THE EFFECT OF THERMAL ENVELOPE UPGRADING IN RESIDENTIAL DWELLINGS

W.R. Jones, P.E.
ASHRAE Member

ABSTRACT

Sixteen houses were thermally upgraded and their energy consumptions and power demands monitored for one year before and after the retrofit. The work was inspected for problems; costs were also noted. Airtightness fan tests were performed before and after to show the reductions in natural air change rates. The energy data were analyzed to take out the effect of weather and other random usage variations. Predictions of the upgrading effect were calculated using the HOTCAN computer program. Consumption savings averaged 6% and demand savings 13%, both with much individual variation. HOTCAN overpredicted consumption and demand both in absolute terms and as percentage reductions. The fan tests did not give reliable indications of the effects of airsealing. A few minor problems were seen; lowered natural air change rates required occupant accommodation in a few cases and exhaust fans in one house. There was a societal net benefit in most cases.

INTRODUCTION

A concerted effort is being made to reduce the space heating requirement of new housing by increasing insulation levels and paying greater attention to the reduction of air infiltration; however, the global savings resulting from this course of action remain limited since the majority of the housing stock that will exist in the foreseeable future has already been built. If a substantial reduction in residential energy use is to be achieved, upgrading the thermal envelopes of existing houses must be undertaken. There is very little information available on the energy savings and especially on the reductions in heating demand based on direct field measurements of various upgrading techniques (Oda 1982; Jones 1984).

To accurately determine the effect of thermal envelope upgrading, a history of energy use has to be established prior to upgrading and maintained following upgrading. Since this requires considerable time and effort, energy use comparisons are generally based on calculated values. However, an extensive history of energy use has been established in a group of 49 houses used for a study of dual-energy heating systems (Hicks et al. 1984). Energy use and outdoor temperatures were monitored for two heating seasons (1980/81 and 1981/82), with data collected on a 15-minute interval basis. This has allowed determination of design heat losses and energy consumptions. This project was initiated as a continuation of the dual-energy field trial in 16 houses, in which various upgrading measures were done during the fall of 1982.

UPGRADING WORK

House Choice, Upgrading Categories and Costs

The 49 dual-energy field trial houses were screened for:
-- homeowner willingness to have upgrading work done and monitored and to pay part of the cost (26 houses)
-- acceptable previous heating-demand data
-- no significant auxiliary heating supply
-- no significant lifestyle changes contemplated
-- scope for thermal envelope upgrading.

W.R. Jones is a Utilization Engineer, Electrical Research Department, Ontario Hydro, Toronto, ON.

The 16 remaining houses were divided into the following categories (no insulating without airsealing was attempted because of the potential for causing condensation problems within the wall cavity or attic):

1. Homeowner Airseal: three houses (DIY Seal)[1]
   The homeowner performed basic airsealing measures, such as weatherstripping and caulking, on the advice of a qualified energy auditor. The homeowner was supplied with all necessary materials.

2. Contractor Airseal: four houses (Seal)[2]
   Local airsealing contractors were employed to reduce the rate of air leakage through the extensive use of caulking and weatherstripping and the application of insulating foam behind baseboards, along sill plates, around plumbing stacks, etc.

3. Contractor Airseal and Basement Wall Insulation: four houses (Seal and Basement)
   Local contractors were employed to perform the measures described in category b) and to insulate the basement walls.

4. Contractor Basement Wall Insulation: four houses (Basement)
   Local contractors were employed to insulate the basement walls (and airseal in the same area, although not throughout the rest of the house). The work in house 71-07 was homeowner performed, although with contractor quality (DIY Basement).

5. Contractor Attic Insulation Increase: one house (Attic)
   A local contractor was employed to increase the attic insulation (and airseal in the same area).

Details of the specific work done in each house were left up to the local contractors employed, subject to homeowner and project team approval. Examples of airsealing and basement insulation work are shown in Figures 1 and 2. The location of the houses is indicated in Figure 3. General information on the 16 houses, detailed descriptions of the "before" condition and the upgradings performed, together with the detailed monitoring and results of analysis can be found in Jones (1985).

The costs incurred to do the various upgradings are averaged for each category in Table 1. The total for the 16 houses was $22,180 CAN of which 26% was contributed by the homeowners. To compensate for the different sizes of jobs, the costs per insulated area (basement or attic) or per living (floor) area (airsealing) were calculated. Values ranged between:

1. \$0.83 and \$3.25/m^2 (\$0.08 and \$0.30/ft^2) for homeowner airsealing, depending on effort expended and on the condition of the house.

2. \$4.85 and \$16.92/m^2 (\$0.45 and \$1.57/ft^2) for contractor airsealing; the upper figure may be unrealistically high (separate contractors for airsealing and insulating were utilized), for the next highest value is just \$9.40/m^2 (\$0.87/ft^2).

3. \$23.67 and \$32.98/m^2 (\$2.20 and \$3.06/ft^2) for contractor basement wall insulation (including drywall and basement airsealing). For those jobs where whole-house airsealing was also done, the costs for basement insulation alone ranged down to \$19.23/m^2 (\$1.79/ft^2).
4. \$6.84/m^2 (\$0.64/ft^2) for the one instance of homeowner-installed basement insulation, without drywall (materials only).
5. \$13.15/m^2 (\$1.22/ft^2) for the one instance of attic insulation increase including attic airsealing (separate contractors were used for airsealing and blowing-in cellulose).

Upgrading Inspections

Inspection visits were made during the contractors' work to record the methods used and any problems encountered. Airsealing work employed a variety of materials and techniques, some of which are worthy of concern. One contractor used a caulking that had unacceptably

1 Independent of this experiment, the homeowner of house 71-32 had attic insulation added in the summer of 1982.

2 House 71-25 had insulation added to isolate the cold room in the basement.

strong fumes; a substitute was found. Application of "V Strip" style weatherstripping in sashless slider windows proved less disruptive of window operation than weatherstripping that was screwed down against the panes, which made the windows difficult to open and unremovable for cleaning. Peelable rubber-based caulking was applied to windows in some cases; one brand was easily dissolved when it came in contact with condensation running down the pane, and it became brittle, making it difficult to remove. There were also some general concerns expressed regarding the possible difficulties in emergency egress should the windows be sealed shut. Weatherstripping applied to doors prevented proper closure in some instances. Basement insulation consisted of either wood framing with glass fibre batts, wood framing and rigid expanded polystyrene board, or extruded polystyrene board with custom fasteners.

