The Modular Retrofit Experiment: Design, Scorekeeping and Evaluation

Gautam S. Dutt, Michael L. Lavine,*
Barbara G. Levi, and Robert H. Socolow

PU/CEES Report No. 202

July 1985

This paper will be published in the Scorekeeping Issue of Energy and Buildings (vol. 9, 1985/6; editor Margaret F. Fels).

*Present address: School of Statistics, University of Minnesota, Minneapolis, MN 55455

Center for Energy and Environmental Studies
Princeton University
Princeton, NJ 08544

Abstract

The Modular Retrofit Experiment (MRE) was a collaboration between five gas utilities and Princeton designed to provide well documented measurements of energy savings associated with house retrofits. Two retrofit strategies were evaluated -- a one-day visit by "house doctors", using instrumented energy analysis, and the same house-doctor treatment followed by additional, major retrofits. The 138 houses in this experiment included a group of control houses that received no treatment. All three groups showed significant energy savings, measured using the Princeton Scorekeeping Method (PRISM). Median percent savings (± standard errors) for the control, house-doctor, and major-retrofit houses were 9.8 (±1.4), 15.3 (±1.9), and 21.9 (±1.2), respectively. The savings in the control group closely agree with the average gas savings in the utility service areas over the same period of time. Our analysis indicates that the full potential of the one-day house-doctor visit was not realized in the MRE. Nevertheless, estimates of costs and savings reveal that house doctoring was more cost effective than the more conventional measures installed in the subsequent contractor retrofits.

ACKNOWLEDGEMENTS

The research was largely supported by the United States Department of Energy under Contract No. DE-AC02-77CS20062. We were helped immeasurably by the New Jersey homeowner participants and by our collaborators in the Consolidated Edison Company, Elizabethtown Gas Company, New Jersey Natural Gas Company, Public Service Electric and Gas Company, and South Jersey Gas Company. Among the many contributors to the effort at Princeton are Margaret Fels, Richard Fye, Kenneth Gadsby, Miriam Goldberg, Diane Harwood, David Harrje, Gregory Linteris, John Pinkerton, Cathy Reynolds, Joseph Romano, Daniel Stram, and Robert H. Williams.

Note

This paper will be published in the Scorekeeping Issue of Energy and Buildings (Volume 9, 1985/6; editor, Margaret F. Fels). The method of analysis is the Princeton Scorekeeping Method (PRISM), described in the introductory paper to the issue. See also M. F. Fels, "The Princeton Scorekeeping Method: An Introduction", Princeton University Center for Energy and Environmental Studies, Report No. 163, March 1985.

Glossary of PRISM parameters:

NAC	Normalized Annual Consumption
α	Base-level consumption
β	Heating slope
τ	Reference temperature

Table of Contents

Introduction 1

Experimental Design 2

The House-Doctor and Major-Retrofit Strategies . . 3

Individual-House Results 8

Resulting Energy Savings 9

Economic Analysis 11
A. Cost Estimates 12
B. Lifetime Estimates 13
C. Return on Investment 14

Conclusions 15

References 17

Tables

Figures

<u>List of Tables</u>

TABLE 1. Characteristics of MRE houses

TABLE 2. Retrofit treatments applied in each module

TABLE 3. Quality of NAC results for MRE houses, by treatment group

TABLE 4. Distributions of raw and control-adjusted savings for MRE by treatment group

TABLE 5. Summary of analysis of variance (ANOVA) on MRE savings

TABLE 6. Summary of median PRISM results for MRE

TABLE 7. Comparison of savings in control groups with aggregate savings for all houses in the same utility service area

TABLE 8. Cost and payback of retrofits in the MRE

List of Figures

Fig. 1 Location of the seven MRE modules.

Fig. 2 Histograms of NAC for the seven MRE modules before the retrofits and for all modules combined. Using PRISM, gas consumption during 1978-9 is weather-normalized to a nine-year normalization period. Arrow indicates median for each sample. Dotted arrow for Total corresponds to aggregate of all gas-heating customers in New Jersey [10].

Fig. 3 Histograms of percent savings by treatment group. Percent savings for each house are calculated as $[NAC_{pre} - NAC_{post})/NAC_{pre}]*100$.

Fig. 4 Results of the return-on-investment analysis. Parameters of analysis are i_f, the real fuel-price escalation rate in % per year; ITC, the income tax credit; and the return on investment, in % per year.

INTRODUCTION

The thrust of the buildings research at Princeton University's Center for Energy and Environmental Studies has been the evaluation of energy conservation measures in actual houses and the application of scientific design to these studies. Our first field study of identical townhouses at Twin Rivers, N.J. in the early 1970's taught us many valuable lessons [1]. The first was that a house can lose heat through many previously unrecognized paths that are not easily modeled in theoretical calculations nor readily located by observation. The second was that diagnostic instruments greatly enhance the ability to find these heat "bypasses". A third lesson was that dramatic savings are possible when measures to plug the bypasses are coupled with more conventional retrofits such as insulation [2].

This research at Twin Rivers led us to develop a procedure including an instrumented energy analysis accompanied by on-the-spot measures to correct many of the obscure but major energy losses identified during the analysis [3]. The procedure is generally called the "house-doctor" approach. Using it, we were able to bring about significant energy savings in three houses that were already insulated [4].

While these results were exciting, they could only be relevant for large-scale residential conservation if we could generalize our techniques to a wide variety of housing types and transfer our skills to those who had no experience in research. Thus we designed the Modular Retrofit Experiment (MRE) [5]. To set an example for careful evaluation of home energy-conservation projects, we included a control group and formulated a weather-corrected estimate of energy savings. Another component of the MRE was a model format for utility participation in conservation research. The five participating utilities were the four natural gas utilities in New Jersey -- Elizabethtown Gas Company (EG), New Jersey Natural Gas Company (NJNG), Public Service Electric and Gas Company (PSE&G) and South Jersey Gas Company (SJG) -- and Consolidated Edison Company (CE) of New York.

EXPERIMENTAL DESIGN

According to our design for the MRE, Princeton agreed to train utility personnel as house doctors, and to specify the retrofit measures that the utilities would then perform in various groups of gas-heated homes. The utilities agreed to assume all responsibilities for interactions with the homeowners and to provide the fuel consumption data, from which Princeton would estimate the energy savings. Homeowner cooperation permitted us to gain access to billing data and to do additional monitoring of the homes.

The MRE encompassed 138 single-family detached houses spread over seven "modules" (Fig. 1). A few modules in locations elsewhere in the United States were the sites of related experiments, but their results are not presented here [6,7,8]. Each MRE module was chosen so that the 18 to 24 houses within it were similar in style and vintage, and were located within a single development. The modules span a distribution of housing styles and vintages typical of the New Jersey-New York area (Table 1).

The utilities selected the sites of the modules in their service areas and supplied a list of candidate houses from each module. Princeton screened for houses with a poor history of billing data,* secondary

*For the original MRE analysis, a precursor of the Princeton Scorekeeping Method (PRISM) was developed. R^2 values were used as a house-selection criterion. The results reported here are from the current version of the PRISM software (see introductory paper to this issue [9]).

heat sources or other features that introduce irregularities into gas consumption [5]. Figure 2, which gives the distribution of pre-retrofit NACs across houses in each module, shows that the MRE houses were quite different across modules but, in all, were representative of New Jersey housing. (The median pre-retrofit NAC for all MRE houses was 153 GJ_{th}/year vs. an average of 159 GJ_{th}/year for all gas-heated houses in New Jersey for the same period [10].)

