	16		3	.9194	82.00	(64.47)	.365	(1.598)	.0259	(.0025)	484.03	(17.69)
H	165	6/10/83 - 10/12/84	16		6	.8110	73.00	(19.82)	.686	(.431)	.0307	(.0058)	570.93	(34.24)
H	164	12/11/83 - 12/ 2/84	50		3	.8819	59.17	(3.81)	.307	(.100)	.0448	(.0033)	406.30	(18.11)

Appendix F

Normalized Thermal Load (NTL) Calculation

This appendix will examine the suitability of the Princeton Scorekeeping Method (PRISM) program as a computational tool for the evaluation of the normalized thermal load (NTL) as defined by Equation 4.1 in the text of this report.

Calculation of the standard error of the normalized thermal load

It is well documented that the normalized annual consumption (NAC) as calculated by the PRISM program is better determined than the individual alpha, beta or T_{ref} fitting parameters due to the presence of internal cancellations within the calculation for the NAC (22). Thus, a slope beta with a 10 percent standard error can be used along with the corresponding alpha and T_{ref} to calculate an NAC with a standard error of 5 percent or less. A central question in the present analysis is whether or not the normalized thermal load as defined in Equation 4.1 of the report is an equally reliable measurement of building performance.

In order to answer the above question, the total differential of Equation 4.1 is required. Writing the total differential of the normalized thermal load (NTL) from Equation 4.1 yields:

$$\Delta \text{ NTL} = H_0 \ (68°F) \ \Delta\beta + D_0 \ (68°F) \ \Delta\varepsilon \qquad \text{(F1)}$$

Since $\Delta\beta$ may be obtained from the output of the PRISM program, we need only to determine $\Delta\varepsilon$. Substituting from Equations 4.2 and 4.3 yields:

$$\varepsilon = \beta \ (T_{ref} + \alpha/\beta - T_{set})$$

$$= \alpha + \beta \ (T_{ref} - T_{set}).$$

The total differential of ε is then:

$$\Delta \ \varepsilon = \Delta\alpha + \beta \ (\Delta \ T_{ref} - 0) + \Delta\beta \ (T_{ref} - T_{set}).$$

From the above result and Equation F1, we may write the standard error of the NTL as follows:

$$\sigma_{NTL} = [(H_0 \ (68°F) \ \sigma_\beta + D_0 \ (68°F) \ (T_{ref} - T_{set}) \ \sigma_\beta)^2 + (D_0 \ (68°F) \ (\sigma_\alpha - \beta\sigma_{T_{ref}})^2]^{\frac{1}{2}} \qquad \text{(F2)}$$

The first squared term in Eq. F2 represents the contribution to σ_{NTL} due to the standard error in the slope β. This term becomes zero for $T_{ref} = \bar{T} + \delta \ T$, where $\bar{T}$ is the annual average ambient temperature below the normalization temperature (see next section on Seasonality), and $\delta \ T$ is the difference between the actual setpoint temperature and the normalized setpoint temperature. For this T_{ref}, the house

is, on the average, totally heated by internal and solar gains and the NTL is independent of β.

The second squared term in Equation F1 represents the ordinate error in the load line point (T_{ref}, α). If we assume perfect negative covariance between α and T_{ref}, this term is zero, leading to the unacceptable conclusion that $\sigma_{NTL} = 0$ when $T_{ref} = \bar{T} + \delta T$, as discussed above. Therefore, we write the term includes the negative covariance, hence the minus sign, but leave the term in the equation, since an inspection of the PRISM output in Table E-1 shows that this term is indeed not zero. This approximation is equivalent to assuming that the correlation coefficient between α and T_{ref} is equal to -1.

Finally, with the exception of the above covariance, the errors are assumed to be independent, and are therefore summed in the conventional manner shown.

The results of applying Equation F2 to the PRISM output parameters is shown in Tables F-1 and F-2. These are similar to Tables 4.1 and 4.2 of the text, but include additional columns on the right for the standard errors of the NAC parameters and of the NTL. As stated in the text of the report, for any given house, the percent standard error of the NTL appears to be at least twice as large as the percent standard error of the NAC, but less than the percent standard error of the slope β. However, because the NAC is larger than the NTL, the absolute errors of the NTL are better than this, and range from one and one-half to two times greater than the absolute errors of the NAC. Thus, even though the NTL also benefits from the presence of internal cancellations among the fitting parameters it is not as well determined as the NAC.

Because of concern with the completeness of Equation F2, an alternative expression for calculating the standard error of the NTL was provided by Princeton University. Application of this expression to ten houses reduced the standard error of the NTL in these cases by about a factor of two, yielding values for the standard error of the NTL comparable to those associated with the NAC. The principal investigator feels that this matter needs further thought, since this reduction in the standard error resulted from the addition of non-zero terms for the covariances between the variables α and β and between β and T_{ref}. Because these variables are assumed to be physically independent for the NTL model, their non-zero covariances represent an artifact of the PRISM model that needs to be used with caution. In any case, the standard error developed here appears to be a good upper bound for the precision to be expected from the NTL model.

Empirical test of the PRISM curve fitting algorithm for the calculation of the normalized thermal load.

The PRISM program is designed to find a value for T_{ref} that yields the greatest r-squared statistic for the calculation of the NAC. A central concern in the application of the PRISM program to the current

analysis was whether or not this criterion would be adequate for the determination of the NTL as defined in Equation 4.1 of the text. Since the model defined by Equation 4.1 is a true heating only model, it should be independent of summer energy use as represented by the PRISM parameter alpha. In the current model T_{ref} and alpha are used to specify a point in the point-slope specification of the load line shown in Figure 4.1. While it can be readily shown with the assumption of perfect data, that the point-slope definition of the load line in Figure 4.1 does indeed yield an invariant value for the NTL for various values of alpha (23), it seemed prudent to test the ability of the PRISM program to actually do this.

To test the ability of the PRISM program to calculate the parameters required for the calculation of the NTL in Equation 4.1, additional PRISM runs were made for the houses shown in Table F-3. The PRISM runs shown were made using data files that had been prepared by setting the energy consumption values to zero for all meter reading periods during which the average ambient temperature was above 55°F. The temperature of 55°F was chosen because it was about equal to the average value of the reference temperatures obtained for these houses when the full data sets were used. The effect of setting the energy consumption values to zero is to remove these data from the PRISM analysis, as demonstrated by the reduced number of readings shown in Table F-3, as compared to those shown in Tables F-1 and F-2. Physically, this data selection process corresponds to removing the summer energy consumption data for each house.

The results of the above analysis are shown in Tables F-4 and F-5, where the normalized thermal load is again calculated using Equation 4.1. As can be seen by comparing Tables F-4 and F-5 with Tables F-1 and F-2, the results for the normalized thermal load are nearly the same for both the complete and truncated sets of input data. A more detailed comparison of these results is shown in Figure F-1. The histogram in Figure F-1 shows the distribution of the percent difference between the normalized thermal load calculated using each data set. Out of 45 houses, all but 3 fall within the plus and minus 5 percent error limits shown in Figure F-1. The mean and standard deviation for this distribution are .44 and 2.77 respectively, as shown by the superimposed normal curve. Eliminating the values that lie outside the limits shown yields a mean and standard deviation of 0.09 and 1.91 respectively. These are reassuring results demonstrating that the point-slope specification required for the calculation of the NTL may be adequately quantified by the PRISM program, even though this algorithm is designed to optimize the NAC and not the NTL.

The effect of seasonality on the calculation of the normalized thermal load.

It has been demonstrated that a seasonal component to household energy consumption exists that is small in amplitude and sinusoidal in character (24). The purpose of this discussion is to briefly explore in a theoretical way the impact that seasonality in energy consumption

could have on the calculated value of the NTL. Assume that a seasonal building load may be represented by the following linear equation:

$$\text{Seasonal Load} = \delta\ (Tc - T) \tag{F3}$$

where δ and Tc are constants, and T is the ambient temperature. This seasonal load may be thought of as the first term in the expansion of a sine function about an inflection point given by Tc. Using previous ideas as a starting point (25), we may learn about how the NTL handles this seasonal load by solving for the value of Tc that leaves the NTL unchanged. That is, we seek T_c such that:

$$\text{NTL with seasonal load} = \text{NTL without seasonal load} \tag{F4}$$

From the definition of NTL we can write:

$$\begin{aligned}\text{NTL with seasonal load} &= H_o\ (T_n)\ (\beta + \delta) + \\ &\quad D_o\ (T_n)\ [\varepsilon + \delta\ (Tc - T_{set})] \\ &= H_o\ (T_n)\ \beta + D_o\ (T_n)\ \varepsilon\end{aligned} \tag{F5}$$

where the normalized set point temperature is given by T_n

Solving yields:

$$Tc - T_{set} = -\ H_o\ (T_n)/D_o\ (T_n) = -\ (T_n - \bar{T}) \tag{F6}$$

where $\bar{T}$ is the average ambient temperature for those days with an average temperature below T_n.

