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LOCATING AND ELIMINATING OBSCURE BUT MAJOR ENERGY LOSSES IN RESIDENTIAL HOUSING

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ABSTRACT

Major energy losses in residential buildings can prove very elusive to the energy auditor. As a result, conventional choices of retrofit can easily overlook major problem areas. This paper outlines a number of experimental approaches for determining the energy consumption of a building, with emphasis on air infiltration. The combined use of depressurization of the house and infrared scan permits the location of "bypass" routes through which warm air is leaving the structure. These losses tend to undermine the effectiveness of insulation, as well as to lower comfort in the dwelling. Several types of bypasses are described and evidence for their widespread existence is documented. The impact of retrofitting these and other energy loss sites is also discussed with regard to side effects on the occupants and building structure.

INTRODUCTION

This paper is based on our experiences, and those of our colleagues at Princeton, in (a) studying the energy losses in, and retrofitting, some 30 townhouses at Twin Rivers, N.J.,[1] (b) studying attic heat losses in 17 other houses,[2,3] (c) analyzing the retrofit potential of an old 50-unit apartment complex,[4] (d) studying the performance of 10 houses equipped with heat pumps,[5,6] and (e) analyzing the potential energy savings to be obtained in four detached houses by state-of-the-art retrofits.[7]

Measuring the energy savings obtained from a set of retrofits is often difficult. In Section II, we discuss one way of evaluating retrofit savings, using our Twin Rivers study as an example.

Estimating the magnitude of various energy losses in a house is necessary if the proper retrofits are to be made. Ways of finding the major energy losses are presented in Section B. We have found that significant heat losses from a house during winter take place through unfamiliar paths which we call "bypasses" (Section C).

Bypass heat losses occur when energy is transmitted through routes other than that contemplated in the residential design. Examples include air flow moving through insulation or air recirculating in wall cavities.

Finally, in Section D we note that energy conserving retrofits in a house may have potentially harmful side-effects, which must be considered while planning a retrofit strategy.

A. RETROFIT EVALUATION

One way of determining the effectiveness of a set of retrofits in a house is to take the "energy signature" of the house before and after the retrofits. The data base for this procedure is either detailed measurements or the utility billing data for a number of intervals

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during the heating or cooling season. With these data in hand one can construct a graph as shown in Fig. 1. The slope of this graph, the rate of energy use per degree reduction in outside temperature, is a useful measure.[8,9] As meaningful retrofits are performed this slope becomes less steep. If the internal temperature is reduced, the graph is displaced to the left without change of slope.

The reference temperature is the point at which the graph in Fig. 1 intersects the temperature axis. It is the temperature below which furnace heat input is needed to keep the house at a specified thermostat setting.* This point is determined by the thermostat setting, the average "free" heat obtained from the sun, appliances and occupants, and the slope of the graph. The intercept F of the graph on the vertical axis is a measure of the free heat. Both shifts in slope and reference temperature resulting from retrofits lead to energy savings.

From such "before and after" signatures, we have established the savings resulting from retrofitting more than thirty townhouses at Twin Rivers, N.J. In these retrofits reduced air infiltration was attempted by tightening window and door seals. Attic insulation was upgraded from a nominal R-11 to a nominal R-30[10] and some of the air leakage paths connecting living space and attic were sealed. Subsequent analysis showed that sealing these air leaks was the most important retrofit.[11] Finally, the furnace supply ducts and the electric or gas water heater were both wrapped with R-7 insulation. The net energy savings from this series of retrofits was found to be $\sim$ 25%, with a documented average 35% reduction of air infiltration[12] representing about two-fifths of the savings, and the attic retrofits most of the rest. Payback in energy savings of capital expended was of the order of 3-4 years.[13]

In one home the retrofitting process was taken even further by one of our colleagues.[9] Attention was given to further improvements of windows and doors. Thermal shutters (to R8) were added to some windows, plastic multilayer internal stormers were added to others, and an internal storm door added to the patio door. Air infiltration was further suppressed (from 0.7 to 0.3 per hour) by sealing the band joist in the basement and small openings into the attic. Finally, the basement outer walls (including the band joist) were covered with R-11 insulation. The results of all these changes revealed 68% energy savings in the heating season.**

The house was sold subsequent to the experiments and the new owner was able to achieve comparable energy savings in the following winter. A two-thirds savings in a reasonably insulated, recent townhouse suggests that the potential savings in older housing would be even higher.

If certain changes had been made to that house at the time of construction (e.g. sealing the internal cavities of the cinder block party walls at the attic floor level), an additional 7% energy could have been saved leading to a potential 75% savings for new house construction.

In order to plan a suitable retrofit package, one needs to know what the major energy losses are. These are not always obvious, as will be shown in Section C; on-site inspection and measurement may be necessary. Techniques for locating the major components of energy use are discussed in the following section.

B. DIFFERENT APPROACHES TO FINDING IMPORTANT ENERGY LOSSES

In addition to the traditional note pad and measuring tape, whereby one carefully records the equipment and appliances operating in the residence and measures areas of windows, ceilings, floors, etc., an array of energy loss detection -- a "house doctor" kit -- is suggested.