The 18 houses initially chosen within each module were randomly assigned to three equally sized groups, depending on the conservation treatment they were to receive. One group, the house-doctor group (HD), was given a one-day visit by two or three house doctors. A second group, the major-retrofit group (MR), received both the house-doctor visit and a subsequent major retrofit by a contractor hired by the utility. The third group remained untouched and served as the control group (C). Ultimately, the number of houses in some groups differed from the original six for various reasons. The final numbers of houses within each treatment group in each module are shown in Table 1.

THE HOUSE-DOCTOR AND MAJOR-RETROFIT STRATEGIES

Retrofits sought to reduce fuel used for space heating and water heating. Heating fuel may be saved by reducing interior temperature, by improving heating-system efficiency and by reducing house heat loss. One of the first steps in the thermal analysis of a house is to define a thermal envelope and to identify ways of reducing the flow of heat across this boundary either by conduction or by convection [11]. Conductive losses are reduced by providing an insulating layer around the envelope that encloses the heated interior. Because of time and budget constraints, house doctors are usually unable to add much insulation. They may, however, add some insulation to the attic door or trap door in an effort to complete the thermal envelope.

House-doctor visits focus on convective heat losses. There are two types of convective losses -- air leakage and convective loops. Air leakage, by definition, involves air which enters the house interior, is heated and then leaks out. Air leakage contributes to house ventilation. By contrast, in a convective loop air circulates in an enclosed cavity driven by density differences and carries heat from the house interior to the outside. In a closed convective loop, heat flows in and out of the cavity by conduction. The air circulating in the convective loop does not mix with house air and does not contribute to house ventilation. An example of a closed convective loop, which we first discovered at Twin Rivers, is a masonry block party wall extending from basement to roof [12]. The warm air in the wall cavity between adjacent living spaces is lighter than cooler air in the attic part of the wall cavity. The result is a convective pattern that carries heat from living space to attic, bypassing attic insulation. Sometimes, convective loops and air leakage are combined at the same location [11]. Convective heat losses are easily remedied by stopping air flow through an appropriate boundary in the thermal envelope. Finding them is the problem.

A typical house-doctor call is a one-day visit by trained specialists. The house doctors use a house pressurization device called a blower door in conjunction with an infrared viewer to locate air leaks and convective loops [3]. The pathways for convective heat loss are sealed using polyethylene film, expanding foam, fiberglass stuffing, gaskets and occasionally caulking and weatherstripping. The team also addresses other energy-using features of the house. They install a double-setback clock thermostat, and they perform a furnace efficiency measurement, and a furnace tune-up, if necessary. The remaining measures in the house-doctor package are intended to reduce the fuel used to heat water: reducing the maximum flow rate of showers by installing flow restrictors or low-flow shower heads, reducing the hot water temperature to 50°C (120°F), provided the homeowner consents, and insulating the water heater and the first three meters of hot water pipe. Actual treatments in the MRE were less extensive and varied across modules (Table 2).

House doctors of varying experience and background participated in a two-day training session at Princeton in November 1979. Since each house-doctor team generally retrofitted 12 to 18 houses, most of their work was carried out on the early part of a learning curve. Post-experiment surveys showed variable proficiencies among the house doctors that enabled some to find and fix thermal defects better and others to excel at addressing specific homeowner concerns (see longer version of this paper [13]). Two lessons were learned. First, proper interpretation of the diagnostics and establishment of retrofit priorities during the house-doctor visit were two skills that were difficult to transmit, and a more extensive house-doctor training program would have been desirable. Second, the ideal house doctor should possess psychological skills to promote energy-conserving practices. These "empathic" qualities for house doctors are no less important than the technical ability to make building diagnostics, and they deserve further attention.

In addition to finding defects suitable for on-the-spot fixing, house doctors also record those defects that require a more substantial effort to remedy, and these form the basis of recommendations for the contractor retrofits. The primary focus of these retrofits is the reduction of conductive losses across the thermal envelope. That goal calls for adding insulation in several areas, including the attic or roof, the basement walls or the living space walls (see [11,13]). Contractors may lower conductive losses across windows and doors which form part of the boundary surrounding the heated interior, by installing storm windows and storm doors. Contractors may also add roof vents, not to save energy but to mitigate the moisture problem that sometimes is exacerbated when attics with inadequate ventilation receive additional insulation.

Princeton's recommendations for contractor retrofits for the major-retrofit houses varied considerably from module to module, and the utilities modified these recommendations to differing extents. We recommended the addition of attic or roof insulation in all modules, and wall insulation for two houses in Edison and for all the houses in Wood Ridge. The Wood Ridge residences are older and had uninsulated balloon-frame walls that constitute a serious heat loss. EG did add wall insulation to the two houses in Edison, but PSE&G did not add any to the houses in Wood Ridge.

Some of the residences needed insulation in areas unique to their design, and these were addressed in various ways. Many of the houses had uninsulated basements or crawl spaces. NJNG incurred considerable expense to insulate and finish the basement walls in Freehold and to insulate the crawl space walls in Toms River with rigid styrofoam insulation. These various major retrofit actions are summarized in Table 2.

The control group was included to measure the changes in gas consumption that might occur due to factors other than the utility-sponsored retrofits. Because all houses were assigned to one of three groups following homeowner consent, residents in the original control groups knew of their participation in the experiment. This knowledge could conceivably have altered their energy-related behavior. Subsequently the control-group houses in four modules (NJNG and SJG) were retrofitted -- before a decision was made to extend the duration of the experiment. For these modules, additional "blind" control houses were selected, and the original control houses were added to the house-doctor group.

We became aware as the MRE progressed that the observed savings were not likely to represent the full potential of the house-doctor approach, for several reasons. First, the inadequacy of our training program left many conservation opportunities untouched. Second, the requirements of filling out a long audit form for collecting data for the study, and the one-day time limit imposed by the experimental design, meant that not all of the needed house-doctor retrofits could be completed. Finally, not all the retrofits were installed and some installations were poor -- especially where outside contractors instead of utility personnel performed the house-doctor retrofits. Nevertheless, the problems we encountered in our attempt to control tightly all the aspects of our experiment were not so great as to negate any of our qualitative findings, reported below.

INDIVIDUAL-HOUSE RESULTS

One important goal of the MRE was to establish straightforward procedures for calculating the energy savings that resulted from the various levels of treatment. Our method for averaging out the weather differences was the first application of PRISM to a controlled experiment.

Since the R^2 value for the fit of the consumption data to degree-days was used as a pre-selection criterion, it is not surprising that the R^2 values for the pre-retrofit period were uniformly high. Half of the houses had R^2s of 0.99 or better, and the lowest value was 0.91. What is reassuring is that the R^2s do not substantially deteriorate in the post-retrofit period. The median remains 0.99 in each of the three groups (C, HD, MR), and only 5% had R^2 below 0.90.