Solving for Tc yields:

$$Tc = \bar{T} + (T_{set} - T_n). \tag{F7}$$

For the case where the setpoint temperature equals the normalization temperature, we see that the NTL remains unchanged for Tc equal to the average ambient temperature for the heating season. That is, a seasonal addition to the load below temperature $\bar{T}$ with an equal subtraction from the load above temperature $\bar{T}$ does not change the NTL. This indicates that a seasonal load that has an inflection point, such as the average value point of a sine function, located to coincide in time with, that is in phase with, the temperature for the heating season, will have a reduced effect on the NTL. This occurs since the seasonality defined above loads in an equal but opposite way on the two terms in Equation 4.1. While more work on this effect is required, it is reassuring to see that the NTL would probably not be severely affected by data containing a seasonal component.

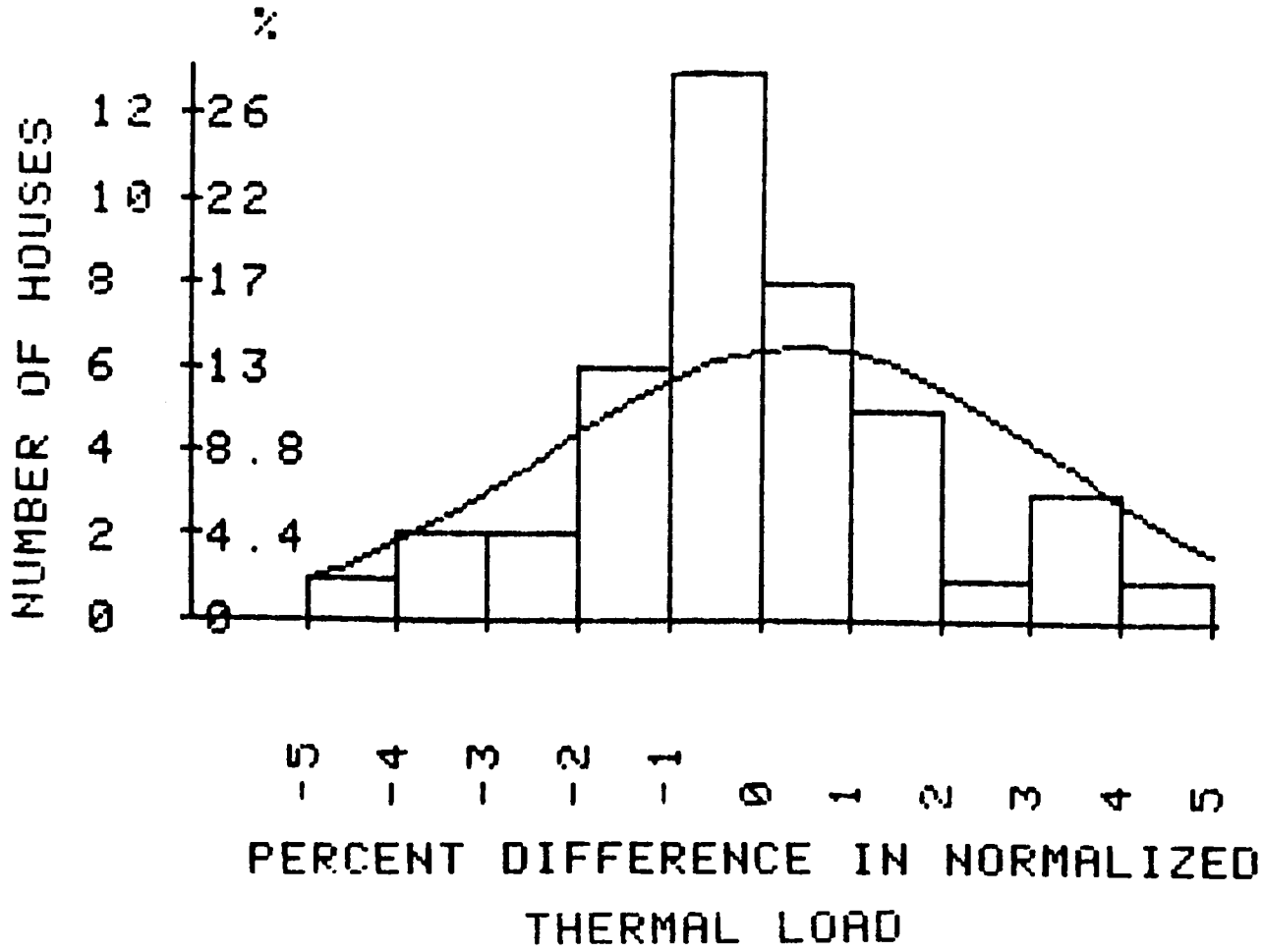


FIG. F-1 Distribution of percent difference in normalized thermal load (NTL) calculated with full and truncated data sets using Eq. 4.1. Truncated data sets exclude all energy consumption values for those measurement periods with an average temperature above 55 F.

TABLE F-1. Prism program results and normalized thermal load (NTL) values for houses with simultaneous gas and electric meter reading dates. Standard error of the NTL is shown in the last column.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)	STD ERROR OF SLOPE (CCF/DD)	STD ERROR OF BASELOAD (CCF/DAY)	STD ERROR OF REF TEMP (F)	STD ERROR OF THERML LOAD (CCF/YR)
BUILDER A											
1	58.01	.794	.0413	77.24	86	367	453	.0042	.113	4.84	34
2	41.46	1.006	.0346	70.54	35	308	343	.0036	.047	3.13	18
3	47.12	.548	.0338	63.33	-16	300	284	.0033	.057	3.5	22
4	52.01	1.103	.0365	82.23	149	324	473	.0038	.082	4.17	26
5	57.68	.638	.0423	72.76	82	376	458	.0034	.089	3.73	30
6	42.61	.909	.0349	68.66	7	310	317	.0037	.052	3.3	19
7	61.07	.767	.0266	89.90	137	236	373	.0025	.079	4.86	20
8	70.01	.809	.0292	97.72	232	260	492	.0033	.206	9.52	36
BUILDER D											
26	54.01	1.157	.0436	80.55	132	388	519	.0038	.08	3.47	26
27	55.97	.746	.0546	69.63	73	485	558	.003	.065	2.29	26
28	60.2	1.411	.0596	83.87	169	530	699	.0044	.116	3.45	34
BUILDER G											
41	60.71	.689	.0366	79.54	153	325	478	.0022	.057	2.77	21
42	63.2	.746	.0391	82.28	138	348	485	.0026	.081	3.45	24
43	54.38	1.152	.0573	74.48	74	509	583	.0035	.072	2.35	24
44	58.38	.421	.0426	68.26	3	379	382	.0028	.064	2.86	24
45	61.01	.582	.0407	75.31	62	362	424	.0027	.072	3.06	23
46	58.2	.699	.0466	73.20	70	414	484	.0027	.063	2.55	23
47	59.01	.981	.036	86.26	178	320	498	.0027	.066	3.32	22
48	57.97	1.346	.0483	85.84	150	429	580	.0042	.092	3.67	30

TABLE F-1 Continued.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)	STD ERROR OF SLOPE (CCF/DD)	STD ERROR OF BASELOAD (CCF/DAY)	STD ERROR OF REF TEMP (F)	STD ERROR OF THERML LOAD (CCF/YR)
BUILDER M											
84	51.06	1.035	.0864	63.04	-179	768	589	.0145	.182	5.55	98
82	47.57	.359	.04	56.55	-30	356	326	.0039	.059	3.25	30
83	55.8	.864	.0516	72.54	47	459	506	.0038	.078	2.92	28
85	60.74	.459	.0534	69.34	-7	475	467	.0031	.082	2.71	27
BUILDER N											
94	45.29	1.332	.05	71.93	71	444	515	.0066	.101	4.19	36
95	48.89	.871	.0461	67.78	10	410	420	.0049	.087	3.71	30
96	59.01	1.082	.0347	90.19	221	308	529	.0053	.159	7.36	43
97	54.22	1.197	.0418	82.86	178	372	550	.0058	.142	5.79	41
BUILDER P											
110	52.95	.512	.0484	63.53	-91	430	339	.0065	.089	4.56	46
111	61.29	.645	.0309	82.16	136	275	410	.0022	.047	3.15	22
112	49.04	.912	.032	77.54	101	284	385	.0073	.076	6.82	50
113	40.01	1.513	.0486	71.14	47	432	479	.0099	.057	4.52	48
114	43.91	1.028	.0708	58.43	-269	629	361	.0154	.105	5.66	86
115	48.63	.988	.0404	73.09	27	359	386	.0048	.049	3.52	29
117	44.01	1.258	.0553	66.76	-27	492	465	.0063	.047	2.99	36
119	64.95	.069	.0619	66.06	-30	550	520	.0094	.227	7.23	99
108	49.87	1.176	.0569	70.54	32	506	538	.0047	.061	2.55	29
109	49.8	1.032	.0435	73.52	81	387	467	.0035	.045	2.45	22
116	57.01	.546	.0285	76.17	88	253	341	.0041	.081	5.82	36

