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RESIDENTIAL ENERGY CONSERVATION— THE TWIN RIVERS PROJECT

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ABSTRACT

In a study of energy consumption in residential housing conducted since 1972 in a Planned Unit Development at Twin Rivers, New Jersey, two approaches to energy data collection and analysis have been taken. In one approach, information available from utility records is used; energy consumption is correlated with house size, house design and outside temperature, and energy conservation resulting from the oil crisis, price increases and retrofits is determined. The second approach uses far more detailed data gathered through the deployment of instrument packages in 29 houses. Internal temperatures, appliance usage and furnace operation are measured, as well as occupant-induced events such as window and door opening times and thermostat settings. Infrared scanning, air infiltration monitoring, wind tunnel testing and detailed experiments in a rented townhouse have complemented the recorded data.

Using both approaches has resulted in an improved modeling of energy related features of typical townhouses and occupant activities and has provided the basis for a retrofit experiment which has achieved 25% gas savings plus 10% electrical savings and has predicted a capital improvement payback period of approximately three years when both heating and cooling seasons are considered, and water heating is included. Additional benefits through a second round of retrofits emphasizing improved operation of the heating equipment look promising for the future.

INTRODUCTION

The magnitude of the task of achieving energy conservation in the existing housing stock of the United States is staggering. There are sixty million homes, nearly all of which (unlike the hundred million automobiles) will be around and occupied fifteen years from now. In virtually every home a reasonable goal would be to try to reduce the energy use by fifty percent without diminishing the associated amenities. To reach that goal will require a multiplicity of activities ranging from basic research, to legislative initiatives on building codes, and reforms of the mortgage market. The applied research community will be called upon for improved modeling, much more flexible and less expensive instrumentation, more thorough biomedical and safety-related research on the side effects of conservation measures, and more informed behavioral research.

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Since July 1972, this project in residential energy conservation has been designed to document, to model and to learn how to modify the amount of energy used in homes. The principal target has been the energy used for space heating; subordinate targets have been hot water heater, air conditioning and appliances. The research approach has strongly emphasized field studies at a single site, the recently built Planned Unit Development of Twin Rivers, New Jersey, Exit #8 on the New Jersey Turnpike. The project has monitored the house construction, interviewed many of those responsible for energy-related decisions in the planning and construction phase, formally surveyed and informally interacted with the residents, obtained a complete record of monthly gas and electric utility meter readings, built a weather station at the site, placed instruments in twenty-eight townhouses (all identical in floor plan) and rented and occupied another of these townhouses ourselves, turning it into a field laboratory.

Twin Rivers consists of a mix of industrial, commercial and residential structures. The latter include single family homes, townhouses and apartments, which are arranged in four quadrants. The weather station was placed on top of the town's bank (at a central location), a choice that also provided security for the equipment. The majority of the work described in this paper was carried out in the three-bedroom, two-floor Quad II townhouses, although portions of the research have been carried out in all parts of the town. The townhouses are of conventional construction, with masonry bearing walls and wood framing for floors, walls and roof. This design provides approximately 720 sq. ft. (67 m^2) of space on each floor. The townhouses sold for approximately $30,000 when they were built and resell for about $40,000 today.

In general, the study has been conducted in townhouses that are as identical as possible, and the instrumentation has been duplicated. For example, a visit to any of the homes would reveal thermistor probes measuring temperatures placed in each of the twenty-eight townhouses at the same locations. The residents of the townhouses are not as identical as the thermistors, although from the viewpoint of some of the social sciences, they would be regarded as a homogeneous sample. Nearly all of the families have small children, typically one when they moved in and another since. For the average family, their townhouse is the first home they have owned, and their past residence often has been an apartment in New York City. Most of the fathers are mobile professionals, and the family annual income, at time of purchase, averaged $20,000.

The population is <u>not</u> homogeneous along many coordinate axes which matter from the standpoint of energy use: they differ in their "temperature preference" (interior temperatures show a standard deviation of $\pm 2°F$ ($\pm 1°C$) in winter), in their understanding of the functioning of their homes, in their attitudes toward sun and toward dryness, and in their (at least expressed) concern for saving money (or energy). The relevant social science discipline for understanding the energy-related behavior that is displayed at Twin Rivers appears to us to be psychology, and psychologists have added a critical component to the research effort during the past two and one-half years.

