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House Doctor Visits — Optimizing Energy Conservation Without Side Effects

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Summary

Residential energy auditing procedures based on computation alone may provide little information on some aspects of energy use. In particular, air infiltration leakage sites and the efficiency of heating systems, both of which strongly influence energy use cannot be properly evaluated without instruments. The addition of a few diagnostic instruments can provide the missing information and improve the quality of the audit.

Princeton University's research efforts have led to the development of a procedure which includes an instrumented audit combined with a partial retrofit and is especially applicable to post-war single family housing. This procedure is known as the "House Doctor" approach and is being tested in a 168-house experiment initiated in October 1979. Preliminary results from a part of this experiment (conducted in collaboration with New Jersey Natural Gas Company and South Jersey Gas Company) indicate a 10 to 15% reduction in total use of natural gas following the partial retrofit measures. Further retrofits based on House Doctor observations led to a cumulative gas savings of 20 to 25% in these houses.

Although the partial retrofit measures carried out during a House Doctor visit save some energy, all of the energy savings that are cost-effective will only be realized after the homeowner has implemented other conservation measures recommended by the auditor. The level of energy savings achieved in a house depends not only on the initial state of the house and the accuracy of the energy audit calculations, but also on the auditor-resident interactions, the resident's keenness, and institutional barriers to energy conservation.

Introduction

Current residential energy auditing procedures in the U.S. are generally based on visual inspection followed by computation and are less sensitive to a number of important components of energy use. Items that are not well diagnosed from visual inspection are:

a) the magnitude of air infiltration
b) the location of the air leakage sites
c) attic bypass heat loss paths
d) other obscure heat loss paths
e) anomalous heat losses in the heat distribution system
f) insulation deficiencies
g) heating plant efficiency

h) the magnitude of standby losses in water heaters
i) hot water use pattern
j) refrigerator and freezer energy consumption

Instrumented diagnostic procedures enable these energy use items to be far better quantified [1,2]. A complete diagnosis involving a great deal of equipment and time may not be a cost-effective way of auditing individual homes for their energy conservation potential. Nevertheless, simple instumented procedures can be designed for inexpensively diagnosing individual homes.

Some of the features that affect energy use also influence other environmental factors in the residence and should be considered when energy conservation is being planned. Reducing air infiltration and adding insulation may lead to condensation in the building and eventually to structural damage. As houses are made more airtight, the concentrations of indoor pollutants could reach unacceptably high levels. The air supply for the furnace or boiler may also become too low either because of improper adjustment or because the house is too tight, possibly leading to a deterioration of air quality.

Diagnostic procedures based on instruments may be used to improve energy audits and provide useful information regarding environmental factors related to energy conservation. The aim of such procedures would be to define ways to reduce all components of energy use without adversely affecting the well-being of the residents or the structural integrity of the house. The House Doctor approach is the first step in developing a procedure of this kind.

The House Doctor Approach

A House Doctor visit to a house consists of an instrumented audit followed by a partial retrofit. Basic instrumentation includes thermometers, a sling psychrometer, furnace test equipment, stop watch and calibrated bucket. Thermometers may be used to measure air temperature in different zones, identify problems of heat distribution and calibrate thermostats. Domestic water heater jacket and output water temperatures are measured to estimate water heater standby losses and to identify homes where the water temperature may be reduced without any loss of amenity. Relative humidity measurement using a sling psychrometer helps to identify moisture problems. The maximum flow rates of showers and faucets can be determined using a calibrated bucket and stop watch. Low flow shower heads, shower flow controllers, and/or faucet aerators are recommended where applicable.

Furnace test equipment constitutes an important part of energy diagnostics for a house. The steady state efficiency of a combustion heater may be determined from a measurement of the stack temperature and gas composition. Other useful furnace data are smoke content in the stack gases (for oil burners) and draft in the flue. These diagnostics and visual inspection enable one to determine whether the furnace should be adjusted to improve its steady state efficiency, whether a replacement (oil) burner is necessary, or indeed whether a replacement heating unit would be cost-effective.