TABLE F-1 Continued.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)	STD ERROR OF SLOPE (CCF/DD)	STD ERROR OF BASELOAD (CCF/DAY)	STD ERROR OF REF TEMP (F)	STD ERROR OF THERML LOAD (CCF/YR)
BUILDER Q											
120	56.67	1.028	.036	85.23	178	320	498	.0029	.065	3.46	24
121	69.53	.912	.0306	99.33	258	272	530	.0028	.138	6.51	30
122	64.01	.794	.0325	88.44	153	289	442	.0031	.106	5.11	27
123	64.48	.588	.0341	81.72	134	303	437	.0025	.087	4	24
124	62.16	.625	.0217	90.96	162	193	355	.0021	.064	4.87	21
125	62.97	1.504	.0299	113.27	371	266	637	.0026	.079	4.47	24
126	41.01	.952	.0374	66.46	37	332	370	.0045	.052	3.46	25
127	63.01	1.264	.0221	120.20	350	196	547	.003	.097	7.42	31
BUILDER R											
128	53.12	.424	.0588	60.33	-96	523	427	.0033	.066	2.09	24
129	42.6	.835	.0582	56.95	-84	517	433	.0036	.041	1.8	22
130	49.15	.673	.0234	77.91	67	208	275	.0031	.048	4.58	20
131	58.01	.99	.037	84.77	157	329	486	.003	.068	3.43	24
BUILDER S											
132	58.36	.603	.0074	139.85	187	66	252	.003	.072	18.03	37
133	63.1	.296	.0381	70.87	42	339	381	.0019	.059	2.57	19
134	64.57	.608	.0363	81.32	149	323	472	.0026	.089	3.92	26
135	68.01	.681	.0248	95.47	181	220	402	.0018	.077	4.75	19
136	65.27	.404	.0323	77.78	72	287	359	.0027	.095	4.58	25
137	68.01	.499	.0246	88.29	150	219	369	.0024	.103	6.36	27
138	60.09	.311	.0361	68.70	7	321	328	.0027	.07	3.4	23
139	62.53	.444	.0327	76.11	104	291	395	.0031	.093	4.86	32
140	43.16	.894	.0497	61.15	-83	442	358	.0055	.068	3.37	31
141	55.51	.512	.037	69.35	46	329	375	.0025	.054	2.76	21
142	55.39	.559	.0386	69.87	-24	343	320	.0021	.046	2.22	14
143	55.85	.358	.0334	66.57	5	297	302	.002	.043	2.47	16

TABLE F-1 Continued.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)	STD ERROR OF SLOPE (CCF/DD)	STD ERROR OF BASELOAD (CCF/DAY)	STD ERROR OF REF TEMP (F)	STD ERROR OF THERML LOAD (CCF/YR)
BUILDER V											
160	57.2	.924	.077	69.20	74	684	758	.0061	.085	2.68	52
158	58.19	.544	.046	70.02	52	409	461	.0036	.082	3.35	32
159	65.49	.363	.0436	73.82	98	388	485	.0035	.122	4.36	36
BUILDER W											
162	56	.614	.0329	74.66	87	292	380	.005	.102	6.35	44
163	82	.365	.0259	96.09	170	230	400	.0025	1.598	64.47	35
165	73	.686	.0307	95.35	217	273	490	.0058	.431	19.82	75
164	59.17	.307	.0448	66.02	-10	398	388	.0033	.1	3.81	30

TABLE F-2 PRISM program results and normalized thermal load (NTL) values for houses with separate gas and electric meter reading dates. Standard error of the NTL is shown in the last column.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)	STD ERROR OF SLOPE (CCF/DD)	STD ERROR OF BASELOAD (CCF/DAY)	STD ERROR OF REF TEMP (F)	STD ERROR OF THERML LOAD (CCF/YR)
BUILDER B											
9	60.28	.166	.044	74.51	73	391	464	.0016	.041	1.71	14
10	58.06	.185	.0448	70.89	34	398	432	.0036	.082	3.41	30
11	51.39	.647	.0421	85.05	190	374	564	.0036	.064	3.19	24
12	61.21	.334	.0451	83.47	197	401	598	.0063	.108	4.62	52
13	61	.298	.04	83.45	175	356	530	.0027	.074	3.15	24
14	55.38	.317	.0375	75.57	89	333	422	.0024	.048	2.58	19
16	61.49	.352	.0374	82.13	129	332	462	.0027	.073	3.54	24
15	55.9	.616	.0441	69.87	19	392	411	.0019	.042	1.84	15
BUILDER C											
17	57.32	.574	.0512	79.66	161	455	616	.0068	.15	5.54	54
19	54.34	.272	.0432	74.06	41	384	425	.0048	.097	4.29	32
20	60.14	.457	.0458	79.07	87	407	494	.0016	.038	1.55	13
21	55.93	.344	.0559	69.60	41	497	538	.0064	.134	4.54	50
24	59.6	.56	.0588	79.33	130	523	652	.0088	.216	6.69	70
BUILDER E											
29	56.14	.006	.036	76.31	102	320	422	.0053	.097	5.68	44
30	55.34	.034	.0439	71.60	43	390	433	.0022	.04	1.91	17
32	51	1.498	.0466	83.15	154	414	568	.0056	.089	3.95	32
BUILDER H											
49	37.43	.041	.0446	65.03	-21	396	376	.0048	.029	2.68	26
50	54.1	.023	.0504	76.18	108	448	556	.0017	.028	1.31	14
52	55.12	.027	.0489	70.19	53	435	488	.0014	.025	1.13	12
51	44	.805	.0614	57.11	-216	546	330	.0039	.059	2.12	21

TABLE F-2 Continued.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)	STD ERROR OF SLOPE (CCF/DD)	STD ERROR OF BASELOAD (CCF/DAY)	STD ERROR OF REF TEMP (F)	STD ERROR OF THERML LOAD (CCF/YR)
BUILDER I											
53	55.43	.516	.05	73.95	101	444	545	.0082	.124	5.14	60
54	59.14	.526	.0446	89.10	265	396	661	.0092	.145	6.88	74
55	55	.332	.0467	69.60	115	415	531	.0071	.109	4.75	60
57	57.93	.512	.0572	72.48	61	508	570	.0098	.157	5.74	75
58	54.9	.487	.0616	69.95	30	548	578	.0078	.112	3.9	54
59	54.77	.519	.0568	72.01	53	505	558	.0105	.152	5.69	71
60	62.64	.293	.0559	77.72	144	497	641	.0058	.129	4.28	52
61	55.94	.492	.051	71.27	-6	453	448	.0074	.114	4.66	48
62	66.25	.247	.0452	77.25	110	402	512	.0088	.245	9.12	86
63	68.48	.136	.0455	80.26	151	404	555	.011	.34	12.55	117
BUILDER J											
65	55	.035	.0531	76.19	93	472	565	.0048	.127	3.92	32
66	49.45	.117	.0644	62.91	-108	572	465	.0094	.123	4.66	60
68	62	.01	.0487	67.54	-5	433	428	.0131	.336	12.5	123
70	54.65	.043	.0514	71.83	3	457	459	.0088	.16	6.14	57
71	63	.038	.0707	71.60	-33	628	595	.0071	.195	4.82	59
72	58.55	.124	.0416	74.51	37	370	407	.0052	.119	5.41	41
67	63	.251	.0569	67.41	-24	506	482	.0062	.171	5.46	60
69	59.58	.88	.0531	76.15	97	472	569	.0052	.123	4.2	42
BUILDER K											
75	56.22	.444	.0487	70.88	33	433	466	.005	.11	4.21	38
73	63.8	.584	.0524	74.95	63	466	529	.0046	.16	4.91	42
74	60.09	1.003	.0464	81.71	199	412	611	.002	.058	2.08	18

TABLE F-2 Continued.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)	STD ERROR OF SLOPE (CCF/DD)	STD ERROR OF BASELOAD (CCF/DAY)	STD ERROR OF REF TEMP (F)	STD ERROR OF THERML LOAD (CCF/YR)
BUILDER T											
148	70.05	.233	.0397	81.46	145	353	498	.005	.299	10.87	60
150	62.71	.273	.0456	78.13	145	405	550	.0041	.122	4.7	41
151	65.31	.404	.0454	85.88	223	404	627	.0032	.11	3.96	32
BUILDER U											
152	55.84	.027	.0519	70.62	8	461	469	.0041	.08	3.27	32
153	53.48	.007	.049	67.50	-17	436	418	.0028	.052	2.21	21
154	49.43	.113	.0421	70.17	70	374	444	.0027	.033	2.17	21
156	57.05	.042	.046	78.62	113	409	522	.0034	.067	3.15	28
157	56.45	.093	.0451	74.92	69	401	470	.002	.037	1.79	16
155	48.66	.497	.0416	60.61	-53	370	316	.0037	.049	2.69	24

TABLE F-3. PRISM short summary output for 45 houses. Houses are identified by CASE ID number and are grouped by builder. Data for these analyses were selected by setting the energy consumption to zero for all meter reading periods with an average outside temperature above 55 ^{o}F.