Air Leakage. Determination of the air infiltration rate and the location of leakage sites is often the most important component of analyzing house energy losses.

Blower Door. In one of the most thorough techniques, an infrared scanner and a "blower-door" are used. In this method a door, with a high flow blower mounted in it, is attached to the

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*In central New Jersey houses we have seen the reference temperatures vary from a high of 68°F to a low of 52°F. Such variations imply a drastically different duration of heating season for the houses in question.

**A 50% saving is associated with the change in slope of the "energy signature," while the remainder results from a reduction of the reference temperature from 62° to 52°F.

frame of an outside door of the house.[14] (See Fig. 2) The blower is first set to pressurize the house slightly.* A hand-held infrared scanner is then used to detect warm spots on the external surface of the building and particularly the attic floor. These areas correspond to sites where warm air is leaking to the outside or into the attic. Next the reversible, variable speed motor on the blower door is used to depressurize the house.** Entry points for cold air on the interior surfaces of the house may then be observed by an infrared scan.[15,16] A test including both pressurization and depressurization helps to identify air leakage paths that do not pass directly through an outside wall. For instance, air leaking through an electrical outlet may travel along an external wall before passing through a suitable opening on the outer surface. Other examples include bypass heat losses through attics, discussed in Section C. Our experience shows that these unusual air leakage routes often dominate the overall leakiness of a building. Under naturally occurring air infiltration, cold air enters the building in a variety of locations and warm air often leaves elsewhere so that an infrared scan alone (on both inner and outer surfaces) reveals only some of the sites that show up in the complete pressurization/depressurization-infrared scan. Without an infrared scanner, the blower door alone may be used to detect some leakage sites but the procedure may be cumbersome, especially for leakage sites that are not easily accessible. In addition to finding leaks, the blower door may be used to generate a pressure vs. leakage rate curve for the house. Such measurements may lead to a leakiness standard for houses.[14,17]

Tracer Gas. Another method of rating air infiltration is by measuring the decay in concentration of a tracer gas, caused by the exchange of house air with the outside. Although automated air infiltration equipment has been developed,[18,19] its use is more appropriate for research studies than for residential energy audit. One variation of the tracer gas approach is to take bag samples of air following the injection and mixing of tracer gas in the house.[18] This approach has even allowed measurements to be made across the country.[20,21] Because the sample bags are expensive (>$10/bag) and require a hand pump for filling, an even simpler, less expensive version has evolved. A bottle of tracer gas and six plastic sample bottles are provided the homeowner together with instructions. The house is seeded with the sulphur hexafluoride tracer gas and then gas samples are taken every half hour by simply squeezing the bottles, which are later analyzed in the lab. This technique yields inexpensive spot checks of air infiltration and can be used to compare the air infiltration of a house before and after a set of retrofits. Wind and temperature data at the time of the test together with a reliable air infiltration model are necessary if interpretation of air infiltration over a wide range of weather conditions is to be made.

A rule-of-thumb in energy loss distribution that was very evident in the Twin Rivers studies[13,22] (now the research is concentrating on older housing) is that roughly 1/3 of the energy losses are traceable to air infiltration; 1/3 to conduction through walls, ceilings and floors (providing all have insulation initially) and 1/3 is lost through windows. (To make major savings each segment must be analyzed for retrofit potential.) In dealing with older homes that lack any insulation,[23] this three-way balance can be greatly altered and insulation probably becomes first priority, with the precautions as stated in Section D.

Conduction. For the analysis of conduction losses the same infrared scan that revealed the leakage sites will also indicate non-uniformities and/or the absence of insulation in walls, ceilings, and floors. For more quantitative information, surface temperature measurements have been found to be useful. Heat loss through a wall may be estimated from measurements of the air and wall surface temperatures. Using the convective-radiative film coefficient for the inside air layer[24] (= 1.47 BTU/ft^2/h°F or 8.35 W/m^2/°C), the heat loss per unit area, Q/A is given by

$$\frac{Q}{A} = 1.47\ (T_R - T_S) = U\ (T_S - T_O) \qquad (1)$$

where T_R, T_S, T_O are the temperatures of the room air, the wall surface and outside (°F) The U-value of the wall (including the outside film coefficient) can then be determined from knowledge of the inside-outside temperature difference. If these measurements are to reveal details of

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*Interior-exterior pressure difference of ≃ 25 Pa is adequate.

**If the house is equipped with a gas or oil furnace, it must be turned off to avoid flow reversal in the flue and injection of combustion fumes into the house.

the R value of the structure, then the measurements must be made on walls or ceilings that have not recently been exposed to the sun, heating ducts, etc. Solar effects should be avoided by choosing a north wall, a west wall in the morning, and so on.

Surface temperature measurements may also be used to estimate window conduction losses.