More unusual and expensive equipment in the House Doctor instrument package are an infrared scanner and a Blower Door. Their principal function is in the identification of obscure heat leaks. In the course of Princeton's research into home energy use, it was discovered that some of the major heat loss components were difficult to find. Many of these involved air leaks connecting living space to unheated attics [3]. The leakage sites are frequently hard to find because they are buried under attic insulation. One way of finding them is to pressurize the house to about 25 Pa with a fan mounted in an exterior door or window. The air leakage sites into the attic are then readily located from the attic by looking at the attic floor through an infrared scanner [1,4].

Air leakage sites elsewhere in the building thermal envelope are found by depressurizing the house again by about 25 Pa and looking for cold air leaks. The leak search is aided by the infrared viewer, but feeling with fingers and using a smoke pencil as a tracer as well as moving cobwebs in basement walls often lead an infiltration detective to a leak.

House pressurization and/or depressurization to find leaks can be carried out by a variety of fans ranging from whole house fans already in place in a house, window fans temporarily installed into a window or a specifically designed high-flow fan mounted in a door. Princeton University researchers have focused on a door-mounted fan called a Blower Door which includes a pressure gauge (reading up to 125 Pa), and is instrumented to indicate the fan rotation speed. Pressure differences across the building shell are indicated on the gauge while the flow rate through the fan can be calculated from fan speed and pressure difference data. Flow rate through the fan plotted against inside-outside pressure difference is the leakage profile of the house and is useful in several ways: (a) a quantitative record of house leakage is obtained, (b) the effect of air infiltration retrofits on house leakiness can be measured, and (c) an excessively airtight house can be identified. The use of leakage profiles are discussed below.

(a) The significance of air leakage on energy use can be calculated if the natural air infiltration rate of the house is known. The air infiltration rate can be estimated from the house leakage profile (obtained using a Blower Door) and some information about the wind, interior-exterior temperature difference, distribution of leaks around the envelope and the topography around the building. Even in the absence of a sophisticated model for estimating the natural air infiltration rate, the house leakage profile can be used to distinguish tight houses from leaky houses. More effort at air tightness can be justified for the leaky houses.

(b) If a leakage profile is available both before and after an air tightness retrofit, the relative success of the effort may be evaluated. If experience shows that a certain type of leak sealing rarely leads to a measurable change in the leakage profile, then it should be eliminated from a catalogue of prominent leaks. For instance, we have found that although electric outlets and switch plates often leak enough to be readily felt, tightening them by placing gaskets under all the plates in a house is quite time consuming and has very little effect on the leakage profile, at least in recent New Jersey houses. This retrofit appears not to be cost-effective if done by a professional contractor. However, if a homeowner does it on his/her own then it may well be worthwhile.

(c) If a house is excessively tightened, there is a higher concentration of moisture and indoor air pollutants leading to increased risk of structural damage or health. These concentrations depend both on the pollutant source strength and the natural air infiltration rate. A preliminary idea of whether a house is likely to be too tight and have an air quality problem can be obtained from its leakage profile.

If a house is so tight that air quality or moisture buildup is a problem, then an air-to-air heat exchanger may be installed to increase ventilation without a substantial energy penalty. The relevant parameters in determining cost effectiveness of installing air-to-air heat exchangers are the cost of infiltration retrofits including the installation of an air-to-air heat exchanger and the amount of energy saved by the retrofit [5]. Again, the availability of leakage profiles preferably converted to natural air infiltration rates leads to a more reliable assessment of heat exchanger cost effectiveness.

Use of a calibrated Blower Door assisted by an infrared viewer permits easy identification of air leakage sites, estimation of their contribution to heat loss, evaluation of the risks of over-tightening and establishing the cost-effectiveness of infiltration and air-to-air heat exchanger retrofits. These instruments also simplify the identification of "convective loop" heat losses and insulation deficiencies.

