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ABSTRACT

In this report we present the results of a joint Lawrence Berkeley Laboratory and Pacific Gas and Electric Co. experiment designed to measure the additional energy savings achieved by adding two person-days of house doctoring to a standard energy audit. We compare a house doctor and audit treatment to an audit alone and to a passive control group. The results of a fourth treatment, house doctoring, audit and contractor retrofits, have not yet been analyzed. The treatments were applied to randomly selected groups of 10 houses each in Walnut Creek, California.

The difference in energy savings between the treatments, based on monthly utility bills, were not statistically significant due to wide variation in savings and the loss of several houses from each group. Predicted energy savings, based in part on measured air leakage area reductions, indicated that the retrofit package completed during house doctoring had a Cost of Conserved Energy of 42¢/therm.

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INTRODUCTION

Recent advances in the study of residential energy use have identified important paths for heating and cooling losses that previously eluded diagnosis and repair. Many such paths, once identified, can be repaired by an appropriate low-cost measure. A complete energy conservation retrofit, including repair of these recently discovered heat loss paths, can reduce the energy used to heat a house by 50% or more.[1] Unfortunately, skilled contractors able to carry out these new measures are not, as yet, readily available to homeowners.

"House Doctoring," a procedure designed to commercialize these new retrofit techniques, is now being developed at several institutions and small businesses. House doctoring focuses on using new instrumentation to find and fix problems otherwise difficult for a homeowner to diagnose and, while in the house, installing as many other low-cost measures as is possible. Two of the important diagnostic tools used by a house doctor are an infrared scanner and a "blower door," (a device which can slightly pressurize and depressurize the house). With these instruments infiltration rates can be quantitatively measured and otherwise hard-to-find leaks quickly identified and repaired. In addition, the effectiveness of an attempt to reduce leakage can be checked immediately. Other measures generally undertaken by house doctors include insulating water heaters, installing low-flow showerheads, and replacing furnace filters. Accomplishing these measures in one visit is potentially much more cost effective than visits by separate contractors for each kind of measure.

Although data on savings achieved in research houses are available, reliable data on savings generated by "real world" house doctor programs on occupied houses are scarce. To help rectify this scarcity LBL, in co-operation with Pacific Gas and Electric Company (PG&E), tested a pilot house doctor program modeled after the Princeton Modular Retrofit Experiment (MRE).[2] PG&E supplied the billing records, provided and paid the energy auditors used as house doctors, paid for the retrofit materials, and helped defray LBL's costs. LBL provided data analysis before and after the experiment, trained the house doctors, selected the retrofit materials, provided instrumentation, and organized the materials, house doctors, and transportation during the retrofit period. This report will examine the results of the program, specifically the energy savings as determined from utility bills and engineering calculations, and make recommendations for improvements in house doctoring.

DESIGN OF EXPERIMENT

We designed our experiment to measure the incremental costs and energy savings resulting from adding house doctoring to a conventional energy audit. The experiment was also intended to provide more information about the sources of infiltration in California housing and the best methods for reducing leakage rates in these houses. To these ends we planned to compare the energy savings resulting from four treatments:

Full Retrofit (Group A): This group received a PG&E Home Energy Survey, approximately two person days of house doctoring, and conventional contractor retrofits.*

House Doctoring (Group B): This group received a PG&E Home Energy Survey and about 2 person days of house doctoring.

Audit Only (Group C): This group received a PG&E Home Energy Survey alone.

Blind Control (Group D): This group received no treatment.

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* A "Home Energy Survey" was the pre-RCS computerized audit used by PG&E at the time of the experiment. For a complete list of measures involved in house doctoring see Table 1. The contractor retrofits included attic insulation, double pane windows, outside combustion air intakes for furnaces, fluorescent light fixtures, and duct taping and insulation.

As the study site, we chose a subdivision in Walnut Creek CA, a suburban community 30 miles east of San Francisco. Walnut Creek has an average of 2900 heating degree-days per year (base 65°F), close to the average for PG&E's service territory (2750 HDD). We then selected 615 houses on three contiguous meter-reading routes as potential participants in the experiment.

The analysis used to calculate savings (see Analysis section) requires a good correlation between weather and energy use. Accordingly, for each house we calculated the least-squares fit between monthly gas use from utility bills and local degree-day data and eliminated the 400 houses for which this fit had a correlation coefficient (r^2) of less than 0.90. This first screening accomplished a partial elimination of factors (such as heated swimming pools, electric heat, long unoccupied periods, etc.) that distort the gas-use to weather correlation.

After the r^2 elimination, PG&E subcontracted for a phone survey of the remaining houses to determine the homeowners willingness to participate in an energy conservation experiment. Homeowners interested in participating were randomly assigned to a treatment group. Because we did not want participants to be aware of the other experimental groups, we described the experiment to each homeowner as involving only the treatment for which they had been selected. The homeowners were then asked a series of questions regarding occupancy changes, heating fuels, pools, etc. (The complete questionnaire is reproduced as Appendix A.) The houses, (now fewer than 54 in each group due to disinterested homeowners and those we could not contact) were scored 0 to 9 on the basis of their answers to the above questions. Within each group, the ten houses with the highest scores were selected to participate. This second screening reduced the 215 houses to the 40 which took part in the experiment.

Because they were to be passive controls we did not describe the experiment or conduct the occupancy and energy use portion of the telephone survey when selecting the group D houses. The final sample of group D houses is thus from a slightly different population, with respect to suitability for the analysis of savings, than the other groups. An analysis of variance, however, shows all groups to be representative of the 215 potential participants with respect to initial energy use.

Six energy auditors from local PG&E offices were trained by LBL at a two week seminar covering use of the blower door, scanner, and retrofit techniques used in house doctoring. Each trainee worked in at least three different training houses before working on the experimental houses. The house doctoring and conventional audits of the experimental houses took place in November and early December 1980. Two house-doctor teams of two persons operated each day during this period using a van containing the necessary tools and materials. A third team was available to purchase needed supplies as those in the vans were depleted or as the house doctors encountered new situations.

