THE TWIN RIVERS PROGRAM ON ENERGY CONSERVATION IN HOUSING: FOUR-YEAR SUMMARY REPORT

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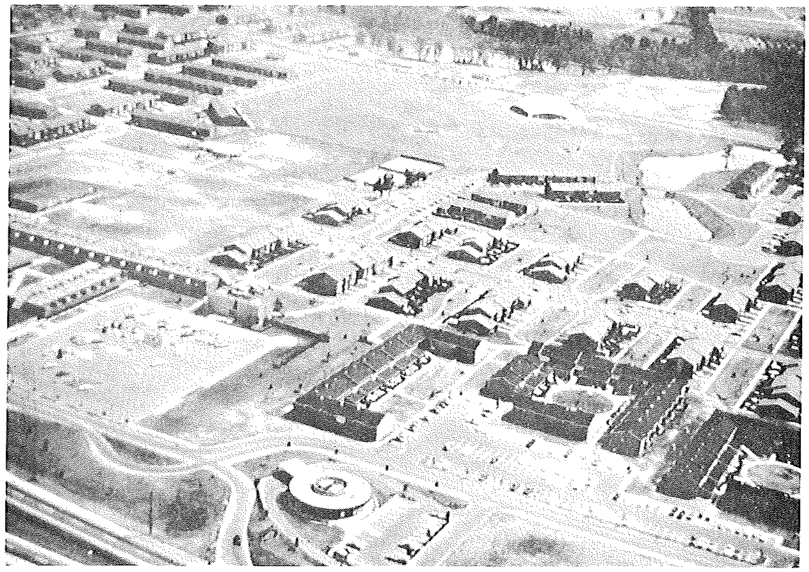
I. INTRODUCTION

Since July 1, 1972, our research group at the Center for Environmental Studies at Princeton University has been engaged in an enterprise 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 heating, air conditioning, and appliances. Our research approach has strongly emphasized field studies at a single site, the recently built planned unit development of Twin Rivers, N. J., twelve miles from our campus. About 12,000 people are living in close to 3,000 homes. Our group 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 (so far) twenty-eight townhouses (all identical in floor plan), and rented and occupied another of these townhouses ourselves, turning it into a field laboratory.

Photo Page 1 shows an aerial view of Twin Rivers, and a front view of the townhouse we have rented. Twin Rivers consists of a mix of industrial, commercial, and residential structures, and the latter include single family homes, townhouses, and apartments. Our weather station was placed on top of the town's bank (at the central foreground of the aerial photograph), in part to provide security for the equipment. The majority of the work described in



AERIAL VIEW OF TWIN RIVERS QUADS I AND II, LOOKING SOUTH-EAST. DARK ROOFS ARE APARTMENTS, LIGHT ROOFS ARE TOWNHOUSES. CIRCULAR BUILDING IN FOREGROUND IS THE BANK, WHERE OUR WEATHERSTATION IS LOCATED. GEODESIC DOME AT TOP IS SCHOOL.

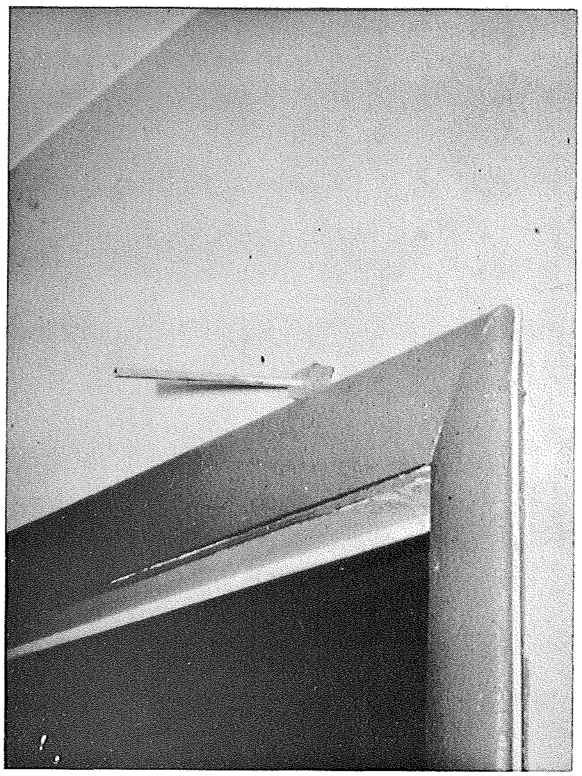
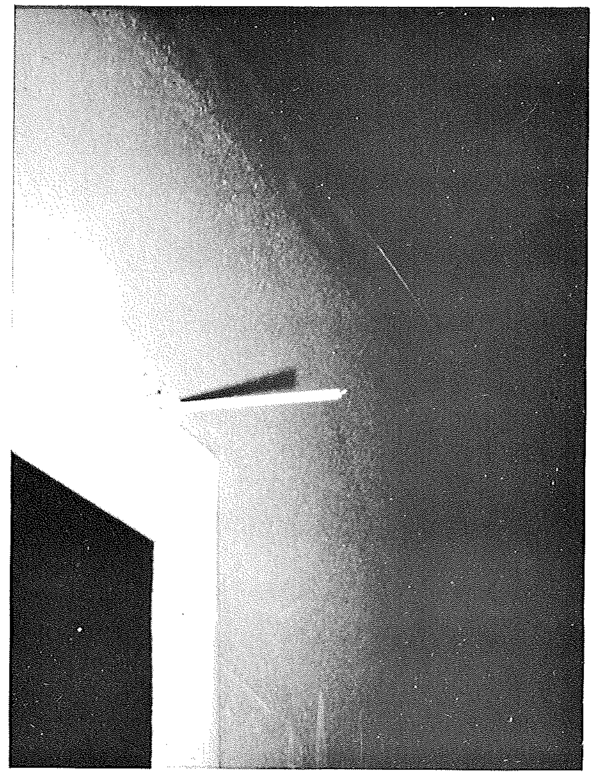
FRONT VIEW OF QUAD II TOWNHOUSE RENTED BY PRINCETON. MASONRY FIREWALLS PROJECT BEYOND THE STRUCTURE IN BRICK. CENTRAL PROJECTION (WITH WINDOWS OF LIVING ROOM AND MASTER BEDROOM) TERMINATES ONE FOOT ABOVE GROUND LEVEL (BEHIND BUSHES).

this report was carried out in the two-floor Quad II townhouses (at the top left of the aerial photograph), 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 and roof, and provide approximately 720 square-feet (65 m^2) of space on each floor. They sold for approximately $30,000 when they were built, and sell for about $40,000 now when there are resales.*

In general, we have worked in houses that are as identical as possible, and duplicated our instrumentation as well. Photo Page 2 shows two thermistors measuring "hall temperature" above the door to the basement in two of the twenty-eight three-bedroom townhouses where we have made that same measurement.

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 model family, their townhouse is the first home they have owned, and their roots are in apartments in New York City. About half are Jewish, ninety-six percent are white, most of the fathers are mobile professionals, and the family annual income, at time of purchase, averaged $20,000. A large

*Details of the Twin Rivers townhouses are found in Appendix A, and the local weather in Appendix B.

TYPE YSI #44204 LINEARLY-COMPENSATED THERMISTORS READ TEMPERATURE ABOVE DOOR TO BASEMENT IN HALLWAY OF TWO "IDENTICAL" TOWNHOUSES.

number of the fathers commute to New York City on buses that leave Twin Rivers every five minutes in the morning; the town is one-half mile from Exit 8 of the New Jersey Turnpike, and the 50-mile trip takes 55 minutes.

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 $\pm 2^{o}F$ in winter), in the interest they have for their homes (four years later, some of the originally unfinished basements have dropped ceilings and paneled walls, others are as bare as at the time of purchase), in their attitudes toward sun and toward dryness, and in their (at least expressed) concern for saving money. 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.