The "engineering" portions of the research program are emphasized here, with engineering, as will be seen, defined quite broadly, but not so broadly as to include the studies of residential behavior and of the politics behind the construction of the town. Results of these studies are available in References (1) and (2). This paper is divided into two main sections: section one cites the results that could, in principle, have been obtained without doing measurements within the houses. This group has strived to invent analytical methods by which a population of homes could be monitored using only data from the gas and electric meters and data from a nearby weather station. In principle, this portion of the research could be widely imitated, at relatively low cost. The overwhelming dominance of outside air temperature as a predictor variable in the winter heating season renders the monitoring of performance, across residences and over time, a remarkably productive exercise. Section one presents a quantitative description both of the voluntary conservation which occurred following the "energy crisis" in the autumn of 1973 and of the results of deliberate modifications, retrofits, of the townhouses this past winter. Section two describes results which required entry into the townhouses, first of all to observe, but also to leave instruments behind. Three <u>h</u>ighly-<u>i</u>nstrumented <u>t</u>ownhouses (HIT 1, HIT 2, and HIT 3) have produced a total of 200 channels of data which have been transmitted over telephone lines to the project laboratory twelve miles (19 km) away. Three winters and two summers of data have been obtained, and retrofits were performed in the middle of the third winter (December 1975 to January 1976). Details can be found in Ref. (3).

The remaining twenty-five townhouses have been lightly instrumented, with a 9-channel "Omnibus" package that records data onto a tape cassette within the home. It is this instrumentation, and some of the associated methods of data reduction, which begins to resemble the equipment and analysis which will hopefully assist in the efforts, on a wider scale, to conserve energy in housing - the justification of the necessity for a field approach. Although the Twin Rivers townhouses represent average construction practice there are certain problems related to the details of design which became high priority items for energy savings in the retrofit program. See Refs. (3) and (4) for details.

Two most helpful approaches in the detection and quantification of energy losses in the homes has been the use of infrared scanning and automated air infiltration measuring equipment. In both the measurements of conduction and air infiltration, Dr. Richard Grot, National Bureau of Standards, has played a major role. The infrared photography has revealed a number of areas with higher than desired energy losses such as: the party walls, the overhanging window and closet sections, the overheated attic, and the warm air distribution system. The air infiltration measuring units have clearly shown the relatively minor role of summer air infiltration (~7% of heat gain) versus the winter contribution (~33% of heat loss). Both of these approaches to energy analyses are augmented by weather station data, e.g., the role of wind and temperature differential are important in determining weather penetration into the structure and the levels of air infiltration (see Refs. (3), (5) and (6)).

SECTION ONE: VARIATION ACROSS HOUSES

The single result that is best known from this program is represented by the histograms in Figure 1. In nearly identical townhouses of a single community, winter gas consumption for space heating varies by more than three-to-one. And in townhouses absolutely identical in floor plan, shell materials, orientation, and appliance package, winter gas consumption varies by two-to-one. Every existing computer program would predict a single value for the gas consumption of the 28-unit subsample in Figure 1.

The gas consumption plotted here is the average of two six-month winters (November 1971 to April 1972 and November 1972 to April 1973). As a matter of practice, houses are excluded from consideration if one is otherwise forced to use "estimated" meter readings. The large sample in Figure 1 contains townhouses with two, three, and four bedrooms, successively larger (18, 22 and 24 ft. wide, or 5.5, 6.7 and 7.3. m), differing from one another with respect to window area and number and size of overhangs. Some of the townhouses in the large sample are end units and, thereby, have additional exterior wall surface. Front doors face each of the four compass directions. (The town axis lies about 10 degrees east of north). About half of the units have double glass windows and/or patio doors, these having been options at the time of purchase. The shaded subsample in Figure 1 has no variation in any of these parameters, except that units may face either east or west (see Refs. (3) and (7)).

Regression analyses, to explore the determinants of the variability shown by the large sample in Figure 1, have been done several times by our group, taking the consumption in various winters and in various portions of the town as dependent variables (Ref. (8)).

The quantitative results of the regression analysis of the data shown (for the large sample of 210 townhouses) are embodied in the following linear equation:

$$\underset{}{GC} = \underset{(112)}{806} - \underset{(17)}{213D2} + \underset{(17)}{108\ END} + \underset{(21)}{75D4} - \underset{(8)}{19INS} \qquad R^2 = 0.54 \tag{1}$$

Here gas consumption (GC) is in hundreds of cubic feet* per six-month winter; D2, END, and D4 are dummy (0-1) variables taking the value 1 for two-bedroom, end position, and four-

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*If G is measured in Gigajoules and INS in m^2, the equation becomes:

$$GC = \underset{(12.3)}{88.7} - \underset{(1.9)}{23.4\ D2} + \underset{(1.9)}{11.9\ END} + \underset{(2.3)}{8.3\ D4} - \underset{(0.09)}{22\ INS} \tag{1a}$$

bedroom, respectively, and INS is the number of hundred square feet of double glass (mean = 1.4, or 13.0 m^2). Standard errors of the coefficients are given in parentheses.