The house doctors began each visit by measuring and photographing the house and doing an initial pressurization test. They then turned to reducing infiltration in the attic, crawlspace, and interior which usually required most of the day. After infiltration reduction they installed low flow showerheads, faucet aerators and new furnace filters as needed. Table 1 presents a more complete list of the measures.* The visit concluded with a final pressurization test and the audit recommendations. Insulating water heaters and installing intermittent ignition devices (IIDs), both possible house doctor tasks, were, in this study, performed by other PG&E employees for legal and safety reasons respectively.

The house doctors spent an average of approximately six hours in each house. Long commutes for some of the house doctors reduced the average time spent on the houses below the 8 hours originally planned. However, the time expended by the workers who installed the IIDs and water heater blankets brought the total time expended by all workers to approximately 2 person-days per house.

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* For a complete description of the materials and procedures used by a house doctor see The House Doctor Manual[3].

Table 1. Measures Typically Installed During a House Doctor Visit. Items with asterisks are measures emphasized during the Walnut Creek project.†

Hot Water System

* 1. Install low-flow showerhead(s).
2. Install faucet aerator(s).
* 3. Insulate water heater.
* 4. Turn water heater thermostat down to 120 °F, or 140 °F if house has an automatic dishwasher.
5. Insulate first 5 feet of hot water pipe from water heater.

Furnace System

* 6. Replace air filter, if necessary.
* 7. Test and adjust to maximum steady-state efficiency.
8. Set fan "off" control to 90 °F.
* 9. Seal leaky ducts in attics and basements.
10. Install clock thermostat.

Heat and Air Leakage

* 11. Seal over dropped ceilings.
* 12. Seal around pipes, electrical wires, and exhaust vents in attics.
* 13. Stuff openings around furnace flue and chimney with fiberglass or caulk.
* 14. Weatherstrip attic and basement/crawlspace hatch or door.
* 15. Insulate attic hatch or door with R-19 fiberglass.
* 16. Seal around pipes, wires, and chimneys in unheated basement/crawlspace.
17. Install a fireplace plug if no damper is present.
* 18. Install foam gaskets behind leaky switchplates and outlets.
* 19. Caulk around windows, doors, and window A/Cs.
20. Caulk baseboards and around electric baseboard heaters.
* 21. Seal holes behind sink and bathroom fixtures.
22. Insulate band joist
23. Caulk mudsill (only in heated basements).

Appliances

24. Install retrofit fluorescent lamps in much-used areas.
25. Turn on "power miser" switch or turn off "humidity" switch on refrigerator.
26. Give homeowner sample of cold-water detergent.

†For a more complete description of each measure see the House Doctor Manual.[3]

ANALYSIS

One goal of our analysis was to calculate the energy savings, defined as the change in average yearly energy consumption, resulting from the different treatments. To this end we calculated the Normalized Annual Consumption (NAC) for each house. The NAC is the energy consumption predicted for a year with average weather based on consumption data from any particular year. The prediction is based on the correlation between fuel consumption and outside temperature. We used natural gas consumption from utility bills, and daily temperatures recorded at Saint Marys College, located seven miles from the study area. The Saint Marys data were adjusted to better represent the weather in Walnut Creek by using a correlation based on 18 months of data collected at both locations in 1973-74. In order to compare periods of different lengths, we converted both the gas and temperature data to daily averages for each billing period. The data points, 10 or 11 months in our case, were fit to a linear model:

$$G_j = \alpha + \beta(DD_R)_j$$

where:

G_j = average daily gas consumption over period j (therms/day)

R = the reference temperature (base temperature) used to calculate the degree days.

$(DD_R)_j$ = average daily degree-days per day over period j (calculated using reference temperature R)

The term α (therms/day) is an estimate of the component of gas use not directly influenced by the weather, i.e. the gas used for cooking, waterheating, drying clothes, etc. The other term, $\beta(DD_R)_j$, represents the space heating component of gas usage. β (therms/^{o}F-day) is thus an estimate of the total thermal conductivity (including infiltration) of the house divided by the efficiency of the heating system .

For each house we ran least-squares regressions of G_j and $(DD_R)_j$ with R taking on integral values from 35 to 75°F. The regression with the best least-squares squares fit was used to establish the "best" α, β and R. With these parameters we then calculated the Normalized Annual Consumption as:

$$NAC = 365\ [\alpha + \beta\ (DD_R)_{yr}]$$

where $(DD_R)_{yr}$ is the average daily degree days of an average year, with respect to reference temperature R. We calculated the average year using temperature data from 1949 to 1979.

We calculated an NAC for each house before and after treatment. We expressed the effect of treatment as the average change in NAC of the treatment group. We also calculated NACs and changes therein for the average Walnut Creek household using PG&E's data on average natural gas consumed by all individually metered residences in Walnut Creek. The uncertainty for the average Walnut Creek NAC was calculated according to a method proposed by Fels and Goldberg (Princeton).[4]

No electricity consumption model we tested enabled us to calculate an electric NAC with sufficient accuracy to compare the total electricity use of a house in different years. Because the main difficulty was in modeling energy consumed by air conditioners (which in this climate are often controlled manually rather than by a thermostat setting) we used the electricity consumed for uses other than cooling, estimated as follows: We found the average daily consumption for the months December to May, the months where no cooling occurred and for which we had consumption data for both the pre- and post-retrofit period. Assuming the average daily non-cooling use did not change for other months we multiplied the December-to-May figure by 365 to find the yearly non-cooling electricity use. We used the changes in this value between periods and groups to examine the effect of the treatment on electricity consumption and to check for fuel switching.

In addition to the NAC analysis, we calculated monthly infiltration rates for each house using a model developed by Sherman and Grimsrud (LBL).[5] This model calculates the leakage area (a parameter approximating the total cross-sectional area of air leaks) from the results of the pressurization test and calculates monthly infiltration rate from the leakage area and local monthly average wind speeds and temperatures. We then averaged the infiltration rates from November to March to find the heating-season infiltration.

Using the change in heating-season infiltration for a particular house, and the average degree-days per year for the best-fit reference temperature for that house, we calculated the savings in gas consumption that might be expected from the infiltration reduction portion of the house doctor visit. This value, however, will not show the added savings that can be obtained when infiltration reduction also reduces convection losses, such as in the attic where the effect of covering dropped ceilings or an open wall cavity is to break a convective loop carrying heat from an uninsulated surface to the attic space.