A more important measure of the quality of the PRISM results is the standard error of the estimate, particularly for NAC. Of all the NACs estimated (276 = 138 houses x 2 periods), 60% had a relative standard error within 3% of the estimate. NAC was equally well determined in all the groups, for both periods (Table 3). The change in NAC, i.e., the estimated savings, had a median standard error of about 6 GJ_{th}/year (60 ccf/year), or about 4% of the median pre-NAC value. Therefore, according to statistical theory, savings of 8% (i.e., twice the standard error of the percent savings) or more may be considered statistically significant at a 95% confidence level.

RESULTING ENERGY SAVINGS

The purpose of our analysis is to test the ability of the house-doctor and major-retrofit options to reduce energy consumption, compared with what has happened in the control group. Figure 3 compares the distribution of percent savings for the three groups. As summarized in Table 4, the median progresses from 9.8% for the control group, to 15.3% for the house-doctor and 21.9% for the major-retrofit group (including house-doctor visit). Since the distributions are broad and overlapping, it is important to test carefully how different these three distributions really are.

One simple tool for this purpose is analysis of variance (ANOVA). First, the overall hypothesis that the mean changes in NAC for the three groups are all equal was tested and rejected strongly for both absolute and percent savings (Table 5). We can say with 99.9% confidence that the differences among the three groups were not due to chance alone. Differences between control and house-doctor houses, and between house-doctor and major-retrofit houses, were equally strong. Differences among the three groups were also highly significant for the individual modules. These tests provide strong evidence that the savings in the house-doctor houses were significantly greater than those in the control houses, across all the modules. Similarly there is strong evidence that the savings in the major-retrofit houses were significantly larger than in the house-doctor houses.

For each house, PRISM parameters α, β, τ, and NAC, together with the weather-normalized estimate of heating use, $\beta H_0(\tau)$, were compiled for both pre- and post-retrofit periods. The individual-house values are reported elsewhere [14]. Their median values, and their median changes from the pre- to the post-retrofit periods, are shown in Table 6, for each of the three groups. Median standard errors for all parameters are also shown. Changes in β, βH_0 and NAC are highly significant for each group including the control group. (The p-value associated with each change is 0.0001; see Table 6.) The results suggest that the savings were predominately in space heating rather than appliance usage. Further, although τ is not well determined, the drop in β is sufficiently significant, and the decrease in τ sufficiently small, to suggest that these savings were due largely to shell improvements. Additional analyses of the components of the MRE energy savings are reported elsewhere [13,15].

The total savings (ΔNAC) for the house-doctor and major-retrofit groups may be looked at either in absolute terms or adjusted by the reduction in energy use in the control group. For the MRE control group, the median savings in NAC is 10% of its pre-retrofit values. While this appears large, it is roughly the same as the change in NAC over the corresponding two-year period for the aggregate of all New Jersey gas-heated households [10]. As shown in Table 7, the same comparison holds individually for each module, between the control-group savings within each module and the corresponding utility-wide average savings in the service area of the gas utility for the appropriate pre- and post-periods. This supports our conclusion that the control-group savings do not represent a contamination of these houses by their participation in the experiment.

With no control adjustment, the median house-doctor house saved 22 GJ_{th}/yr (200 ccf/yr, or 15.3%) while the median major-retrofit house saved 36 GJ_{th}/yr (330 ccf/yr, or 21.9%); see Table 6. Adjusting for the control group*, median savings become 9 GJ_{th}/yr (80 ccf/yr, or 7.9%) for the house-doctor and 20 GJ_{th}/yr (180 ccf/yr, or 13.7%) for the major-retrofit houses. Absolute and control-adjusted savings by module are compared in Table 8.

The MRE savings are quite different when adjustment for a control group is made. Our experience, as well as the experience of others reported in this issue ([17,18], among others) leads us to believe that it is imperative to maintain a control group in experiments of this nature and to compare savings in the treatment groups against those in a control group.

ECONOMIC ANALYSIS

Homeowners and other potential sponsors of home energy-conservation retrofits need to know not only the predicted energy savings associated with a given retrofit package but also the probable cost and expected lifetime. We have estimated the costs and lifetimes associated with the MRE measures and have used them together with gas savings to compute a range of possible returns on investment. The economic analysis involves several parameters that cannot be as definitively determined as the gas savings. The costs that were directly assessed in the MRE were those incurred by the utilities, and these are not a perfect guide to estimate how much an individual homeowner might have paid for the same retrofits. Further, the calculation involves a variety of uncertain retrofit lifetimes and uncertain projections of the real-fuel price escalation rate. The

*The savings for each house is adjusted by the median savings for the control group of the corresponding module (see [9]).

assumed values of these parameters and the resulting returns on investment are discussed in the following sections.

A. Cost Estimates

The utilities provided estimates of their expenditures for the house-doctor and major-retrofit treatments. The house-doctor cost estimates vary by a factor of two, largely because of differences in accounting. For example, the utilities amortized the diagnostic equipment in different ways, and some hired contractors for the house-doctor work. PSE&G had the lowest estimate of house doctoring, basing their estimate on a contractor bill and excluding the cost of their own personnel. For our economic analysis, we have used the utility figures as a guide and have judged the cost of a two-person, one-day house-doctor visit to be $325 (1980$) per house if done as part of an ongoing program.

The costs of the major retrofits were billed directly to the utilities by the contractors and thus are explicit figures. To this contractor cost we have added $325 for the house-doctor visit.

From the estimates of costs and first-year savings we can compute the simple payback period, as one step towards judging the value of conservation investments. The costs, first-year savings, and simple paybacks by module and treatment group are summarized in Table 8. The simple payback period, averaged over all modules, is about six years for the house-doctor treatment and thirteen years for the major-retrofit groups, using the treatment savings adjusted by the controls. Note that the costs of the retrofits are not adjusted for any additional retrofit investment that may have been undertaken by the homeowners.

B. Lifetime Estimates

The MRE did not investigate the lifetimes of the retrofit measures, nearly all of which are expected to be of greater duration than our two-year experiment. Few conservation experiments have been concerned with lifetime estimates, although they are clearly important parameters. We present here our best estimates of the range of lifetimes associated with the MRE retrofits.

One important action of the house doctor is the elimination of attic and other thermal bypasses. Such bypasses are generally located in remote areas which should be free of disturbance. Most of the materials should be intact for at least 10 years. For similar reasons, attic insulation should be expected to perform well for 10 to 15 years. The major threat to attic insulation is excess moisture, which can degrade its performance. Some of the MRE houses were given roof vents to alleviate the problem.

The water-heater jacket should remain in place as long as the water heater lasts but only if it is properly installed. The installations we inspected in the MRE were generally adequate. Most of the water heaters are likely to be replaced within 10 years but the newer models are generally better insulated than the retrofitted ones.

The clock thermostat is a mechanical device naturally subject to some failure, but its durability is probably as high as that of a battery-operated clock. A more important question regarding the clock thermostat, however, is whether it continues to be used for temperature setback at night. This behavioral aspect of the thermostat at present cannot be reliably predicted on a long-term (say, 10-year) basis, and this topic merits some carefully planned behavioral research.

Most of these retrofits could be evaluated by visual inspection after a period of about five years. It might be difficult to find all the bypasses that we're plugged, but the areas where the plugging is coming undone would be apparent. In the absence of such inspections, we estimate a lifetime of between 10 and 15 years for the non-behavioral aspects of the retrofits.