Each of the numerical coefficients in Equation 1 has significance. The constant, 80600 cu. ft./winter (88.7 GigaJ./Winter, is the consumption rate for the average three-bedroom interior townhouse with no double glass, and should be compared to its design heat loss of 41,000 Btu per hour, for a 70°F design temperature difference (310 Watts/°C), or 600 Btu per hour per degree Fahrenheit temperature difference between indoors and out* (Ref. 3). The other coefficients in Equation 1 indicate that a choice of the two bedroom home reduces consumption 20 ± 2%, end units increase consumption 13 ± 2%, four bedroom designs increase consumption 9 ± 3% and insulated glass lowers consumption 2 ± 1%.

Electric consumption in summer in the Quad-II townhouses, which is almost one-half air conditioning, is uncorrelated with gas consumption in winter. Here, two possible cancelling effects are: a) those profligate with gas are likely to be profligate with electricity, and b) those preferring warm indoor temperatures in winter (and, so, setting their thermostats high) are likely to be more tolerant of warm weather in summer (and, so, will use their air conditioners less).

Regression models of summer electric consumption have had similar results to those obtained for winter gas. However, a smaller proportion of the variation has been explained by the same independent variables, between 30 and 40 percent. The size of the unit explains the most variance, but savings due to double glass and to having a north-south orientation, of 8 ± 3 percent and 4 ± 2 percent respectively, are also observed. No effects due to being an end unit are statistically significant during the cooling season.

Details of energy effects on residential housing as influenced by such factors as orientation, new owners, housing design etc. may be found in Section III of Ref. (3).

VARIATIONS WITH OUTSIDE TEMPERATURE

Winter gas consumption is strongly predicted by a linear relation involving the single independent variable: average outside temperature. This statement holds whether one is exploring individual houses or averages over many townhouses, and whether one is looking at hourly, daily, or monthly data. The strength of the outside temperature as a predictor increases both as one moves to longer time periods (and smooths over the effects of variations in sunniness, windiness, and electricity consumption) and as one averages over a larger number of houses (and smooths over the effects of absences from the house, sporadic modifications of the residence, and erratic thermostat behavior).

Figure 2 shows a plot of the mean rate of gas consumption, averaged over 16 three-bedroom, interior townhouses, versus average outside temperature, for 18 winter months, November through April of the 1972, 1973, and 1974 winters.** The data come from the monthly meter readings by the gas utility, and the gas consumption rate is plotted in cubic feet per day, so as to eliminate artificial effects of varying numbers of days between meter readings. The "average outside temperature" is actually the average of the mean daily high temperature and the mean daily low temperature during the period between meter readings, except that days where the average of the daily high and the daily low exceeded 65°F (18°C) were excluded. The average outside temperature, so defined, is also the average number of heating degree days (with 65°F reference temperature) in the time interval, and it is therefore directly calculable from National Weather Service data forms which report daily degree days. The 16 houses used to generate Figure 2 are our first set of "Omnibus" houses, where we are carrying out a series of designed experiments to study the effect of retrofits.

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*One is making several errors. The wind speed for the heat load calculation is taken to be 15 mph (24 km/h), a high value because the heat load is to be estimated for worst weather conditions (to size a furnace); winds on the average are more like 10 mph (16 km/h). Solar heating through the windows and heat generation by the appliances are entirely neglected in this calculation. Air infiltration, 33 percent of the conventional heat load (at 3/4 exchange per hour) is modeled crudely. And there are entire heat loss mechanisms involving internal air circulation, which are not included.

**Throughout this paper, the "1972 winter" is the winter containing January 1972, etc.

The Omnibus sample is somewhat enriched in houses with very high and very low rates of gas consumption; it is otherwise typical.

The data in Figure 2 show a clear pattern: one line passes through the data of the 1972 and 1973 winters (its $R^2 = 0.90$), and the data of the 1974 winter (except for April) fall below that line. The "energy crisis" of the autumn of 1973 left a strong imprint on Twin Rivers. Here we concentrate on the first two winters. The model postulated to fit the data is:

$$G + B\ (R-T), \qquad (2)$$

where G is the gas consumption rate, T is the outside temperature (assumed less than R) and the two parameters, B and R, are:

B: The basic performance index for the heating system. B measures the extra gas consumption rate required to contend with an extra °F of cold temperature outdoors. By means of this single parameter, the accomplishments of a retrofit program, for example, may be tracked with considerable accuracy. A convenient unit of measurement, used consistently throughout this paper, is <u>cubic feet</u> per degree day, (cubic feet of natural gas, with 1025 btu per cubic foot; Fahrenheit degree days), or Megajoules per °C-day. B is the slope of the line drawn in Figure 2.

R: the temperature at which the furnace first comes on in °F. R is the best "reference temperature" for degree day calculations, because then gas consumption is <u>proportional</u>, not just linearly related, to degree days. R is the temperature intercept of the line drawn in Figure 2.