This report is confined to the "engineering" portions of the research program, 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, studies which are available in other reports of our group.* This report is divided into two main parts: Part One cites the results that could, in principle, have been obtained without doing

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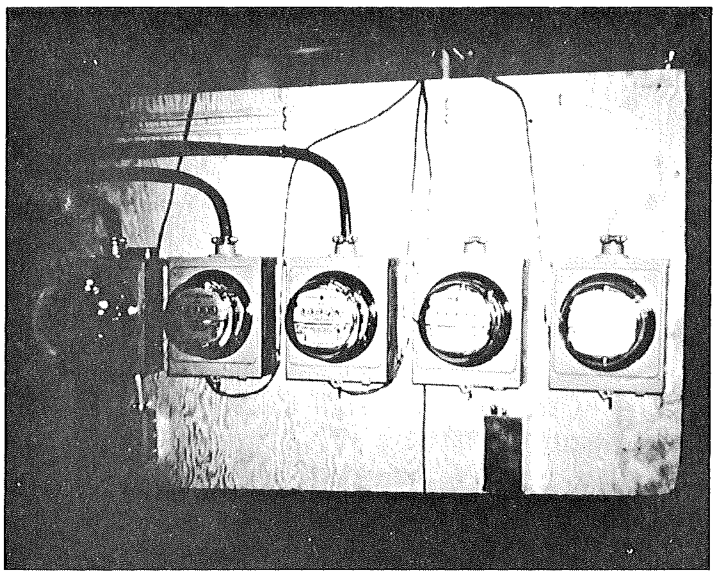
*A chronology of the building of Twin Rivers, however, is included here, in Appendix D. A complete list of Princeton reports to date constitutes Appendix G.

measurements within the houses. Our 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. Part One presents a quantitative description of both the voluntary conservation which occurred following the "energy crisis" in the autumn of 1973 and of the results of our deliberate modifications ("retrofits") of the townhouses this past winter.

Part Two describes results which required our entry into the townhouses, first of all to look around, but also to leave instruments behind. Three highly instrumented townhouses (HIT 1, HIT 2, and HIT 3) have produced a total of 200 channels of data which have been transmitted over telephone lines to our research laboratory at the engineering school.* 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).

Photo Page 3 shows the bank of electric meters by means of which we broke down the electric load onto its major components; in particular, this permitted us to separate out the huge contribution

*Some details about instrumentation are found in Appendix E.



BANK OF ELECTRIC METERS IN TOWNHOUSE BASEMENT SEPARATE THE USAGE OF AIR CONDITIONER, HOT WATER HEATER, RANGE, DRYER, AND EVERYTHING ELSE.

ELECTRIC HOT WATER HEATER FOLLOWING RETROFIT. WRAPPED IN FOIL BACKED R-7 INSULATION.

of the hot water heater.* The Photo also shows one of the hot water heaters post-retrofit, wrapped in two inches of foil-backed fiberglass to reduce standby losses (with a handsome payback period).

The remaining twenty townhouses have been more lightly instrumented, with a 9-channel "Omnibus" package that writes 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 assist in the efforts, on a global scale, to conserve energy in housing. The reader of Section Two, we hope, will become persuaded of the necessity of a <u>field</u> approach to energy conservation. The Twin Rivers townhouses are not badly built. Yet there turned out to be generic problems related to details of design, which, on criteria of cost effectivenss, became the first order of business in a retrofit program. An observer with some experience and training had to be on the scene to pinpoint these problems and to advise on remedies.

Photo Page 4 shows two such interactions. In the photo at the top, Richard Grot,** of the National Bureau of Standards (a co-inventor of the research program, with Harrje and Socolow, when he was on the faculty at Princeton) adjusts the controls of the Bureau's infrared

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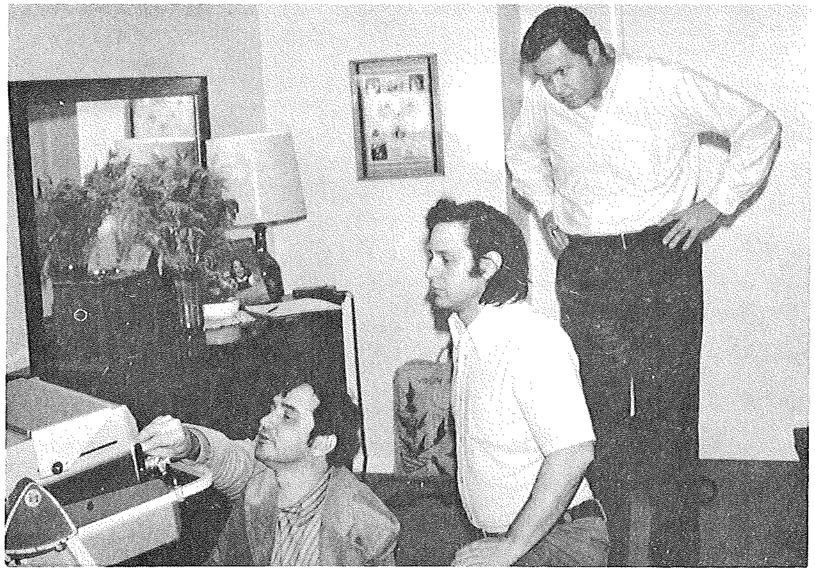
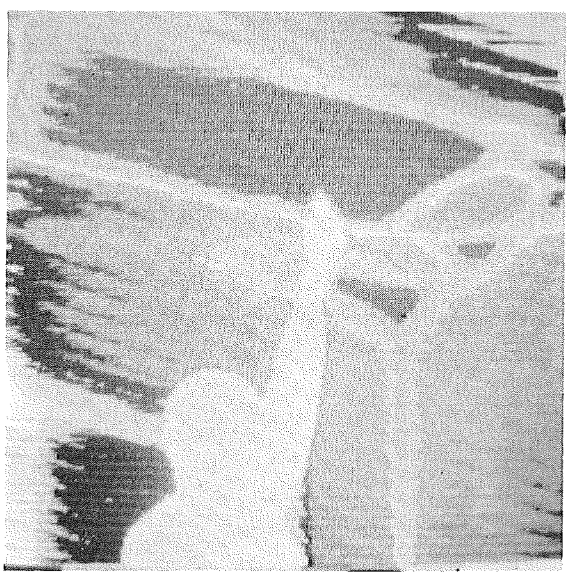
*For more details about appliance use, see Chapter X.

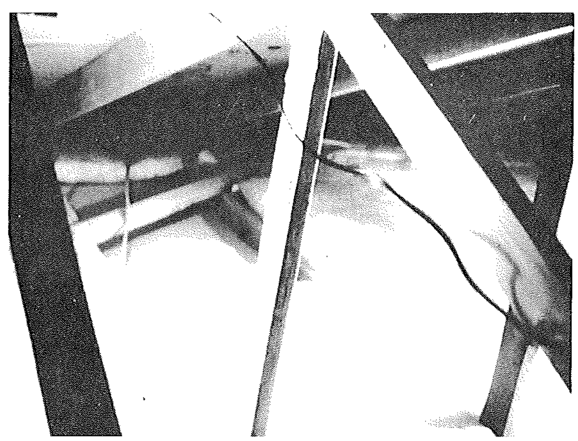
**Appendix H contains a complete list of all those associated with the research program here at Princeton over the past four years, and a partial list of those beyond the university who have assisted our research, including members of our advisory committee, program monitors, supporters of satellite research programs, and subjects of interviews.



INFRARED EQUIPMENT IN MASTER BEDROOM, BEING TUNED BY RICHARD GROT, NATIONAL BUREAU OF STANDARDS, AND WATCHED BY LYNN SCHUMAN (N.B.S.) AND OWNER OF HOME.



INFRARED PHOTO REVEALS ANOMALOUS COLD PATCH IN UPSTAIRS CEILING.



CAUSE OF PATCH IN LEFT PHOTO IS TRACED TO MISSING BATT OF ATTIC INSULATION.

camera. Behind him is Lynn Schuman, his research assistant, and behind him is the owner of the house. The equipment is in his bedroom. In another such bedroom, when the small camera scanned the ceiling, it picked up a thermal anomaly (bottom left) which was confirmed to be a missing panel of insulation (bottom right).

The intrusion shown by Figure I-4 is probably more substantial than it needs to be. It is a central and continuing goal of our research group to assist in the invention of a kit of instruments and algorithms that can diagnose a house in minimal time and at minimal cost.