C. Return on investment

We have calculated the return on investment for the MRE treatment groups. This quantity allows one to compare directly the cost effectiveness of conservation measures with other investments. Figure 4 shows two curves based on our return-on-investment calculation, corresponding to two different values of possible lifetimes of retrofits. The vertical scale depends on the real fuel-price escalation rates. We show scales for 0%, 4% and 8% per year. The latter two rates bracket the escalation rates implicit in a natural gas price projection by the American Gas Association [19].

The horizontal scale changes if the current federal income tax credit (ITC) is included, as illustrated by the scales for ITC = 0% and 15%. In Fig. 4, the arrows indicate the simple payback periods as estimated in the MRE for the house-doctor and major-retrofit houses. Depending on the assumptions, the real rate of return ranges from 10 to 26% for the house-doctor group and from -6 to 12% for the major-retrofit group [13]. For investment decisions from a homeowner's perspective these rates of return should be compared to the best alternative investments available to the homeowner after correcting for inflation and income tax. The numbers represent the wide variation in conclusions possible and underscore the importance of accurate determination of retrofit lifetime.

CONCLUSIONS

The design of the MRE and its scorekeeping methodology enabled us to obtain firm information about conservation actions and their related savings. Several quantitative findings emerged. One is the magnitude of the gas savings -- about 10% in the control group, 15% in the house-doctor group, and 22% in the major-retrofit group. A second finding is that, even though the MRE may not have achieved the full potential of house doctoring, the house-doctor visits were cost-effective and most of the contractor retrofits showed attractive returns on investments as well. A third finding is that the gas savings have a large variability across and within modules. Among the sources of the spread in savings are the varying needs for and ease of house doctoring among houses, the differences in receptivity to house-doctor measures among the residents, and the differing abilities of house doctors.

None of these lessons would have emerged without a carefully designed experiment of two years' duration. The methodology employed in the MRE can be readily adapted to test other retrofit strategies.

References

1. R.H. Socolow, ed., Saving Energy in the Home: Princeton's Experiments at Twin Rivers, Ballinger Publishing Co., Cambridge, MA, 1978.

2. F.W. Sinden, A two-thirds reduction in the space heat requirement of a Twin Rivers townhouse, in Saving Energy in the Home, op. cit.;, also Energy and Buildings, 1, 243-260, 1977/78.

3. D.T. Harrje, G.S. Dutt, J. Beyea, Locating and eliminating obscure but major energy losses in residential housing, ASHRAE Transactions, Vol. 85, Part II, 1979.

4. G.S. Dutt, If home energy savings is such a good idea, why don't more people do it?, in Home Remedies: A Guidebook for Residential Retrofit (ed., T. Wilson), Mid-Atlantic Solar Energy Association, Philadelphia, PA, 1981.

5. G.S. Dutt, D.T. Harrje and R.H. Socolow, The Modular Retrofit Experiment (MRE) - Research Plan, Princeton University, Center for Energy and Environmental Studies Working Paper No. 50, Princeton, NJ, December 1979.

6. B.C. O'Regan, B.S. Wagner, and J.B. Dickinson, Results of the Walnut Creek house doctor project, Energy 9, 75-85, 1984.

7. Minneapolis House Doctor Training Program, Funded by Comprehensive Employment Training Act (CETA), Robert Henderson, Project Manager, Minneapolis Energy Office, Minneapolis, MN, 1980.

8. D.L. Sliger, Modular Retrofit Experiment (Princeton Project), Tennessee Valley Authority, Division of Energy Conservation and Rates, June 1980.

9. M.F. Fels, PRISM: an introduction, Energy and Buildings, this issue.*,**

10. M.F. Fels and M.L. Goldberg, Measuring Household Fuel Consumption on the Standard Living Cycle, Energy 7, 489-504, 1982.

11. D.T. Harrje, G.S. Dutt, and K.J. Gadsby, Isolating the building thermal envelope, in Proc. Soc. Photo-Opt. Instr. Engrs, 254, 50, 1981.

12. J. Beyea, G.S. Dutt, and T. Woteki, Critical significance of attics and basements in the energy balance of Twin Rivers townhouses, in Saving Energy in the Home, op. cit.; also Energy and Buildings, 1, 261-269, 1977/78.

13. G.S. Dutt, M.L. Lavine, B.G. Levi, and R.H. Socolow, The Modular Retrofit Experiment: Exploring the House Doctor Concept, Princeton University, Center for Energy and Environmental Studies Report No. 130, Princeton, NJ, June 1982 (the longer version of this paper).

References (cont'd)

14. M. Fels, D. Harwood, M. Lavine, The Modular Retrofit Experiment: Summary Scorekeeping Tables, Princeton University, Center for Energy and Environmental Studies Report No. 131, Princeton, NJ, June 1982.

15. G.S. Dutt, D.I. Jacobson, and R.H. Socolow, Air Leakage Reduction and Energy Savings in the Modular Retrofit Experiment, Princeton University, Center for Energy and Environmental Studies Report No. 113, Princeton, NJ, February 1983.

16. The New Jersey Energy Data System, designed for the New Jersey Department of Energy by Princeton University, Center for Energy and Environmental Studies, 1978-1982; see M.F. Fels, A Fundamental Energy Data System for States: The New Jersey Prototype, Princeton University, Center For Energy and Environmental Studies Report No. 128, Princeton, NJ, February 1982.

17. M.L. Goldberg, A Midwest low-income weatherization program seen through PRISM, Energy and Buildings, this issue.*

18. E. Hirst, Electricity savings one, two and three years after participation in the BPA residential weatherization pilot program, Energy and Buildings, this issue.*

19. American Gas Association, Consumer Impact of Indefinite Gas Price Escalator Clauses under Alternate Decontrol Plans, AGA Report No. 1981-13, Arlington, VA, 1981.

*"This issue" indicates the Scorekeeping Issue of Energy and Buildings (editor, Margaret F. Fels; volume 9, early 1986; published by Elsevier Sequoia S.A., Lausanne, Switzerland).

**See also M.F. Fels, "The Princeton Scorekeeping Method: An Introduction", Center for Energy and Environmental Studies, Report No. 163, Princeton, NJ, March 1985.

TABLE 1
Characteristics of MRE houses

Module Name (utility)	House Vintage	House Size[a] (m^2)	House Type	Number of Houses by Group			
				Control (C)	House Doctor (HD)	Major Retrofit (MR)	Total
NEW JERSEY							
1. Edison (Elizabethtown Gas)	1960's	170 (150-200)	Split-level	6	5	6	17
2. Freehold (New Jersey Natural Gas)	1960's	230 (all)	Two-story	6	12	6	24
3. Toms River (New Jersey Natural Gas)	1970's	84 (72-91)	One-story	6	12	6	24
4. Wood Ridge (Public Service Electric and Gas)	1920's	130 (110-170)	Two-story	6	6	6	18
5. Oak Valley (South Jersey Gas)	1950's	130 (all)	Split-level	6	9	6	21
6. Whitman Square (South Jersey Gas)	1960's	190 (140-220)	One- and two-story	4	9	5	18
NEW YORK							
7. New Rochelle (Consolidated Edison)	1950's	130 (110-160)	One-story	6	5	5	16
TOTALS				40	58	40	138

a. Mean value of house area is shown (with range indicated in parentheses).