Appliances and Heating/Cooling Equipment. Evaluation of appliances and space conditioning equipment is another critical component in a house energy audit. Using flue-gas analysis equipment one can quickly determine the steady-state efficiency of oil or gas-fired furnaces. Often, retuning the burner can result in instant improvement at minimal cost (e.g. a recent adjustment of an oil burner in one test home increased its efficiency from 72% to 81% -- equivalent to a 13% fuel savings for less than an hour's effort). Older oil burners often have no potential to exceed a steady-state efficiency of 70%, whereas newer designs can operate above 80%.[22]*

In 10 heat pump homes which were studied, the coefficient of performance averaged 1.5 instead of its nominal value of 2.0. Here performance degradation was traced to the excessive use of defrost and auxiliary heat, and problems associated with initial installation of ducting, and controls.[5,6]

Water heating and refrigeration are two other items that should not be ignored. In many areas of the country water heating expense exceeds that for space heating. The surface temperature probe again proves helpful in estimating both storage and distribution losses.

In the case of refrigerator performance evaluation, we have developed a simple wattmeter that records the energy used over a period sufficiently long to adequately take into account compressor, defrost and fan cycles. Using this instrument one can readily spot refrigerators and freezers that are consuming as much as double or more the electrical energy of other comparably sized units.

C. UNFAMILIAR "BYPASS" HEAT LOSSES

In the course of our research, we have documented and quantified anomalous winter heat losses which can account for a significant fraction of house heating energy use.

We define bypass heat loss to be the result of heat transfer that bypasses the conductive or conductive-radiative heat transfer between two regions of the house. Defined in this manner, heat transfer between the interior and exterior of the building by air infiltration constitutes a bypass.

Our experiments in occupied houses in Twin Rivers, N.J. and elsewhere have revealed two kinds of bypasses. In the first kind, heat is transferred by air movement. This air flow may be recirculatory in nature and does not always contribute to the net exchange of living space air with the outside (i.e., does not constitute air infiltration). The second type of bypass heat loss involves walls of hollow masonry materials such as cinder block, where air flow within the cavities permits vertical heat transfers between two regions connected by the wall.

Attic Bypasses at Twin Rivers. Our search for bypass heat loss paths dates back to 1976 when the attic air temperatures measured in a number of instrumented Twin Rivers townhouses were observed to be substantially greater than predicted by a simple theoretical model. In that model, which we refer to as the two-resistance model,[11] the living space, attic and outside were each characterized by a single temperature T_H, T_A and T_O, respectively. The heat transfer rate between living space and attic, and between attic and outside are equal, and each is proportional to the appropriate temperature difference. The attic heat balance may be expressed as:

$$W_{HA} (T_H - T_A) = W_{AO} (T_A - T_O) \qquad \text{(IV.1)}$$

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*A change from 70% to 85%, a 15% improvement implies a 21% energy savings. Since some newer designs tend to have less stack losses between firing cycles, the annual savings may be even larger.

The heat fluxes are related to the temperature differences by the constants of proportionality, W_{HA} and W_{AO}, referred to as conductances for convenience. In a simple two-resistance model W_{HA} is made up of conduction through the attic floor, while both conduction through the roof as well as ventilation of the attic (with outside air) constitute W_{AO}. This model predicts that

$$\lambda \equiv \frac{T_H - T_A}{T_A - T_O} = \frac{W_{AO}}{W_{HA}} \equiv \lambda_t \qquad \text{(IV.2)}$$

The ratio, λ_t, is approximately constant provided the contribution of attic ventilation to W_{AO} is small or steady. Based on handbook conductivities[24] and ventilation characteristics of Twin Rivers attics,[25] a value of

$$\lambda_t = \frac{W_{AO}}{W_{HA}} = 8.9$$

was obtained. Based on measured temperatures for a sample of Twin Rivers townhouses,

$$\lambda \equiv \frac{T_H - T_A}{T_A - T_O}$$

was observed to have an average value of 1.0. This discrepancy, $\lambda = 1.0 \neq 8.9 = \lambda_t$, refutes the model expressed in Equation (IV.2). In physical terms, for any given inside and outside temperatures, the measured attic temperatures were much larger than those predicted by Eq. (IV.2).

Possible causes for this discrepancy were investigated and it was shown that the attics were too warm largely because of heat transfer paths other than conduction through the attic floor. During this process, three such bypass heat loss paths were uncovered. In each case, a suspected heat loss path was eliminated by a suitable retrofit in one or more townhouses. The change in the extent of the discrepancy when temperature data were substituted in Eq. (IV.2) before and after the retrofit determined whether the suspected heat loss path was indeed significant. Such data can also be used to quantify the equivalent conductance of the bypass.[11,26] Thus, temperature measurements in semi-exterior spaces may serve as a measure of the heat flow through the space. The three bypasses are outlined below.

Furnace Shaft Bypass. A metallic flue from the furnace, located in the basement, passes through the Twin Rivers attic. This is surrounded by a rectangular shaft, open at both ends, which connects basement with attic. Warm basement air may pass through this shaft into the attic. (In a similar fashion warm air can travel upward in the opening that surrounds plumbing vent pipes.)

Party Wall Gap Bypass. Twin Rivers townhouses are of wood frame construction and separated from each other by cinder block fire walls that extend from basement to attic. There is a space between the gypsum board side walls and the party walls which also connects the basement and attic and permits air flow between these spaces.

Both of the above bypasses are of the FIRST KIND - i.e., they involve air flow into and out of the attic. They were largely eliminated by stuffing the openings at the attic floor level with compressed fiberglass during a series of retrofits. (See Section II and Ref. 10).