RESULTS AND DISCUSSION

Of the 40 houses originally selected and treated, we eliminated 16 from the savings analysis. Nine houses with heated pools, spas or hot tubs were included in the original sample because of a poorly worded question in the phone survey (see Appendix A). We eliminated these houses because the pattern of natural gas use by these items renders calculation of an NAC unreliable. We also dropped houses due to change of owners or obvious meter reading errors. From the infiltration analysis we eliminated only three houses, each because of problems with the blower door data.

Table 2 presents age, size, and occupancy data for the remaining houses in groups A, B, and C. Most were one-story ranch-style tract houses. A few were two-story tract houses. All houses had very low attics (4′ or less at the ridge) with internal cross-bracing and 18" crawl spaces. All houses had gas-fired forced-air furnaces, gas water

Table 2. General Characteristics of the Walnut Creek Experimental Houses by Treatment Group.

Treatment Group	Avg. Size (ft^2)	Avg. Vintage	Avg. # Residents	Total # in Final Sample[a]	1-story	2-story
(A) House Doctor	1950±550	1962±6	4.0±1.3	6	5	1
(B) House Doctor	2490±520	1966±4	3.5±1.4	7	4	3
(C) Audit Only	2500±210	1968±5	4.5±0.8	6	5	1

[a]All averages are based on the final sample of houses used to find the average energy savings, not the initial sample of ten.

heaters and central or room air conditioners. Gas was the more common fuel for both stoves and clothes dryers.

These 24 houses, judged acceptable for the experiment by all criteria, had an average r^2 for the gas and weather correlation of 0.98. This high r^2, resulting from the use of the phone survey and post visit eliminations, implies that .90 was too low a cut-off value to use in the original r^2 elimination (see Design section). Using a cut-off value of about .96 would have reduced the number of houses called during the phone survey, saving time and expense expended on that process, without eliminating any of the houses we picked for the final sample using the original method.

Table 3 presents the average pre-retrofit NAC, post-retrofit NAC, and savings for each treatment group. The savings presented for group A show only the effects of the audit and house doctoring because the contractor measures were installed at the very end of the post retrofit data collection period used for this paper. In other words, with respect to the results presented here, houses in groups A and B received essentially identical treatments and will be referred to collectively as the house doctored groups. As a further comparison we have included the "pre-retrofit" and "post retrofit" NACs for the average of all single family residences in Walnut Creek, calculated using data from the same months used for the test groups.

The average natural gas savings (average percent change in NAC) for the two groups receiving house doctor visits are 11.3%±7.3% for group A and 11.5%±9.8% for group B. (The uncertainties given are 95% confidence intervals.) The savings for the audit-only group are 9.4%±9.8% and those for the blind controls 6.8%±20%. The NAC for the average of Walnut Creek single family residences showed a reduction of 7.0%±12. The average initial consumption for this group is smaller than that for the experimental groups due to inclusion of condominiums and some individually metered apartments.

Table 3. Natural Gas and Electricity Savings by Treatment Group.

Natural Gas: Normalized Annual Consumption(NAC)[a]

Group	Pre Visit avg. NAC[a] (therms/yr)[b]	Post Visit avg. NAC[a] (therms/yr)[b]	Change in avg. NAC (therms/yr)[c]	Avg. Percent Change in NAC (%)[c]	Number of Houses
(A) House Doctor[d]	1220±375	1075±313	-145±126	-11.3±7.3	6
(B) House Doctor	1335±259	1177±241	-158±127	-11.5±9.8	7
(C) Audit Only	1346±391	1204±306	-142±156	-9.4±9.8	6
(D) Control	1377±535	1262±434	-115±213	-6.8±20.	5
WC Resid. Avg.[f]	878±97	-816±77	-61±113	-7.0±12.	

Electric: Non-Cooling Consumption[e]

Group	Pre Visit avg. elec. (mwh/yr)[b]	Post Visit avg. elec. (mwh/yr)[b]	Change in avg. elec. (mwh/yr)[c]	Avg. Percent Change in elec. (%)	Number of Houses
(A) House Doctor	10.3±5.1	10.3±3.6	0.0±5.7	0.0	6
(B) House Doctor	9.5±4.2	8.7±4.3	-0.8±2.8	-5.5	7
(C) Audit Only	12.1±3.1	11.7±4.3	-0.4±0.5	-4.0	6
(D) Control	10.8±5.2	9.8±3.9	-1.0±2.1	-9.4	5
WC Resid. Avg.[f]	7.0	6.7	-.3	-4.0	

[a]An NAC is calculated by normalizing any specific consumption data to a year with average weather. [b]Mean value ± standard deviation. [c]Mean value ± 95% confidence interval. [d]Because group A did not receive the extended retrofits until July 1980, the savings shown are almost entirely from house doctoring. [e]We calculated the non-cooling electricity consumption by normalizing the average daily consumption from Dec-May to a full year. [f]The "Walnut Creek Residential Average" is based on PG&E's total consumption for individually metered residential units in Walnut Creek. The gas category has 1800 meters of which 15% are multifamily and the electric, 2450 meters, of which 37% are multifamily. In both cases, most of the individually metered multifamily units are condominiums.

Although each of the treated groups (A, B, and C) did show a statistically significant drop in natural gas consumption between the pre- and post-retrofit periods, the overlapping confidence intervals make it impossible to decide whether or not additional savings resulted from adding house doctoring to an audit. Subtracting the audit savings (group C) from the house-doctor savings (group B) one gets 2.1%±12%. Neither the average savings for the audit group nor those for house doctor group differ significantly from the average savings of the blind control group. The average savings of electricity consumed for non-cooling uses also shown in Table 3, are not significantly different from zero or from each other. We expected this finding as none of the measures we undertook specifically addressed this electric usage.