The research program is not at an end. Both of the sponsoring agencies, the Energy Research and Development Administration and the National Science Foundation, are continuing their support, and several of the satellite programs remain in effect. However, a plateau has been reached: at least in broad outlines, we know what needs to be done. 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 one of them a reasonable goal would be 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 on window coatings and low-speed aerodynamics to legislative iniatives on building codes and reforms of the mortgage market. The applied research community will be called upon for more disciplined models (the morass surrounding the subject of "oversized" furnaces is one of many from which energy-use-in-a-house must be extricated), 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. In all these areas, our group hopes to remain fully involved, and it hopes to have more company.

Part One

What You Can Learn From Outside the House

The dependent variable, over and over again in this section, is the gas consumed at the furnace or the total electricity consumed by appliances, as metered monthly by the two public utilities. Our data run from 1971 to 1976. Gas and electricity consumption will be tracked: 1) across months, to develop a typical yearly profile in units of both energy and dollars (Chapter II); 2) across houses, to establish the roles of structure and behavior in the observed variations in consumption in similar units (Chapter III); 3) relative to outside temperature, to establish the extraordinary robustness of that physical variable and its ability to underpin useful and simple physical models (Chapter IV); 4) across years, to explore the energy conservation that has occurred since the "energy crisis" in the autumn of 1973 (Chapter V); and across the same houses before and after our program of physical modifications, "retrofits," in the winter of 1976 (Chapter VI).

II. YEARLY PROFILES OF ENERGY USE

In this chapter we discuss how the average Twin Rivers resident uses the town's two main energy carriers - gas and electricity - during the year. Figures II-1 and II-2 present the rate of energy consumption across months averaged over the 248 two-floor townhouses in Quad II at Twin Rivers. In these townhouses, gas is used exclusively for space heating (and, rarely, for outdoor barbecues). Electricity is used for all other purposes and adds up to about 6,000 kilowatts for the entire town, half a percent of the electric power produced at an average power plant.* Therefore, we use data on gas and electric consumption from 1973, and we normalize the variable (and non-coincident) periods between meter readings to 30-day periods. The spread in consumption of each energy source may be seen from the markers of one standard deviation departures from the mean.**

Gas consumption and electric consumption are normally measured in different units, hundred of cubic feet and kilowatt hours,

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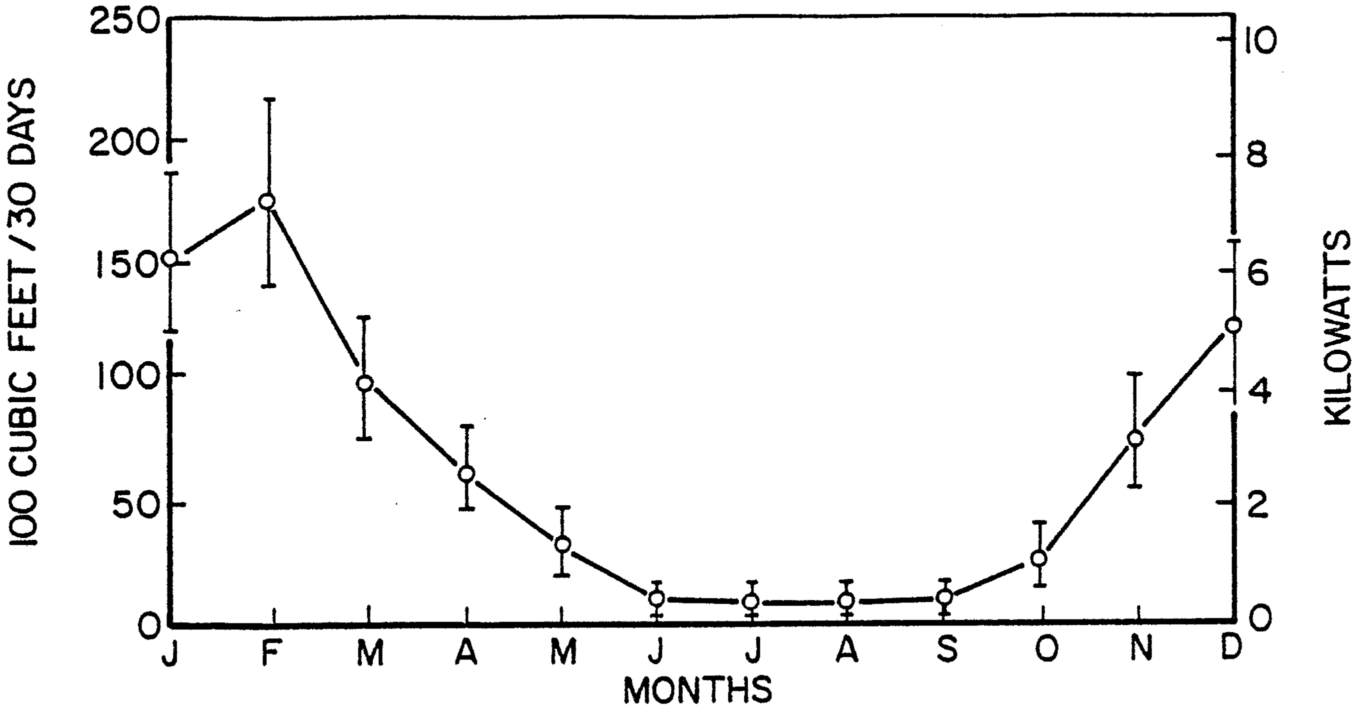
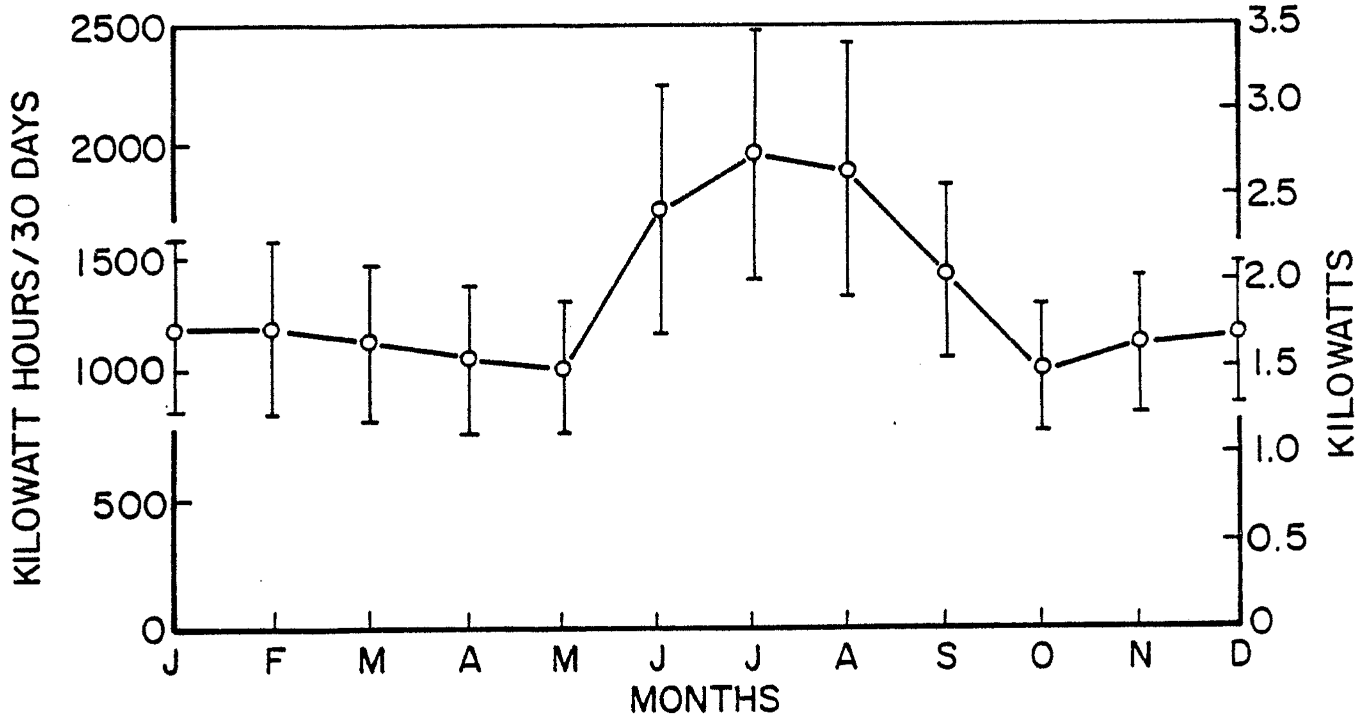
*As discussed in Chapter V, the year to year variation in per house energy consumption over the 4-year period 1971-75 is quite small, with the exception of a 10% conservation in gas use from the 72-73 to the 73-74 winter.