Party Wall Convection Bypass. This bypass is of the SECOND KIND, where air movement within the cavities of the cinder block party wall considerably enhances heat transfer into the attic from the living space and the basement. This bypass cannot be readily eliminated once a building is in place. To prove its existence, both party walls in a Twin Rivers attic were covered over with R-11 fiberglass insulation batts. The effect on the attic temperature proved the existence of this bypass path. However, since each party wall is exposed to two different attics, adding insulation to one side does not eliminate this heat loss. Later, in a pair of townhouses, a retrofit procedure for eliminating this bypass heat loss path was conducted. In that experiment, holes were drilled into the block cavities of the party wall at the attic floor level and cellulose insulation was blown in as a plug to prevent warm air in the cavities from reaching the attic.[2] This retrofit was able to eliminate only about 60% of the party wall conductance. One reason for this is that all the cinder block cavities are not equally accessible, especially those near the eaves. While the cost-effectiveness of such a retrofit may be questionable, it should be emphasized that elimination of this bypass in a new house is trivial, e.g. by laying a course of solid masonry blocks in the party walls at the attic floor level.

The discovery of these bypasses led to the formulation of a three-zone model for heat transfer connecting basement, attic and living space.[27] The relative contribution of the basement and living space to the party wall convection bypass is shown in Fig. 3.

The practical consequence of these bypasses is that the Twin Rivers attic, as built, loses about 5 times as much heat as it would in the absence of these paths. The attic heat loss then accounts for about 35% of the heat loss for the entire house. The two easier retrofits alone would lower the fuel consumption of a Twin Rivers townhouse by 20%.[27]

Attic Bypasses in Other Houses. The importance of attic bypasses on house heat loss at Twin Rivers led us to wonder if such paths were present in other housing styles as well. Features found in Twin Rivers, such as party walls, are not common in single family housing (although it is the norm in row housing). Nor do metallic furnace flues surrounded by open shafts run through all attics (but masonry chimneys usually have openings around them). A survey of 15 houses of various styles (all with insulated attics) was carried out during the winter of 1977-78. Most of these houses did not have the bypasses identified in Twin Rivers attics. A simpler experimental procedure, using only three maximum-minimum thermometers,[2] showed that these attics too were invariably warmer than predicted by the model in Eq. (IV.2). The attics in our sample lost between 3 and 7.5 times as much heat as their insulation level would predict.*

The next step was to identify and eliminate these bypasses.

One of the houses surveyed -- a split level colonial -- had a warm attic despite the lack of all Twin Rivers-type bypasses. A detailed study showed that the two bathtubs in the floor below the attic had dropped ceilings. Interior wall cavities communicated with the space above the dropped ceilings. This space was covered over by insulation batts and could not be seen from the attic. When the wall cavities were sealed off from the space above the dropped ceilings, the attic temperature showed much better agreement with the two-resistance model.[2,3] The estimated seasonal savings from this retrofit in this gas heated New Jersey house was $69, assuming a gas price of $.40 per 100 cu. ft. The dropped ceiling bypass (or similar condition above the second floor stairs ceiling) has been identified in other houses as well. This relatively easy retrofit (often a plastic vapor barrier can provide the seal), with large potential savings, is very cost-effective.

Other specific bypasses remain to be discovered. Ultimately it will be possible to create a catalog of such paths so that retrofit need not be preceded by measurement.

Basement Bypasses. In the traditional model of basement heat loss, walls above grade (without the benefit of any ground insulation) have a large conductance. Walls below grade have rapidly decreasing conductance with increasing depth.[29] However, in light of our experience with cinder block bypasses to attics (Fig. 3), one might expect convection patterns within the cavity walls to permit walls below grade to lose heat at a higher rate. A basement wall heat loss model including such a convective path is shown schematically in Fig. 4. Preliminary measurements of heat flux and surface temperature distribution in hollow and solid basement walls confirm this hypothesis. These results indicate that basement walls will lose much more heat than suggested by the traditional models of two-dimensional conduction, developed for solid walls.[30,31]

Thermal Bridges. We have defined bypass heat losses to be those other than conduction or conduction-radiation. However, in many calculations of heat loss, uninsulated portions are ignored and the insulation is assumed to exist over the entire surface in question. The most prominent uninsulated part of a wall or attic is the wood frame. However, since wood is a relatively good insulator in its own right, the omission of the wood frame from heat transfer calculations does not usually result in a major underestimate of the heat loss.

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*Interestingly enough, we have found records of unexplained warm attics reported in 1941.[28] Using their data, we calculate an attic heat loss twice the predicted value.[2]

However, our experience with attics shows that attic doors and trap doors are often uninsulated and may add significantly to the heat loss through the attic. This is especially true in the context of high insulation levels recommended for attics today.[32] For instance, if the uninsulated portion of the attic floor (say a door) represents 2% of the total area, and the U-value for insulated and uninsulated portions are 0.03 and 0.5 Btu/ft^2/h/°F respectively, then even a one-dimensional heat transfer calculation indicates that the uninsulated door adds about 30% to the overall U-value of the attic floor. In reality, adjacent regions of dissimilar insulating values will lead to departures from one-dimensional heat transfer, and an even higher heat flux than predicted by the 1-D model may result.