The large uncertainty in the natural gas savings of the treatment groups is due to the wide variation in the individual savings (see Fig. 1) and to the small final sample size. (Appendix B presents the savings for each house.) One possible driving force for this variation was the large increase in energy prices during the experiment. Gas prices rose from 29¢ to 44¢/therm (+52%) and electricity from 4.3 to 9.4¢/kWh (+118%) during the course of the experiment.* Possible mechanisms by which this price increase may have caused variation in savings are:

1. Large changes in thermostat settings, hot water use, appliance use, etc. (i.e., the "level of service" purchased by the customer) in some houses and possibly no change in others. In this moderate climate, even small changes in the thermostat setting can cause large changes in energy use due to the high sensitivity of heating load to indoor temperature.

2. Variation in response to the audit suggestions among treated houses and completion of typical audit measures, or other measures, by some of the blind control houses.

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* These are the prices per kWh and therm paid by a homeowner using 200 therms/month and 1000 kWh/month during a winter month.

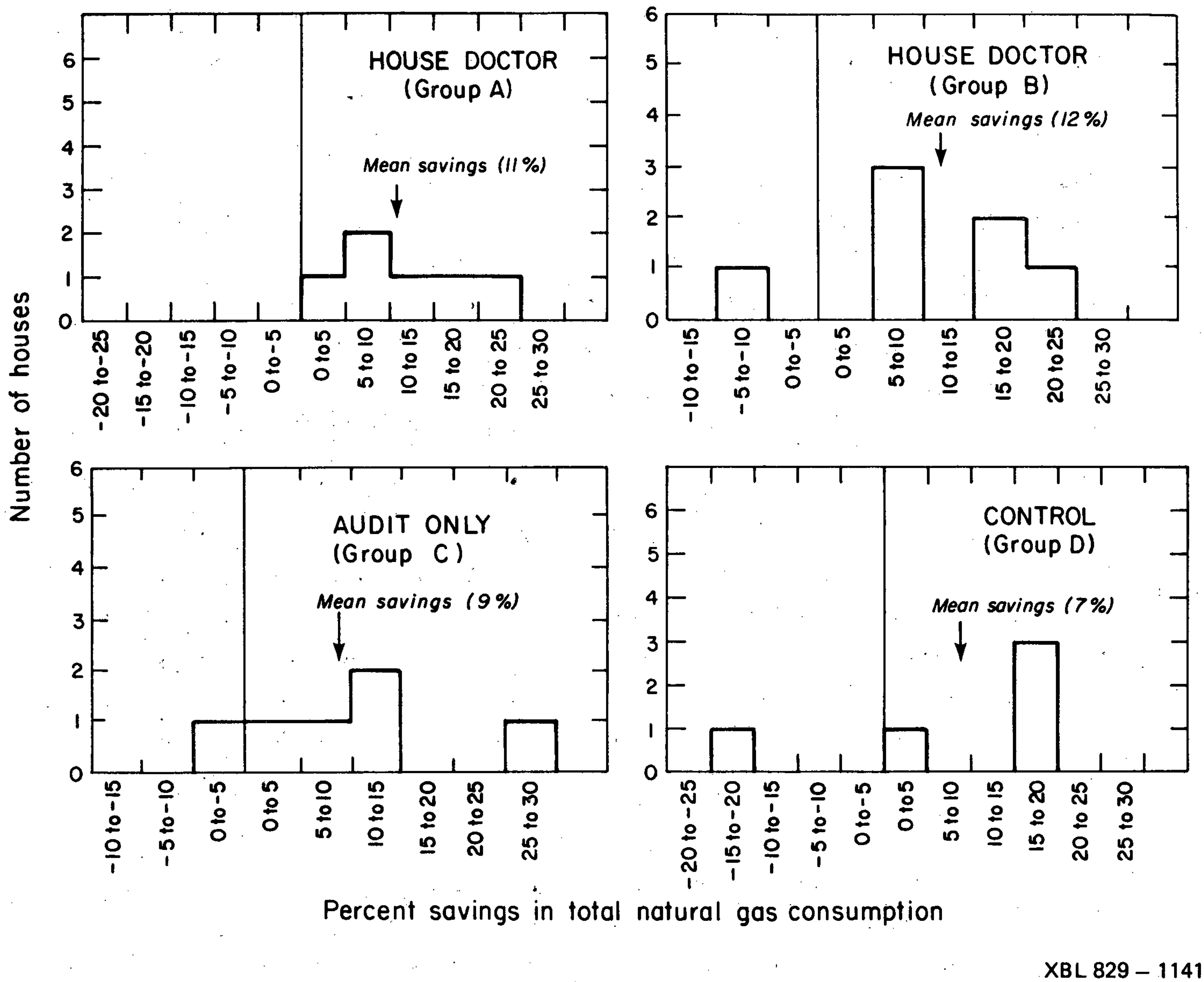

Figure 1. Histograms of Energy Savings by Treatment Group.