TABLE 2
Retrofit treatments applied in each module

	MRE MODULE						
HOUSE DOCTOR ACTION	EDISON (EG)	FREEHOLD (NJNG)	TOMS RIVER (NJNG)	WOOD RIDGE (PSEG)	OAK VALLEY (SJG)	WHITMAN SQUARE (SJG)	NEW ROCHELLE (CE)
1. Make ceiling air tight beneath insulation	○	●	●	NA	●	●	●
2. Seal leaks and tighten building shell	●	●	●	●	●	●	●
3. Insulate and weatherstrip attic doors	○	●	●	○[a]	●	●	●
4. Install clock thermostat	◐	●[b]	●[b]	○	●	●	●[b]
5. Insulate water-heater tank and some piping	○	●	●	○	●	●	●
6. Install low-flow shower head or shower flow controller	○	◐	◐	○	◐	◐	●
7. Reduce hot water temperature	○	◐	◐	◐	◐	◐	◐
8. Adjust furnace efficiency	○	○	○	○	○	○	●[c]
MAJOR RETROFIT ACTION							
1. Insulation of crawl-space wall or ceiling, or basement wall	◐	●	●	NA	○	NA	●
2. Insulation of attic to R30 if < R13[d]	●	●	●	●[e]	◐	◐	●[f]
3. Insulation of walls	◐	NA	NA	○	NA	NA	NA
4. Insulation of band joist	●	●	●	○	●	●	○
5. Insulation of second-floor overhang	◐	●	NA	NA	NA	NA	NA
6. Insulation in other areas	●	NA	NA	●	●	◐	○
7. Installation of storm doors/windows	NA	NA	NA	NA	◐	◐	◐
8. Installation of roof vents	●	NA	NA	●	●	○	NA

NOTES

a. Limited amount of weatherstripping was done.

b. Action was taken in all houses in which the action had not previously been taken.

c. Action was taken in all houses in which the furnace efficiency was below 75%.

d. Insulation was blown in to cover joists.

e. Because of interference with a floored attic, insulation was added in this module just up to R19.

f. Three inches of cellulose insulation were added to existing 3 inches of rockwool.

○ ACTION NOT TAKEN (although recommended by Princeton)

◐ ACTION TAKEN IN SOME HOUSES

● ACTION TAKEN IN EVERY HOUSE

NA Action not recommended by Princeton or not applicable

TABLE 3
Quality of NAC results for MRE houses by treatment group[a]

		Control (C)	House Doctor (HD)	Major Retrofit (MR)
Pre:	NAC_{pre} (GJ_{th}/yr)	152.6	143.3	158.0
	se(NAC_{pre}) (GJ_{th}/yr)	4.3	3.7	3.6
	[se(NAC_{pre})/NAC_{pre}]*100	2.9%	2.9%	2.6%
Post:	NAC_{post} (GJ_{th}/yr)	139.3	116.0	119.3
	se(NAC_{post}) (GJ_{th}/yr)	3.7	3.1	3.2
	[se(NAC_{post})/NAC_{post}]*100	2.7%	2.6%	2.6%
Savings:	ΔNAC[b] (GJ_{th}/yr)	14.3	21.5	35.6
	se(ΔNAC) (GJ_{th}/yr)	6.7	5.4	6.4
	% ≡ ($\Delta NAC/NAC_{pre}$)*100	9.8%	15.3%	21.9%
	se (%)[c]	3.7%	3.8%	3.3%

a. Median of the individual-house PRISM results is shown for each sample.

b. $\Delta NAC = NAC_{pre} - NAC_{post}$, i.e., a positive value indicates savings.

c. Formulae for calculating the standard error of the estimated total and percent savings for each house are given in [9], where they are illustrated by application to one MRE house.

TABLE 4
Distributions of raw and control-adjusted savings for MRE by treatment group[a]

	Control (C)	House Doctor (HD)	Major Retrofit (MR)
N	40	58	40
Consumption			
NAC_{pre} (GJ_{th}/yr)	152.6 (±9.5)	143.4 (±8.3)	158.0 (±10.7)
NAC_{post} (GJ_{th}/yr)	139.3 (±7.1)	116.0 (±6.7)	119.3 (±9.0)
Savings[b]			
ΔNAC (GJ_{th}/yr)	14.3 (±2.6)	21.5 (±3.1)	35.6 (±3.4)
$\% \equiv (\Delta NAC/NAC_{pre})*100$	9.8 (±1.4)	15.3 (±1.9)	21.9 (±1.2)
Savings relative to control group			
ΔNAC_{adj} (GJ_{th}/yr)	--	8.6 (±2.1)	19.6 (±2.1)
$\% \equiv (\Delta NAC_{adj}/NAC_{pre})*100$	--	7.9 (±1.4)	13.7 (±1.6)

a. For each estimate, the median (± standard error of the median) is shown. The standard error of the median is calculated as the inter-quartile range (the middle 50%) divided by $\sqrt{N}$. A 95% confidence level is associated with approximately double this quantity.

b. Positive $\Delta NAC = NAC_{pre} - NAC_{post}$ indicates savings.

c. For each house, the control-adjusted savings are obtained as follows: $\Delta NAC_{adj} = C_{adj} * NAC_{pre} - NAC_{post}$ where C_{adj} is the median value of $[NAC_{post}(C)/NAC_{pre}(C)]$ for the control group in the corresponding module (see [9]).

TABLE 5
Summary of analysis of variance (ANOVA) on MRE savings

Savings measure[a]	Treatment groups compared	Effects	Degrees of freedom[b] numerator/denominator	Observed F-value	Critical region[c] for $p \leq 0.001$	p-value
RAW	C vs. HD vs. MR	Treatment	2/128	30.02	F > 7.30	0.0001
		Module	6/128	9.33	F > 4.02	0.0001
RELATIVE	C vs. HD vs. MR	Treatment	2/128	35.35	F > 7.30	0.0001
		Module	6/128	5.88	F > 4.02	0.0001
RELATIVE	C vs. HD	Treatment	1/89	21.61	F > 11.60	0.0001
		Module	6/89	5.58	F > 4.13	0.0001
RELATIVE	HD vs. MR	Treatment	1/90	15.88	F > 11.58	0.0001
		Module	6/90	4.58	F > 4.12	0.0004
RELATIVE	C vs. MR	Treatment	1/71	109.69	F > 11.82	0.0001
		Module	6/71	2.65	F > 4.27	0.0226

a. RAW savings = $\Delta NAC = NAC_{pre} - NAC_{post}$; RELATIVE savings = $\Delta NAC/NAC_{pre}$.

b. Because of the sensitivity of ANOVA to outliers, one house (control house T113) is eliminated from the ANOVA calculation. House T113 is a control house with a 40% savings, which are attributable to a shift to heavy wood use during the course of the experiment. This house is eliminated from other calculations involving mean rather than median values (Tables 7 and 8).

c. Shown is the F-statistic resulting from the ANOVA calculation and, for comparison, the F-value which would correspond to a significance level of 0.001. With one exception, the latter is lower, indicating that the probability that the differences were due to chance alone is less than 0.001.

