ENERGY AUDITS OF EXISTING RESIDENTIAL BUILDINGS IN-SITU WITH A MICROPROCESSOR

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ABSTRACT

In this paper we describe an energy audit procedure developed for determining economically optimal retrofits for a residential building. This audit is a microprocessor-based, interactive, site and house specific package addressing conservation, solar, and wind measures.

A dynamic model of heating and cooling loads with algorithms to calculate internal heat and solar gains is used to evaluate fuel savings. Special attention is given to the estimation of monthly average air infiltration rates, using a model correlating pressurization results with air infiltration under natural weather conditions. Load calculations are checked against existing utility records of fuel use.

Retrofits optimized for maximum net life-cycle savings can be further adjusted on site in accordance with the homeowner's preference.

Keywords: Energy audit, retrofits, residential energy conservation, simplified energy calculations, degree-days, air infiltration.

INTRODUCTION

Energy conservation is an urgent political issue in the United states. Since the building sector alone accounts for a third of national energy consumption, new building standards that mandate energy-conserving building practices have been promulgated and are being implemented at the state and national level. Yet, the process of replacing the existing housing stock, with its large energy requirements, with energy-efficient structures will be slow; already, almost 80% of the 1990 housing stock has been built.

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- Interaction with the homeowner: Most retrofits will be selected on the basis of economics. However, this selection can be altered at will, if the homeowner indicates any preference or dislike for it.

- Update of retrofits: Retrofits will be chosen from a master list of several hundred retrofits. The information on thermal merit, expected lifetime and cost contained in this list will be updated regularly to reflect innovations in the building sector.

- Economic optimization: Life-cycle cost-benefit analysis will be used to compare the savings of different retrofits. Discount rate, energy cost escalation, and term of the analysis can be specified by the auditor.

- Partial retrofit: Commonly overlooked sources of energy loss will be corrected as part of the audit visit. This partial retrofit alone is expected to reduce energy consumption by 10-25%.

- Energy calculations: The stringent requirements of high calculation speed, small storage space, and ability to compare the most diverse retrofits will be met by new algorithms for heating and cooling loads that combine the simplicity of steady-state methods with the accuracy of dynamic procedures.

- Air infiltration: Special attention will be given to an accurate evaluation of air infiltration rates before and after retrofits. A new model has been developed for this purpose, based on equivalent leakage areas, terrain class description, and weather parameters.

- Use of microcomputers: All of the information from the house being audited will be fed into a portable microcomputer with floppy-disk data storage programmed to yield retrofit packages optimized for maximum life-cycle savings.

AUDIT PROCEDURE

The audit procedure we are developing will be administered by two trained auditors during a four-hour visit. It will be based on actual measurements; draw on a large and regularly updated list of retrofitting options; optimize suggested retrofits on the basis of maximum net life-cycle savings; and directly involve homeowners in the selection of retrofits. The four distinct phases of the audit are described below.

Phase 1: Information Gathering

The homeowner initiates the audit process by calling the local utility company. At the outset, the "medical history" of the house is established: The resident is requested to furnish fuel bills for the previous two years and to indicate the types of fuel used for heating and cooling and for major appliances. If fuel bills are not available, authorization is sought to obtain them direct from the utility company or the fuel oil dealer. Based on this inweather data, we arrive at a score representing the overall thermal efficiency of the building (in kWh/^{o}C-day) for the heating or the cooling season. This score will be an important reference point for making recommendations in the context of the audit and subsequently, for evaluating actual energy savings. In the section on fuel bill analysis, we describe the procedure for determining thermal efficiency in more detail.

The results from all these measurements will be entered in standardized forms consistent with the computer input format.

The following instruments will be used during the audit:

- Blower door for pressurizing the house to find and measure leakage. The cost is \$100 - \$2,000, depending on the sophistication of the assembly.

- Differential pressure gauge for measuring induced pressure difference between inside and outside. Cost: \$50

- Portable infrared scanner to find air leaks under depressurization and faulty or missing wall insulation. Cost: \$7,000.

- Smoke sticks as an alternative to the infrared scanner, where this is too expensive; Cost: \$5

- Portable surface and air temperature probe with digital readout; Cost: \$500.

- Furnace efficiency testing kit for analyzing the temperature and consumption of flue gases. Cost: \$200.

- Portable Watt-hour meters for measuring the electric consumption of major such appliances as a refrigerator or a freezer. Cost: \$100.

- Miscellaneous tools such as hammer, knife, drill, screwdrivers, and caulking guns. Cost: \$30.