**For gas, the coefficient of variation (the standard deviation divided by the mean) is systematically larger in the mild months than in the cold months (it is 0.32 in November and 0.29 in April, compared with 0.23 in January and 0.22 in February), a fact to which we return in Chapter IV. For electricity, the standard deviation is roughly proportional to the mean, that is, the coefficient of variation hovers around .28 with an excursion, never larger than 0.03 that appears to us to be random. It is, specifically, not larger in the summer; air conditioning does not impose a large randomizing element, contrary to our expectations.



MEAN AND STANDARD DEVIATION OF 1973 GAS CONSUMPTION

FIGURE II-1

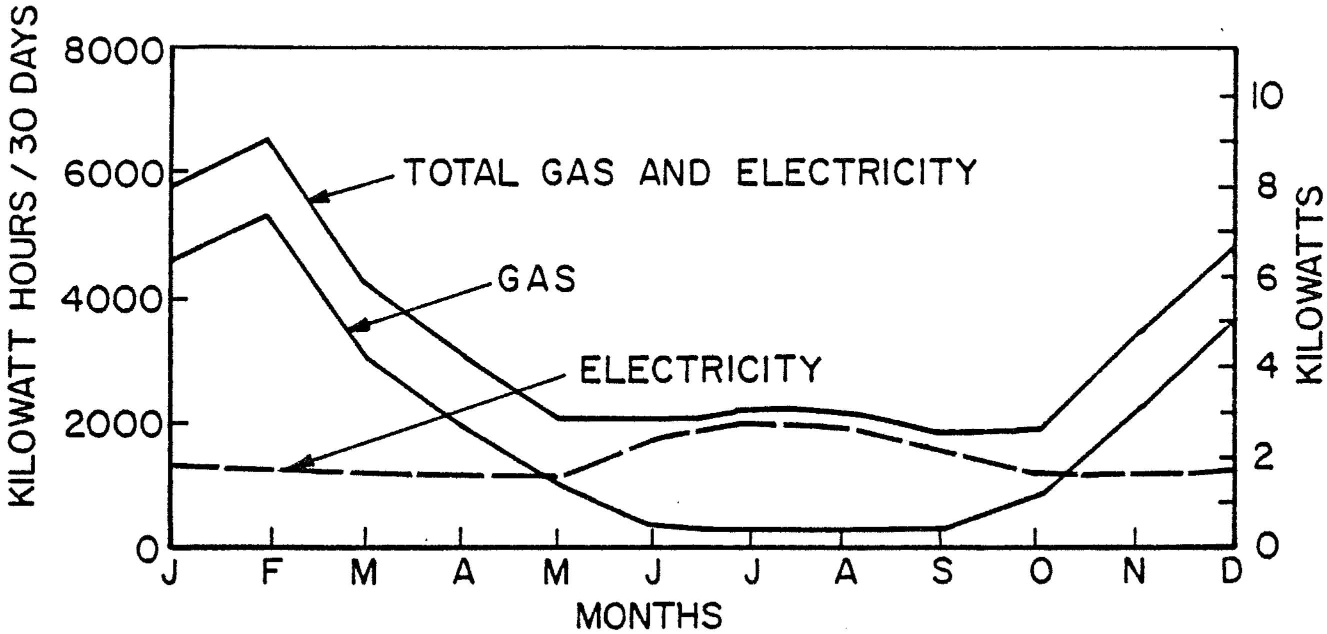


MEAN AND STANDARD DEVIATION OF 1973 ELECTRICITY CONSUMPTION.

FIGURE II-2

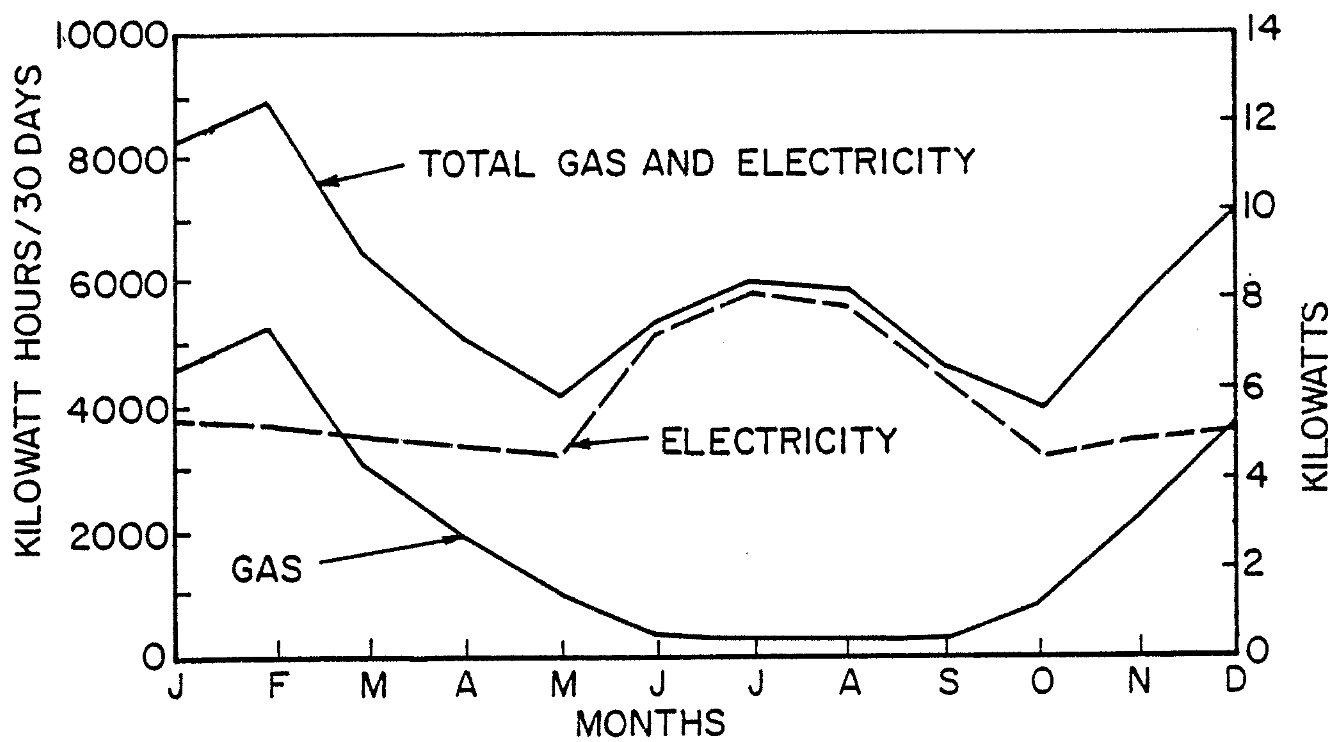
respectively, and they are rarely superposed. We do so, however, in Figures II-3 and II-4, for the units are commensurable: both are units of energy. One may argue, nonetheless, about the best way to combine them. Figure II-3 converts one energy unit into the other by considering the thermal energy content, at the house, of the chemical energy in the gas and the electrical energy in the wires. (Then 1 cubic foot = 1025 btu and 1 kw-hr = 3413 btu.) Figure II-4 converts one energy unit into the other via consideration of the fossil fuel energy consumed by the economy to provide the gas and electricity: to do this, the electrical energy is simply weighted by a factor of three, which represents the conversion inefficiency of the electric power, while the gas energy is left unchanged. (In the process, various 10-percent effects are swept under the rug, including the energy used to pump the gas from Louisiana and the electrical energy losses in power lines and transformers.)