Convective loops are enclosed air spaces which are heated mostly by conduction through a living space wall or ceiling but then transmit their heat to the outside or unheated spaces (generally attics). The transfer of heat within the space is by natural convection (hence the term convective loop) while transfer to the unheated space may be by conduction or air leakage. Examples include hollow masonry basement walls transmitting heat to the outside, and fire walls in townhouses losing heat to the attic [6]. Eliminating convective loops offers excellent retrofit potential since eliminating them does not make the house more airtight and therefore has no air quality penalty.

Insulation deficiencies occur because of (a) oversight or negligence at time of construction e.g. portions of walls or ceilings with missing pieces of insulation, (b) improper installation of retrofit measures -- all of the areas not covered, and (c) degradation of the insulation from settling, shrinking, moisture condensation, etc. In basements, crawlspaces and accessible attics, these deficiencies can be seen without instrumentation. In hidden spaces (especially walls), an infrared scanner is very useful.

Many of the obscure heat losses identified by the pressurization/infrared scan technique are best taken care of while the instrumentation is in place in order to make sure that the heat loss is indeed eliminated and to take into account any consequence of excessive airtightness.

Another item that should be addressed while the instrumentation is in place is furnace efficiency. The steady state efficiency of the furnace can be measured by a variety of test equipment. Some of these have a relatively short response time so that efficiency improvement following furnace adjustment can be readily measured. Furnace tune-ups are sometimes performed by furnace service persons but should be included in a comprehensive energy audit.

Princeton's House Doctor procedure includes a set of "on-the-spot" or"partial" retrofits along with its instrumented energy audit. The partial retrofits addressed in one version of the procedure are listed in Table 1. Items 1, 2 and 3 seek to reduce water heater standby losses. Items 4 and 5 reduce hot water consumption. Items 6 to 14 address obscure heat losses. Items 15 to 17 seek to improve efficiency of heat delivery from the furnace while item 18 reduces building envelope heat losses by a programmed reduction in interior temperature. Items 3-5 may affect the residents' lifestyle and would be carried out only with their consent.

TABLE 1

Retrofits to be Done During House Doctor Visit
(where applicable)

1. Insulate water heater with 9 cm (R-11) foil-backed fiberglass insulation.
2. Insulate first 3 meters of hot water pipe from water heater.
3. With homeowner's permission, turn water heater temperature down to 50°C. Show homeowner how to turn temperature up if 50°C is unsatisfactory.
4. With homeowner's permission, install low-flow shower head(s) or DOE shower flow controllers. Leave old one behind. Show homeowner how to change it back, if unsatisfactory.
5. With homeowner's permission, install sink faucet aerators.
6. Install foam gaskets behind a few leaky switchplates and electrical outlets. Leave a set of gaskets for homeowner to install on the rest of the switchplates and outlets.
7. If attic door or trap door is not insulated, then staple or glue (R-30) insulation on door. (Use R-19 if R-30 will not fit). Add additional weight (e.g. a brick) if a trap door is too light to seal properly.
8. Weatherstrip attic door.
9. Seal around plumbing pipes and electrical wires where they penetrate the attic floor.
10. Stuff openings around furnace flue with fiberglass
11. Seal openings over dropped ceilings using polyethylene sheeting and duct tape.
12. Seal leaky ducts in attics and basements.
13. Seal (with caulking compound or caulking rope) the gap between foundation wall and sill plate.
14. Seal other major leakage sites identified during the audit.
15. Replace furnace air filter, if necessary.
16. Adjust furnace to maximum steady-state efficiency.
17. Set back plenum temperature at which furnace fan goes off to 38°C.
18. Install clock thermostat.