The result of a least square's fit of the model to the twelve data points from the 1972 and 1973 winters is:

$$G\ \left(\frac{\text{cu.ft.}}{\text{day}}\right) = 21\text{x}\ (62°\text{F} - T) \text{ or } G\ \left(\frac{\text{MegaJ.}}{\text{day}}\right) = 42\text{x}\ (17°\text{C} - T) \qquad (3)$$

To what can we relate the system performance index, B, here 21 cu. ft. per °F-day (42 MegaJ./°C-day), and the reference temperature, here 62°F (17°C)? A simple physical model leads to Equation 2 and answers the question. It is the heat balance equation, expressing the conservation of energy:

$$e_s G + e_e E + e_s S = K(T_{in} - T) \qquad (4)$$

where G, E, and S are the rates at which gas, electricity, and solar energy are introduced into the structure; e_g, e_e, and e_s are the efficiencies by which each of these energy sources heats the structure; T_{in} is the average indoor temperature, and K is the rate at which heat is lost, per degree Fahrenheit temperature difference between temperatures inside and outside. The left hand side of Equation 4 is a simplified representation of heat gains: it omits smaller heat gains (for example, the 100-watt contribution of each person metabolizing his or her food) and lumps all electricity uses into a single term. The right hand side of Equation 4 is a simplified representation of heat losses: heat losses due to conduction, convection, and radiation will be nearly proportional to $(T_{in} - T)$, but the model neglects the effects of variable winds and the latent heat lost to the evaporation of indoor water. (K is essentially the quantity estimated in the conventional heat load calculations). The equality of heat gains and heat losses is valid only when the time interval being considered is long enough that storage effects can be neglected. Using this approach a typical winter heater assignment would be 67% furnace, 20% electric appliances and 13% solar.

The details of a two-variable probabilistic model of the gas consumption for a set of houses, temperature models for individual houses, and variations of electrical consumption are covered in Section IV of Ref. (3).

VARIATION ACROSS YEARS: CONSERVATION

Conservation in the 1973-76 Winter

The winter 1973-76 was a time of salience for energy. Twin Rivers residents were onfronted with hour-long lines at gas stations and, although they were spared the dire arnings to those whose homes were heated by oil that the supplies might not last through he winter, they were deluged with pleas to conserve, in particular, to turn down their hermostat. The data show the response that winter in gas consumption to have been by ar the largest of any response, in either gas or electric consumption, over the five years (1971-76) since the town began.

Consider the total winter gas consumption in the thirteen "Omnibus" townhouses for which data are complete, for the 1972, 1973, 1974, and 1975 winters. There were no changes of owners in those houses in that period. Three houses reduced their winter energy consumption by more than 10 percent between 1972 and 1973; eight (including two repeats) between 1973 and 1974; and two (both repeats of 1973 to 1974) between 1974 and 1975. None of the 13 increased its gas consumption by more than 10 percent in a single winter between 1972 and 1973 or between 1973 and 1974, but 3 of the 8 who came down more than 10 percent between 1973 and 1974 climbed back up more than 10 percent between 1974 and 1975. The net result of wuch two-way movement in Twin Rivers as a whole, as will be seen below, was a small additional reduction in gas consumption between 1974 and 1975.

As was seen in Figure 2, the reduction in mean gas consumption between November 1973 and April 1974 occurred in all months except April, relative to the best fit of the data of the previous two years. The absolute amount conserved was largest in the two coldest months, January and February 1974. The variation of gas consumption across houses remained exactly as it had been in the previous two years; quantified by the standard deviation divided by the mean, the 1974 winter months fall amidst those of the previous two winters, when account is made for outside temperature.

The pattern of conservation across houses over the four-month winters 1972, 1973, and 1974 have been compared for the split-level units in Quad II. At the nearby station of the National Weather Service at Trenton, there were, respectively, 3291, 3151, and 3251 degree-F-days (1828, 1751, and 1806 degree-C-days) during each four month period, and so one might have expected a drop in consumption of 4 percent from the first winter to the second and a climb of 3 percent from the second winter to the third. Instead, the pattern is approximately symmetric about the line of equal consumption for the first two winters ('73 vs. '72) and the pattern is well balanced. In contrast, the winter 74 data versus winter 73 is considerably below the line. The data clearly show the effects of an effort at conservation, and it shows, furthermore, 1) that conservation occurred whether households earlier were high or low on the scale and 2) that the amount of conservation averaged about the same independent of initial consumption level. The pattern appears quite consistent with a reduction of average interior temperature by an amount independent of the initial temperature, and it would be amusing to try to generate the pattern using two random variables, one for initial temperature, another for shift in temperature. The behavioral scientist appears now to have a second factor to explain: not only who is high and who is low but also who is responsive and who is not. The two factors appear to be nearly independent.