Figures II-3 and II-4 give rather different impressions of the relative significance of gas and electricity: Figure II-3 gives the correct impression that during the winter the thermal content of the electrical energy used for appliances plays a subordinate, but far from a negligible, role in the thermal energy balance of the house. (In May and October, the thermal content of the energy used is about equal.) The "second use" of electrical energy consumed in the home (as thermal energy) deserves a closer accounting than it has generally received; as we will see in Section Two, a kilowatt hour



RATE OF THERMAL ENERGY RELEASE AT THE HOUSE BY GAS AND ELECTRICITY USE

FIGURE II-3



RATE OF FOSSIL FUEL ENERGY CONSUMPTION FOR GAS AND ELECTRICITY USE

FIGURE II-4

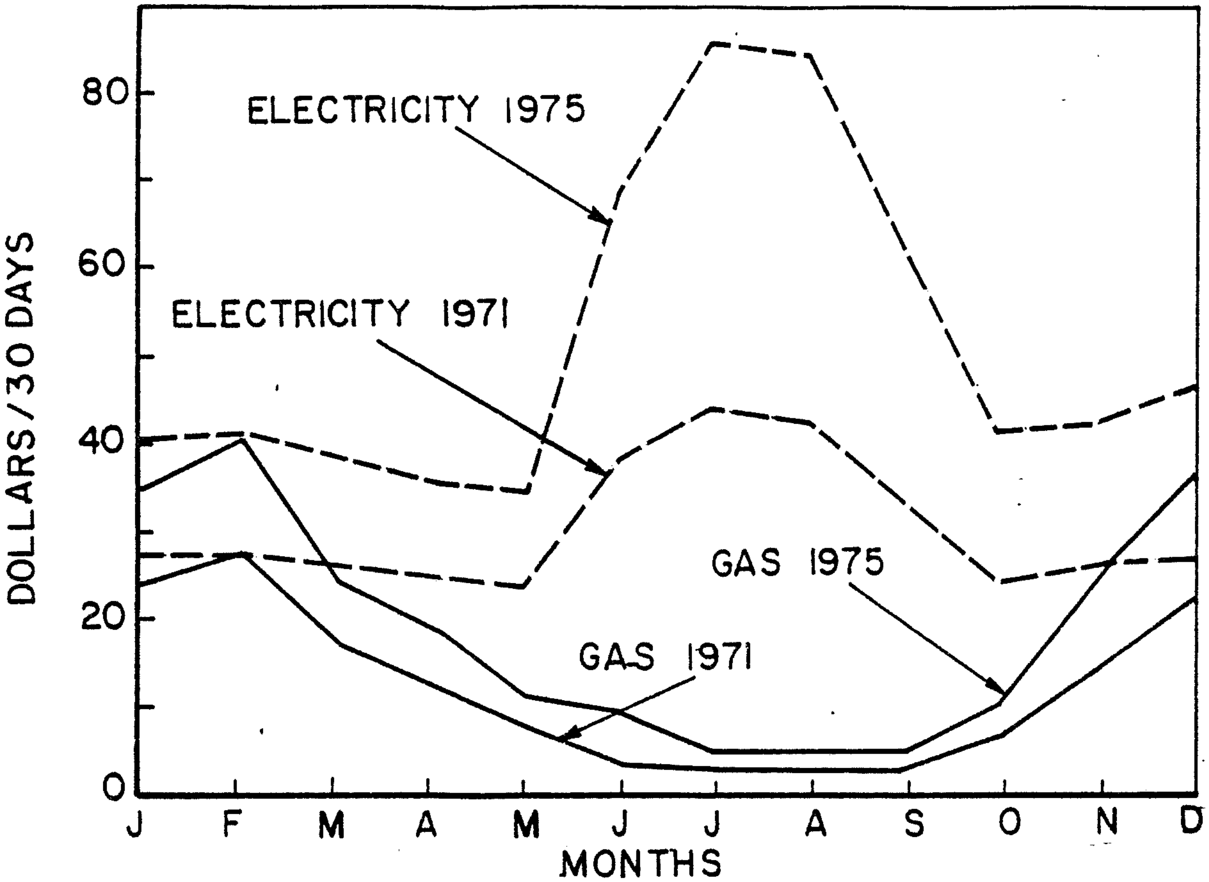
used by the hot water heater at Twin Rivers plays a much smaller role in the thermal energy balance than a kilowatt-hour used by other electric appliances. An analogous "second use" for gas in the summer time is, fortunately, small, for it is a perverse one: the 7 hundred cubic foot per month gas usage from June to September is for pilot lights, almost none of which are shut off: the electric air conditioners probably consume some additional energy to remove that heat.

Figure II-4 gives the correct impression that in terms of the drain imposed on natural resources, space heating is dominated by appliance use: of the approximately 72,000 kilowatt-hours released by the combustion of fossil fuels to supply a Twin Rivers house annually, about one-third (24,000 kw-hr) is released by burning gas at the furnace, and about two-thirds (48,000 kw-hr) is released at some electric power plant, providing 16,000 kilowatt-hours of electricity at the home. Our more detailed field measurements permit us to break down that latter annual total roughly as follows: 8,000 kw-hr for hot water heating, 2,500 kw-hr for air conditioning -- all appearing in the summer bulge in Figure 1, 2,500 kw-hr for refrigeration, and 3,000 kw-hr for eveything elese. Relative to national averages (as found, for example in the oft cited SRI report), space heating is about on target, while the non-space heating amenities at Twin Rivers require about twice as much energy -- the first, because Twin Rivers has an average climate (4500 degree days), and the second, because the houses are heavily applianced (containing a

2-ton, 24,000 Btu-hr central air conditioner, an 80 gallon, 4.5 kw hot water heater, a 15 to 18 cubic foot refrigerator, range, washer, dryer, dishwasher, and, more often than not, two TV's and a freezer).

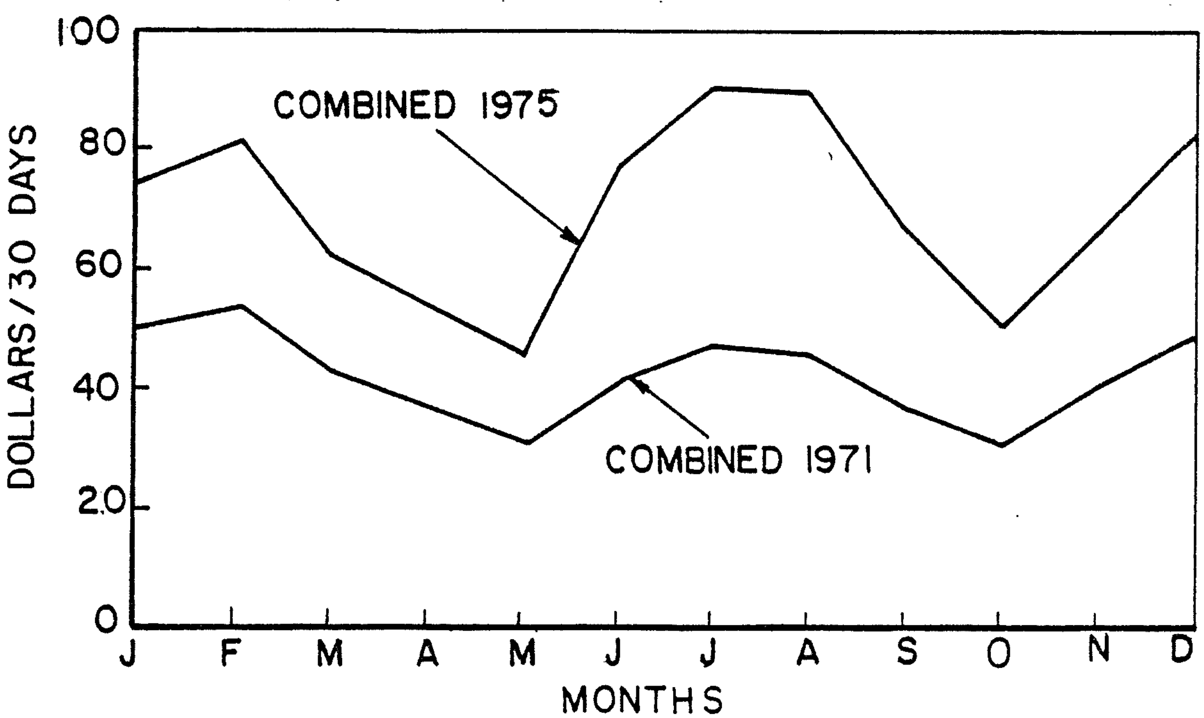
The relatively greater significance of electricity as opposed to gas is even more conspicuous when the two sources of energy are combined by their recent dollar costs, as in Figures II-5 and II-6. Figure II-5 gives the average per house costs over months of gas and electricity separately, using the 1973 energy profile of Figure II-3 and 1971 and 1975 rate schedules. Figure II-6 shows the combined utility bill delivered monthly to the average townhouse resident in 1971 and 1975. The costs to the homeowner of both energy sources have increased by about two thirds over the four years, but the relative costs have changed little.* The total cost of a year's worth of gas has climbed from $138 to $221; the total cost of a year's worth of electricity has climbed from $359 to $616. The strong emphasis on gas space heating in our research cannot be justified on the basis of costs alone; we have addressed so much of our attention to space heating in part because physical models are particularly powerful tools in that analysis and in part

*Details of the recent price histories of electricity and gas at Twin Rivers are found in Appendix C, including a special June through October 0.7 cents per kilowatt hour increase for electric consumption over 800 kwh. This measure, in force since June '75, shows up as a higher 1975 summer bill compared to winter 1975, while for 1971 the opposite is true.