The Modular Retrofit Experiment

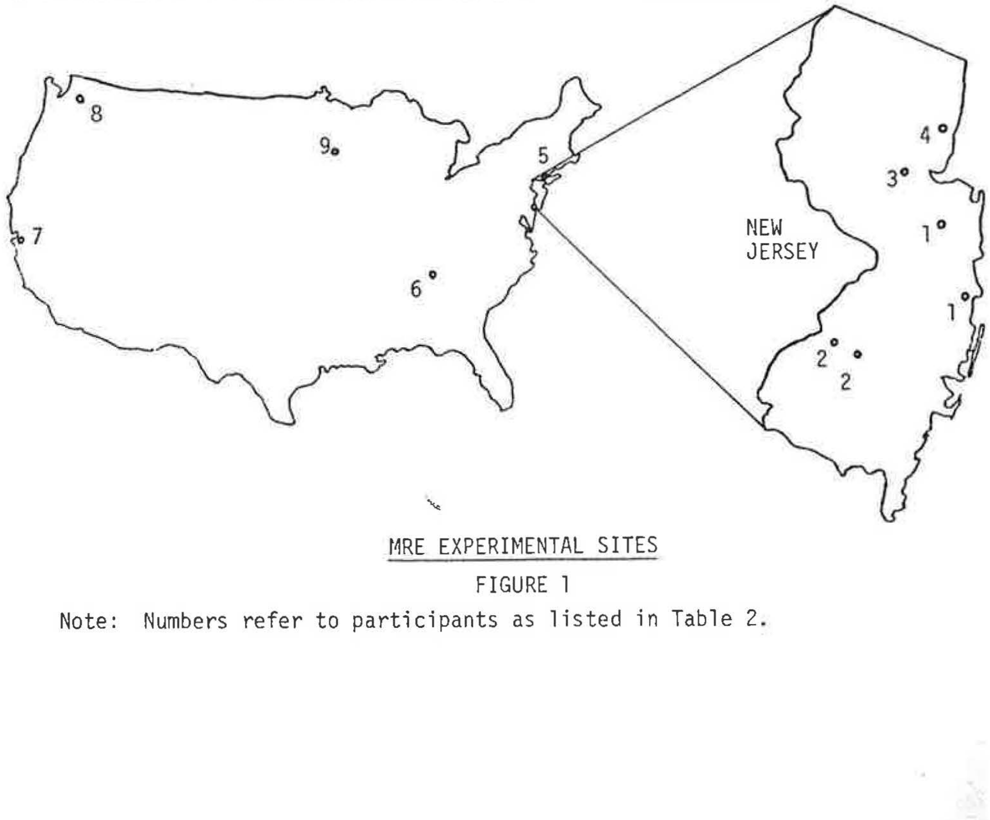
In order to field test the House Doctor concept and determine the fuel savings that may be realized in housing of various styles and vintage, the Modular Retrofit Experiment (MRE) was designed in 1979 [7]. The experiment was carried out in cooperation with a number of other organizations several of whom are natural gas utilities in New Jersey (See Table 2 and Fig. 1).

TABLE 2

Participants in the Modular Retrofit Experiment

			No. of Houses in Experiment
1.	New Jersey Natural Gas Company	Utility	36
2.	South Jersey Gas Company	"	36
3.	Elizabethtown Gas Company	"	18
4.	Public Service Electric and Gas	"	18
5.	Consolidated Edison Company	"	18
6.	Tennessee Valley Authority	"	18
7.*	Pacific Gas and Electric Company	"	18+
8.*	Bonneville Power Administration	"	18+
9.	Minneapolis City Energy Coordination Office	City Government	18+

* Experiment designed and monitored by the Energy Efficient Buildings Program of the Lawrence Berkeley Laboratory.



MRE EXPERIMENTAL SITES

FIGURE 1

Note: Numbers refer to participants as listed in Table 2.

The experiment was divided into 18-house sets of houses called Modules. Each Module consists of houses of the same style and vintage, often within a single development. Six houses in each Module were randomly assigned as "controls", six houses assigned to a "House Doctor" group, while the remaining six were in a "House Doctor plus Contractor Retrofit" group. The first group received neither a House Doctor visit nor any other retrofit; the second gets a House Doctor visit including an instrumented energy audit and partial retrofit; the third group gets a House Doctor visit followed by more substantial energy conservation retrofits based on the House Doctor's recommendations. All three groups had a gas submeter installed in order to measure gas input to the house and was read weekly during the Winter of 1979-80 and monthly since [7].