Conservation: A Five-Year Viewpoint

The average monthly gas consumption for 151 Quad II townhouses, in "cubic feet per degree day," is plotted for eighteen consecutive cold winter months (December 1971 through Jan. 1976) in Figure 3. This figure extends the data of Figure 2 beyond April 1974, and it "normalizes" the consumption for the effect of weather by dividing by degree days. In calculating "degree days" here, a reference temperature of 65°F (18.3°C) was used; this is nearly always the form of easily available data.

However, the intercept in Figure 2 is 62°F (18°C). The effect of using a reference temperature higher than the intercept turns data which appear linear when plotted as in Figure 2 into data which do not lie on a horizontal line when plotted as in Figure 3. The quantitative statement of the departure from the horizontal is the following:

If the gas consumption for two time periods, with average temperatures T_1 and T_2, actually falls on a straight line passing through zero gas consumption at temperature R, the values of gas consumption per degree day, calculated using a reference temperature R_o, will differ from one another by the fraction:

$$f(T_1,T_2,R,R_o) = \frac{(T_1-T_2)(R_o-R)}{1/2[(R-T_1)(R_o-T_2) + (R-T_2)(R_o-T_1)]} \quad (5)$$

of their own value. The colder the time periods being compared, and the smaller the difference in average outside temperature between them, the less it matters having the best reference temperature.

For example, if T_1 = 30°F, T_2 = 32°F, R = 62°F, and R_o = 65°F (-1.1°C, 0°C, 16.7°C and 18.3°C respectively), the value of the ratio in (5) is f = 0.006, a little more than 1/2 percent. When the ratio in (5) is large (say, 0.10 or more), either because the time periods are mild or because they differ substantially in outside temperature, plots like Fig. 2 are preferable to plots like Fig. 3.

There must be considerable utility, however, especially in a context of public policy, in having an index, like cubic feet per degree day, that gives an immediate indication of the performance of a house. Indeed, the voluntary conservation portrayed in Figure 3 can be summed up as: "The gas consumption index of the average house hovered between 18 and 19 (36 and 38) for the 1972 and 1973 winters, but dropped to a new level, between 16 and 17 (32 and 34), at the start of the 1974 winter and has stayed there ever since."

Annual average consumption per degree day will be even less subject to distortions as outlined in Equation 5: The value of the error f, will inevitably be very small, because the average outside winter temperatures will be so nearly the same from year-to-year. The annual indices for the past five winters are 17.8, 17.7, 16.4, 15.9, and 15.7 cubic feet per degree-F-day (35.2, 35, 32.5, 31.5, 31 Megajoules per degree-C-day). From the first to the last, the drop is 12 percent.*

We fully expected to find a similar pattern of conservation when we looked at electricity consumption in summer. However, there is no evidence of such conservation. The price of electricity more than doubled between 1971 and 1976, boosted by a special surcharge deliberately intended to discourage on-peak usage of air conditioners. Each summer the residents of Twin Rivers express anguish over their electric bills, and they compare bills with one another. Yet, apparently, they do not conserve (see Ref. (3)).

There was no apparent conservation of electricity during the 1974 winter relative to the average of the previous two winters. An analysis of mean consumption over houses gave average monthly winter readings of 1227, 1210, and 1207 kilowatt hours for the 1972, 1973, and 1974 winters, a negligible variation.

Price and Price Response

The price of energy has been rising at Twin Rivers. The marginal prices of both electricity and gas approximately doubled between 1971 and 1976. There is considerable interest in many quarters in capturing the joint experience of rising prices and reduced consumption in a single index, the elasticity of demand. The data are a testament to the apparent absence of any demand elasticity at all for summer electricity, including summer air conditioning.

A robust regression on annual data for gas consumption per degree day and marginal price (with no correction for inflation) tested the model (C = Gas consumed per degree day, P = marginal price) and resulted in:

$$\ln C = \ln P + (\text{const}), \qquad (6)$$

and yielded the five year average elasticity:

$$\varepsilon = -0.24 \pm 0.04 \qquad (7)$$

The R^2 of the fit was 0.91.

The data clearly tell a more complicated story than is captured by a constant elasticity, however: First, consumption went down, the price went up. There is no way in which our data can refute the economist who says "Ah ha, price anticipation!" or the sociologist who says "the conservation campaign of the mass media was highly effective" or the engineer who says "after turning the thermostat down, it wasn't easy to find the next thing to do." There is common sense in all three statements.

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*The first four "winters" here are averages over six winter months, November to April; "winter 1976" is an average over the first three months.