AVERAGE MONTHLY ELECTRICITY AND GAS BILLS FOR QUAD II TOWNHOUSES FOR 1971 AND 1975

FIGURE II-5



AVERAGE MONTHLY COMBINED UTILITY BILLS FOR QUAD II TOWNHOUSES FOR 1971 AND 1975

FIGURE II-6

because gas is becoming rapidly more scarce, to the point where, in New Jersey at least, there is a direct connection (almost, for politics may intervene) between saving a cubic foot in a residence and having an extra cubic foot available to keep a factory operating. The coming scarcity of natural gas is probably not yet fully internalized in the regulated price, and a future renormalization of Figure II-6 is to be anticipated. That will give gas a larger fraction of the total dollar outlay for household energy.

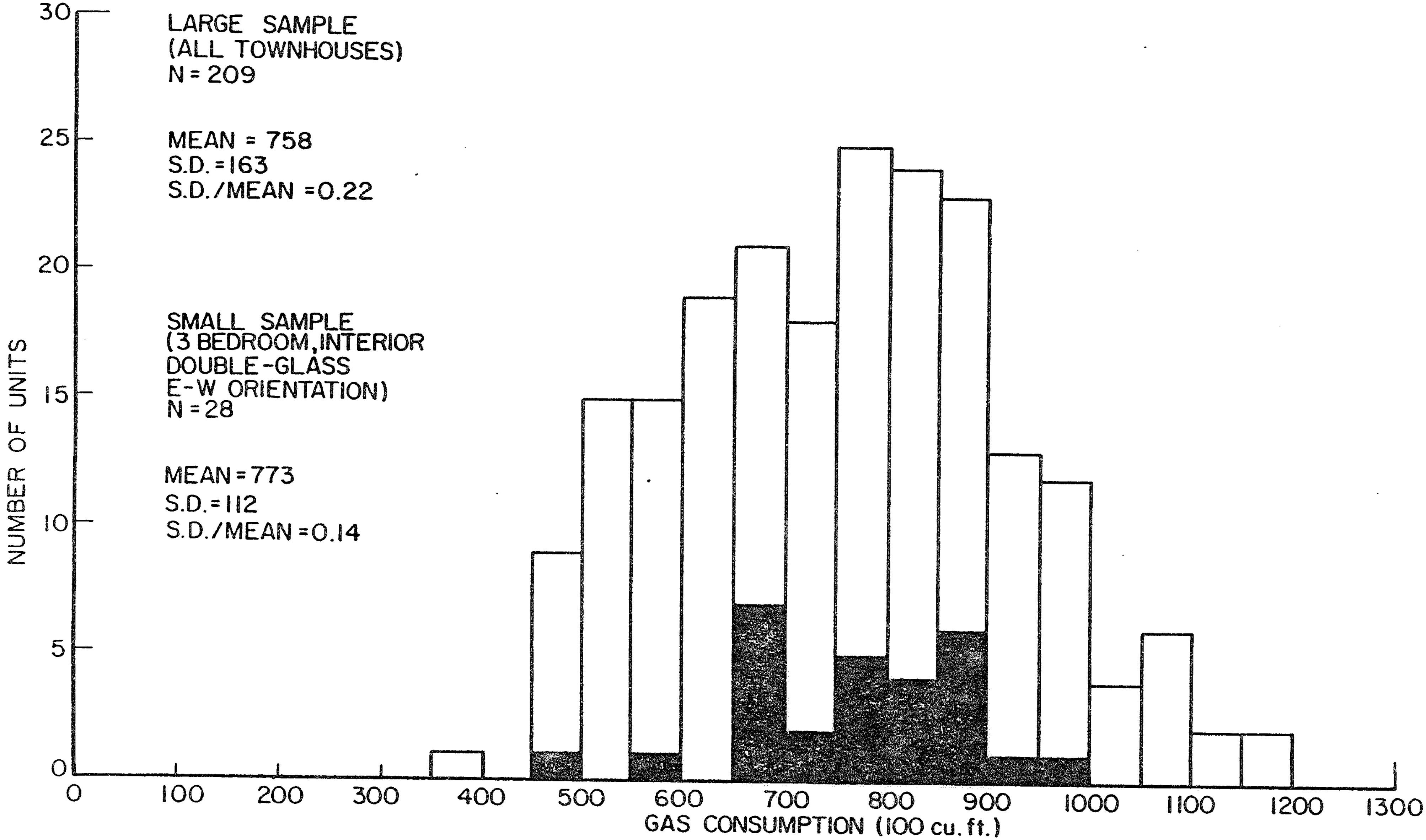
III. VARIATION ACROSS HOUSES

A. Introduction

In this chapter, from an analysis of energy use averaged over houses, across the months of a typical year, we proceed to an analysis of the energy used by individual houses in an average month (or season). We will investigate to what extent the recorded variation in space heating and cooling energy consumption from one house to another can be explained by quantifiable differences between such houses, like size, orientation or double-pane windows.

The single result our program is probably best known for is represented by the histograms in Figure III-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 III-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 always in our program, houses are excluded from consideration if one would otherwise be forced to use "estimated" meter readings. The large sample in Figure III-1 contains townhouses with two, three, and four bedrooms, successively larger, (18, 22 and 24 feet wide, respectively), and differing from one another with respect to window area and number and size of overhangs, about



AVERAGE OF TWO SIX-MONTH WINTERS (1971-72, 1972-73)

FIGURE III-1

which we will have more to say below. Some of the townhouses in the large sample are end units (someone has to be on the end), 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 III-1 has no variation in any of these parameters, except that units may face either east or west.

Regression analyses, to explore the determinants of the variability shown by the large sample in Figure III-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. Results have been consistent with one another when the same portion of the town is examined for various winters, but detailed numerical results, such as the energy penalty for an end wall or the energy benefit of double glass, have not always been consistent when different portions of the town were compared. There are several structural variations when one shifts from one part of the town to another that may well be responsible for these apparent inconsistencies. As the four "Quads" of Twin Rivers were built, roughly one year apart, there were changes in construction materials and procedures, among them: 1) in the first Quad, the side wall two-by-fours were tacked to the masonry party walls, but when cracks developed as a result of differential settling, the builder left the side walls free standing in the later Quads; 2) the furnace was placed at the edge of the basement, in Quad III, to allow freer movement in the basement, but at the cost of greater duct length; 3) the insulation level was upgraded in Quad IV (from R-7* to R-11 in the walls and from R-11 to R-19 in the ceiling) and the double glass windows became mandatory, in direct response to the 1974 tightening of the Minimum Property Standards of the Federal Housing Administration; and 4) in Quads III and IV, gas hot water heaters, dryers, and ranges replaced their electric counterparts, in response to the termination by the Public Utility Commission of previously permissible arrangements between the electric utility and the builder. A few of the consequences of these variations have been extracted by our group, and are presented in this report. However, we have concentrated most of our attention and instrumentation in a single portion of the town, the Quad II townhouses.**

B. <u>Assigning energy-weights to the built-in differences between houses.</u>

The quantitative results of the regression analysis of the data shown in Figure III-1 (for the large sample of 209 townhouses) are

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*R-7 is an engineering shorthand for an insulation layer with a resistance of 7 sq. ft.-hour-of/Btu, or 1.2 m^2-^oC/watt.