Phase 3: Partial Retrofit

Some of the air leakage sites found during pressurization of the house are sealed by the auditor. Priority is given to large leaks that are specific to the house, such as hidden air shafts and concealed holes. The sealing materials are caulking compounds, quick-drying foam, and duct tape. Other sources of energy loss addressed by the partial retrofit are poorly joined or disconnected heating ducts; dirty furnace air filters; air shafts in the living space, attic or basement; missing fireplace dampers; and broken window panes. Open chimneys are temporarily stuffed with packed fiberglass or mineral wool-insulation; later, a more permanent measure will be applied, e.g. chimney covers or glass doors, chosen from the list of suggested retrofits produced by the audit. Broken windows are temporarily sealed with polyvinyl sheets, pending replacement of the broken pane. All other cracks and holes are marked with colored tape to indicate the need for future retrofitting measures and are taken into account in the cost-effectiveness calculation of the audit.

The water heater insulation is upgraded with a fiberglass blanket, unless the name plate indicates that it already complies with a new standard approved by DOE. If the hot water temperature exceeds $60^{\circ}C$ ($140^{\circ}F$), the water heater thermostat is set back to about $50^{\circ}C$ ($120^{\circ}F$). The shower head is replaced with a low-flow model if the measured maximum water flow exceeds 12 liters/min (3 gpm). Similarly, any excessive hot water flowrates in kitchen and bathroom faucets will be reduced, by adjusting valves or by installing flow restrictors.

In forced-air heating systems, the limit temperatures for the furnace blower switch may be reset to insure maximum heat recovery from the furnace heat exchanger.

The energy savings from all these measures combined are estimated at 10-25% (Maulhardt et al., 1979). This partial retrofit alone should make the energy audit worthwhile to the residents, even if none of the suggested, more extensive retrofitting measures are implemented.

temperature above which no heating is required. Here, degree-days are defined as:

$$DD(T_b) = \sum_{i=1}^{30} |(T_b - T_{out,i})|_+ \qquad (1.1)$$

where $T_{out,i}$ is the average outside temperature for day i;
T_b is the base temperature (^oC);
$|\ldots|_+$ indicates that only positive differences are to be counted in the sum.

The base temperature can be calculated from:

$$T_b = T_{in} - \frac{F}{H} \qquad (1.2)$$

where T_{in} is the indoor thermostat setting (^oC);
F is the "free heat" (Kwh/day); and
H is the "overall heat transmission coefficient" (Kwh/^{o}C-day).

Free heat in this context is defined as the sum of all heat gains that are not related to the heating system,i.e., the sum of sensible heat gains from appliances, people, and solar radiation.

The overall heat transmission coefficient expresses the change in daily marginal sensible heating or cooling needs of the house for every degree of colder or warmer outside temperature. It includes heat conduction through the building envelope and air infiltration.

In this audit, we are considering retrofits and thermostat schedules that may substantially alter the base temperature from day to night and from month to month. For these retrofits, the single base temperature in the definition of degree-days is not sufficient. We must use more sophisticated load algorithms that can treat time-varying thermostat settings and envelope resistances and that consider the effects of thermal storage. However, most existing building energy analysis programs are too large to be installed on a microcomputer and take too much calculation time to be practical in a field audit. Given these requirements and constraints we devised the concept of "dynamic degree-days" and "dynamic degree-nights" for a month, a generalization of degree-days with variable base temperature. Dynamic degree-days and degree-nights are functions of four variables whose values may change from month to month:

$$DD = DD(T_{b,d}, T_{b,n}, \Delta T, \tau) \qquad (2.1)$$

$$DN = DN(T_{b,d}, T_{b,n}, \Delta T, \tau) \qquad (2.2)$$

where $T_{b,d}$ is the base temperature during the day (^{o} C);
$T_{b,n}$ is the base temperature during the night (^{o} C);
ΔT is the magnitude of the thermostat set back (^{o} C);
τ is the time constant of the house.

The day and night base temperatures are defined by analogy to the base temperature in eq. (1.2), using separate day and night values of thermostat setting, free heat, and heat transmission coefficient. The time constant of the house is defined as:

$$\tau = \frac{C}{H} \qquad (3)$$

The location efficiency, e_p, denotes how much of the free heat produced by the p-th part or within the p-th space contributes to the overall free heat within the living space. For walls, windows, and doors enclosing the living space, $e_p=1$ by definition. For attached spaces, such as basements, attics, etc., $e_p<1$. The actual value is calculated in the individual program modules.

Devices and people whose waste heat contributes to free heat (e.g. water heaters, refrigerators, lights, and building occupants) are characterized in terms of only two variables:

- Free heat F_d (kWh/day);
- Location p_d (e.g. d-th device located in p-th space).

Again, algorithms specific to the heat source in question are used to calculate the values of the two variables for each device, with and without retrofits.