CONSUMPTION BEFORE AND AFTER RETROFITS

A systematic program of retrofits was launched at Twin Rivers during the 1976 winter (see Ref. (5)). By the space-age word "retrofit" we refer to physical modifications of an existing structure designed to improve its performance, in this case its performance as a system to provide comfort at minimum energy cost. Hence, the retrofits were chosen on the basis of anticipated cost effectiveness and represent first steps to take in home energy savings. The defects in the houses being addressed by retrofits will be detailed in Section 2. Here, we present some summary results concerning the savings in actual gas which resulted from the retrofits. There are two objectives here. The first is to emphasize the "bottom line": The full retrofit package reduced average winter gas consumption by 25 percent. The second is to exercise the techniques developed, to demonstrate the high level of confidence with which this claim can be asserted.

Through monitoring temperatures and electric and gas consumption, hourly, in the periods both before and after retrofit it can be shown that not only was house energy consumption reduced but also the townhouses became more comfortable, with less temperature difference between upstairs and down, and less draftiness (at least as measured by the reduced responsiveness of gas consumption to outside wind velocity). Moreover, the detailed modeling now in progress suggests that full benefit from the modifications in townhouse characteristics will not have been derived until further minor modifications are carried out. For example, it appears that the justification for lowering the fan-off temperature in the furnace control system becomes even stronger following the insulation of the ducts. The detailed data should also permit us to separate, at least to some degree, the consequences of the separate retrofit packages and to identify interactions, if the savings turn out not to be linear. Finally, the detailed data should permit some of our townhouse models to be checked, to learn, for example, whether the attic temperature was lowered as much as expected by the attic retrofits, and, if it wasn't, to gain further insight into the deficiencies of current modeling.

The choices for what is considered a first phase of retrofit were made to reduce conduction losses, lower air infiltration levels, and improve distribution of energy from the furnace. The basis for the choices were data from the instrumented homes, infrared scanning information, air infiltration monitoring, and special experiments in the rented townhouse (5). Group A, located in the attic, emphasized reduced conduction loss by raising the insulation level to R-30 (0.19 $W/m^2{}^\circ C$) as well as sealing the crack existing between the attic frame floor and the masonry firewalls (outside caulking of this frame - masonry joint is also included). Group B, located in the basic living area, concentrates on improved door and window seals to reduce air infiltration losses. Improved tightness of the basic living area with reduced drafts and increased comfort was the aim here. Caulking around window frames was also included both inside and out. Group C, located in the cellar, emphasized the reduction of the losses from the warm air ducts and registers to this lightly used area and reduced the losses from the hot water storage tank. Two inch-thick fiberglass duct wrap with aluminum foil backing was used in both cases. Insulation also extended to the living room window overhang which included two ducts and registers. In addition to the three retrofit groups just described, in all but a limited number of control homes, the air shaft connecting the basement to the attic (surrounding the furnace flue) was sealed at the attic floor (Group D). The primary effect of this seal is to reduce air infiltration loss of warm air from the basement to the attic (see Refs. (3) and (5).

The retrofits were implemented in two segments during the week of January 19-23 and during the two weeks from February 13 to 27. Eight of the sixteen houses received retrofits in the first period, only two of them received the full package. By the end of the second period all sixteen had received some retrofit. The effect of the first series of retrofits was visible almost instantly in the data obtained by daily monitoring of the gas and electric meters. Figure 4 shows two average rates of gas consumption, one for the eight "control" houses. Averages were computed every four days, and variations in weather were crudely incorporated by dividing by the degree days based on a 65°F (18.3°C) reference temperature. The two lines were nearly one before the retrofits were performed (the selection of the "first eight" was made in part to accomplish this) and separated immediately into two groups one having a performance index averaging just above 15 cubic feet per degree day (30 Megajoules/°C-day) and the retrofitted group averaging around 12 (24 Megajoules/°C-day).

Neither before nor after retrofit were the average gas consumption rates flat over time. Figure 4 gives a clue about the source of the detailed variations of the lines, for it shows the four-day average outside temperature moving roughly oppositely to the gas consumption rate. This is what one would expect if the data (of gas consumption versus outside temperature) in fact lay on a line with a lower intercept than 65°F (18.3°C), as was seen in the plot of monthly data in Figure 2. In Figure 4 it is clear that this correction alone cannot account for all the variations! When the period over which data are averaged becomes as short as four days, effects of variations in average windiness and sunniness begin to be exhibited. Nonetheless, the first step in flattening the characteristic performance index does seem to be to adjust for a lower intercept; following the method embodied in Equation 5 (with R set equal to 62°F or 16.7°C), whenever a comparison is made between performance indices for period differing appreciably in average outside temperature.