CASE ID		TIME PERIOD	N OF READS	DATASET LABEL	N OF ITS	R-SQ	TREF	SE OF TREF	BASELOAD PER DAY	SE OF BASE	SLOPE PER HDD	SE OF SLOPE	NAC, CCF PER YEAR	SE OF NAC
H	1	12/18/83 - 12/14/84	31		2	.6807	73.00	(-9.90)	.165	(-9.900)	.0415	(.0053)	493.62	(46.45)
H	2	12/18/83 - 12/14/84	31		6	.8213	39.82	(4.66)	1.060	(.099)	.0347	(.0041)	485.85	(21.49)
H	3	12/18/83 - 12/14/84	31		3	.7889	52.69	(14.57)	.387	(.436)	.0332	(.0036)	311.64	(67.97)
H	4	12/18/83 - 12/14/84	31		6	.7341	56.11	(24.54)	.966	(.830)	.0362	(.0044)	565.22	(113.52)
H	5	12/18/83 - 12/14/84	31		4	.7846	65.00	(54.82)	.277	(2.310)	.0434	(.0046)	450.89	(202.01)
H	6	12/18/83 - 12/14/84	31		5	.8333	36.80	(4.14)	1.059	(.081)	.0367	(.0044)	475.13	(18.74)
H	7	12/18/83 - 12/14/84	31		2	.7850	73.00	(-9.90)	.326	(-9.900)	.0289	(.0028)	420.77	(24.70)
H	8	12/26/83 - 12/14/84	30		2	.5727	73.00	(-9.90)	.865	(-9.900)	.0264	(.0043)	591.93	(34.50)
H	9	10/12/83 - 12/ 6/84	9		6	.9914	46.95	(3.44)	.670	(.093)	.0467	(.0030)	432.58	(15.58)
H	10	10/12/83 - 12/ 6/84	9		4	.9481	59.00	(27.18)	.158	(1.118)	.0444	(.0049)	347.60	(134.44)
H	11	10/ 3/83 - 11/28/84	9		2	.9572	58.73	(16.16)	.382	(.593)	.0410	(.0041)	404.85	(74.41)
H	12	10/ 3/83 - 11/28/84	6		1	.9104	64.00	(-9.90)	.209	(-9.900)	.0451	(.0071)	427.35	(31.88)
H	13	10/ 3/83 - 11/28/84	9		3	.9497	60.00	(32.50)	.339	(1.209)	.0400	(.0044)	394.36	(139.08)
H	14	11/ 1/83 - 12/28/84	9		1	.9750	64.00	(-9.90)	.047	(-9.900)	.0363	(.0022)	300.08	(16.35)
H	16	10/18/83 - 12/ 7/84	9		1	.9495	44.77	(7.48)	.870	(.160)	.0412	(.0069)	467.61	(27.82)
H	15	9/18/83 - 12/23/84	43		11	.9053	57.22	(10.63)	.578	(.396)	.0406	(.0023)	459.02	(52.13)
H	41	12/19/83 - 12/21/84	29		11	.8347	53.00	(24.53)	1.013	(.817)	.0354	(.0034)	553.96	(124.27)
H	42	12/19/83 - 12/21/84	29		2	.7822	59.00	(68.23)	.981	(2.543)	.0378	(.0040)	604.60	(317.01)
H	43	12/19/83 - 12/21/84	29		6	.8977	49.00	(5.75)	1.427	(.256)	.0582	(.0048)	777.39	(42.83)
H	44	12/19/83 - 12/21/84	29		2	.8397	59.00	(56.49)	.400	(2.369)	.0425	(.0037)	423.36	(295.25)
H	45	12/19/83 - 12/21/84	29		3	.8094	49.00	(8.26)	1.044	(.261)	.0414	(.0049)	563.45	(43.77)
H	46	12/19/83 - 12/21/84	29		11	.8851	59.00	(46.60)	.650	(2.155)	.0468	(.0034)	543.20	(268.57)
H	47	12/19/83 - 12/21/84	29		7	.7699	53.00	(30.13)	1.237	(.986)	.0348	(.0041)	632.55	(149.86)
H	48	12/19/83 - 12/21/84	29		8	.7734	49.00	(9.21)	1.789	(.337)	.0479	(.0063)	864.22	(56.48)

TABLE F-3. Continued.

CASE ID		TIME PERIOD	N OF READS	DATASET LABEL	N OF ITS	R-SQ	TREF	SE OF TREF	BASELOAD PER DAY	SE OF BASE	SLOPE PER HDD	SE OF SLOPE	NAC, CCF PER YEAR	SE OF NAC
H	53	9/20/83 - 11/16/84	8		6	.8666	55.22	(14.97)	.518	(.553)	.0503	(.0117)	474.06	(80.19)
H	54	9/20/83 - 11/16/84	7		2	.8623	64.00	(39.69)	.254	(1.625)	.0465	(.0113)	454.86	(147.54)
H	55	9/20/83 - 11/16/84	8		5	.8821	55.18	(13.94)	.312	(.482)	.0471	(.0103)	380.63	(69.99)
H	57	9/20/83 - 11/16/84	8		7	.8839	59.00	(21.11)	.434	(.991)	.0578	(.0121)	536.12	(119.71)
H	58	9/20/83 - 11/16/84	8		4	.9370	61.00	(17.81)	.139	(.892)	.0611	(.0094)	478.85	(95.78)
H	59	9/20/83 - 11/16/84	8		5	.8468	58.74	(20.99)	.325	(.905)	.0560	(.0142)	480.71	(114.92)
H	60	9/20/83 - 11/16/84	8		5	.9356	64.00	(24.58)	.203	(1.242)	.0564	(.0078)	513.04	(113.30)
H	61	9/20/83 - 11/16/84	8		11	.9173	60.92	(19.24)	.248	(.793)	.0509	(.0090)	446.29	(90.53)
H	62	9/20/83 - 11/16/84	8		3	.7278	60.00	(38.75)	.601	(1.343)	.0425	(.0153)	507.25	(153.29)
H	63	9/20/83 - 11/16/84	7		1	.6429	71.00	(-9.90)	.398	(-9.900)	.0366	(.0122)	504.07	(65.61)
H	110	12/26/83 - 12/26/84	8		2	.9374	68.00	(******)	-.106	(8.373)	.0460	(.0085)	370.73	(557.28)
H	111	12/26/83 - 12/26/84	7		4	.9970	50.38	(2.27)	.902	(.041)	.0339	(.0017)	487.90	(6.53)
H	112	12/26/83 - 12/26/84	8		7	.9568	60.00	(21.10)	.663	(.504)	.0295	(.0043)	441.63	(54.28)
H	113	12/26/83 - 12/26/84	8		5	.9691	41.44	(4.73)	1.460	(.086)	.0479	(.0082)	681.69	(17.70)
H	114	12/26/83 - 12/26/84	8		6	.9699	41.12	(4.58)	1.128	(.131)	.0750	(.0125)	640.16	(27.09)
H	115	12/26/83 - 12/26/84	8		6	.9826	41.53	(3.55)	1.121	(.063)	.0473	(.0060)	556.35	(13.06)
H	117	12/26/83 - 12/26/84	8		5	.9834	44.23	(4.29)	1.249	(.099)	.0551	(.0070)	651.83	(18.07)
H	119	12/26/83 - 12/26/84	6		1	.8356	69.00	(-9.90)	-.053	(-9.900)	.0590	(.0131)	523.02	(88.48)
H	108	1/23/84 - 1/28/85	32		6	.8734	46.39	(4.83)	1.337	(.174)	.0583	(.0063)	717.09	(31.64)
H	109	1/23/84 - 1/28/85	32		6	.8720	44.32	(3.94)	1.226	(.104)	.0453	(.0049)	609.02	(20.30)
H	116	12/12/83 - 12/10/84	25		2	.5904	72.00	(-9.90)	.128	(-9.900)	.0284	(.0049)	333.64	(39.39)

TABLE F-3. Continued.