Implications of Bypass Paths for Energy Saving Retrofits. Our experiments indicate that there is a large energy savings potential from cost effective retrofits. We estimate that the winter heat loss through attic bypasses in one and two story single family wood frame houses alone accounts for about 20% of all residential space heating energy use (and 2% of all the energy use) in the U.S.[2]

We have also shown that because attic bypasses short-circuit installed insulation, full benefits from the addition of insulation are not realized if bypasses are left unchanged.[2,3] Elimination of attic bypasses should therefore precede or accompany the addition of attic insulation.

Our initial search for bypasses involved a trial-and-error approach: a potential bypass path was retrofitted to see if it had any effect. Since then the method using blower doors and infrared scans has been utilized as discussed in Section B and illustrated in Fig. 5.

The principal lesson learned from bypasses and thermal bridges may be summarized as follows. Once the major heat leaks have been treated and reduced, the originally smaller leaks become more important. For instance, conduction from living space accounts for most of the heat input to an uninsulated attic, and bypasses are small in comparison. However, if attic heat loss is reduced by adding more and more insulation then a point is reached when conduction through the attic floor is no longer the dominant heat input. In fact, as our survey indicates, even attics with only R-11 insulation lose about 3 to 5 times as much heat as can be accounted for by conduction through the insulation alone.[3] Nowadays, much higher insulation levels in attics are recommended.[32] These standards are based on calculations where only living space ceiling conduction constitutes heat input to the attic. In the flood of guidelines, standards, and recommendations based on theoretical models, very few attempts at validation are apparent. Our experience suggests that extrapolating models (without prior validation) to high insulation levels may generate misleading results.

D. SIDE-EFFECTS FROM RETROFITS

In addition to the intended energy savings, there are other effects which may result from retrofits -- some beneficial, some potentially harmful. For instance, room temperatures may equalize after a retrofit leading to more comfort.[33] On the other hand, insulation packed improperly around a light fixture might lead to fire; or a retrofit-induced moisture problem might eat up fuel savings in repair bills.

It is important to identify potentially harmful side-effects as early as possible both to protect the health, safety, and investment of the public as well as to guard against a retrofit backlash. (A few horror stories about unexplained side-effects could lead to millions of home owners needlessly foregoing beneficial retrofits.)

It is also important to obtain a full understanding of side-effect phenomena, especially moisture flow, so that conservative precautions do not foreclose energy-saving retrofits unnecessarily.

There are presently three potential side-effects which are receiving major attention: increased risk of fires, indoor air pollution, and moisture problems.

Fire Safety. Complaints have been recorded in connection with flammable foam and in connection with the placement of insulation around light fixtures. Building codes now require protective coverings from flammable foam insulation and, obviously, care must be taken in insulating around light fixtures and other heat sources. The present safety standards associated with recessed ceiling lighting[34,35] may lead to attic bypasses unless specific procedures are worked out that ensure safety while eliminating the bypass.

In the process of retrofitting, electrical wires may be sandwiched between thermal insulation, and the insulation may fill electrical outlets. Temperature buildup associated with tests on thermally insulated electrical wiring, as opposed to an actual history of fires, have produced concern. Until all the required data can be collected, one must proceed cautiously in this area.

However, insulation retrofits can also help to prevent fires. By blocking air flow, particularly in balloon-frame walls without fire stops, the rate of fire spread should be reduced. In any case, it is important for those of us in the retrofit field to keep track of fire statistics.

Indoor Air Pollution. Indoor air pollution has recently received quantitative attention.[36-39] When a house is tightened up to save energy, forced ventilation may be necessary in high source areas of moisture and pollution such as kitchens and bathrooms. This will enable us to retain acceptable air quality while reducing energy loss from excessive air infiltration.

Concern over air quality, as well as recognition of the desirability of fresh air from a comfort point of view, suggests that heat (and moisture) recuperation techniques be given increased attention. Such techniques provide the desired ventilation with minimum energy loss, since incoming air can be conditioned with outgoing air. It has already been demonstrated that it is possible to tighten up the shell of the house to 0.1 air exchanges/hr. and then control ventilation through a heat and/or moisture exchanger.[40,41]

Moisture Problems. Moisture problems are already detracting from the positive aspects of retrofitting. Concern over possible condensation has led, in some cases, to abandonment of wall insulation as a retrofit.* Since moisture flow is largely associated with air flow (diffusion through walls and ceilings is usually small),[42] it fits naturally into Princeton's air infiltration studies. From a theoretical point of view, it is not yet possible to give definite answers as to when to forego insulation because of moisture. The key variables have not yet been identified. (This, perhaps, explains why there is such a controversy over this subject.) However, some general principles are applicable in indicating where to look for problems first.

In a house with a furnace, outside air must be drawn into the furnace room of the house to make up for air leaving through the flue. Stack effects based upon the inside-outside temperature difference tend to produce exfiltration at the top of the house, infiltration at the bottom. Since it is outgoing warm, moist air which might condense, it follows that the first place to look for problems is at the top of walls, rather than at the bottom, and on the second story rather than the first. Regions of high moisture sources, such as bathrooms, kitchens, etc. are the other obvious places to look.