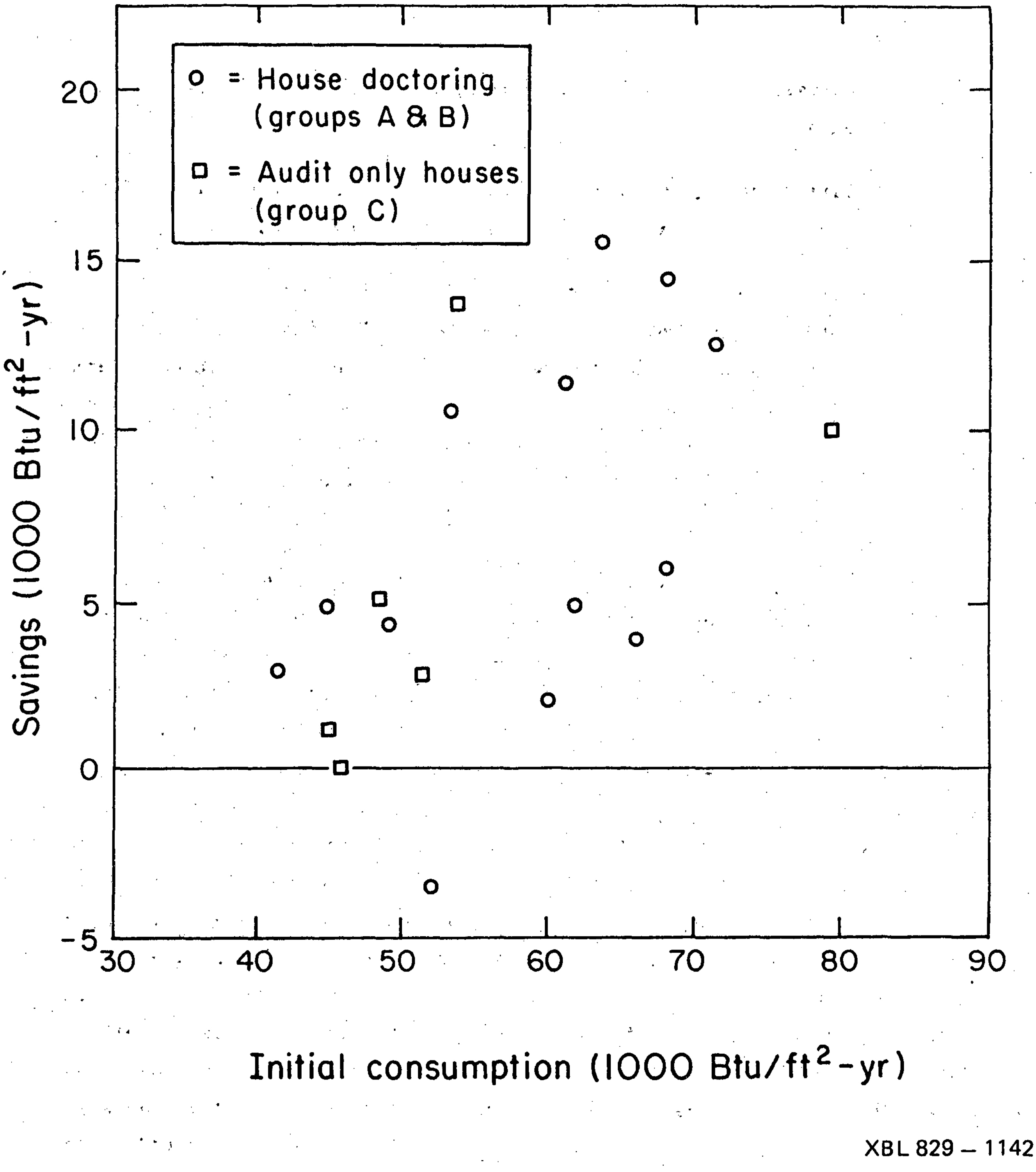

Figure 2. Scatter Plot of Natural Gas Savings per Square Foot Versus Initial Natural Gas Consumption Per Square Foot.

Additional sources of variation, not specifically affected by price changes, are:

3. Changes in the number of occupants (which occurred despite the phone survey).

4. Variation in the success of the house-doctor retrofit efforts due to the quality of the work or the type of house.

5. Variable errors in our corrections for weather differences between pre- and post-retrofit years. For instance, one winter significantly sunnier than another would not only cause a bias in the NAC calculation, but the bias would be different from house to house. (As our pre-retrofit and post-retrofit data periods differ by only 9% in total degree-days this effect is unlikely to have been important.)

We did not measure several parameters that would have allowed us to determine which of the possible mechanisms listed above were responsible for the variation and the savings observed. For example, measuring inside temperatures and submetering furnace gas use would have allowed us to compare the effects of efficiency changes (changes in the building shell and heating equipment) to the effects of changes in thermostat habits. With a record of all conservation measures completed or purchased by each homeowner we could have distinguished the importance of these actions relative to house doctoring. Using accurate data on these parameters to adjust the NAC for the effects of unintended changes in the households we could have reduced the variation in the measured savings and perhaps calculated a more certain value for the savings from house doctoring. Alternatively, an experiment using a larger initial sample could use such data to eliminate houses where the conditions changed beyond previously selected limits. Although we collected some of this information by telephoning homeowners, the "self-reported" data did not correlate well with the observed consumption changes, and we did not make any adjustments on this basis.

Although our NAC calculations have not allowed us to quantify the savings resulting from house doctoring, our other results do permit us to suggest improvements in house doctoring. Based on our infiltration calculations and predicted energy savings for the various measures completed by the house doctors (see Analysis section) we will examine the relative cost effectiveness of these measures.

Table 4 presents the average infiltration rate in air changes per hour (ach) before and after treatment for groups A, B, and C. The houses in our experiment had low initial infiltration rates, the average of all houses pressurized was .49 ach. The national average for residential infiltration is thought to be between 0.7 and 1.0 ach (A sample of 400 homes, biased in favor of energy efficiency has shown an average of 0.70 ach.[6]) The two house doctor groups differed in average initial infiltration and, apparently, in suitability for house doctoring. The average reduction was .07 ach for group A and .20 ach for group B. (The individual results of pressurization tests and infiltration calculations are presented as Appendix C.)

Table 5 presents the predicted savings from infiltration reduction and non-infiltration measures completed by the house doctors in the group B houses. As mentioned in the methods section the infiltration savings will not include the additional savings resulting from reduction in convective loss through sealing of bypasses but, due to the design of the houses, we feel these savings were small in this experiment. We assumed that water heater turndown was equally likely to result from an audit as from house doctoring and did not include the savings as part of house doctoring. The predicted average savings for group B, from all measures included on Table 5, is 144±29 therms/yr, or approximately 11% of the pre-retrofit average NAC.

In Table 6 we present a cost breakdown of a house doctor visit in which all the measures emphasized in our program were installed. Because each house did not receive each measure, the actual cost per house varied. The average cost for the house doctor visits to the group B houses was $457. The visits to the audit only houses cost $90 thus the average incremental cost of adding a house doctor visit to an audit

Table 4. Pre- and Post-retrofit Infiltration Characteristics of Walnut Creek Houses by Treatment Group.