In the House Doctor procedure recommended for the Modular Retrofit Experiment, a pair of trained technicians spend a full day in each house. Suggested partial retrofits were shown in Table 1. The House Doctors also examined features of the house as they related to energy use for space and water heating. These observations led to the formuation of conservation measures to be installed by a retrofit contractor in the 6 houses assigned to the "contractor" group. Retrofits were picked from Table 3 on the basis of cost-effectiveness calculations.

Each collaborative group made some changes to the experimental design. In particular, a number of partial and contractor retrofits were not considered. One utility which adhered closer to the suggested procedure than some of the others is New Jersey Natural Gas Company. Their experimental houses made up two Modules -- one a set of small (approx. 80 m^2 floor area) one-story "ranch" houses and the other moderately large (233 m^2) two-story "colonial" houses. Both groups of houses were built around 1970. The main omissions from the partial-retrofit list are items 15, 16, and 17 -- all related to increasing the furnace efficiency. Furthermore, the water heaters were insulated (item 1) with R-7 insulation (0.81 $W\ m^{-2}\ °C^{-1}$) instead of the recommended R-11 (0.52 $W\ m^{-2}\ °C^{-1}$). The House Doctor partial retrofits were completed during February 1980; comparing gas use data for the houses before and after these retrofits led to a preliminary estimate of gas savings averaging 18% for the "House Doctor" group of houses [8]. However, the "control" houses also reduced their gas use by about 8%, so that the net reduction in gas use amounts to 10%. Subsequent data collected during the 1980-81 winter indicates a 10-15% savings [9] and is consistent with the preliminary estimates.

TABLE 3

Contractor Retrofits

(partial list)

1. Attic Insulation
2. Wall insulation (where none is present)
3. Floor or basement wall insulation (including band joist)
4. Storm windows and other window/door treatment
5. Weatherstripping and caulking (including basement and attic doors).
6. Duct insulation in unconditioned spaces
7. Fireplace damper repair

Two observations deserve emphasis. First, natural gas was used for space heating, water heating, and for other uses, but the partial retrofits primarily address space heating and, to a lesser extent, water heating energy use. Although the data does not permit an accurate estimation of space heating savings separately we expect it to be a larger percentage than the savings of total gas use. Second, furnace adjustment was not done by these utilities and could add to energy savings in many cases. Another participant in the MRE, Consolidated Edison, included (gas) furnace tuneups in their list of partial retrofits. Six of the twelve houses tested had a steady state efficiency below 75% initially and were adjusted. A 9.2% reduction in fuel use may be inferred from their efficiency improvement data [10]. The sample size is too small to make any wide ranging projections, but the savings potential from a furnace tuneup could be large and should be considered for the House Doctor visit. Since it is quickly done, a furnace tuneup can prove to be one of the most cost-effective retrofits.

Consolidated Edison's diagnosis of 12 furnaces also revealed high levels of carbon monoxide in the stack gases in a few houses. They corrected the problems during the same visit. In addition they found one defective switch and a couple of improper flue installations that were hazardous. The ability to identify and avert hazardous operating conditions is a side benefit of greater significance than the energy savings.

Following the House Doctor visits, additional conservation measures were installed in 12 houses in the New Jersey Natural Gas part of the Modular Retrofit Experiment. These "contractor" retrofits consisted of additional attic insulation and insulation on the wall of the crawlspace or basement, including band-joist insulation. These houses already had wall insulation and storm windows. In addition, crawlspace vents were closed and attic venting area increased to reduce air infiltration and moisture problems respectively.

Total natural gas savings based on 1980-81 data averaged 23% [9]. Additional cost-effective retrofits exist but were not considered. These include furnace and water heater retrofits such as flue dampers, and insulating window shutters or shades. These retrofits were not considered because contractors who could do them at a reasonable cost could not be identified. This is a characteristic feature of the energy conservation industry. A number of measures that are cost-effective at present energy prices are not widely available.