Because of the house-specific nature of air flow, and occupant-specific nature of moisture sources, one should not expect to find moisture problems, if any, to the same extent in all houses. This makes the situation especially frustrating to energy-minded individuals, who see the use of wall insulation being threatened in millions of homes in order to prevent problems in a few. Perhaps some kind of retrofit insurance would be in order here.

The problem with walls, as opposed to attics, is that there is no current consensus about the need to ventilate them. When insulation is added to existing walls, the temperature of the outer sheathing will drop, increasing the potential for condensation. However, the addition of insulation might also stop the very air flow that is the source of moisture in the first place.** Furthermore, the sensible heat content of the air flow reaching the sheathing will warm it and thus deter condensation. Thus, theoretical arguments cut both ways. Actual inspection of more walls should help resolve which effects are dominant.

The situation in attics differs from walls in that there is a firm consensus about the need for ventilation. Also, it is usually easy to inspect an attic at a later date for signs of moisture problems. The homeowner can be instructed to make yearly inspections.

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*The large TVA home retrofit project did not include wall insulation.

** Moisture transport by diffusion through the wall may be dealt with, when necessary, by painting the interior wall surface with a low-permeance paint.

Our work on attic bypasses confirms that the amount of moisture entering an attic may be quite large, much larger than permeable flow through the ceiling alone could accomplish.* There are two types of bypasses, those involving flow of living space air into the attic and those involving recirculating air. The former will be associated with the moisture problem. Blocking such bypasses is the first step to reduce the amount of moisture entering attics, so that bypass reduction is actually safer in the moisture context than adding insulation. In any case, any attic retrofit which lowers the attic temperature could conceivably introduce a new moisture problem, so it is important to check for proper ventilation.

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*This large moisture influx has implicitly been assumed by moisture experts for many years, and has been the basis of large ventilation requirements for attics.

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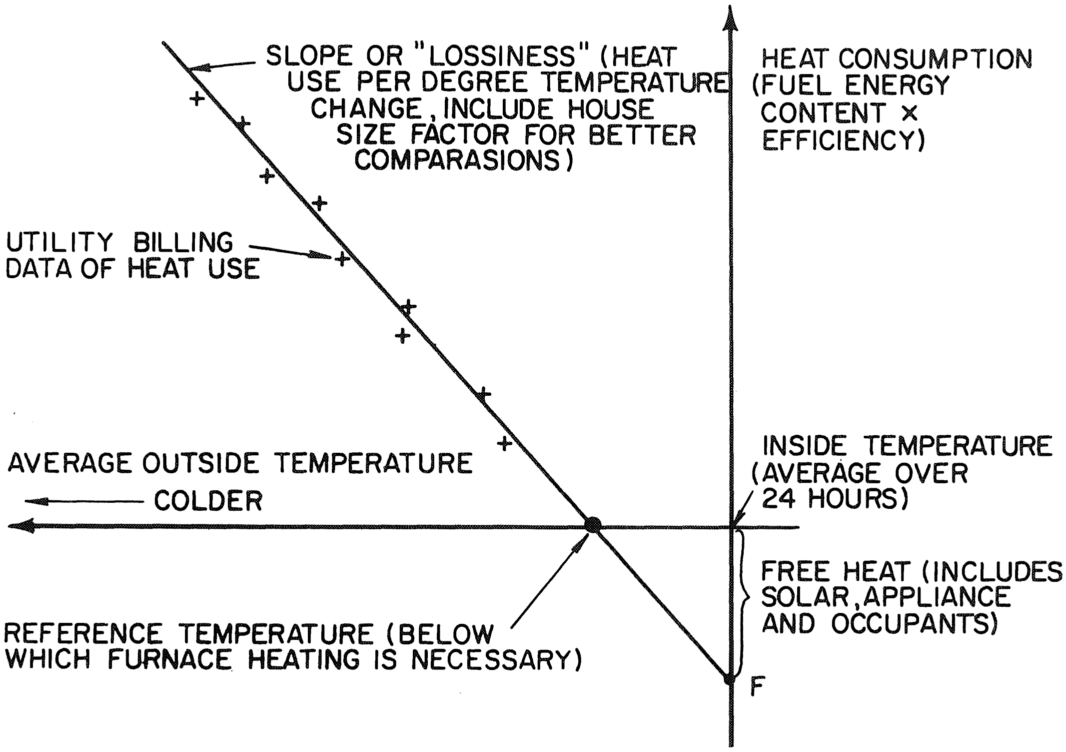

Fig. 1 "Energy Signature" of the house, where heat consumption is compared to prevailing outside temperature