PREDICTIONS

Method

HOTCAN, a microcomputer program originally developed by the Division of Building Research in Saskatoon for estimating the space heating requirement of residences (Dumont et al. 1982; Lux 1982), was chosen as the most appropriate predictive model. One of the assumptions of this experiment is that no significant changes in lifestyle occurred between the "before" and "after" heating seasons. This implies that predictions of the reduction in energy used after upgrading should be better modeled than is absolute consumption. Because the natural air change rate is an input to HOTCAN, only the transmission heat loss factor is a prediction of the program.

The component areas were taken from site measurements or house plans. The insulation levels were derived from site inspection, knowledge of building constructions eras, and engineering judgement. The nearest available weather data location was used for each house. Design heat losses were corrected to the actual house location based on design temperature differences, and energy consumptions based on degree-days.

Results

From historic oil consumption data, normal annual consumption can be calculated. Comparison with the predicted consumption (with average ac/h) shows an average overprediction of 100% (ranging from 30% to 250%). The particular assumptions of basement temperature, heat gains, natural infiltration rate, etc., may contribute to this error, but are not expected to account for anywhere near all the inaccuracy. Any retrofits or other conservation efforts since 1977/1980 would only increase the problem. Without a detailed investigation of HOTCAN (beyond the scope of this study), no full explanation of this state of affairs is possible.

The percentage reductions in demand and energy with the average of before and after air change rates are listed in Table 2. There are no predictions for the airsealing-only cases, nor for the airsealing component of the other categories.

The two main characteristics of these predictions are: (1) their relatively large magnitudes in most cases, and (2) the fact that the energy reductions are always larger than the demand reductions.

RESULTS

Airtightness Tests

To give an indication of the airsealing improvements achieved, airtightness tests were commissioned both before and after the thermal upgradings.[3] Considerable effort was expended to have all the tests done in accordance with the then latest draft of the CGSB (1982) Standard, but this was unattainable. Most of the tests meet all the data verification requirements of a later draft of the standard (CGSB 1984). The final test outputs (equivalent leakage areas relative to the above-grade envelope area) are shown in Table 3 together with the resulting airtightness reductions. The comparison of the "before" and "after" airtightness results shows possible difficulties in up to half the houses tested. In houses 71-04, -09, and -25, the near-zero reduction in airtightness does not correspond to the amount of sealing work done nor to the evident reduction in natural infiltration actually observed by the homeowners. The test equipment used in house 71-04 seemed to have calibration

[3] Work had already begun on house 71-07 before this experiment was initiated, so no "before" test is available for this house.

difficulties, which could have contributed to the problem. The increase observed in house 71-10 (where a small reduction would be expected) was partly due to difficult-to-close slider windows and a particularly ill-fitting attic hatch, which was disturbed just before the second test. However, the increase is so large that we must entertain the possibility that a real "opening" of leakage sites occurred. The relatively low reductions for houses 71-27 and -33 are less than the reductions of 40% or more that are normally expected. In contrast, the large reduction for the attic airseal and reinsulation (house 71-28) is questionable. The large reduction in house 71-32 is probably due more to the attic work done than the homeowner airseal. For most of these troublesome results, no specific cause is obvious, although the general accuracy of individual tests (often taken as ±10%) plus the repeatability problems due to retest, especially in different weather conditions, may explain some of the difficulties encountered.

Natural air change rates were derived from the measured fan depressurization test results using C.-Y. Shaw's correlation (1981) for cold, windy conditions (see Table 3):

$$I = 4.53 \frac{C}{v} \qquad (1)$$

where
I is the air change rate in ac/h
v is the house volume in m^3
C is the fan test flow coefficient in $L/s \cdot Pa^n$

The natural air change rate predictions give increases after upgrading in five cases. For houses 71-14, -25, -04, and -15, there is a corresponding significant decrease in the fan test flow exponent (n) because of the upgrade (house 71-10 has other difficulties). This suggests that some dependence on n may be necessary to properly correlate air change rate and airtightness in the case of retrofit changes to the same residence, probably because of altered leakage site distributions. As well, testing of the correlation (Shaw 1981, Figures 8 and 9) suggests a prediction accuracy of just ±25%. This makes distinguishing small changes due to upgradings somewhat problematic. The absolute values of the air change rate predictions (ranging from 0.14 ac/h to 0.77 ac/h) are as expected for typical construction. For the purposes of calculating energy and demand reductions, the average of the "before" and "after" air change rates was assumed.

Homeowner Questionnaires

In order to monitor the homeowner's reactions to the upgradings and any changes in house-operation (e.g., increases in condensation due to the airsealing), informal and formal surveys were conducted throughout the experiment.

A number of homeowner complaints were received soon after upgrading. Most were related to a decrease in natural ventilation after airsealing, coupled with the normal increase in indoor relative humidity in the autumn. In part, the initial comments reflect the need to get used to a new regime of house operation. More importantly, the lack of mechanical ventilation devices to deal with a lowered natural ventilation rate is evident in those cases where significant problems are described. Still, the availability of openable windows means that such problems need not get out of hand. Project personnel kept an eye on such problems and offered advice concerning moisture control, etc., to the homeowners.

Generally, the responses to the June 1983 survey were much more temperate than those received immediately following the upgrading (fall 1982). Some criticisms of the upgrading workmanship were noted, although most homeowners expressed satisfaction. The majority of homeowners indicated a significant improvement in comfort level. Three respondents felt that the thermal upgrading had caused problems of increased humidity or poor air quality. Other respondents did not report any change in this regard.

Hourly Monitored Data

The primary monitoring instrumentation was a digital demand recorder (DDR) connected to the plenum heater in each house. This recorded the electrical energy consumption in each 15-minute interval throughout the heating season. This paper deals with the data from the 1981/1982 (Hicks et al. 1984) and 1982/1983 heating seasons, the latter beginning after the completion of the upgradings in October/November 1982 and continuing until mid-May. A detailed manual review of the computer translation of the monthly DDR magnetic tapes showed the need to correct various errors, delete outage periods (including half of the "after" heating season for house 71-15), and attempt to compensate for manual night setback in houses 71-06, 71-07, 71-12, and 71-22. Hourly outdoor temperatures were obtained from the nearest airport weather station (see Figure 3). The DDR data were accumulated over hourly intervals to correspond to the available temperature data.