TABLE 6
Summary of median PRISM results for MRE*

	Control (C)	House Doctor (HD)	Major Retrofit (MR)
# houses	40	58	40
R^2 pre	0.991	0.990	0.992
R^2 post	0.989	0.989	0.987
τ pre (^oC)	18.0 (1.3)	17.5 (1.4)	18.2 (1.4)
τ post (^oC)	17.8 (1.1)	17.2 (1.2)	16.9 (1.2)
$\Delta\tau$ (^oC)	0.4 [--]	0.5 [--]	1.2 [--]
p-value	0.188 [--]	0.013 [--]	0.0001[--]
α pre (kW_{th})	1.54 (0.24)	1.41 (0.25)	1.58 (0.25)
α post (kW_{th})	1.43 (0.22)	1.30 (0.19)	1.58 (0.18)
$\Delta\alpha$ (kW_{th})	0.01 [0.35%]	0.16 [11.5%]	0.07 [5.0%]
p-value	0.788 [0.662]	0.002[0.0001]	0.141[0.255]
β pre ($W_{th}/^oC$)	478 (29)	428 (27)	462 (28)
β post ($W_{th}/^oC$)	415 (26)	381 (24)	362 (25)
$\Delta\beta$ ($W_{th}/^oC$)	41 [8.8%]	54 [12.3%]	90 [20.0%]
p-value	0.0001[0.0001]	0.0001[0.0001]	0.0001[0.0001]
(βH_o)pre (GJ_{th}/year)	105.6 (6.19)	101.3 (6.65)	99.8 (6.76)
(βH_o)post (GJ_{th}/year)	97.9 (5.99)	75.7 (4.87)	70.1 (4.93)
$\Delta(\beta H_o)$ (GJ_{th}/year)	12.6 [12.7%]	18.6 [19.3%]	30.7 [30.4%]
p-value	0.0001[0.0001]	0.0001[0.0001]	0.0001[0.0001]
NAC pre (GJ_{th}/year)	152.6 (4.31)	143.4 (3.69)	158.0 (3.61)
NAC post (GJ_{th}/year)	139.3 (3.72)	116.0 (3.15)	119.3 (3.19)
ΔNAC (GJ_{th}/year)	14.3 [9.8%]	21.5 [15.3%]	35.6 [21.9%]
p-value	0.0001[0.0001]	0.0001[0.0001]	0.0001[0.0001]

*For each set of houses, the following four lines of results are shown for each parameter Θ (=α,β,τ,NAC):

medians:
- median for Θpre (median for s.e. of Θpre)
- median for Θpost (median for s.e. of Θpost)
- median for change $\Delta\Theta=\Theta$post$-\Theta$pre [median for relative change $\Delta\Theta/\Theta$pre]

significance: p-value for total change [p-value for relative change].

Here s.e. = standard error. Note that a positive value of $\Delta\Theta$ indicates savings. The p-value is calculated from the Wilcoxon signed rank test of the hypothesis that the median change was zero; a p-value of 0.01 indicates significance at the 1-p = 99% confidence level.

Because of the arbitrariness of the zero in the ^oC temperature scale, no relative (%) change is given for $\Delta\tau$.

TABLE 7
Comparison of savings in control group with aggregate savings for all houses in the same utility service area

MODULE (utility)	PERCENT SAVINGS MRE CONTROL Median	Mean	ALL UTILITY CUSTOMERS[a]
EDISON (EG)	7.9%	7.2%	10%
FREEHOLD (NJNG)	4.8	6.1	3
TOMS RIVER (NJNG)	-1.6	0.5	4
WOOD RIDGE (PSEG)	11.0	10.8	11
OAK VALLEY (SJG)	11.8	10.2	11
WHITMAN SQUARE (SJG)	11.2	11.2[b]	12
NEW ROCHELLE (CE)	11.2	12.1	--[c]

a. Percent savings differ slightly for two modules in the same utility area if the pre- and post-retrofit dates are different. Aggregate savings are estimated from a variation of PRISM applied to average per-customer billing data for gas-heating customers served by the relevant New Jersey utility [10]. Data are from the New Jersey Energy Data System [16].

b. This value excludes the control house (T113) with the anomalously high savings (40%). If that house is included the mean savings for this group is 18.3%; the median remains 11.2%.

c. Aggregate data from the New York utility were not available.

TABLE 8
Cost and payback of retrofits in the MRE

Module	Energy Savings[a] (GJ_{th}/year)			Savings Relative to Control Group[b]		First Year Savings[c]		Major Retrofit Cost[d]	Simple Payback Period (years)[e]	
	Control	House Doctor	Major Retrofit	House Doctor	Major Retrofit	House Doctor	Major Retrofit		House Doctor	Major Retrofit
Edison (EG)	12.2	25.5	40.8	13.1	28.3	$ 60	$135	$1,370	5	10
Freehold (NJNG)	11.8	30.2	46.1	19.2	34.6	90	165	2,562	4	16
Toms River (NJNG)	0.0	7.1	17.6	6.6	17.1	32	80	1,272	10	16
Wood Ridge (PSEG)	17.5	22.5	27.2	4.4	7.1	21	34	961	15	28
Oak Valley (SJG)	14.2	28.3	29.1	15.3	16.6	70	80	911	5	11
Whitman Square (SJG)[f]	17.5	27.2	37.2	11.2	19.8	55	85	664	6	8
New Rochelle (CE)	20.5	25.7	33.0	5.2	13.1	25	60	1,008	13	17
All modules	13.1	23.1	32.9	11.1	20.4	$ 55	$ 95	$1,270	6	13

a. Mean savings are used throughout to be consistent with the cost data.
b. An analogue of the control adjustment formula given in footnote c to Table 4 is used, with means replacing medians.
c. Gas prices the year after retrofits ranged from $0.45 to $0.55 per therm. We assume a price of $0.50/therm ($4.70/GJ_{th}).
d. We estimate the cost of house-doctor treatment for all homes to be $325 (1980$).
e. Computed as cost divided by first year savings.
f. The control house (T113) is eliminated from the calculation because of the extreme sensitivity of mean values to outliers; see footnote b to Table 5.