CASE ID		TIME PERIOD	N OF READS	DATASET LABEL	N OF ITS	R-SQ	TREF	SE OF TREF	BASELOAD PER DAY	SE OF BASE	SLOPE PER HDD	SE OF SLOPE	NAC, CCF PER YEAR	SE OF NAC
H	53	9/20/83 - 11/16/84	8		6	.8666	55.22	(14.97)	.518	(.553)	.0503	(.0117)	474.06	(80.19)
H	54	9/20/83 - 11/16/84	7		2	.8623	64.00	(39.69)	.254	(1.625)	.0465	(.0113)	454.86	(147.54)
H	55	9/20/83 - 11/16/84	8		5	.8821	55.18	(13.94)	.312	(.482)	.0471	(.0103)	380.63	(69.99)
H	57	9/20/83 - 11/16/84	8		7	.8839	59.00	(21.11)	.434	(.991)	.0578	(.0121)	536.12	(119.71)
H	58	9/20/83 - 11/16/84	8		4	.9370	61.00	(17.81)	.139	(.892)	.0611	(.0094)	478.85	(95.78)
H	59	9/20/83 - 11/16/84	8		5	.8468	58.74	(20.99)	.325	(.905)	.0560	(.0142)	480.71	(114.92)
H	60	9/20/83 - 11/16/84	8		5	.9356	64.00	(24.58)	.203	(1.242)	.0564	(.0078)	513.04	(113.30)
H	61	9/20/83 - 11/16/84	8		11	.9173	60.92	(19.24)	.248	(.793)	.0509	(.0090)	446.29	(90.53)
H	62	9/20/83 - 11/16/84	8		3	.7278	60.00	(38.75)	.601	(1.343)	.0425	(.0153)	507.25	(153.29)
H	63	9/20/83 - 11/16/84	7		1	.6429	71.00	(-9.90)	.398	(-9.900)	.0366	(.0122)	504.07	(65.61)
H	110	12/26/83 - 12/26/84	8		2	.9374	68.00	(88888)	-.106	(8.373)	.0460	(.0085)	370.73	(557.28)
H	111	12/26/83 - 12/26/84	7		4	.9970	50.38	(2.27)	.902	(.041)	.0339	(.0017)	487.90	(6.53)
H	112	12/26/83 - 12/26/84	8		7	.9568	60.00	(21.10)	.663	(.504)	.0295	(.0043)	441.63	(54.28)
H	113	12/26/83 - 12/26/84	8		5	.9691	41.44	(4.73)	1.460	(.086)	.0479	(.0082)	681.69	(17.70)
H	114	12/26/83 - 12/26/84	8		6	.9699	41.12	(4.58)	1.128	(.131)	.0750	(.0125)	640.16	(27.09)
H	115	12/26/83 - 12/26/84	8		6	.9826	41.53	(3.55)	1.121	(.063)	.0473	(.0060)	556.35	(13.06)
H	117	12/26/83 - 12/26/84	8		5	.9834	44.23	(4.29)	1.249	(.099)	.0551	(.0070)	651.83	(18.07)
H	119	12/26/83 - 12/26/84	6		1	.8356	69.00	(-9.90)	-.053	(-9.900)	.0590	(.0131)	523.02	(88.48)
H	108	1/23/84 - 1/28/85	32		6	.8734	46.39	(4.83)	1.337	(.174)	.0583	(.0063)	717.09	(31.64)
H	109	1/23/84 - 1/28/85	32		6	.8720	44.32	(3.94)	1.226	(.104)	.0453	(.0049)	609.02	(20.30)
H	116	12/12/83 - 12/10/84	25		2	.5904	72.00	(-9.90)	.128	(-9.900)	.0284	(.0049)	333.64	(39.39)

TABLE F-4. Normalized thermal load (NTL) values calculated using Eqs. 4.1 - 4.3 and PRISM output parameters shown in Table F-3 for houses with simultanious gas and electric meter reading dates. For those cases showing indeterminate values for the standard errors of the base load or reference temperature, the standard error of the NTL was calculated using only the first term of Eq. F-2.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)	STD ERROR OF SLOPE (CCF/DD)	STD ERROR OF BASELOAD (CCF/DAY)	STD ERROR OF REF TEMP (F)	STD ERROR OF THERML LOAD (CCF/YR)
BUILDER A											
1	73	.165	.0415	76.98	83	369	452	.0053	-9.9	-9.9	52
2	39.82	1.06	.0347	70.37	34	308	342	.0041	.099	4.66	19
3	52.69	.387	.0332	64.35	-6	295	289	.0036	.436	14.57	24
4	56.11	.966	.0362	82.80	154	322	475	.0044	.83	24.54	29
5	65	.277	.0434	71.38	67	386	453	.0046	2.31	54.82	44
6	36.8	1.059	.0367	65.66	-25	326	301	.0044	.081	4.14	20
7	73	.326	.0289	84.28	102	257	359	.0028	-9.9	-9.9	26
8	73	.865	.0264	105.77	271	235	506	.0043	-9.9	-9.9	42
BUILDER G											
41	53	1.013	.0354	81.62	169	315	483	.0034	.817	24.53	24
42	59	.981	.0378	84.95	162	336	498	.004	2.543	68.23	25
43	49	1.427	.0582	73.52	59	517	576	.0048	.256	5.75	26
44	59	.4	.0425	68.41	5	378	383	.0037	2.369	56.49	25
45	49	1.044	.0414	74.22	50	368	418	.0049	.261	8.26	27
46	59	.65	.0468	72.89	66	416	482	.0034	2.155	46.6	23
47	53	1.237	.0348	88.55	195	309	505	.0041	.986	30.13	25
48	49	1.789	.0479	86.35	156	426	582	.0063	.337	9.21	31

TABLE F-4 Continued.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)	STD ERROR OF SLOPE (CCF/DD)	STD ERROR OF BASELOAD (CCF/DAY)	STD ERROR OF REF TEMP (F)	STD ERROR OF THERML LOAD (CCF/YR)
BUILDER P											
110	68	-.106	.046	65.70	-58	409	351	.0085	8.373	*****	70
111	50.38	.902	.0339	76.99	99	301	400	.0017	.041	2.27	13
112	60	.663	.0295	82.47	134	262	397	.0043	.504	21.1	45
113	41.44	1.46	.0479	71.92	57	426	483	.0082	.086	4.73	42
114	41.12	1.128	.075	56.16	-333	667	333	.0125	.131	4.58	61
115	41.53	1.121	.0473	65.23	-75	420	346	.006	.063	3.55	30
117	44.23	1.249	.0551	66.90	-24	490	466	.007	.099	4.29	42
119	69	-.053	.059	68.10	5	524	530	.0131	-9.9	-9.9	121
108	46.39	1.337	.0583	69.32	13	518	531	.0063	.174	4.83	35
109	44.32	1.226	.0453	71.38	56	403	459	.0049	.104	3.94	24
116	72	.128	.0284	76.51	90	252	342	.0049	-9.9	-9.9	53

TABLE F-5. Normalized thermal load (NTL) values calculated using Eqs. 4.1 - 4.3 and PRISM output parameters shown in Table F-3 for houses with separate gas and electric meter reading dates. For those cases showing indeterminate values for the standard errors of the base load or reference temperature, the standard error of the NTL was calculated using only the first term of Eq. F-2.

BUILDER OR UNIT NUMBER	REF TEMP (F)	BASELOAD (CCF/DAY)	SLOPE (CCF/DD)	T PRIME (F)	TEMP INDEPEND'T LOAD (CCF/YR)	TEMP DEPEND'T LOAD (CCF/YR)	NORMALIZED THERMAL LOAD (CCF/YR)	STD ERROR OF SLOPE (CCF/DD)	STD ERROR OF BASELOAD (CCF/DAY)	STD ERROR OF REF TEMP (F)	STD ERROR OF THERML LOAD (CCF/YR)
BUILDER B											
9	46.95	.67	.0467	71.15	32	415	447	.003	.093	3.44	21
10	59	.158	.0444	71.34	40	395	434	.0049	1.118	27.18	40
11	58.73	.382	.041	86.83	206	364	570	.0041	.593	16.16	31
12	64	.209	.0451	83.49	198	401	598	.0071	-9.9	-9.9	54
13	60	.339	.04	83.48	175	356	531	.0044	1.209	32.5	39
14	64	.047	.0363	77.42	105	323	428	.0022	-9.9	-9.9	17
16	44.77	.87	.0412	76.08	71	366	437	.0069	.16	7.48	44
15	57.22	.578	.0406	71.46	36	361	397	.0023	.396	10.63	17
BUILDER I											
53	55.22	.518	.0503	73.67	98	447	545	.0117	.553	14.97	87
54	64	.254	.0465	86.88	246	413	660	.0113	1.625	39.69	107
55	55.18	.312	.0471	69.24	111	419	530	.0103	.482	13.94	90
57	59	.434	.0578	72.04	55	514	569	.0121	.991	21.11	99
58	61	.139	.0611	70.48	39	543	582	.0094	.892	17.81	85
59	58.74	.325	.056	72.76	65	498	562	.0142	.905	20.99	115
60	64	.203	.0564	77.35	140	501	641	.0078	1.242	24.58	72
61	60.92	.248	.0509	71.49	-2	452	450	.009	.793	19.24	75
62	60	.601	.0425	80.02	138	378	515	.0153	1.343	38.75	131
63	71	.398	.0366	92.80	253	325	578	.0122	-9.9	-9.9	116

APPENDIX G.

Homeowner Survey and Statistical Results

Please respond to each question or statement with a single number or a "yes" or "no" in the blank next to the question. If a question or statement does not apply to you circle the "na"(not applicable). This survey is for research house number _____.

1) How many people twelve or older live in your house? _____
How many people under the age of twelve live in your house? _____
During the past year our household: increased by _____ or decreased by _____ member(s).

2) What is the usual setting of your thermostat: When someone is at home? _____
At night? _____ When no one is at home? _____

3) There is general agreement in our household as to the thermostat setting. _____

4) Including everybody, the number of people usually at home during the day is _____.

5) We usually change the filter in our furnace once a year. _____

6) This past year we burned either kerosine or wood to help heat our home. _____

7) As far as I know the builder who built my house is still in business. _____

8) We sometimes open windows during the winter to just get in some fresh air. _____

9) We have a solar hot water system installed in our home. _____
It seems to work fairly well. _____ or na

10) We have movable window insulation in most of our windows. _____
This window insulation seems to work fairly well. _____ or na

11) Each day during the winter we regularly remove and replace the window insulation in our home. _____ or na

12) We have a gas kitchen range. _____ We have an electric kitchen range. _____
We have a gas clothes dryer. _____ We have an electric clothes dryer. _____
We wash and dry about _____ loads of laundry a week.

13) Our house has an air-to-air heat exchanger. _____
It seems to work fairly well. _____ or na

14) We run our heat exchanger on a regular basis during the winter. _____ or na
The heat exchanger runs about _____ hours per day or na.