**Beginning in the fall of 1975, an expansion of the instrumentation effort into the Quad III townhouses was begun. Nine units are now instrumented in Quad III.

embodied in the following linear equation:

$$\underset{(112)}{GC = 806} - \underset{(17)}{213{*}D2} + \underset{(17)}{108{*}END} + \underset{(21)}{75{*}D4} - \underset{(8)}{19{*}INS} \qquad \text{(III.1)}$$

Here gas consumption (GC) is in hundreds of cubic feet per six-month winter; D2, END, and D4 are dummy variables taking the value 1 for two-bedroom, end position, and four-bedroom respectively, and zero otherwise, and INS is the number of hundred square feet (9 m^2) of double glass (variable mean = 1.4). Standard errors of the coefficients are given in parentheses.

Each of the numerical coefficients in Equation III.1 is telling us something. The constant, 806 hundred cubic feet per winter, is the consumption rate for the average three-bedroom interior townhouse with no double glass. It can be compared to the heat loss through the shell of the townhouse over the winter. The properties of the shell of this townhouse are summarized in its design heat load, which turns out to be 41,000 btu per hour, for a 70°F design temperature difference; the calculation is highly stylized, and it is summarized and criticized in Chapter VII and Appendix A. The shell, therefore, approximately,* leaks 600 btu of heat every hour,

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*One is making <u>several</u> errors. The wind speed for the heat load calculation is taken to be 15 mph, 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, and the effect on the calculation of the heat transmissivity of window glass is considerable. Six percent of the heat loss is through the basement walls below ground, where the full 70°F temperature difference is not operating. 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.

or 14,000 btu every day, for each degree Fahrenheit temperature difference across the boundary (300 Watt/°C), the energy content of about 14 cubic feet of natural gas. The total heat loss rate through the shell over a heating season is then found by adding the degrees temperature difference between inside and outside for each day in the heating season. If the temperature inside were 65°F, the "degree days" reported by weather stations would be just this value; at Trenton, the average for the two six-month periods was 4288 degree-days (based on a reference temperature of 65°F). An interior temperature of 72°F is a much closer estimate, and as the temperature during the six-months (182 days) rarely exceeded 65°F, one can estimate the full heat loss by adding 7°F x 182 days to the conventional degree days, finally obtaining a heat loss equivalent to the energy content of

$$\frac{14}{100} \times (4288 + 7 \times 182) = 780$$

hundred cubic feet of natural gas. The furnace burned 806 cubic feet of natural gas, and had that been the only source of energy compensating for the heat loss, one could have claimed a 97 percent system efficiency for the furnace. But gas is far from the only heat source: the electric and the solar loads are considerable. How best to treat the three loads together, and in what language best to discuss "efficiency," is a recurrent subject in this report. Suffice it to say here that system efficiency is a slippery concept, for one cannot free oneself from a comparison either to the efficiency of use of some other fuel or from reference to some variant of a heat load calculation.

One can obtain insight into the heat load calculations themselves by examining the other four regression coefficients in Equation III.1. The saving of 213 hundred cubic feet of gas per winter, relative to the three bedroom unit, for a two-bedroom unit and the penalty of 75 hundred cubic feet for a four-bedroom unit are, in percent, a saving of 26 percent and a penalty of 9 percent respectively. The standard heat load calculation gives 33,000 and 48,000 btu/hr for the two- and four-bedroom units respectively, and hence, relative to 41,000 btu/hr for three-bedroom units, predicts a saving of 20 percent and a penalty of 17 percent respectively. In calculating differences, some of the problems inherent in heat load calculations should be reduced, so one looks for reasons exterior to the heat load calculations to account for the greater than expected savings in two-bedroom units and the less than expected penalty in four bedroom units.

The complicated architectural design of the three bedroom units with respect to overhangs (discernible in Photo Page 1) may be the culprits, for these overhangs, both in front and in back of the house, create exposed edges through which heat is lost readily. The sun may be the benefactor, for the 28 percent additional glass area for four-bedroom units and the only 17 percent reduced glass area for two-bedroom units, relative to the 200 square feet of glass in three bedroom units, give a bonus (relative to the heat load ratios) to both the two- and the four-bedroom units from solar heat gains through the glass. Solar heat gains are not included in the heat load calculation, which (we repeat) is designed to help size a furnace for worst weather. Finally, the remarkably low gas consumption in the two bedroom units may be partly behavioral: they are often occupied by couples without children and are empty during the day; the average setting of the thermostat may be lower. Indirect corroboration that a portion of the two-bedroom effect is behavioral rather than structural will be found in Chapter IV.

The penalty for the end unit, shown in Figure III-1, 108 hundred cubic feet, or 13 percent, is to be compared with an increment to the design heat load of 7800 btu per hr per 70°F, or 19 percent, 1 1/2 the regressed number. The sharing of walls, which comes with townhouses, and even more with apartment buildings and beehives, is an important concept from the standpoint of energy conservation.

The bonus for double glass, 19 hundred cubic feet of gas per 100 square feet of double glass, or 2.4 percent per 100 square feet (9 m^2), can be reexpressed, by multiplying by the heat loss rate, 600 btu per hour per °F, obtained earlier, as a reduction in the "U-value"* of the window of 0.14 btu/hr ft^{2}°F. This is about 40 percent of the expected reduction of U-value in going from single to double glass (1.1 and 0.75 are the usual values assumed for a ratio of glass area to total window area of 80%). Many explanations, but none conclusive, have been offered to understand why double glass in the field does not seem to live up to its laboratory performance.

Of the 54 percent of the variation in gas consumption explained by the regression equation III.1, 45 percent can be assigned to

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*The heat transferred through a building section per unit time, area and degree F temperature difference. See Appendix A for further details.

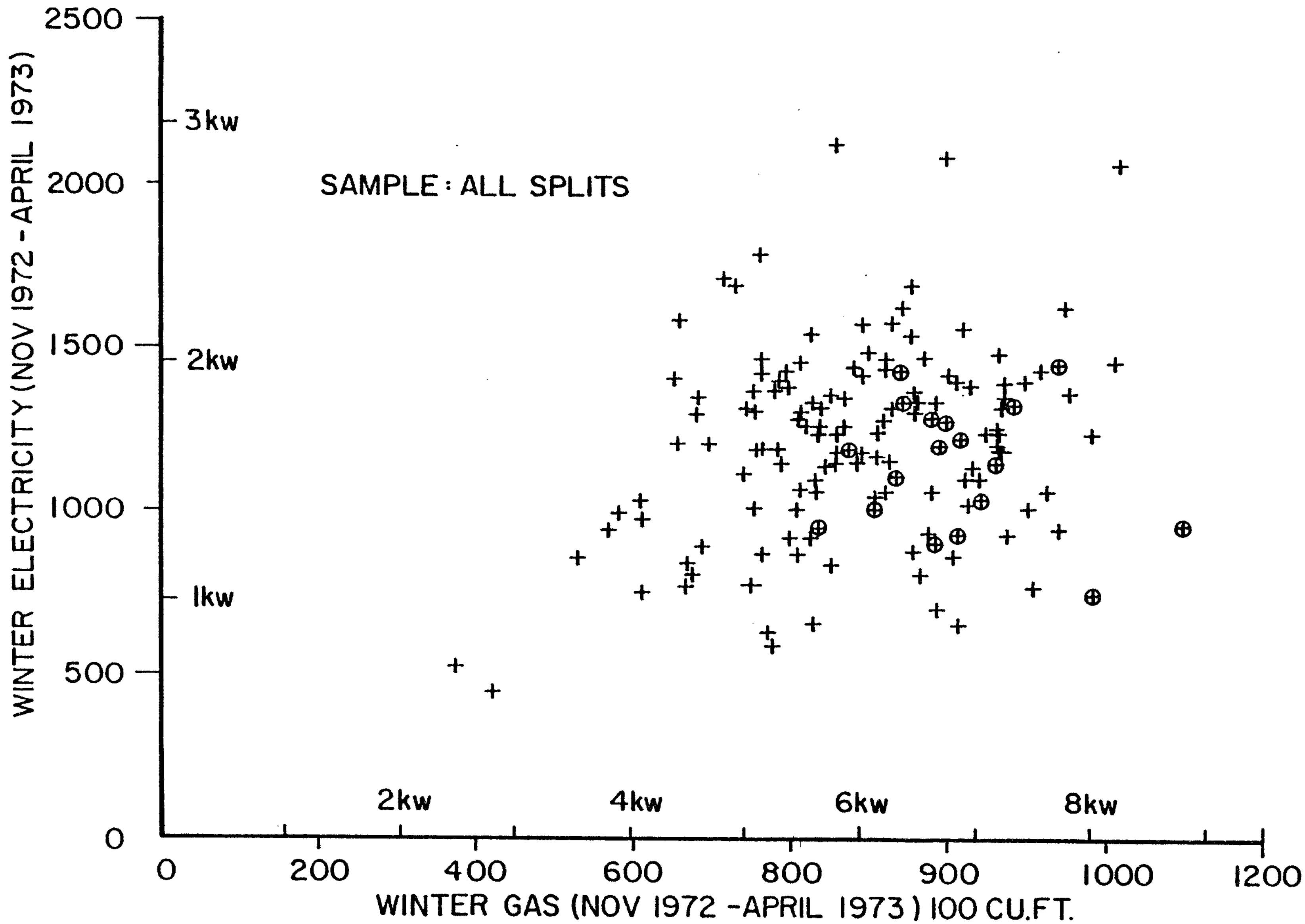
the two-bedroom dummy variable and 6 percent to the end-unit dummy variable, in a step-wise regression. The overall pattern has been repeated in countless regression efforts analogous to the one described here: between 50 and 55 percent of the variation is accounted for, most of it by number of bedrooms. Additional variables have occasionally yielded a percentage point or two while being statistically significant: 2 to 5 percent savings due to a north-south orientation (where a larger winter solar heat gain should result) and a 5 percent penalty for a location on the windward (westward) side of the town are two such examples.