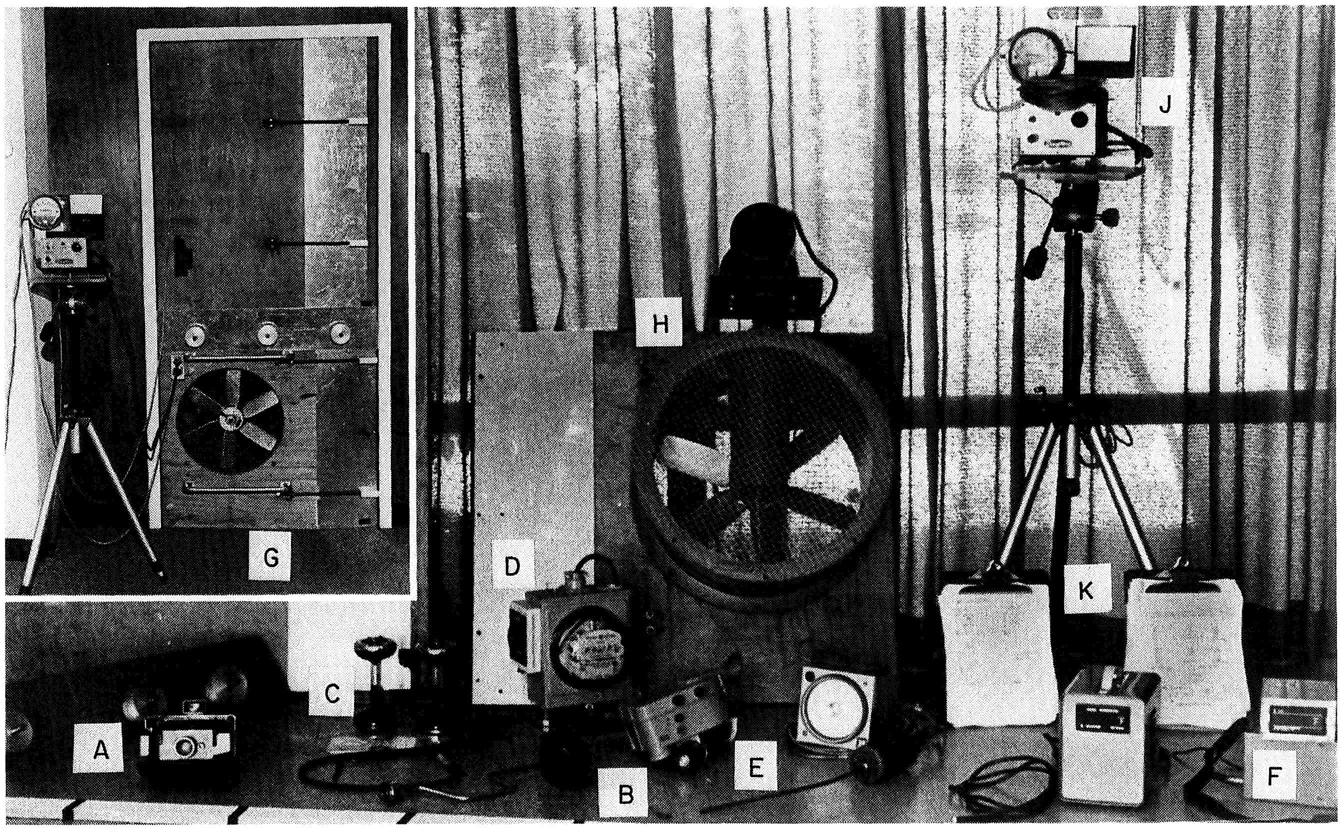

Fig. 2 The energy auditing equipment includes: camera A; measuring stick to appear in outer wall photographs B; furnace efficiency measuring devices C; appliance energy consumption meter D; portable infrared scanning equipment E; temperature measurement probes (AC and battery powered) F; (insert) the blower door assembled in a doorway where principle components include G; the lower door (18-in.) blower powered by a variable speed DC motor H; and blower door control panel with differential pressure and rpm readout J. Clipboards, K, are used to record on-site data.

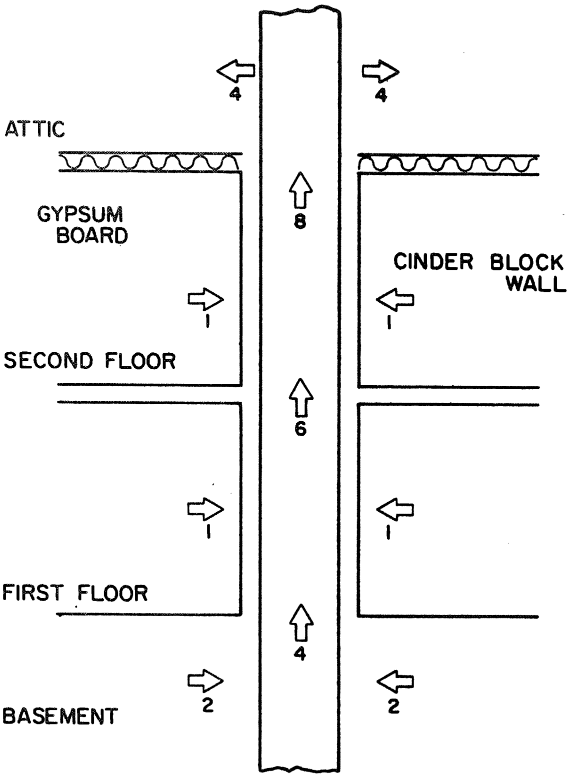

Fig. 3 Heat transfer by convection within hollow party walls between adjacent Twin Rivers townhouses