Monthly Space Heating Energy Consumption

The plenum heater consumptions were obtained by summing the DDR outputs over calendar months. To this was added the relatively small amount of back-up oil consumed (monitored by timing oil furnace operation). Monthly average consumptions per degree-day for before and after upgrading were compared from November to April, showing a consistent pattern: although roughly constant in the coldest part of the winter, the monthly after/before consumption ratios increase significantly at both ends of the heating season. Most houses exhibit this effect, which suggests that consumption <u>increases</u> after upgrading in the shoulder seasons.

Comparison with the HOTCAN predictions shows: (1) the predictions are roughly a factor of two too high, (2) the monthly profiles are quite similar, except (3) in the shoulder seasons, the actual consumptions fall off much faster than do the predictions.

Yearly Energy Consumption

The yearly total (oil plus electricity) energy consumptions were normalized using degree-days to account for weather variations (1981/1982 was cooler than normal and 1982/1983 warmer) and are shown in Table 4. The proportion of the total consumption provided by oil averaged 8.2% for 1981/1982 and 4.6% for 1982/1983. In most cases this proportion is small enough that missing, extrapolated, etc., data do not affect the overall results significantly.

The before totals are compared to the 1977/1980 averages in Table 4 to indicate the consistency of space heating energy consumption. On average, usage shifted just 300 kW•h/year (1.0 MBtu/year); individual differences are never more than 35% of the historic consumption. Six houses show reductions from the historic usage, probably due to retrofitting activities. The majority have increases, suggesting lifestyle changes. Some of the variations may be due to the need to make weather corrections.

The category-average consumption reductions shown in Table 4 bear the expected relationship to each other, although the absolute reductions are relatively modest. The uniqueness of each house and its occupants and of the specific upgradings performed allows for the individual variations seen. Houses 71-26 and 71-32 show consumption increases; both have absolute reductions that disappear when the weather variations are discounted. The reduction expected for house 71-26 (DIY seal) is small and may have been swamped by lifestyle changes. Two of the four night-setback houses (71-06 and -22) show zero consumption reductions. The zero reduction for house 71-25 is not readily explained, although a significant bypass leak from the second storey to the basement through the heating duct passageway was observed during the "after" fan test.

Because the predictions use before/after averaged air change rates, the absolute comparison is made with the average of the "before" and "after" normal yearly consumptions. Consumption is overpredicted from 20% to 170%, and 80% on average. This error is comparable to that seen with respect to historic oil consumption, and cannot be fully accounted for by the assumptions used in the predictions. Predictions of percentage consumption reductions (Table 2 vs. Table 4) are grossly overstated in most cases: a factor of three on average. And the predictions do not include airsealing effects. Part of the problem in predicting reductions is due to the trouble already seen in predicting absolute values. The other possible source of error could be a real lifestyle effect, which mere physical modeling of the building envelope can never uncover.

Space Heating Demand

<u>Analytical Technique</u>. The DDR/temperature data embody the overall space heating characteristic of each house, i.e., the rate of change of heating demand with temperature. The determination of the reduction in this demand/temperature slope is complicated by a number of conditions, which introduce peculiarities and significant scatter:

1. The backup oil furnace, which supplies some energy at colder temperatures.
2. Other weather effects.
3. Household operation and lifestyle effects.
4. Extra scatter close to the house balance temperature.
5. Nonsymmetry of heating/cooling close to the balance temperature.
6. DDR digitizing errors.
7. Temperature offsets between the house and the nearest weather station.
8. House time constant effects.
9. Plenum heater replacement in the spring of 1983.
10. The assumption that demand varies linearly with temperature.

The best-fit analysis to determine the houses' characteristic slopes is as follows:

1. The hour-average electric heating demands were combined with the corresponding outdoor temperatures (with deletions as discussed before).
2. From plots of demand vs. temperature, engineering judgement was used to determine the appropriate upper and lower temperature limits (common to "before" and "after") to exclude the phenomena in 1, 4, and 5 above.
3. The remaining data for each house were sorted into temperature bins and averaged. The best-fit straight line (termed the heating system load (HSL) line) was calculated, weighing the data by the number of points making up the average demands. The standard error of the slope of this line is in all but two cases less than 1% of the slope. The goodness of fit is also indicated by an R^2 above 0.9 in 23 of the 32 cases. This confirms the appropriateness of modeling the HSL lines as straight lines. The cases with data problems discussed before (houses 71-12, -15, -22) do show somewhat higher slope standard errors and lower R^2 than for the bulk of the data but not enough to indicate significant difficulties.
4. Using the normal outside design temperature for each house location and assuming 22°C inside, the design heat loss (an indication of the required furnace size) was calculated from the HSL line slope (see Table 5).

Example plots to illustrate the analytical technique are shown in Figures 4 to 6.

Results. There are significant demand reductions (Table 5) in all but three cases. House 71-22 may show the complication introduced by manual night-setback (another setback house, 71-12, also shows a reduction much less than for the other houses in its upgrade category). The airtightness test results for house 71-10 suggest a possible unsealing of the structure, consistent with the demand increase seen here, which swamped the effect of basement airsealing and insulation. The small decrease measured for house 71-06 may be the result of manual night-setback, as well as the difficulties in adding insulation to a partly finished basement (both inside and outside insulation were applied; the transition, and the stairwell work, may not be too effective). The category-average reductions bear roughly the expected relationship to each other, although the homeowner airsealing gave larger reductions than anticipated. Comparison of the percentage energy and demand reductions house by house shows no obvious relationship. On the average though, the demand reductions are twice the energy decreases.

HOTCAN gives values 40% larger than the measurements on average (ranging from -10% to +110%). This is better than the consumption comparison, as it should be (there are many fewer complications and assumptions involved), but it is still rather too large for confidence in the predictions. Estimation of the percentage demand reductions is quite close on average and in most cases to the actual percentage decreases, although the effect of airsealing is not included in the HOTCAN results. This close correspondence may thus be somewhat fortuitous.