Treatment Group	Leakage Area (LA) Pre Visit (cm^2)	Leakage Area (LA) Post Visit (cm^2)	Pre Visit Specific LA (cm^2/m^2)	Post Visit Specific LA (cm^2/m^2)	Pre Visit Infil.[a] (ach)	Post Visit Infil.[a] (ach)	Change in ach	Number of Houses
(A) House Doctor[b]	1104±317	940±257	6.0±1.5	5.1±1.4	.48±.11	.41±.10	-.07	10
(final sample)[c]					(.53±.06)	(.44±.08)	(-.09)	(6)
(B) House Doctor	1495±444	969±219	6.7±2.1	4.4±1.4	.58±.19	.38±.12	-.20	9
(final sample)[c]					(.56±.19)	(.40±.14)	(-.16)	(7)
(C) Audit Only	1109±202		4.7±1.2		.39±.07			8
(final sample)[c]					(.37±.07)			(4)

[a]Values given are average infiltration during the heating season, presented as group mean ± standard deviation.

[b]The infiltration reduction presented for the A group is due to house doctoring only.

[c]Values in parentheses apply to houses in the final sample used for energy savings analysis: see text.

Table 5. Predicted Energy Savings, Group B Houses.

Measure	Average Savings (Therms/yr)[a]	Number Houses Retrofitted	Total Savings (Therms/yr)	Estimated Uncertainty (%)
Infiltration Reduction	51	7 (all)	357	40
Duct Sealing	29	7 (all)	203	50
IID	80	3	240	30
Water Heater Blanket	31	4	124	30
Low-flow Showerhead	43	2	86	50
TOTAL			1010	20
AVERAGE			144±29	

[a]The savings gained from installing low-flow shower heads are based on a reduction of 2 gallons per minute at 11 minutes/day use. The savings for sealing ducts are based on an average decrease in duct losses from 12% to 9%. Savings for water heater blanket and IID are from reference 7.

Table 6. Cost Breakdown for a House Doctor Visit[a]

HOUSE DOCTOR AND AUDIT

1. Labor ($12/hour)	Cost/house
a. Infiltration Reduction, 10 person-hours	$120
b. Water heater insulation and low-flow showerhead, 1 hour	12
c. Audit, 1.5 person-hours	18
d. Set up/take down, 2 person-hours	24
e. Installation of intermittent ignition device (IID), 2 person-hours	24
f. Travel Time, 1.5 person-hours	18
Total 18 person-hours	$216
2. Materials	
a. Water heater blanket	$15
b. Infiltration reduction materials	60
c. Showerhead	10
d. Intermittent ignition device[b]	60
Total	$145
3. Grand Total	$361
4. Grand Total + 50% Overhead	$542
5. Infiltration reduction alone (labor, materials, and 50% overhead)	$270

AUDIT ONLY (includes blower-door test)

1. Labor ($10/hour)	Cost/house
a. Set up/take down, 2 person-hours	$24
b. Audit, 1.5 person-hours	18
c. Travel time, 1.5 person-hours	18
Total 5 person-hours	$60
2. Total + 50% Overhead	$90

[a]This cost breakdown uses a labor rate slightly above that paid to the house doctors in our project (approx. $10/hr), and assumes all measures emphasized in the Walnut Creek project were successfully installed. Because not all measures were installed in every house, the average cost for a house doctor visit in the Walnut Creek project, using $12/hr, was $457. [b]In this study intermittent ignition devices (IIDs) were installed by PG&E furnace servicemen. The $60 cost quoted for IIDs is the bulk rate paid by PG&E.

was $367. The average cost for the infiltration reduction portion of the visit was $270 per house, the non-infiltration retrofit measures averaged $97. These last costs include labor, materials, and overhead, but exclude transportation and set up times as we assumed the house doctor was already in the house for the audit. The costs for non-infiltration measures include the labor and materials for each house where the measure was installed and, because the house doctor must spend a little time on a measure even to discover it cannot be installed, 1/2 of the labor for each house where it was not installed. In calculating all costs, we used a labor rate 30% above that paid to the house doctors in our experiment. This should remain reasonable even given the greater amount of training and skill that would be necessary to implement the suggestions below.

The Cost of Conserved Energy* (CCE) for the infiltration reduction portion of the visit (including the effects of duct sealing), based on predicted savings, is 48¢/therm (group B only). The CCE of the non-infiltration related house doctor activities, based again on predicted savings, was 21¢/therm (group B only). For each of the non-infiltration measures, there were houses in which that measure could not be installed without more materials, training, or time. The lower CCE of the non-infiltration measures indicates that the overall cost effectiveness of house doctoring could be increased, at least in this type of housing and climate, by diverting some time and expense from infiltration reduction to achieve a greater success rate with other measures. For example, more time spent explaining the use and benefits of low flow showerheads, and stocking the vans with more plumbing equipment in order to install them in more situations, would increase the savings from this measure without raising the CCE above that for infiltration reduction. Additional measures, such as installing reflective window screens for cooling reduction or retrofit switches for "instant-on" TV sets, could be added to the

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* The Cost of Conserved Energy is equal to the cost of the treatment, multiplied by a capital recovery factor, and divided by the therms saved per year. The capital recovery factor is calculated on the basis of the expected useful life of the retrofits and the real interest rate. We have used 10 years, a conservative estimate, and 6% per year.

house doctor repertoire.

In colder climates, however, where each cm^2 of leakage area causes more energy use, and in leaky houses, infiltration reduction will likely remain an important function of house doctoring. Based on pressurization data, pre-retrofit infiltration losses in our houses were responsible for 10% of total fuel consumption, on the average, with a range of 7.5% to 18%. The predicted average percent savings from infiltration reduction (group B) was 4% of the total consumption, with a range of 1% to 7%. The small contribution of infiltration to the fuel bill limited the percent savings available from infiltration reduction and the mild climate limited the absolute savings.

Our research indicates that in other parts of the U.S. housing stock, including areas of mild climate, infiltration levels may be higher and the leaks easier to correct than in our Walnut Creek sample. Scattered pressurization tests done by LBL have found many houses leakier than those in Walnut Creek. We have measured infiltration rates up to 2 ach. In addition to low initial infiltration rates, the houses in the Walnut Creek project had low crawlspaces and attics which hampered the detection and sealing of leaks. Much of the U.S. housing is older than that in Walnut Creek and, due to designs common in older housing, more suited to house doctor infiltration reduction.* This evidence, and the positive correlation between the reduction in infiltration and the initial infiltration rate (Figure 3), suggests that more than twice our average savings of .2 ach (group B) could be expected in a significant fraction of houses across the country.