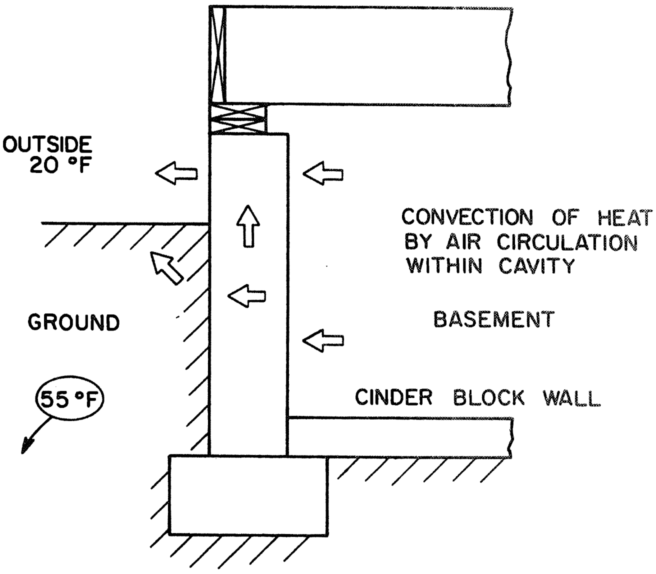

Fig. 4 Wall cavity convection and basement heat loss

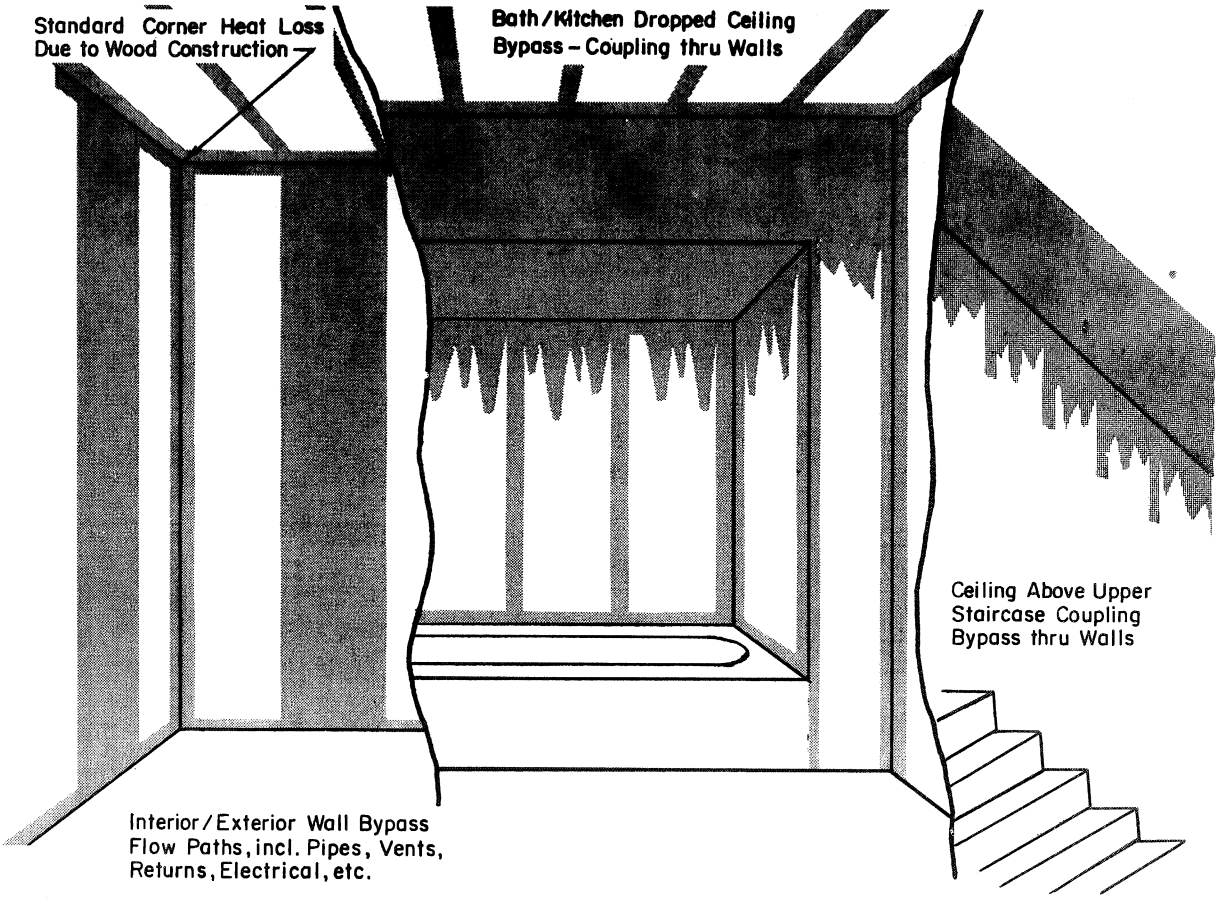

Fig. 5 Bypass routes as uncovered using infrared scanning and depressurization of the building (schematic of thermal graduations as seen with portable 1 R scanner)