DISCUSSION

Predictions

HOTCAN. The two main areas of possible uncertainty in the HOTCAN calculations are basement heat loss and air change rate. The former is in general the largest component of the total heat loss. There is the possibility that floating rather than fixed basement temperatures, incorrect above-grade wall resistances, two-dimensional heat flow in the header area, or different-than-assumed soil thermal conductivity conditions could account for the overgenerous predictions. Our use of average air change rates to obtain baseline consumptions and heat losses for percentage reduction determinations indicates the difficulty in using this model for airsealing retrofits when the critical parameter is a user-specified input. Other specific house details, such as enclosed or attached garages, crawl spaces (connected to or sealed from the house), overhangs, partly insulated basements, etc., may not be properly accounted for.

Air Change Rates. If HOTCAN accurately calculates the transmission components of heat loss, a measure of the air change rate can be had by subtracting that value from the measured HSL slope. This result can then be compared to the prediction based on the airtightness test results and C.-Y. Shaw's correlation. However, more than half the "measured" air change rates are negative. Thus, nothing can be said about the accuracy of the air change rate predictions based on airtightness fan test results. The comparison of those predictions with the results expected from the airsealing methods used and homeowner comments does suggest some serious difficulty in properly indicating the effects of airsealing retrofits.

Upgrading Problems

Workmanship, Materials. The inspections and homeowner comments were generally positive about the upgrading work done. A few problems (sealant odor, stuck doors, etc.) were noted, however. This could be expected for a labor-intensive process that requires much custom work and entails a significant (although short-term) disruption of someone's home.

Longer-Term Concerns. The major potential problem resulting from upgrading (especially airsealing) work concerns changes to the long-term indoor air quality, if compensations for the reduced natural ventilation are not made. From the comments made by the homeowners, almost all houses showed signs of being tighter (fewer drafts, window condensation, etc.). Comments obtained at different times were somewhat contradictory in some cases, possibly indicating accommodation to new humidity and ventilation regimes. There are also indications of alterations to house operation and living habits (venting dryers outdoors, turning off humidifiers, airing the house, etc.) to alleviate air quality or humidity situations. Only one house (71-22) had a problem that required remedial action. (The addition of another adult in 1983/1984 may have contributed to the appearance of mold in the bathroom at that time; bathroom and kitchen fans were added in the fall of 1984). In general, the levels of airsealing attained in this study did not significantly affect air quality, or they could be accommodated with straightforward lifestyle changes or, in the limit, with the retrofit of a rudimentary ventilating system.

From the point of view of an organization promoting upgrading work, one important question is whether one can ascertain with a fan test at the time of upgrading if a problem may arise so remedial measures could be instituted immediately. Comparison of fan test reductions with the homeowner comments gives an indication of the ability to anticipate trouble. For houses with tightening evident from the comments, one looks for significant reductions in the fan results; for humidity or air quality problems, one also looks for low absolute values for after-upgrading airtightness (below 2 cm^2/m^2 ($ft^2/10^4\ ft^2$)) or natural air change rate (below 0.3 ac/h). Using these criteria, there is a correlation between testing and reality in seven cases; there is none in seven cases; two houses have no homeowner comments for comparison. Although this record is none too good, the one significant problem house (71-22) was identified (although not strongly) by its fan test results. Depending on fan tests to show underventilation situations may not be prudent at the present state of the art. Work is proceeding elsewhere (BEST 1984) to refine a set of tests (tracer gas, airflows, backdraft potential, etc.) to characterize the performance of ventilating systems; these more direct measures are probably better at discovering potential difficulties.

Only six houses had exhaust fans and in some of them the fans were unused. Even leaky houses, which depend on natural ventilation, have periods of low ventilation, in mild, calm weather. Mechanical ventilation can ensure adequate fresh air in all circumstances. Thus it may be prudent when promoting airsealing retrofits to include provision for installing exhaust fans where they do not exist and to educate the homeowners to utilize them if problems appear.

Lifestyle Changes

Many of the homeowners altered their living habits to accommodate the changes in their indoor environment caused by the upgradings. Many of these alterations have a direct impact on energy consumption and demand requirements. These are intrinsically measured in this experiment and are the likeliest reason for the inaccuracies seen in the reduction predictions. It is significant that the errors on the energy side and, thus, the assumed lifestyle effects on energy consumption are larger than the demand errors and their presumed lifestyle causes. This suggests that alterations in occupant activity vary with weather, i.e., the extent of change decreases as it gets colder outside.

The above observation leads naturally to a discussion of the change in balance point temperature observed on upgrading these houses. The balance point temperature is that outdoor temperature below which a house's heating system first begins to be required. The space heating needed above this temperature is supplied by "free" heat: solar gains, appliance waste heat, gains from occupants, etc. The base temperature used to determine degree-days (18°C, 65°F) is meant to correspond to an average balance point temperature, but it has recently been determined that for present-day house construction and appliance usage, 14°C (57 F) is a better value (Crow 1984). Any given house has an individual balance point temperature determined by the structure and the occupants' habits. The temperature intercept of the HSL line measured in this study is a direct determination of this quantity. Table 6 lists these values both before and after upgrading. The average "before" balance point temperature is the same as the value suggested by Crow (1984); this may be somewhat fortuitous because the absolute values of these temperatures are prone to error because of offsets between the local climate and the airport weather data used. But the remarkable result is the almost consistent increase (independent of any offset) in balance point temperature after upgrading. This effect has also been observed in a number of recent reports of upgrading field studies similar to this one (Collins et al. 1983; Herendeen et al. 1983; Englund et al. 1983). In all these cases, this phenomenon is termed an anomaly or not discussed explicitly, and assumptions are made to avoid the issue in analyzing the data. The quality of the data in this experiment and the existence of these other instances lead me to conclude that this balance point crossover after upgrading is a real effect that must be taken into account when determining the savings due to retrofit. No simple structure-based energy predictor (like HOTCAN) can do this job, only actual measurements as in this study. Because the effect seems most likely to be a result of changes in occupant lifestyle, a proper prediction can only be developed with the help of sociologists, etc., and the taking of detailed occupant as well as structural data. Without going to this obvious complication, organizations sponsoring upgrading work are strongly urged to significantly discount (perhaps by a factor of three) savings estimated from simple physical models.