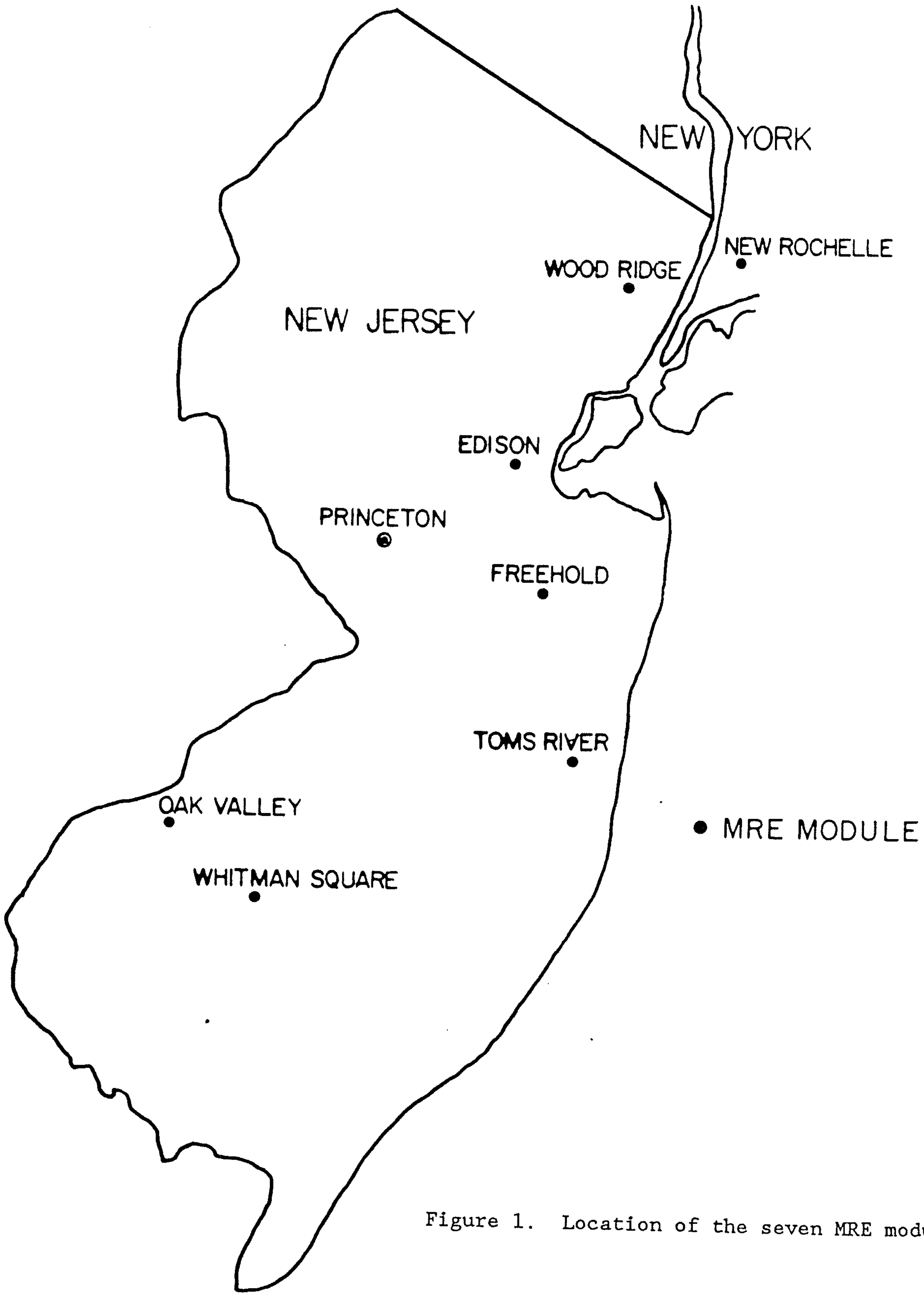

Figure 1. Location of the seven MRE modules.

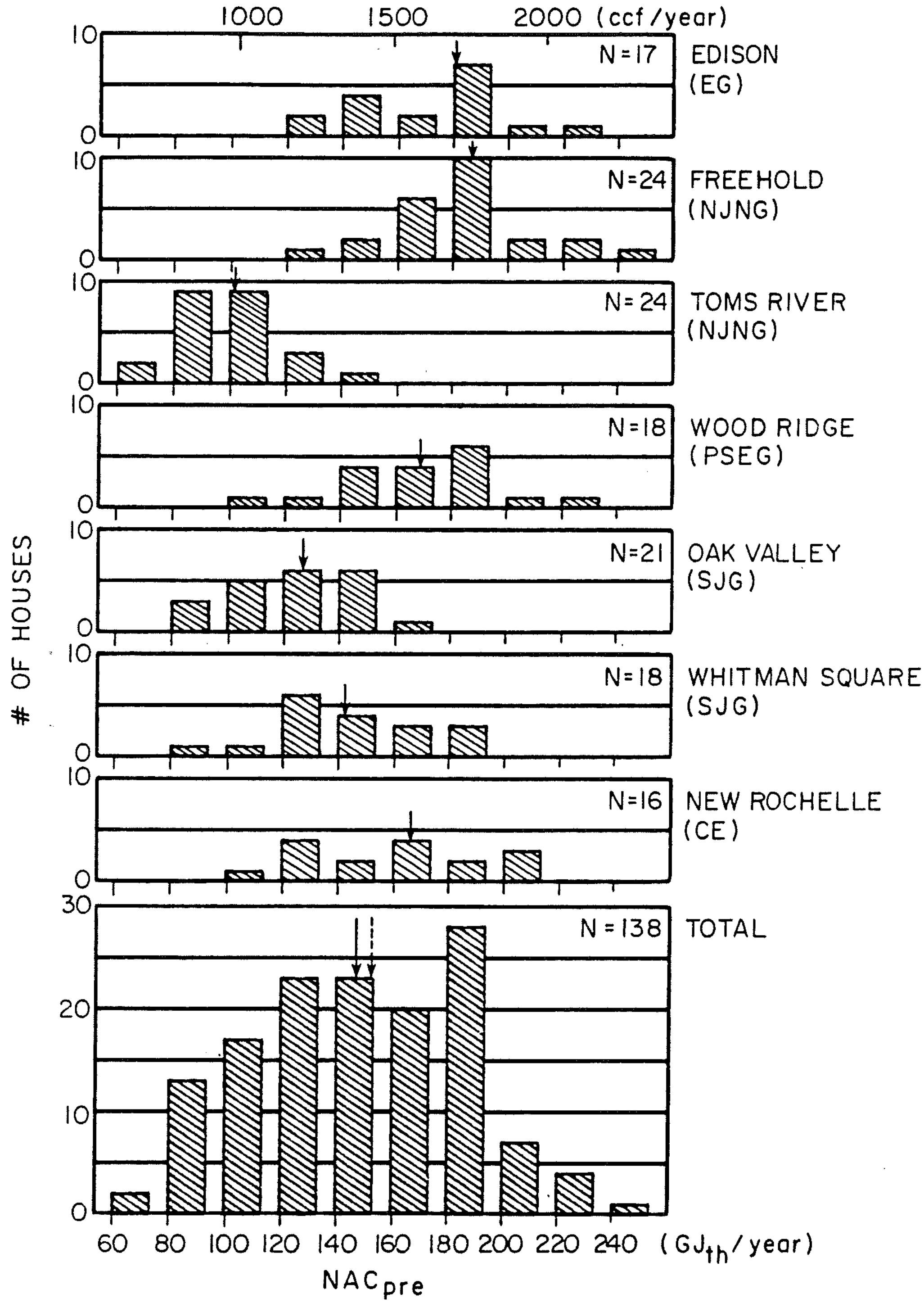

Figure 2. Histograms of NAC for the seven MRE modules before the retrofits and for all modules combined. Using PRISM, gas consumption during 1978-9 is weather-normalized to a nine-year normalization period. Arrow indicates median for each sample. Dotted arrow for Total corresponds to aggregate of all gas-heating customers in New Jersey [10].