During optimization of all possible retrofit configurations, the thermal merits of all parts or spaces (with retrofits installed as appropriate) are combined as follows:

$$UA = \sum_{p=1}^{N_p} e_p \, UA_p \qquad (4.1)$$

$$L^f = \sum_{p=1}^{N_p} L_p^f \qquad L^w = \sum_{p=1}^{N_p} L_p^w \qquad L^c = \sum_{p=1}^{N_p} L_p^c \qquad (4.2)$$

$$F = \sum_{p=1}^{N_p} e_p \left(F_p + \sum_{\text{for } p_d=p} F_d\right) \qquad (4.3)$$

Note in the last equation the lumping together of the free heat from a part or space (e.g. the solar energy captured through the windows of an attached space) and the free heat of any appliance located within it (e.g. a water heater in that attached space). This equation is evaluated twenty-four times: for each month, day, and night. The other equations are evaluated only four times: for winter, summer, day, and night.

At this point, the volumetric air infiltration rate, $\dot{V}$, is evaluated on the basis of leakage areas and weather data, as described in the section on air infiltration. Then, the overall heat transmission coefficient of the house is calculated for each configuration of retrofits as follows:

$$H = UA + \rho c_p \dot{V} \qquad (5)$$

where ρc_p is the volumetric heat capacity of air (kWh/k-m^3);
$\dot{V}$ is the volumetric air infiltration rate (m^3/hr).

This formula is evaluated four times, for winter, summer, day, and night. The time constant of the house is estimated separately for winter and summer, by using:

$$\tau = \frac{C}{\hat{H}} \qquad (6)$$

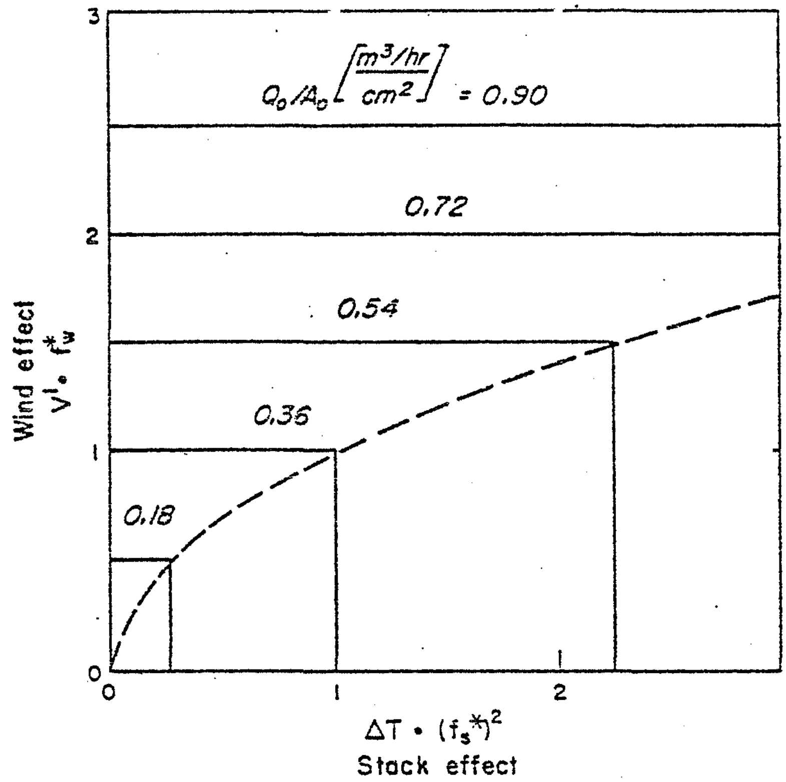

Fig. 1: Predicted infiltration per unit leakage area

R is the fractional ceiling and floor leakage area:

— —— - (7.3)

where A_c, A_f, A_0 are ceiling, floor, and total leakage areas.

The energy savings associated with air-tightening measures are evaluated by estimating the reduction in equivalent leakage area and by indicating whether the reduction occurred in the ceiling, the walls or the floor. The resulting change in overall leakage area and in the ratio R is translated into a change in air infiltration that is reflected in the load algorithm.

<u>Fuel Bill Analysis</u>

For each house, a heating "score," based on a two-year analysis of its fuel consumption, is established to represent the incremental heating energy used for every additional degree of coldness outdoors. This score is expressed in kWh/°C-day. In a house with air conditioning, a similar score is to express incremental cooling energy consumption for every additional degree of outdoor temperature increase.

The score for the heating season is equal to the slope of the line in Fig. 2. This line is a least squares fit to all points in this plot of average natural gas consumption for heating versus average outdoor temperature, for a typical house. Each point represents one monthly fuel bill. In the terminology of the previous sections, it can be shown that the heating score obtained from this line must equal

SUMMARY

We have described a new, computerized audit which, by using measured field data and novel calculation algorithms, attempts to go beyond the simple walk-through audits currently in use in the U.S. Validation of the audit in a group of houses will begin in the autumn of 1980. Training materials, program documentation and instrumentation specifications will be prepared at the same time. In the future, we expect to implement a program of regular updates of the audit and its components.

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