Cost-Effectiveness

The upgrading costs and energy and demand reductions seen in this experiment can be used, with certain assumptions, to give annualized net benefits for the upgrading work performed (see Table 7). The costs are annualized assuming a 50-year life for the upgrading work (similar to the life of the house itself) and a 3% real interest rate. The homeowner savings were calculated using the 1982 Ontario average end rate of 3.58¢/kW•h. Although the detailed benefits of decreased demand and energy are those appropriate to Ontario, it is expected that the overall result is similar to what would be obtained using data for other utilities.

A net societal benefit occurs for ten of the houses and for the overall average. It should be noted that the annualized costs, and thus net benefits, are relatively sensitive to the economic parameters chosen. It must also be emphasized that not all costs or benefits can be quantified in strict economic terms. For example, decreases in cold drafts can make air-sealing worthwhile even if energy savings do not fully cover the costs incurred. Similarly, insulating a basement can create usable living space at modest cost.

Very roughly, the costs and benefits for each category of upgrading track together. No firm conclusion can be drawn concerning the comparison between categories, e.g., whether air-sealing is better than basement insulation. From Table 7, it can be seen that only six homeowners see net benefits from energy savings due to the upgradings. The utility benefit helps create a net societal benefit. When the contributions of energy and demand savings are isolated (see Table 8), the utility's savings are seen to be due to the demand savings being more than twice the energy penalty (due to the purely energy-based charge in the residential sector). It can be concluded that demand reductions due to thermal envelope upgradings are more important than energy savings, but that present consumer price signals via utility rates do not reflect this fact at all. Utilities may need to contribute toward the capital costs of upgrading if the full economic benefit of such work is to be obtained.

Ability to Generalize

Three aspects of this field trial tend to lessen our ability to generalize from the results obtained. First, the winter before upgrading was significantly colder than normal while the winter after was much milder than normal. Thus, direct comparison of raw measured data was not appropriate, and a weighing based on standard degree-days was used to obtain comparable consumptions for normal weather. The vast majority of weather-based variations are taken care of by this stratagem. The small standard errors of the slopes of the heating system load lines obtained from the statistical analysis of the measured data prove the correctness of our demand reduction determinations.

Another difficulty is the modest number of houses studied in this experiment. However, there are reasons to suggest that some generalizing is justified. Standard retrofitting materials and techniques and good workmanship were used in the upgradings. Groups of four houses with the same category of upgrading allow some averaging and comparison with other categories. And all 16 houses show some consistent results, albeit with individual scatter. For example, the overpredicting of the consumption reductions is common to almost all the houses.

The third problem in this experiment is the use of supplemental space heating devices even after careful screening of the participants and inclusion in the legal agreement with them of a clause prohibiting such use. It is assumed that no significant change in such house operation (e.g., fireplace usage) occurred between 1981/1982 and 1982/1983 as a function of outdoor temperature, so that the relative changes due to the upgradings were determined correctly even if absolute demands or energy consumptions were not quite.

CONCLUSION

1. Sixteen typical Ontario houses had their thermal envelopes variously upgraded (homeowner and contractor-performed airsealing, basement and attic insulation) and were monitored before and after the change to obtain consumption and demand reductions, costs, and indications of any difficulties encountered. Data analysis was performed to eliminate gross effects of weather between the two years.

2. Space heating consumption reductions averaged 6% and ranged from -11% to +15%; demand reductions averaged 13% (-6% to +30%). More extensive upgradings showed larger savings, on average. Explanations for the anomalous results are offered in the text.

3. Predictions of the expected reductions were made using HOTCAN and average measured air change rates. Consumption was overpredicted 80% on average; the percentage savings calculated were three times larger than those measured. HOTCAN gave demands 40% too large, although the percentage savings are comparable to those measured.

4. The airtightness measurements using fan depressurization and the results of C.-Y. Shaw's correlation to give natural air change rates do not correspond well to the work done or the consumption reductions measured.

5. Only a few problems were encountered because of this upgrading work; they were not serious or were simply rectified.

6. Most upgradings show a societal (homeowner plus electric utility) net benefit.

7. Some of the anomalous results and the difficulty in predicting upgrading effects are ascribed to lifestyle effects. Such effects are also thought to account for the increase in balance point temperature after upgrading seen in this study.

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TABLE 1

Average Upgrading Costs

Category	Number of Houses	Average Cost CAN$
DIY Seal	3	260
Seal	4	770
Seal & Basement	4	2810
Basement	3	1660
DIY Basement	1	670
Attic	1	1460

TABLE 2

HOTCAN Predictions
(average ac/h)

Category	House Number*	Annual Heating Consumption kW•h	Energy Reduction %	Design Heat Loss kW	(MBtu/h)	Demand Reduction %
DIY Seal	14	29700	--	11.1	(38)	--
	26	28000	--	12.1	(41)	--
Seal	22	34000	--	14.6	(50)	--
(Basement)	25B	23200		12.0	(41)	
	25A	22900	1	11.9	(41)	1
	27	28700	--	11.7	(40)	--
	33	24200	--	10.3	(35)	--
Seal & Basement	04B	45500		15.8	(54)	
	04A	25500	44	10.6	(36)	33
	09B	46900		18.9	(65)	
	09A	33200	29	14.9	(51)	21
	12B	29100		11.9	(41)	
	12A	17800	39	8.7	(30)	27
	34B	32300		12.4	(42)	
	34A	23200	28	9.9	(34)	20
Basement	06B	40300		16.9	(58)	
	06A	30300	25	14.5	(49)	14
	10B	27000		11.6	(40)	
	10A	20700	23	10.2	(35)	12
	15B	32400		12.3	(42)	
	15A	25600	21	10.4	(35)	15
DIY Basement	07B	42600		17.0	(58)	31
	07A	25200	41	11.7	(40)	
Attic	28B	36800		15.0	(51)	
	28A	31700	14	13.3	(45)	11
Attic & DIY Seal	32B	22000		9.8	(33)	
	32A	19500	11	9.0	(31)	8
Average (assuming - is 0)			17			12