The nine fully retrofitted (ABCD) houses become a fascinating subset for further study. Table 1 shows the remarkable extent to which the nine houses retained their identity as high and low users of gas: the breakdown into 2 houses high, 5 houses in the middle, and 2 houses low was preserved, except for one small switch. (The correlation between pre- and post-retrofit for these nine houses was 0.81.) Moreover, the coefficient of variation within the group did not diminish: both before and after, the standard deviation was 17 percent of the mean.

These results can only be accounted for in one of two ways: either the reasons for such variation are structural, but lie in areas untouched by our retrofits (e.g., the performance of the furances) or they are behavioral. As discussed previously, this cannot be a sharp line, for people often express their behavior by doing something to the structure, and variations in temperature setting alone do not give the full explanation. We appear to be left with the fascinating quandary that large differences in consumption can result from variations in behavior within the houses that are not related to gross defects in structure nor to interior temperature settings (even though both of the latter are important). Examples of such behavior are whether interior doors are left open or closed and when drapes are drawn. Such explanations of variability across houses still lie in the future.

We are inevitably asked about the payback period for the savings observed. The AD and C retrofits were done by contractors, at $190 and $135, respectively. The B retrofit was done by our technicians; per house, the materials cost approximately 25 dollars, but the labor would have brought the total cost to at least $75 (although many households would have accomplished this task during their "spare" time). At $400 per house, 3 dollars per million btu ($3 per Gigajoule), 80 million btu or Gigajoules (800 hundred cubic feet) per winter, and 25 percent savings, the payback period considering only winter savings comes to 7 years.

There are several reasons why this is a very high estimate of the payback period: 1) Savings in summer and in winter electricity are not included; they are currently being documented, however, estimates are that this item alone will reduce the payback period to less than 3 years (Ref. 5). 2) The cost of natural gas is almost certain to go up, in constant dollars. 3) Once the effects of the various retrofits are separated from one another, a more cost-effective package of retrofits can be recommended; e.g., if the attic retrofit alone saved 15 percent, its payback period would be 4 years or if the water heater wrap were separated from C, the payback period would be a few months. 4) No price is placed on improved comfort, a very important consideration before items such as night setback can even be considered. 5) Finally, in some circumstances, neighbors and entire communities, bargaining collectively, should be able to obtain even lower prices for the retrofits.

SECTION 2: A CLOSER LOOK AT THE TOWNHOUSE

The energy flow between the townhouse and the outdoors and within the townhouse itself can be modeled at varying degrees of complexity. Questions arise as to how many zones should be considered in this home heat transfer problem. How should the heat generated by the furnace, the appliances, the people and the sun be distributed? What about the boundary conditions imposed by weather and ground temperature or, in the case of the townhouse, the temperature of the neighbors' houses? The combination of internal heat sources and external boundary conditions will determine the equilibrium temperature(s) inside the house.

In a one-zone model of the townhouse, the interior heat sources are assumed to be uniformly distributed in space; they are best characterized by their heat output per unit time, rather than by some temperature. For example, the townhouse furnace produces 80,000 btu per hour (23.4 kilowatts) of heat when running steadily, of which a certain fraction, the overall furnace efficiency, actually heats the house. The appliances provide heat to the dwelling in varying amounts. The refrigerator and the range (where it is not vented) return all the heat they generate to the townhouse, as is the case for the smaller appliances and lighting. The dryer exhausts most of its heat to the outside. In the case of the water heater only about .3 of the used energy aids in heating the house. Each occupant provides approximately 400 btu/hr (100 watts).

The solar flux entering the house through the front windows (with a measured optical transmission of 75% for double glass, assuming the drapes are completely open) can be described as a heat source with a maximum level on a sunny Dec. 21st (12:40 EST) of 17,000 btu/hr or 5 kilowatts (for a townhouse with the most favorable orientation) and a year round, all-orientation and weather average of 1500 btu/hr of .44 kw.

Just as the internal heat sources are best characterized by their heat production, the boundary conditions are best thought of in terms of temperatures that, in conjunction with internal heat sources, determine the heat flux across the house boundaries and the equilibrium inside temperature. The outside weather influences the thermal balance of the house primarily through the air temperature, the wind velocity and the solar flux intensity. The solar flux striking the walls and the roof and the infrared radiation exchange between house surface and the sky can be combined with the prevailing air temperature to determine the "sol-air temperature,"* that will then be treated as the new outside temperature, different for the two outside walls and the roof. On a sunny summer day, the sol-air temperature for a wall facing the sun may exceed the air temperature typically by 20-70°F (11-39°C), depending on the time of the day.

Wind enters our heat transfer problem in two ways: high wind speeds both increase the outside film coefficient of the shell and the air infiltration, raising both convective-radiative and mass flow heat transfer through the house shell. The ground temperature and the indoor temperature of the next door neighbor (for row houses) play a minor, although not negligible, role at the remaining boundaries.