Improved Procedures and Commercialization

The House Doctor procedure used during the Modular Retrofit Experiment had a number of drawbacks which became apparent. The calculation of cost-effectiveness of various measures was simplistic. A microcomputer-based computer program, such as the one being developed by Lawrence Berkeley Laboratory, would permit more accurate calculations to be made easily. One especially important component -- the estimation of air infiltration from house pressurization data -- is being addressed by Grimsrud [11] and others [12,13,14].

Diagnostic equipment used in the House Doctor procedure should be extended to include the side effects of conservation -- moisture problems, and air quality in particular.

A sling psychrometer, already a part of the House Doctor kit, may be used to identify humid houses. Frequently, these are houses equipped with humidifiers which are incorrectly set. A simple adjustment may solve the problem. Condensation on the underside of roofs is common enough to warrant the use of a moisture-in-wood probe to rapidly diagnose condensation problems. Solutions include controlling moisture source in attics and increasing the ventilation.

Indoor air pollutants are a concern in excessively tight houses. Such houses are rare and pollutant monitoring is expensive so that it is impractical to instrument each house. Where problems are suspected, however, passive monitors may be left in the house to be mailed later for analysis. With the help of Lawrence Berkeley Laboratory, we have monitored both nitrogen dioxide and radon in a number of houses. As these and other pollutants are better understood, optimal strategies based on source control and/or ventilation will be identified. Pollutant-buildup due to furnace operation may be identified using a carbon monoxide sensor as well as from measurement of the draft in the flue.

The partial retrofits carried out during a House Doctor visit save some energy, but significant savings will only be realized if the homeowner implements the other recommended conservation measures. To some extent the House Doctor procedure itself may be modified to encourage homeowners to save more energy. The encouragement may lead both to the increased installation of conservation measures and to behavioral modifications which save energy e.g. the use of setback thermostats. Princeton University is currently carrying out an experiment to determine whether "empathic" House Doctor visits lead to significantly greater energy savings relative to "purely mechanistic" House Doctor visits [15].

However even the most empathic House Doctors cannot remove various institutional barriers. The homeowner may not know of reliable contractors to install the retrofit measures, may not be able to judge the quality of the installation, or have access to financing [16].

One way to overcome the barriers to conservation is through a one-step home energy management (HEM-ONE) service. The first step in the HEM-ONE approach is marketing, to bring across the message that the potential for energy conservation is large. The next step is a House Doctor visit. Based on the recommendations following the visit, pre-selected contractors would perform the necessary modifications to the house. The quality of the work performed by the contractor or homeowner would be inspected and financing arranged, if requested. In the HEM-ONE approach, the homeowner need make only two decisions after initially requesting the service: which, if any, of the measures should be done by a contractor, and whether any financing is desired. Such a "one-step" process will remove most of the confusion and obstacles confronting homeowners today.

The HEM-ONE service may be organized in many different ways. For instance, a municipal or other publicly owned utility could offer such a service to its customers. Investor-owned utilities could also benefit from providing such a service [17]. Two electrical utilities in Oregon have been permitted to install conservation measures in residences and include the cost into their ratebase. Although their energy auditing procedure is different from the House Doctor approach, the program includes many of the essential HEM-ONE features. A variant of utility financing for conservation is the Bradley plan, proposed by U.S. Senator Bradley in 1979, where a conservation company retrofits a housing community at no expense to the residents. The company is reimbursed, by the utility serving the area, an amount of money proportional to the quantity of energy saved. The price of this "saved energy" is close to the price that the utility would otherwise have to pay to purchase the energy saved.

Scorekeeping

Irrespective of the form of the conservation delivery system, one item should not be overlooked. Actual retrofit cost and energy savings data should be monitored for a sizeable sample of housing to ensure quality control, and improve the conservation effort. Energy savings may be readily computed from fuel billing and commonly available weather data [18]. The scorekeeping activity should be a responsibility of State governments who could use the data as a basis for certification and licensing of energy auditors and retrofit installers [19].

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