* B = Before
A = After

TABLE 3

Airtightness Test Results

Category	House Number	Relative Equivalent Leakage Area $cm^2/m^2 (ft^2/10^4 ft^2)$	Air-tightness Reduction %	Natural Air Change Rate Prediction ac/h
DIY Seal	14B	2.7		0.43
	14A	2.5	6	0.48
	26B	5.6		0.56
	26A	5.2*	7	0.52
Seal	22B	4.2		0.60
	22A	2.3	45	0.27
(Basement)	25B	3.7		0.38
	25A	3.7	2	0.57
	27B	2.7		0.27
	27A	2.1	22	0.21
	33B	4.7		0.62
	33A	3.4	28	0.46
Seal & Basement	04B	3.1		0.21
	04A	3.0*	3	0.28
	09B	3.3		0.53
	09A	3.3	2	0.50
	12B	4.1		0.59
	12A	2.6	38	0.37
	34B	4.3		0.51
	34A	2.5	41	0.34
Basement	06B	4.2		0.52
	06A	3.6	14	0.38
	10B	2.7		0.38
	10A	3.2	-20	0.46
	15B	5.1		0.64
	15A	4.3	16	0.75
DIY Basement	07B	--		--
	07A	5.0	--	0.77
Attic	28B	3.4		0.34
	28A	1.6	53	0.14
Attic & DIY Seal	32B	3.1		0.46
	32A	2.1	30	0.27
			Average 19	

* Poor Data

TABLE 4

Normalized Consumption Results

Category	House Number	Annual Historic Consumption kW•h	Annual Heating Consumption kW•h	Consumption Reductions % Individual	Consumption Reductions % Category Average
DIY Seal	14B	21700	22600		
	14A		21400	5	
	26B	13000	13700		-3
	26A		15300	-11	
Seal	22B	12900	12700		
	22A		12700	0	
(Basement)	25B	15700	17100		
	25A		17100	0	
	27B	20600	16900		3
	27A		15400	9	
	33B	14400	17000		
	33A		16600	2	
Seal & Basement	04B	19400	25100		
	04A		23000	9	
	09B	23500	27200		
	09A		25300	7	
	12B	17700	13100		11
	12A		11000	15	
	34B	17100	17300		
	34A		14800	14	
Basement	06B	20100	16400		
	06A		16400	0	
	10B	19800	20800		
	10A		19800	5	
	15B	15700	13600		8
	15A		11700	14	
DIY Basement	07B	12100	16200		
	07A		14400	11	
Attic	28B	15200	16400		
	28A		14300	13	
Attic & DIY Seal	32B	16300	13900		6
	32A		14100	-2	
Average				6	

TABLE 5

Demand Results

Category	House Number	Design Heat Loss kW	(MBtu/h)	Demand Reductions % Individual	Category Average
DIY Seal	14B	12.4	(42)		
	14A	10.1	(34)	19	
	26B	8.9	(30)		13
	26A	8.2	(28)	7	
Seal	22B	8.3	(28)		
	22A	8.7	(30)	-4	
(Basement)	25B	11.6	(40)		
	25A	9.5	(32)	18	
	27B	9.8	(33)		10
	27A	8.1	(28)	18	
	33B	8.3	(28)		
	33A	7.6	(26)	8	
Seal & Basement	04B	17.7	(60)		
	04A	12.4	(42)	30	
	09B	19.1	(65)		
	09A	15.2	(52)	21	
	12B	8.1	(28)		20
	12A	7.3	(25)	10	
	34B	7.8	(27)		
	34A	6.2	(21)	21	
Basement	06B	8.1	(28)		
	06A	8.0	(27)	1	
	10B	10.5	(36)		
	10A	11.1	(38)	-6	
	15B	7.6	(26)		9
	15A	5.9	(20)	23	
DIY Basement	07B	7.4	(25)		
	07A	6.2	(21)	17	
Attic	28B	9.8	(33)		
	28A	7.8	(27)	20	
Attic & DIY Seal	32B	6.5	(22)		15
	32A	5.8	(20)	10	
Average				13	

TABLE 6

Balance Point Temperatures

Category	House Number	Balance Point Temperature °C (F) Before	After	Increase
DIY Seal	14	13.3 (55.9)	14.8 (58.6)	1.5 (2.7)
	26	11.3 (52.3)	13.7 (56.7)	2.4 (4.3)
Seal	22	13.9 (57.0)	15.2 (59.4)	1.3 (2.3)
	25	11.9 (53.4)	15.3 (59.5)	3.4 (6.1)
	27	11.3 (52.3)	13.5 (56.3)	2.2 (4.0)
	33	14.4 (57.9)	15.3 (59.5)	0.9 (1.6)
Seal & Basement	04	11.5 (52.7)	15.8 (60.4)	4.3 (7.7)
	09	13.1 (55.6)	14.3 (57.7)	1.2 (2.2)
	12	14.7 (58.5)	14.0 (57.2)	-0.7 (-1.3)
	34	15.8 (60.4)	16.9 (62.4)	1.1 (2.0)
Basement	06	12.7 (54.9)	16.8 (62.2)	4.1 (7.4)
	10	16.7 (62.1)	14.8 (58.6)	-1.9 (-3.4)
	15	13.0 (55.4)	12.7 (54.9)	-0.3 (-0.5)
DIY Basement	07	18.1 (64.6)	18.8 (65.8)	0.7 (1.3)
Attic	28	13.1 (55.6)	13.9 (57.0)	0.8 (1.4)
Attic & DIY Seal	32	15.4 (59.7)	17.1 (62.8)	1.7 (3.1)
Average		13.8 (56.8)	15.2 (59.4)	1.4 (2.5)

TABLE 7

Costs and Benefits

Category	House Number	Annualized Costs/Benefits (1982$) Upgrade Costs	Homeowner Savings	Utility Savings	Societal Savings	Net Benefits
DIY Seal	14	16	43	48	91	75
	26	4	-57	37	-20	-24
Seal	22	32	0	-21	-21	-53
	25	46	0	47	47	1
	27	22	54	22	76	54
	33	19	14	14	28	9
Seal & Basement	04	168	75	102	177	9
	09	105	68	94	162	57
	12	86	75	-5	70	-16
	34	78	90	11	101	23
Basement	06	86	0	-18	-18	-104
	10	60	36	-30	6	-54
	15	48	68	27	95	47
DIY Basement	07	26	64	13	77	51
Attic	28	57	75	28	103	46
Attic & DIY Seal	32	>10	-7	22	15	<5
Average		54	37	25	62	8