*In addition to roomier attics and crawl spaces, older housing tends to have problems such as dropped ceilings and other similar bypasses. These localized problems (usually fixed by covering with a layer of plastic and insulation) take perhaps an order of magnitude less effort to correct than leaky ceiling-to-wall joints (one common design in our study had over 150 feet of such cracks) for probably the same infiltration savings.

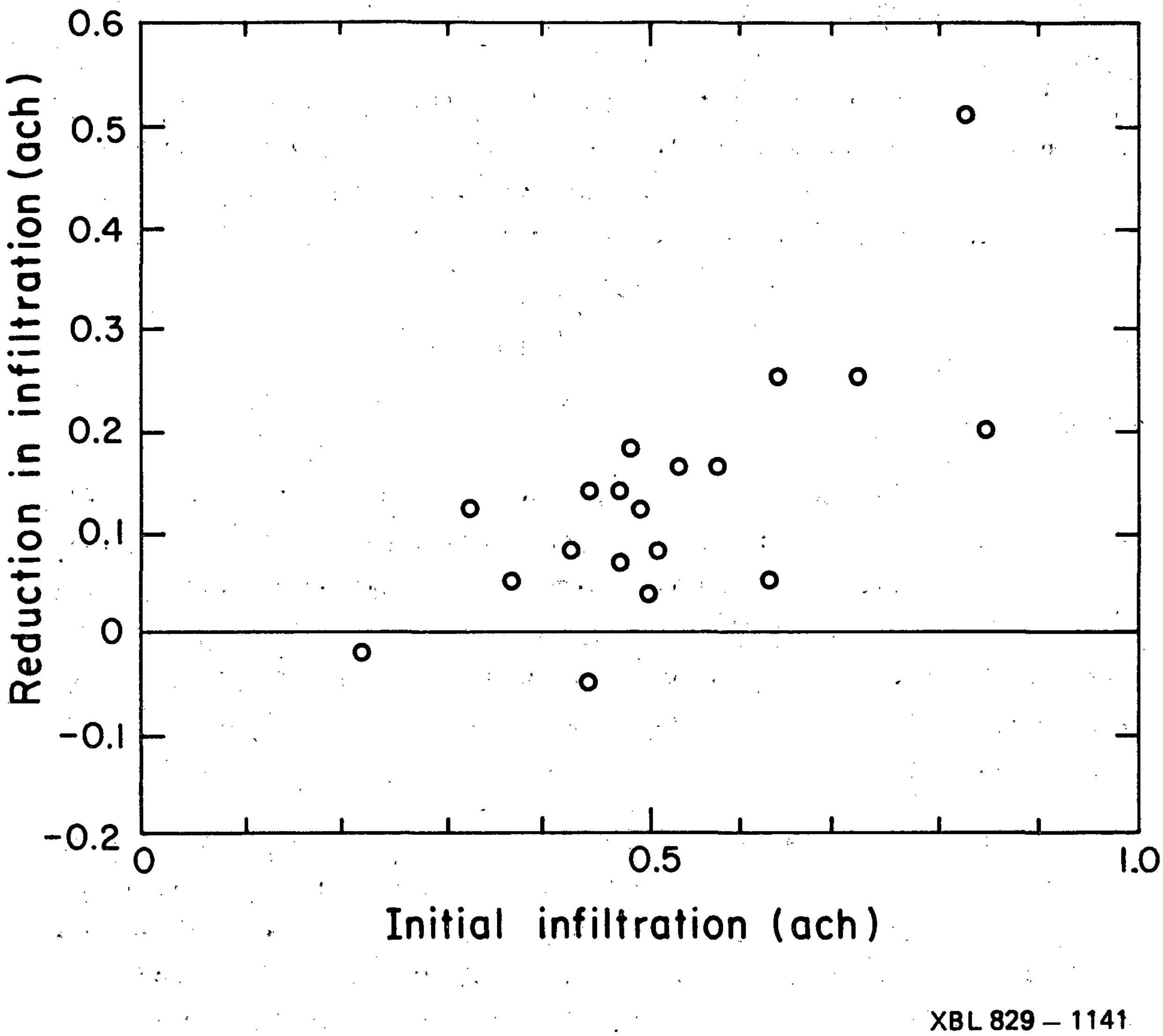

Figure 3. Reduction in Infiltration Rate Versus Initial Infiltration Rate for Walnut Creek House Doctored Houses (Groups A and B). The values presented represent average infiltration for the heating season.

Three tasks remain in the analysis of the Walnut Creek data. The billing data collected for the extended retrofit group after the completion of the contractor retrofits will be analyzed by PG&E and the savings compared to the house doctor and other groups. Analysis of the second year of post retrofit data for the house doctored houses will reveal the durability of the observed decrease in gas consumption and perhaps give a better idea of the source of the savings. Submetered furnace consumption is now available for some of the houses. Analysis of this data will provide a check on the accuracy of the NAC calculations.

CONCLUSIONS

In this study the house doctored, audited, and control houses all showed savings in natural gas consumption but, due to the small sample size, no statistically significant difference was measured between any of the treatments. Although our experiment was inconclusive with respect to the original question, whether adding house doctoring to an conventional audit is cost effective, the results do allow us to draw some valuable conclusions.

As noted in the discussion, experiments that attempt to measure energy savings in occupied houses, especially those with small sample size, require end-use submetering, indoor temperature monitoring, and careful attention to homeowner conservation actions. Without such data even statistically significant changes in energy use may not allow the experimenters to attribute the savings to specific causes. Only thorough data collection can resolve such questions. Fortunately, several low-cost systems for multi-channel data monitoring and storage are being developed.

Houses vary widely in their suitability for house doctoring. House doctoring every house, or every house in an experimental sample, is similar in concept to adding R-19 insulation to ceilings regardless of how much insulation is already present, or whether the house has an attic or a cathedral ceiling. Diagnosing a house before doctoring is, therefore, a part of any reasonable house doctor program. The diagnosis, most likely a pre-visit blower door test and walk-through, will clarify whether major infiltration reduction, completion of non-infiltration measures, or no treatment at all, is appropriate.