15) We have _____ window air conditioner(s). We have a central air conditioner. _____

16) Do you heat your basement or a lower level that is below ground level during the winter?_____ or na if you have no basement or lower level.

17) If you have a basement or lower level what portion of the ceiling is finished:
Very little or none_____; about half_____; all or nearly all_____.
What portion of the floor is covered with either carpet, furniture, or storage boxes:
Very little or none_____; about half_____; all or nearly all_____. or na

18) Do you have heating vents in any of the cement floors in your house? _____

19) If your house has been changed since it was built, please describe the work done on the back side of this survey form. For example, have you built an attached garage, or added insulation to some parts of the house.

That's all. Please seal up this form and place it in the mail to collect your two dollars. Please add any comments on the back. Thank you for your response.

FIG. G-1 Homeowner survey used to obtain information about the design, use, and operation of houses in the research program.

TABLE G-1. MULTREG regression analysis results for the full sample of research houses. Variables are listed in Table 4.5.

VARIABLE	COEFF.	STD ERROR	T VALUE
B0	-112.3634	160.9682	-.70
V5	.4143406	.4630882	.89
V6	2.647634	.9275598	2.85
V7	-.9923517E-01	.1712737	-.58
V9	.8451396	.4100186	2.06
V10	4.013337	2.252858	1.78
V14	18.80659	9.918358	1.90
V23	5.441705	2.717350	2.00
V30	25.46368	11.35739	2.24
V31	50.43434	28.36689	1.78

DEGREES OF FREEDOM = 83
RESIDUAL MEAN SQUARE= 5657.161
ROOT MEAN SQUARE = 75.21410
R-SQUARED = .4421

TABLE G-2. MULTREG regression analysis results for the small south glass area subsample of research houses. Small south glass area is defined as less than 10 percent of the floor area of the house as south glass area. Variables are listed in Table 4.5.

VARIABLE	COEFF.	STD ERROR	T VALUE
B0	-51.38788	61.73095	-.83
V5	1.515487	.5996786	2.53
V6	-1.232515	.5254533	-2.35
V7	-1.542371	.3470264	-4.44
V9	1.970697	.4949947	3.98
V22	-22.64105	12.79313	-1.77
V23	-2.974359	1.694731	-1.76
V27	2.642544	1.259868	2.10
V28	45.11763	21.04764	2.14

DEGREES OF FREEDOM = 33
RESIDUAL MEAN SQUARE= 1051.545
ROOT MEAN SQUARE = 32.42754
R-SQUARED = .6926

TABLE G-3. MULTREG regression analyis results for the medium south glass area subsample of research houses. Medium glass area is defined as more than 11 percent, but less than 20 percent, of the floor area of the house as south glass area. Variables are listed in Table 4.5.

VARIABLE	COEFF.	STD ERROR	T VALUE
B0	460.9326	196.6884	2.34
V5	-1.129386	.4484639	-2.52
V6	2.431568	.9439655	2.58
V7	.5158560	.2320026	2.22
V9	.9215981	.3784457	2.44
V10	-6.996550	2.637106	-2.65
V27	-14.70918	5.098570	-2.88
V29	37.57537	15.64140	2.40
V30	-39.45315	16.04147	-2.46
V31	109.2920	23.38675	4.67
V32	-27.84759	17.37751	-1.60

DEGREES OF FREEDOM = 28
RESIDUAL MEAN SQUARE= 1384.664
ROOT MEAN SQUARE = 37.21108
R-SQUARED = .6533

APPENDIX H.

CIRA and HOTCAN Sample Outputs

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CIRA--------------Computerized Instrumented Residential Audit---------------CIRA

                                Related data...

                      Occupants' Name: OCCUPANT

                           House Name: DUMAX

                     House Area(sqft): 1733

                  House Volume(cuft): 15344

                                City: MINNEATR

                       Latitude(deg): 44.9

                      Altitude(feet): 834

                        Azimuth(deg): 0

       Solar storage factor(unitless): .27

            Thermal time constant(hr): 11.388

                    Free heat(Btu/hr): 2752.79

                     Moisture(lb/day): 3.576

     Building Load Coefficient(Btu/hr/F): Yearly / Heating / Cooling:
         289.137                    300.239                    278.036

        Conduction Coefficient(Btu/hr/F): Total / Ceiling / Floor:
         243.496                    14.5642                    59.5108

              Leakage area(sqin): Total / Ceiling / Floor:
         36.0001                    14.3147                    10.9512

        North/East/South/West/Horizontal December Solar access(%):
      100            60.0001          74.0037          60.0001            100

         North/East/South/West/Horizontal June Solar access(%):
      100            79.9999          45.3528          79.9999            100

        North/East/South/West/Horizontal heating season SA(sqft):
    2.46544          48.6824          149.683          26.3549          3.00985

        North/East/South/West/Horizontal cooling season SA(sqft):
    2.46544          48.6824          149.683          26.3549          3.00985

Heating day/night thermostats(degF)   Cooling day/night thermostats(degF):
        69                  69                  90                  90

Yearly Electric Cons.(kWh)/Cost($) -- Yearly other Fuel Cons.(MBtu)/Cost($):
      10362.5             549.213             34.7767             170.406


CIRA--------------Computerized Instrumented Residential Audit---------------CIRA
```

FIG. H-1. Sample output from CIRA program. Column c of the monthly results was prepared using the built-in calculator mode and is equal to the sum of columns a and b.

	a Dload	b Nload	c Tload	d Sgain	e SpEgy	f Infil	g T gas	h Telec	
Jan:	3.0	6.1	9.126	3.45	11.0	0.22	109	900	:Jan
Feb:	1.0	4.1	5.093	4.31	6.2	0.21	61	804	:Feb
Mar:	0.3	2.7	2.952	5.74	3.6	0.19	36	882	:Mar
Apr:	0.0	0.9	0.903	5.19	1.1	0.18	11	847	:Apr
May:	0.0	0.0	0.000	5.04	0.0	0.14	0	873	:May
Jun:	-0.1	0.0	-.078	5.29	0.0	0.11	0	844	:Jun
Jul:	-0.3	0.0	-.304	5.70	0.0	0.11	0	873	:Jul
Aug:	-0.1	0.0	-.128	5.80	0.0	0.10	0	873	:Aug
Sep:	0.0	0.0	0.000	5.30	0.0	0.12	0	844	:Sep
Oct:	0.0	0.0	0.000	4.89	0.0	0.15	0	873	:Oct
Nov:	1.0	2.7	3.685	2.71	4.5	0.19	45	856	:Nov
Dec:	2.4	4.6	7.064	2.68	8.6	0.21	85	894	:Dec
yr(sum):	7.2	21.1	28.313	56.11	35.1	1.93	348	10362	:yr(sum)
yr(mean):	0.6	1.8	2.359	4.68	2.9	0.16	29	864	:yr(mean)

a = A) - Dload - Daytime sensible load (MBtu)
b = B) - Nload - Nighttime sensible load (MBtu)
d = J) - Sgain - Solar gain (MBtu)
e = E) - SpEgy - Space cond. energy use (MBtu)
f = F) - Infil - Infiltration (ac/hr)
g = G) - T gas - Overall gas use (therm)
h = H) - Telec - Overall elec use (kWh)

FIG. H-1. Continued.

HOTCAN 3.0
NATIONAL RESEARCH COUNCIL OF CANADA, SASKATOON, SASKATCHEWAN, S7N 0W9

NAME: DUMAX
ADDRESS: HUTCHINSON
WEATHER DATA IS FOR MINNEAPOLIS-MINNESOTA (ALTERNATE LOCATIONS)
HOUSE DATA IS STORED IN FILE DUMAX

BUILDING PARAMETERS

ELEMENT	AREA FT2	R-VALUE	HEAT LOSS MIL.BTU	%SEASONAL LOSS
CEILING				
	897	61		
TOTAL	896.95	60.98	3.2	5.39
MAIN WALLS (LESS WINDOWS AND DOORS)				
	736	23		
TOTAL	735.98	23	6.97	11.74
DOORS (LESS WINDOWS)				
	38	15		
TOTAL	37.98	14.99	.55	.93
BASEMENT WALLS ABOVE GRADE				
	679	20		
TOTAL	678.96	19.99	5.99	10.09
SHALLOW BASEMENT AREA: UNATTACHED, INSULATED OUTSIDE				
BASEMENT WALLS BELOW GRADE				
	319	9.1		
TOTAL	319.03	9.08	5.79	9.75
PERIMETER AREA (1 M OR 3.3 FT WIDE)				
	396	8.2		
TOTAL	395.97	8.18	4	6.74
CENTRE AREA				
	440	8.2		
TOTAL	439.98	8.18	2.08	3.5
WINDOWS				
SOUTH WINDOWS	(AVERAGE 2 GLAZINGS SHADING COEFFICIENT = .89)			
	193	2.2(3.5)		
TOTAL	193.03	2.21(3.52)	12.34	20.78
EAST WINDOWS	(AVERAGE 3 GLAZINGS SHADING COEFFICIENT = .8)			
	67	3		
TOTAL	67.03	3.01	4.85	8.17
WEST WINDOWS	(AVERAGE 3 GLAZINGS SHADING COEFFICIENT = .8)			
	34	3		
TOTAL	34	3.01	2.46	4.14

FIG. H-2. Sample output from HOTCAN program. Component areas, R-values, and heat losses are shown, as well as monthly and annual consumption.