TABLE 8

Average Energy and Demand Benefits (1982$)

Sector	Energy	Demand	Total
Homeowner	37	0	37
Utility	-19	44	25
Society	18	44	62

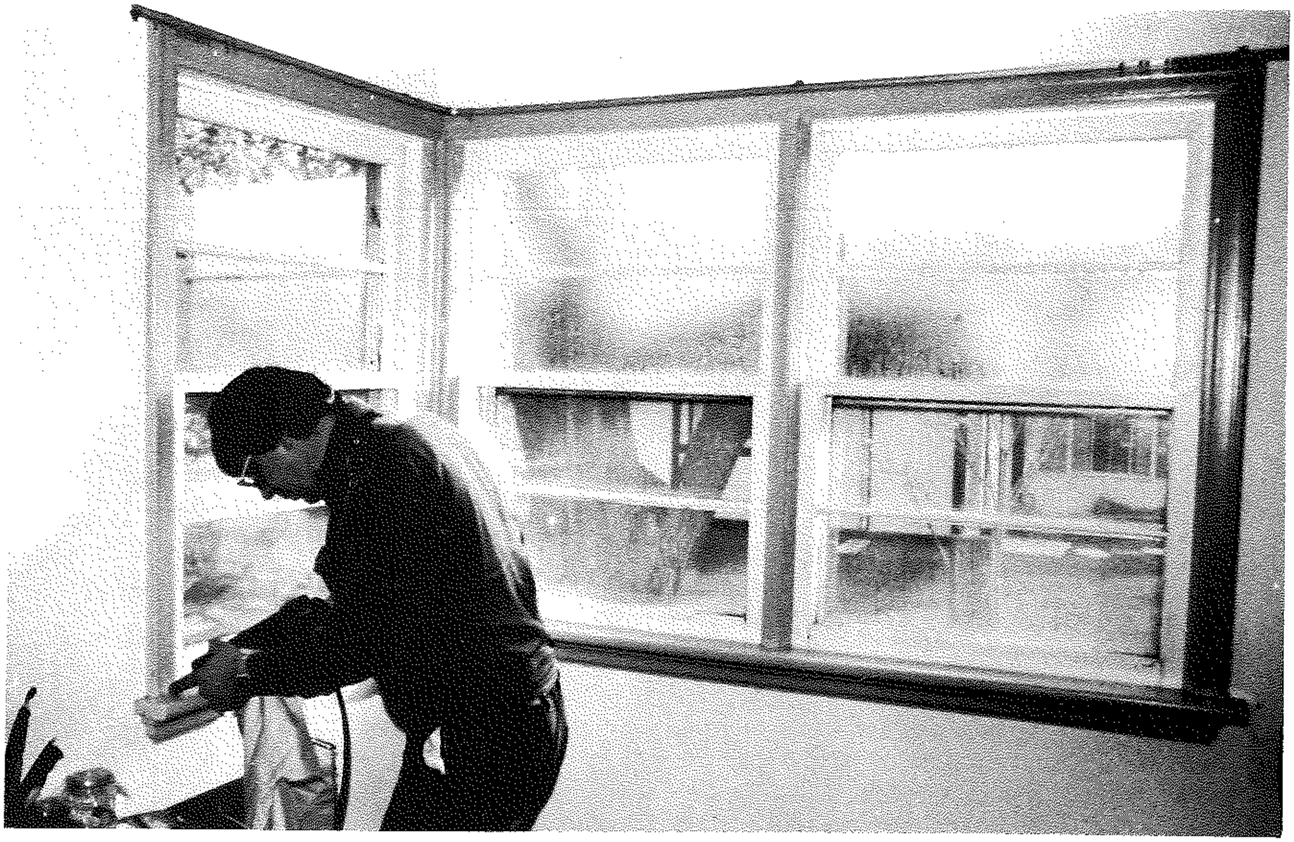

Figure 1. Airsealing a window in house 71-12

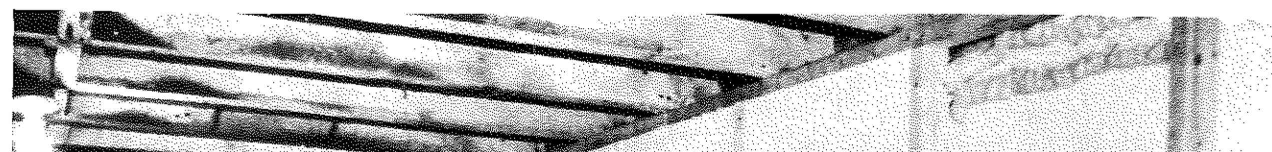

Figure 2. Insulating basement walls in house 71-12

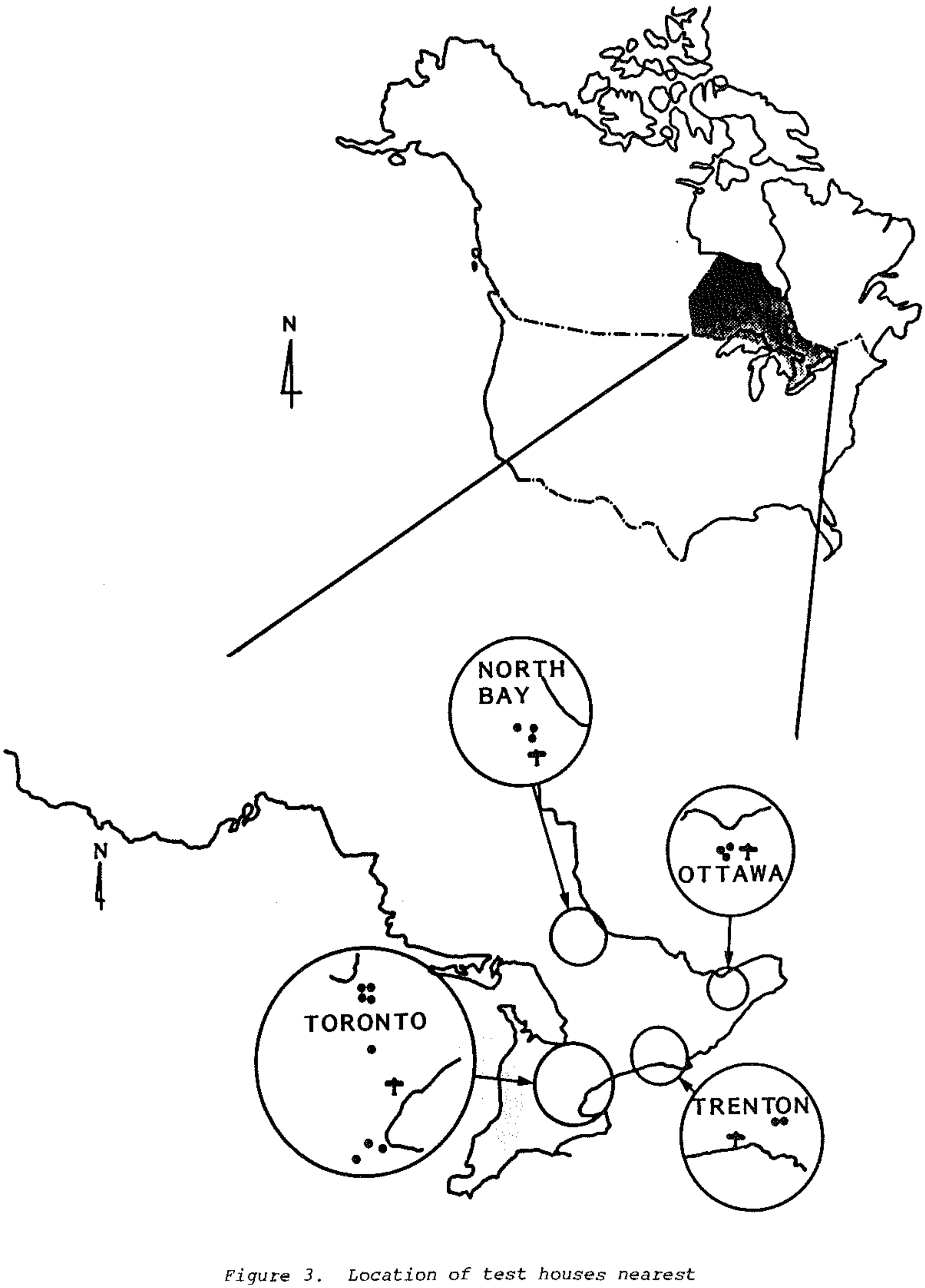

Figure 3. Location of test houses nearest airports