We believe that the retrofit package completed during house doctoring can be cost-effective, even with the problems we experienced. Because results from better monitored houses[8,9] and laboratory experiments support the methods used to calculate the predicted savings, and because our measured savings are not incompatible with the predicted savings, we are confident that the predicted savings for the retrofit package are a fairly good estimate of the savings we would have measured had no other changes occurred in the houses. The CCE for our house doctor visits, based on the predicted savings from the infiltration and non-infiltration measures, and costs including transportation, was 42±8¢/therm. This is cost effective relative to the marginal price of gas to the homeowners in the experiment (67¢/therm, Jan. 1981) and to the price of new natural gas supplies in most locations. A similar house doctor program employing a pre-house-doctoring diagnosis and/or operating in a colder climate should have a significantly lower CCE.

House doctoring can only become increasingly important as conventional retrofits (e.g. attic insulation) reach saturation and the less obvious measures constitute a growing fraction of the conservation potential. Many questions remain to be resolved, however, before beginning a large scale utility house doctor and audit program. Combined with an audit, or as a separate service, house doctor procedures need refinement and house doctor savings need better measurement. We strongly encourage further research into these areas.

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Appendix A. List of telephone survey questions for prospective participants.

Question	Desired Answer
1. Have you lived in this house for the past two years?	Yes
2. Do you plan to move from this house anytime in the next two years?	No
3. Do you have and use any of the following?[a] Wood stove Major electric space heater Hot tub or Sauna Heated Swimming Pool Solar heating	No
4. Have you ever had an Energy Audit, or do you have one now scheduled?	No
5. Do you have and use air conditioning in your home?	Yes
6. Have you added a room, or made any other major structural changes to your house in the last two years?	No
7. Has there been any change in the number of people living in your house in the past two years?	No
8. Do you expect a change in the number of people living in your house in the next two years?	No
9. Have you taken any energy conservation measures in the last two years? For example: Caulking Insulation Furnace Modifications Other	No

[a]In our study this question was mistakenly worded: "In the last two years have you purchased any of the following?".

Appendix B. Measured savings in the Walnut Creek test houses.

Treatment Group	ID	Pre-visit NAC (therm/yr)	Measured Change in NAC (therm/yr)	Measured Change in NAC[a] (%)
	A1	1572	-54	-3.4 ±12.
House Doctor and Extended Retrofit[b]	A3	1062	-93	-8.7 ±5.9
	A6	1086	-192	-17.7 ±9.1
	A7	1790	-382	-21.3 ±6.0
	A9	824	-90	-10.9 ±10.
	A10	986	-58	-5.9 ±5.8
	B1	1123	+76	+6.8 ±7.0
	B2	1115	-100	-9.0 ±11.
House Doctor	B6	1221	-300	-24.6 ±9.3
	B7	1722	-322	-18.7 ±7.3
	B8	1642	-133	-8.1 ±11.
	B9	1116	-222	-19.9 ±6.3
	B10	1405	-102	-7.2 ±8.3
	C1	982	+2	+0.2 ±8.2
	C3	1133	-60	-5.3 ±6.6
Audit Only	C5	1155	-120	-10.4 ±9.1
	C6	2069	-260	-12.6 ±8.2
	C9	1487	-381	-25.6 ±5.0
	C10	1252	-31	-2.4 ±10.
	D2	1195	-195	-16.3 ±20.
Blind Control	D6	1997	-58	-2.9 ±10.
	D7	1886	-286	-15.2 ±8.7
	D8	814	156	19.1 ±18.
	D9	991	-186	-18.8 ±7.5

[a] The 95% confidence interval presented with each savings was calculated with the method used by Fels and Goldberg (Princeton) on monthly aggregate data for communities[4]. However, we have some doubt that the monthly data for individual houses have the necessary independence of error terms for this method to be rigorously applied. For this reason the variance of each individual savings was not used in finding the group average presented in the main text. [b]The savings shown for the extended retrofit group are from house doctoring only. See main text.

Appendix C. Comparison of infiltration characteristics of Walnut Creek test houses before and after house doctoring.

Treatment Group	ID	Floor Area (m^2)	Pre-visit Leakage Area[a] (cm^2)	Post-visit Leakage Area[a] (cm^2)	Pre-visit Infiltration ach[b]	Post-visit Infiltration ach[b]	Percent Change in ach
	A1	245	1518	1298	.48	.41	-15
	A2	176	993	800	.43	.35	-19
	A3	145	980	906	.51	.47	-8
House	A4	174	1020	1126	.45	.50	+11
Doctor	A5	152	959	611	.49	.31	-37
Extended	A6	142	941	802	.52	.44	-15
Retrofit[c]	A7	245	1817D	1309D	.58	.42	-28
	A8	316	866	945	.22	.24	+9
	A9	172	815	567P	.48	.34	-29
	A10	139	1132P	1040	.63	.58	-8
	B1	202	1672P	1269D	.85	.65	-24
	B2	213	1491	1055	.54	.38	-30
	B3	241					
	B4	261	2132	820	.83	.32	-61
House	B5	204	1170	807	.45	.31	-31
Doctor	B6	179	1165	892	.50	.38	-24
	B7	263	948	813	.37	.32	-14
	B8	248	2048	1236	.64	.39	-39
	B9	196	1807	1171	.72	.47	-35
	B10	317	1026	660	.33	.21	-36
	C1	200	1171		.45		
	C2	220	934D		.33		
	C3	206					
	C4	179	1145		.49		
Audit	C5	223	760				
Only	C6	243	905		.29		
	C7	251	1208		.37		
	C8	219	1261		.44		
	C9	259	1401		.39		
	C10	261	1200		.35		

[a] A "P" following a leakage area value indicates that value is based on pressurization data only. A "D" indicates a value based on depressurization data only. [b] The model used to calculate infiltration rates is considered to be accurate to within 20%. [c] The savings shown for the extended retrofit group are from house doctoring only. See main text.

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