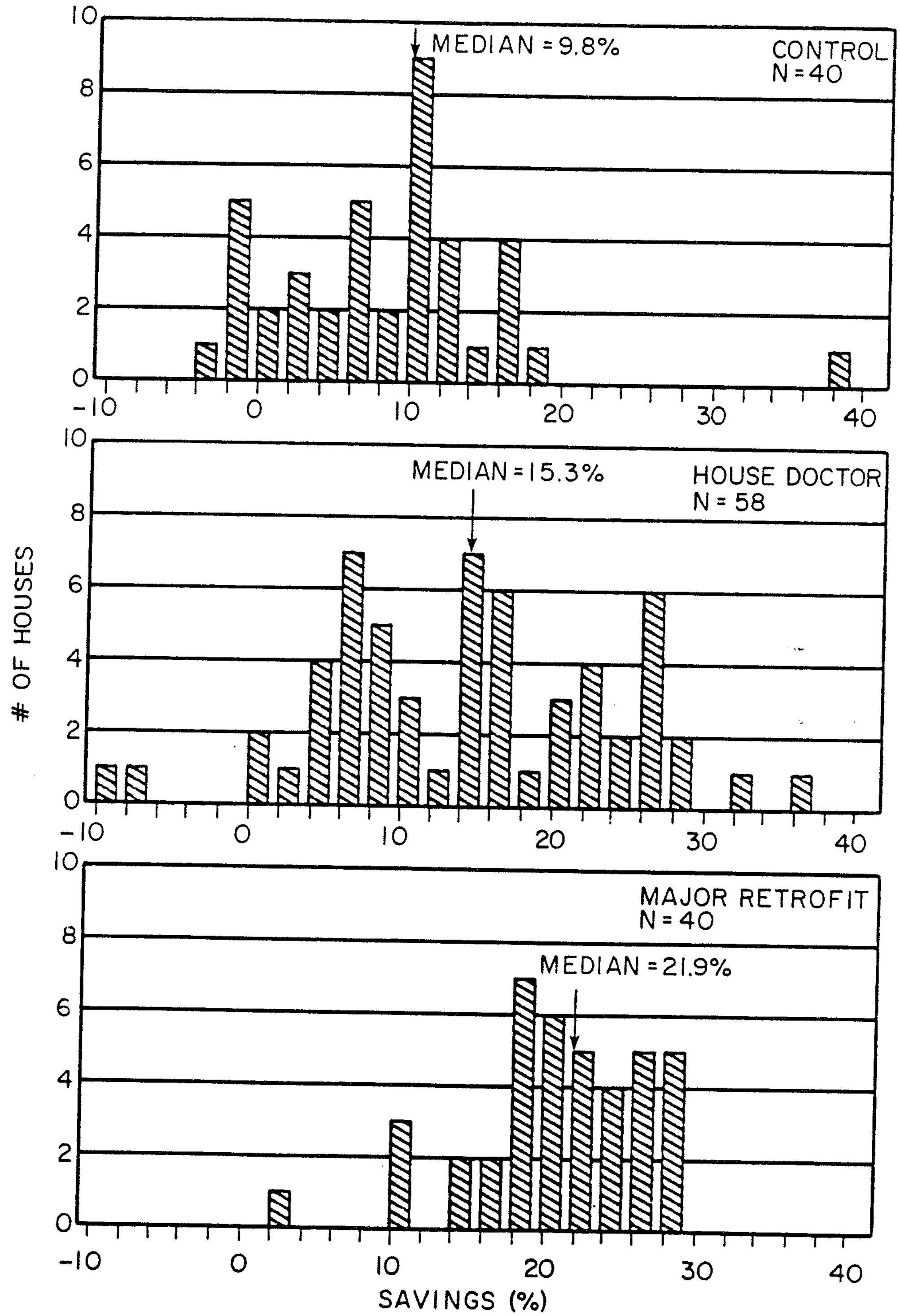

Figure 3. Histograms of percent savings by treatment group. Percent savings for each house are calculated as $[NAC_{pre}-NAC_{post})/NAC_{pre}]*100$.

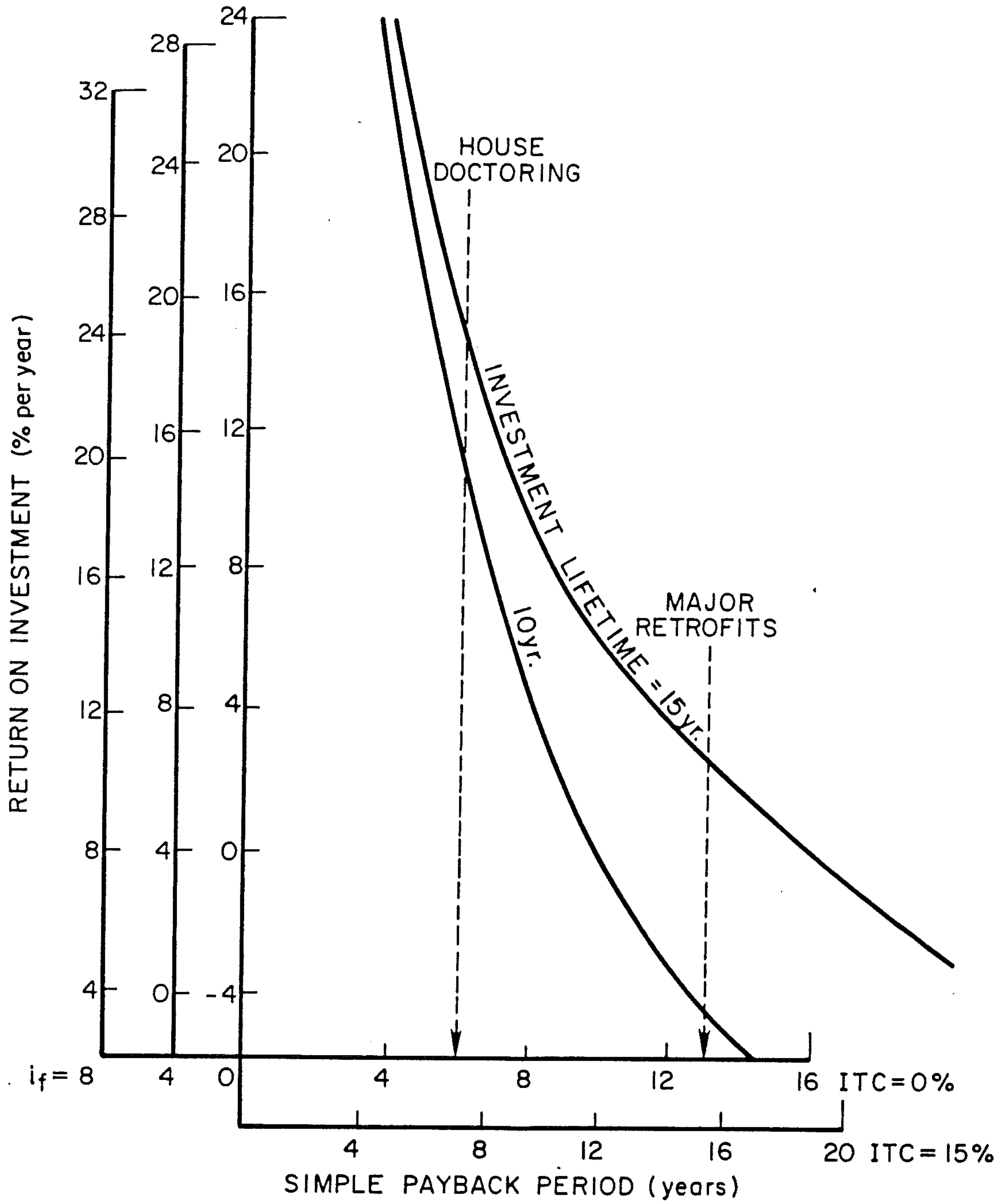

Figure 4. Results of the return-on-investment analysis. Parameters of analysis are i_f, the real fuel-price escalation rate in % per year; ITC, the income tax credit; and the return on investment, in % per year.