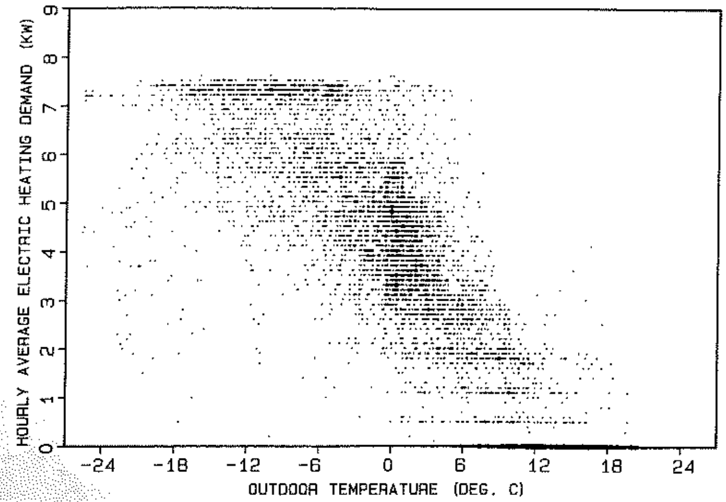

Figure 4. Raw heating demand vs. temperature data for house 71-14 before upgrading (1981-82)

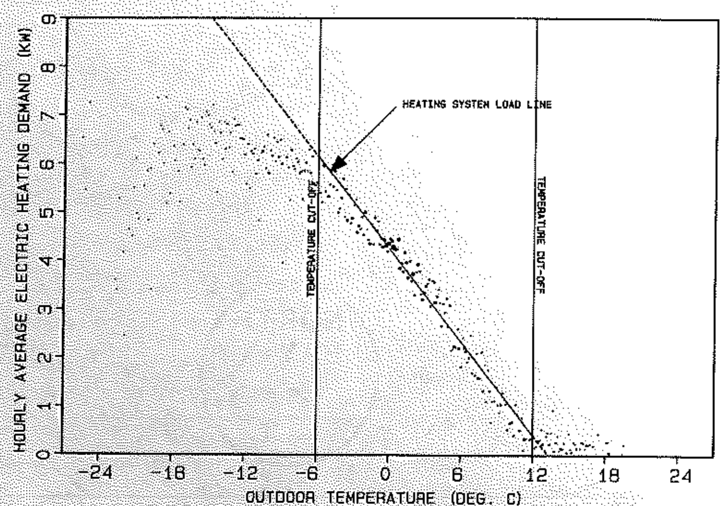

Figure 5. Heating demand vs. temperature, average bin data for house 71-14 before upgrading (1981-82)

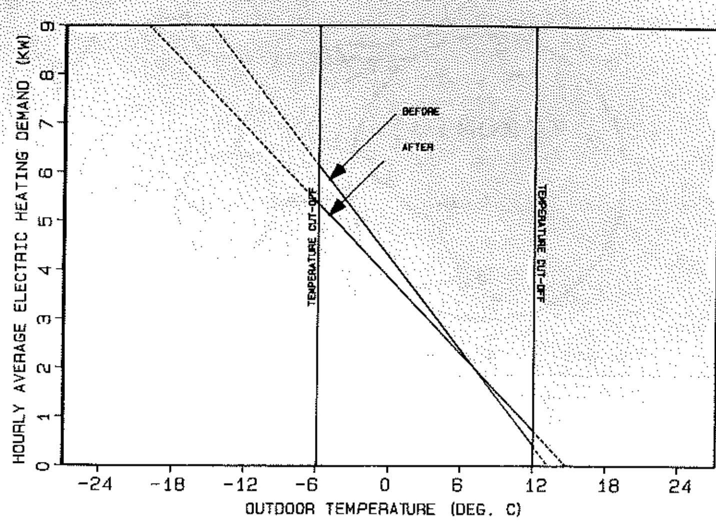

Figure 6. Comparison of heating system load lines before and after upgrading for house 71-14