```
HOTCAN 3.0

VENTILATION
-----------
HOUSE VOLUME = 15343.96 FT3
AIR TIGHTNESS AT 50 PA = 2.93
EFFECTIVE LEAKAGE AREA = 453
SEASONAL HEAT LOSS = 11.11 MIL.BTU (18.71% OF TOTAL)

TEMPERATURES (DEG C) MAIN FLOOR = 20.5
                     BASEMENT = 17
                     RISE ABOVE 20.5 DEG C = 3
THERMAL MASS LEVEL CHOSEN IS (B)

DAILY BASE ELECTRIC CONSUMPTION (KWH/D) = 14
DAILY HOT WATER ENERGY CONSUMPTION (KWH/D) = 14
SENSIBLE HEAT GAIN FROM OCCUPANTS (KWH/D) = 3

SOUTH WINDOWS OVERHANG GEOMETRY:
  AVERAGE WINDOW HEIGHT = 4.6 FT
  AVERAGE OVERHANG WIDTH = 1.7 FT
  AVERAGE HEADER HEIGHT = 1.5 FT
```

FIG. H-2. Continued.

HOTCAN 3.0

DESIGN HEAT LOSS AT -24.4C = 22933 BTUH

AVERAGE MONTHLY POWER

MONTH	THERMAL LOAD BTUH	INTERNAL GAIN BTUH	SOLAR GAIN BTUH	AUX HEAT REQD BTUH
JAN	14661	2883	5146	6628
FEB	13867	2853	6051	4962
MAR	11198	2832	5488	2877
APR	7307	2754	3511	1037
MAY	4023	2484	1535	0
JUN	0	0	0	0
JUL	0	0	0	0
AUG	0	0	0	0
SEP	2768	2170	597	0
OCT	5330	2641	2686	0
NOV	9658	2812	3942	2901
DEC	12972	2849	4583	5535

HEATING SEASON STARTS IN SEP AND ENDS IN MAY.
ESTIMATED ANNUAL SPACE HEATING = 17 MIL.BTU
ANNUAL INTERNAL GAINS FRACTION = .3
ANNUAL SOLAR FRACTION = .41

ANNUAL PREDICTED FUEL COSTS

FUEL COSTS ARE FOR ALTERNATE LOCATIONS AS OF 1985

ENERGY SOURCE	COST PER UNIT	SPACE HEATING	HOT WATER	LIGHTS AND APPLIANCES
ELECTRICITY	$.053/KWH	$269 EFF.= 100%	$270 EFF.= 100%	$270 EFF.= 100%
NATURAL GAS	$.49/THERM	$100 EFF.= 85%	EFF.= 0%	
OIL	$0/IMP GAL	EFF.= 0%	EFF.= 0%	
PROPANE	$0/IMP GAL	EFF.= 0%	EFF.= 0%	
WOOD	$0/TON	EFF.= 0%	EFF.= 0%	

FIG. H-2. Continued.

APPENDIX I.

Cost Analysis

COST ANALYSIS

The figures below represent the approximate extra costs for construction (including material, labor, overhead and profit) to improve energy efficiency of a house beyond a typically designed house constructed in 1980. Cost data was obtained from the 1984 Means Residential Light Commercial Cost Data publication, Builders Insulation of Minneapolis, Marv Anderson Construction, Swanco Construction, local lumber retailers, local furnace retailers, Andersen Windows, Edwards Sales, Davini Associates and the Department of Energy and Economic Development.

Ceilings--It costs an additional $0.02 per R-value per square foot to add blown-in cellulose insulation above an R-25 base (Design #1). Energy trusses are typically used when the ceiling insulation exceeds R-44. Therefore, an additional cost of $14.00 per truss is included for each of the four EEHDP houses.

Walls Exposed to Outside Air--It costs an additional $0.25 per square foot to build Design #2 and an additional $0.36 per square foot to build Design #3. It is assumed that a Design #1 wall includes 2" X 4" studs (16 o.c.) and 3.5" fiberglass batt insulation. It is assumed that a Design #2 wall includes 2" X 6" studs (24 o.c.) and 5.5" fiberglass batt insulation. A Design #3 wall include 2" X 6" studs (24" o.c.), 5.5" fiberglass batt insulation and R5.4 rigid insulation. Cost data used to calculate additional construction costs include: $0.31 per square foot for 2" X 6" studs (16" o.c.); $0.12 per square foot for 2" X 6" studs (24" o.c.); $0.13 per square foot for 5.5" fiberglass batting; $0.11 per square foot for R5.4 rigid insulation, when replacing regular sheathing; and $0.38 per square foot when replacing regular sheathing with R10.8 rigid insulation.

Basement Walls--It costs an additional $0.53 per square foot to increase foundation wall insulation with R5.4 rigid insulation. It costs an additional $0.81 per square foot to increase foundation insulation with R10.8 rigid insulation and $1.41 per square foot to install R21.6 rigid insulation. In addition, a cost of $2.50 per square foot is used for skirting placed over exposed insulation.

Basement Floor--It costs approximately $0.08 per R per square foot to install rigid insulation beneath the basement floor.

Slab-on-Grade Foundation Insulation--It costs approximately $0.28 per square foot to increase insulation from R5.4 to R10.8, $0.10 per square foot to increase R5.4 to R16.2, and $0.88 per square foot to increase R5.4 to R21.6.

Nonsouth Windows--It costs approximately $3.50 more per square foot to install triple-glazed windows instead of double-glazed windows. Window calculations are based on actual window area used for each of the four EEHDP houses.

South Windows--It costs approximately $15.00 per square foot to install additional double-glazed window units in a house.

To determine the cost of additional windows on the south side of EEHDP houses, the following calculation was applied:

- Floor area (ceiling area times 2) times .10 minus nonsouth window area equals south windows required by code.
- Extra south window area equals actual window area minus window area required by code.
- Extra windows on south side times $15.00 equals cost of added windows on south side.

Window Insulation--It costs approximately $10.00 per square foot to install insulating window shades.

Furnace Efficiency--All four EEHDP houses employ natural gas furnaces for space heating. It costs an extra $500 to install recuperative furnaces in EEHDP houses and in Design #3. A simple atmospheric furnace is included in Design #1 and Design #2.

Air Infiltration--The base design is Design #1 which includes natural ventilation and caulking. Design #2 is better sealed for an approximate cost of $100. Design #3 and all EEHDP units include mechanically controlled ventilation for approximately $500 and better sealing for $100. An extra cost of $900 is applied to those EEHDP units equipped with heat recovery systems.

TABLE I-1 Component values for comparison of three designs and four EEHDP units.

	Design #1	Design #2	Design #3	EEHDP Unit #44	EEHDP Unit #97	EEHDP Unit #124	EEHDP Unit #134
Ceiling	R25	R38	R44	R57	R59	R49	R52
Walls Exposed to Outdoor Air	R16	R24	R27.8	R27.8	R33.2	R33.5	R30.5
Basement Walls	R2	R7.4	R12.8	R12.8	R21	R23.6 R12.8	NA
Basement Floor	R.7	R.7	R6.1	R11.5	R.7	R6.1	R.7
Slab-on-Grade Foundation Insulation	R6.1	R6.1	R11.5	NA	R22.3	NA	R16.7
Nonsouth Windows	U.58	U.58	U.33	U.39	U.39	U.58	U.58 U.39
South Windows	U.58	U.58	U.33	U.58	U.39	U.58	NA
Window Insulation	NA	NA	NA	U.39	NA	U.39	NA
Storage Mass	NA	NA	NA	NA	NA	NA	NA
Furnace Efficiency	75%	75%	87%	87%	75%	75%	87%
Air Infiltration	ACH .75	ACH .5	ACH .5	ACH .5	ACH .5	ACH .5	ACH .5

Units 44 and 124 are equipped with heat recovery ventilation and Units 97 and 134 are equipped with mechanical ventilation only.

TABLE I-2 Cost comparisons based on house with dimensions of EEHDP #44.

		Design #1		Design #2		Design #3		EEHDP #44	
	Base Area	Total Cost	Cost Per Ft^2	Total Cost	Cost Per Ft^2	Total Cost	Cost Per Ft^2	Total Cost	Cost Per Ft^2
Ceiling	960 ft^2	0	0	250	.26	365	.38	835	.87