Recapitulating, the apparent complexity of a house can be reduced: the house is idealized as an internally heated and cooled box with a prescribed temperature distribution along its boundaries. If transient effects are neglected, the inside box temperature resulting from our heat transfer problem will be

$$T_{in} = \frac{\sum_j Q_j + \sum_i U_i A_i T_i}{\sum_i U_i A_i} \quad . \qquad (8)$$

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*The sol-air temperature is that temperature which, in absence of all radiation exchange, will cause the same heat flux through the outside walls or the roof, as the combined effect of simple air temperature, solar radiation and infrared radiation exchange (Ref. 12). The energy balance then requires:

$$\alpha I_d + h(T_A - T_S) - \varepsilon \; R = h(T^* - T_S)$$

where α is the wall absorption for solar radiation, ε is the wall emissivity for infrared radiation, h is the wall surface convective-radiative film coefficient, I_d is the direct solar radiation incident on the wall, R is the net infrared radiation exchange from wall to sky, T_A is the air temperature, T_S is the wall surface temperature, T^* is the sol-air temperature. The result is:

$$T^* = T_A + \frac{\alpha}{h} I_d - \frac{\varepsilon}{h} R$$

I_d varies between 30 and 300 btu/(hr sq. ft.) or between 100 and 1000 w/m^2,

$\frac{\alpha}{h}$ varies between 0.15 and 0.30 (°F hr. sq. ft.)/btu (.026 - .052 (m^2°C/w)),

$\frac{\varepsilon}{h}$ R is about 0 for vertical walls (because of adjacent building reflectivity) and about 7°F (4°C) for roofs.

where $\Sigma_j Q_j$ is the sum of all internal heat sources, counting the air conditioner as a negative source

U_i the U-value of the i-th part of the box boundary

A_i the corresponding area

T_i the corresponding temperature i.e., sol-air, ground, or next door neighbor temperature.

The thermostat varies the share, say Q_j, of the furnace or the air conditioner in the term $\Sigma_i Q_i$ in such a way, that T_{in} remains approximately constant.

The real house, however, departs from this simple model in that: 1) there is no uniquely determined house temperature T_{in}, 2) the heat sources are not distributed homogeneously and 3) the house, through partitions and floors, is broken into zones of relatively constant temperature, each satisfying its own heat balance. This requires detailed attic, basement and interior models to adequately describe thermal events.

An item of the overall house model that deserves more detailed discussion is the heat distribution system. The heat actually distributed under steady-state operation is shown in Figure 5. Only 50% of the heat content of the air entering the plenum end of the system reaches the register ends by means of forced convection. About one third of the heat entering the plenum leaks into the basement, another one sixth heats the walls enroute. The communication among zones, the heat capacity of the wall structure and the rate of basement air infiltration determine how much of the furnace output will heat the living space and how it will be distributed between zones. A further reshuffling of the heat distribution caused by the unsteady operation of the furnace and its blower will be discussed in the next subsection.

Another complex issue that influences heat transfer is air infiltration. Direct measurements of air infiltration rates have been made in several townhouses using our automated air infiltration units (Ref. 6). Up to a week of data are obtained in a single run, with output recorded every fifteen minutes or even more often. About 10cc of sulfur hexaflouride (SF_6) are injected into the house (whose volume is about 3×10^8 cc, so that the initial concentration is about 30 parts per billion) and concentrations are read at regular intervals until the concentration drops by a factor of 2 to 10, at which point reinjection occurs. The rate of decay of concentration is a measure of the air infiltration rate of the house: measured values range over a full order of magnitude, roughly from 0.25 to 2.5 home air exchanges per hour.

Underlying our first attempts to analyze the data was a model of the house as a single* well-stirred volume of air, $\hat{V}$, sustaining a single concentration of SF_6. At any given moment, outside air is being added to that volume at some rate, F, and at an equal rate inside air is leaving the house. The measured air infiltration rate, AI, with units of inverse time, satisfies the equation

$$AI = F/\hat{V} \qquad (9)$$

The heat loss associated with that air infiltration rate, assuming that the air enters the house at the outside temperature and warms all the way up to the inside temperature before leaving, is then

$$(\text{Heat loss from air infiltration}) = \rho C_p F \cdot DT = \rho C_p \hat{V} \cdot AI \cdot DT \qquad (10)$$

where ρ and C_p are the density and specific heat of air at room temperature.

Equation 10 neglects an additional source of heat loss associated with air infiltration: the energy of humidification. If the air leaves the house carrying more water vapor than it had when it entered, the energy to evaporate the water into the air must be extracted from the energy sources within the house. The supplementary energy penalty of a humidifier

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*The basement tends to act as a second zone if the basement door remains closed.