Walls Exposed to Outdoor Air	1,464 ft^2	0	0	366	.25	527	.36	527	.36
Basement Walls	406 ft^2	0	0	215	.53	329	.81	329	.81
Basement Floor	960 ft^2	0	0	0	0	524	.55	848	.88
Slab-on-Grade Foundation Insulation	NA	0	0	0	0	0	0	0	0
Nonsouth Windows	101 ft^2	0	0	0	0	354	3.50	354	3.50
South Windows	193 ft^2	1,530(2)	15	1,530(2)	15	2,206(3)	18.50	1,530(2)	15.00
Window Insulation	193 ft^2	NA		NA		NA		1,930	10.00
Storage Mass	687 ft^2	NA		NA		NA		1,223	1.78
Furnace Efficiency	75%	0	0	0	0	500	NA	500	0
Air Infiltration	ACH .75	0	0	100	NA	600	NA	1,500	NA
	TOTALS	1,530	NA	2,461	NA	5,405	NA	9,576	NA

(1) This is a split-entry, passive solar designed unit:
- 16 energy trusses have been assumed
- 2 X 6, 24" o.c. walls, 5.5" batting and 1" polystyrene
- 2" polystyrene on basement walls, skirting assumed

(2) Southside window area is 102 ft^2 greater than required by Design #1

(3) Based on extra glazing on 91 ft^2 and an additional 102 ft^2 of low emissivity windows

TABLE I-3 Cost comparisons based on house with dimensions of EEHDP #97.

		Design #1		Design #2		Design #3		EEHDP #97	
	Base Area	Total Cost	Cost Per Ft^2	Total Cost	Cost Per Ft^2	Total Cost	Cost Per Ft^2	Total Cost	Cost Per Ft^2
Ceiling	1,067 ft^2	0	0	277	.26	405	.38	992	.93
Walls Exposed to Outdoor Air	1,291 ft^2	0	0	323	.25	465	.36	1,757	.82
Basement Walls	768 ft^2	0	0	200	.26	200	.26	300	.39
Basement Floor	1,067 ft^2(2)	0	0	0	0	587	.55	0	0
Slab-on-Grade Foundation Insulation	162 ft^2	0	0	0	0	45	.28	143	.88
Nonsouth Windows	79 ft^2	0	0	0	0	277	3.50	277	3.50
South Windows	28 ft^2	0	0	0	0	98	3.50	98	3.50
Window Insulation	NA	0	0	0	0	0	0	0	0
Storage Mass	NA	0	0	0	0	0	0	0	0
Furnace Efficiency	75%	0	0	0	0	500	NA	0	0
Air Infiltration	ACH .75	0	0	100	NA	600	NA	600	NA
	TOTALS	0	NA	900	NA	3,177	NA	4,167	NA

(1) This is a super-insulated rambler with a walk-out lower level and a wood foundation:
- 19 energy trusses have been assumed
- 2 X 6, 16" o.c. walls with 5.5" batting and 2" polystyrene
- Wood basement 2 X 6, 16" o.c. and 2 X 8, 16" o.c., 5.5" batt

(2) Includes 376 ft^2 slab-on-grade floor

TABLE I-4 Cost comparisions based on house with dimensions of EEHDP #124.

		Design #1		Design #2		Design #3		EEHDP #124	
	Base Area	Total Cost	Cost Per Ft^2	Total Cost	Cost Per Ft^2	Total Cost	Cost Per Ft^2	Total Cost	Cost Per Ft^2
Ceiling	669 ft^2	0	0	174	.26	254	.38	442	.66
Walls Exposed to Outdoor Air	710 ft^2	0	0	178	.25	256	.36	930	1.31
Basement Walls	859 ft^2	0	0	648	.75	889	1.03	1,166	1.36
Basement Floor	669 ft^2	0	0	0	0	368	.55	368	.55
Slab-on-Grade Foundation Insulation	NA	0	0	0	0	0	0	0	0
Nonsouth Windows	10.5 ft^2	0	0	0	0	37	3.50	0	0
South Windows	181 ft^2	870(2)	15	870(2)	15	1,504(3)	18.50	870(2)	15.00
Window Insulation	191.5 ft^2	0	0	0	0	0	0	1,915	10.00
Storage Mass	576 ft^2	0	0	0	0	0	0	1,227	2.13
Furnace Efficiency	75%	0	0	0	0	500	NA	0	0
Air Infiltration	ACH .75	0	0	100	NA	600	NA	1,500	NA
	TOTALS	870	NA	1,970	NA	4,408	NA	8,418	NA

(1) This is a two-level passive solar designed home with a double 2 X 4 wall design:
- 17 half energy trusses have been assumed
- Double 2 X 4, 16" o.c. walls each with 3-1/2" batt and 1" isocyanurate foam
- Basement wall insulated with 4" and 2" polystyrene, skirting assumed

(2) Southside window area is 58 ft^2 greater than required by Design #1

(3) Based on extra glazing on 123 ft^2 and an additional 58 ft^3 of low emissivity windows

TABLE I-5 Cost comparisons based on house with dimensions of EEHDP #134.

		Design #1		Design #2		Design #3		EEHDP #134	
	Base Area	Total Cost	Cost Per Ft^2	Total Cost	Cost Per Ft^2	Total Cost	Cost Per Ft^2	Total Cost	Cost Per Ft^2
Ceiling	668 ft^2	0	0	174	.26	254	.38	541	.81
Walls Exposed to Outdoor Air	1,162 ft^2	0	0	291	.25	418	.36	802	.69
Basement Walls	NA	0	0	0	0	0	0	0	0
Basement Floor	NA	0	0	0	0	0	0	0	0
Slab-on-Grade Foundation Insulation	332 ft^2	0	0	0	0	93	.28	199	.60
Nonsouth Windows	156 ft^2	0	0	0	0	546	3.50	158	3.50
South Windows	0 ft^2	0	0	0	0	0	0	NA	0
Window Insulation	NA	0	0	0	0	0	0	0	0
Storage Mass	NA	0	0	0	0	0	0	0	0
Furnace Efficiency	75%	0	0	0	0	500	NA	500	NA
Air Infiltration	ACH .75	0	0	100	NA	600	NA	600	NA
	TOTALS	0	NA	565	NA	2,411	NA	2,800	NA

(1) This is a two-story, slab-on-grade townhouse:
- 13 energy trusses have been assumed
- 2 X 6, 16" o.c. walls with 5.5" batting and 1" isocyanurate foam
- 45 ft^2 triple-glazed windows on west side, remainder of windows are on east side and double-glazed

TABLE I-6 Insulation values and material data.

	Design #1	Design #2	Design #3	EEHDP #44	EEHDP #97	EEHDP #124	EEHDP #134
Ceiling	R25 Blown-in cellulose	R38 Blown-in cellulose	R44 Blown-in cellulose	R57 16 energy trusses and blown cellulose	R59 19 energy trusses and blown cellulose	R49 17 energy trusses and blown cellulose	R52 13 energy trusses and blown cellulose
Walls Exposed to Outdoor Air	R16(1) 2 X 4 (16 o.c.) 3.5 batt	R24(1) 2 X 6 (24 o.c.) 5.5 batt	R27.8(2) 2 X 6 (24 o.c.) 5.5" batt 1" poly-styrene	R27.8(2) 2 X 6 (24 o.c.) 5.5" batt 1" poly-styrene	R33.2(2) 2 X 6 (16 o.c.) 5.5" batt 2" poly-styrene	R33.5(2) Double 2 X 4 (16 o.c.) 3.5" batt, 1"isocya-nurate	R30.5(2) 2 X 6 (16 o.c.) 5.5" batt 1" isocy-anurate
Basement Walls	R2 No insula-tion	R7.4 1" poly-styrene	R12.8 2" poly-styrene	R12.8 2" poly-styrene	R21 2 X 6 (16 o.c.) 5.5" batt; 2 X 8 (16 o.c.) 5.5" batt	R23.6/ R12.8 4" poly-styrene 2" skirt-ing	NA
Basement Floor	R.7 No insu-lation	R.7 No insu-lation	R6.1 1" poly-styrene	R11.5 2" poly-styrene	R.7 No insu-lation	R6.1 1" poly-styrene	R.7 No insu-lation
Slab-on-Grade Foundation Insulation	R6.1 1" poly-styrene	R6.1 1" poly-styrene	R11.5 2" poly-styrene	NA	R22.3 4" poly-styrene	NA	R16.7 3" poly-styrene

TABLE I-6 Continued.	Design #1	Design #2	Design #3	EEHDP #44	EEHDP #97	EEHDP #124	EEHDP #134
Nonsouth Windows	U.58 R1.72 Double	U.58 R1.72 Double	U.33 R3.03 Low emissivity	U.39 R2.6 Triple	U.39 R2.6 Triple	U.58 R1.72 Double	U.39 R2.6 Double
South Windows	U.58 R1.72 Double	U.58 R1.72 Double	U.33 R3.03 Low emissivity	U.58 R1.72 Double	U.39 R2.6 Triple	U.58 R1.72 Double	NA
Window Insulation	NA	NA	NA	U.39 Insulating shades	NA	U.39 Insulating shades	NA
Storage Mass	NA	NA	NA	Quarry tile	NA	Concrete floor between levels	NA
Furnace Efficiency	75% Atmospheric	75% Atmospheric	87% Recuperative	87% Recuperative	75% Atmospheric	75% Atmospheric	87% Recuperative
Air Infiltration	ACH .75 Natural ventilation caulking	ACH .5 Better sealing	ACH .5 Mechanically controlled ventilation and better sealing	ACH .5 Mechanically controlled ventilation, better sealing and heat recovery	ACH .5 Same as Design #3	ACH .5 Same as EEHDP #44	ACH .5 Same as Design #3

(1) R-value includes R5 for remaining portion of wall
(2) R-value includes R3.4 for remaining portion of wall

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