C. The connection between gas and electricity use.

One variable which has not been successful in explaining the residual variation in gas consumption is the simultaneous electric consumption in the same townhouse. Figure III-2 shows a cross plot of the winter gas consumption versus the winter electric consumption for a sample of 158 split-level townhouses in Quad II. The circled plus-marks are three-bedroom, interior, east-or-west-facing townhouses with single-glass windows. There is no significant correlation either in the large sample or in the small one. Perhaps two effects are cancelling: a) Those profligate with gas are profligate with electricity, and b) more electricity consumed means more heat from electricity and less heat required from gas.*

Electric consumption in summer in the Quad-II townhouses, which is almost one-half air conditioning, is also uncorrelated with gas

*In Chapter IX, direct evidence of the replacement of gas by electricity in space heating is found.



WINTER ELECTRICITY VS. WINTER GAS

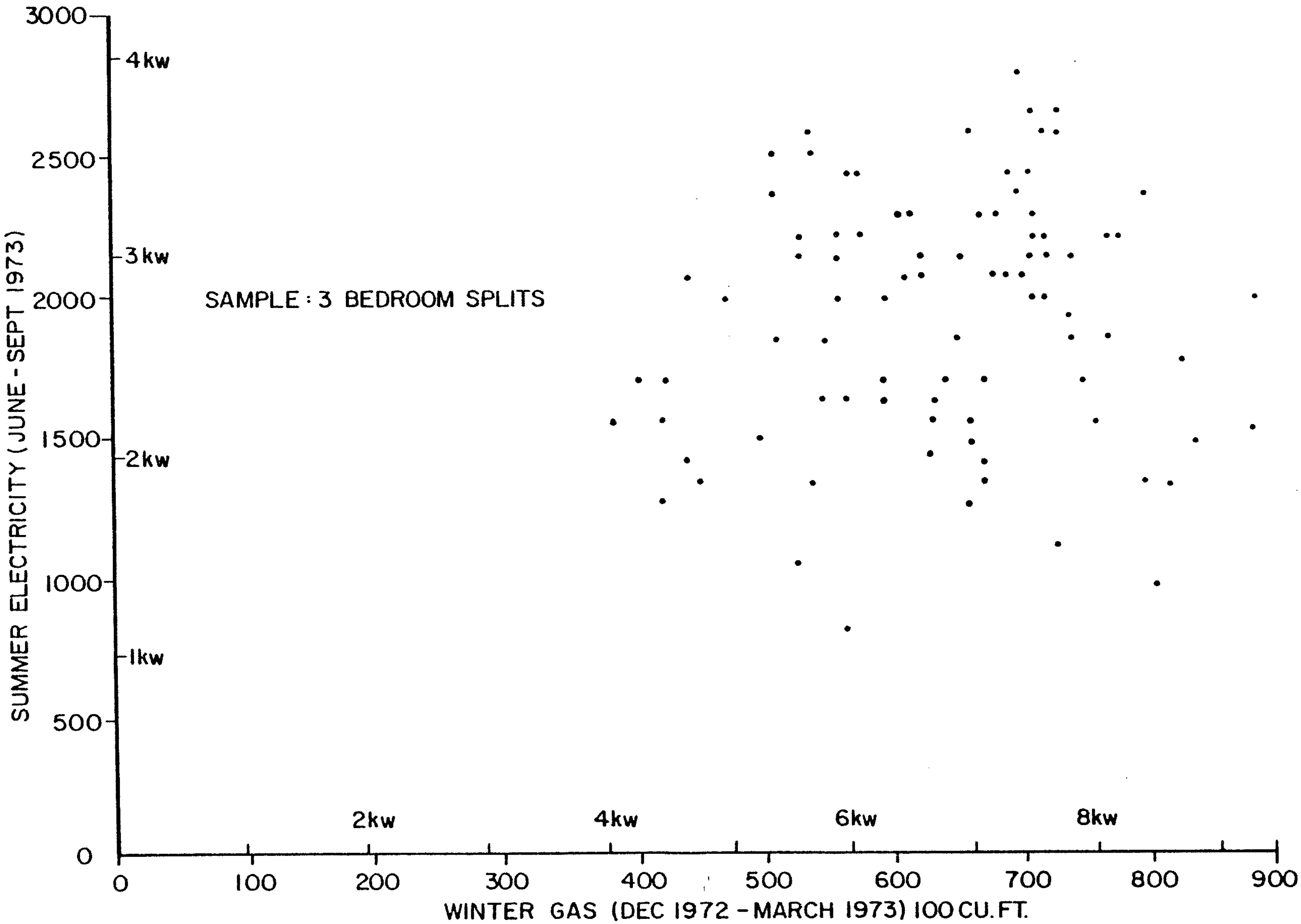
FIGURE III - 2

consumption in winter, as seen in Figure III-3. Here, two possible cancelling effects are: a) those profligate with gas are likely to be profligate with electricity (again), 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 of being an end unit are statistically signficant.

Left to play, however, the regression equation generated one bit of highly suggestive nonsense, a penalty of 10 ± 5 percent (740 kilowatt hours in four months) due to having a 600-watt central vacuum system (another option at the time of purchase); it is quite plausible that those exercising this option are more prosperous and more determined to attend to their comfort.

The effects of compass orientation are reduced in prominence in the townhouses, because they have two exposed walls, with roughly equal glass areas, and north plus south tends to cancel east plus west in summer. Orientation effects are enhanced in a set of apartments with <u>one</u> exposure, as Figure III-4 shows. The control for variations in behavior is the wintertime, where directional differences and



SUMMER ELECTRICITY VS. WINTER GAS

FIGURE III - 3

Figure III-4

AVERAGE ELECTRICITY CONSUMPTION IN 144 QUAD III
APARTMENTS -- ORIENTATION EFFECT

A. Four-month Summer Consumption (kw-hr)

June - September 1972

		2170			N	
Top floor	2180		2000	W		E
		2340			S	
		1500			N	
Bottom floor	1740		1800	W		E
		1960			S	

B. Four-month <u>Winter</u> Consumption (kw-hr)

January - April 1973

		1020			N	
Top floor	960		990	W		E
		1070			S	
		1120			N	
Bottom floor	940		1010	W		E
		900			S	

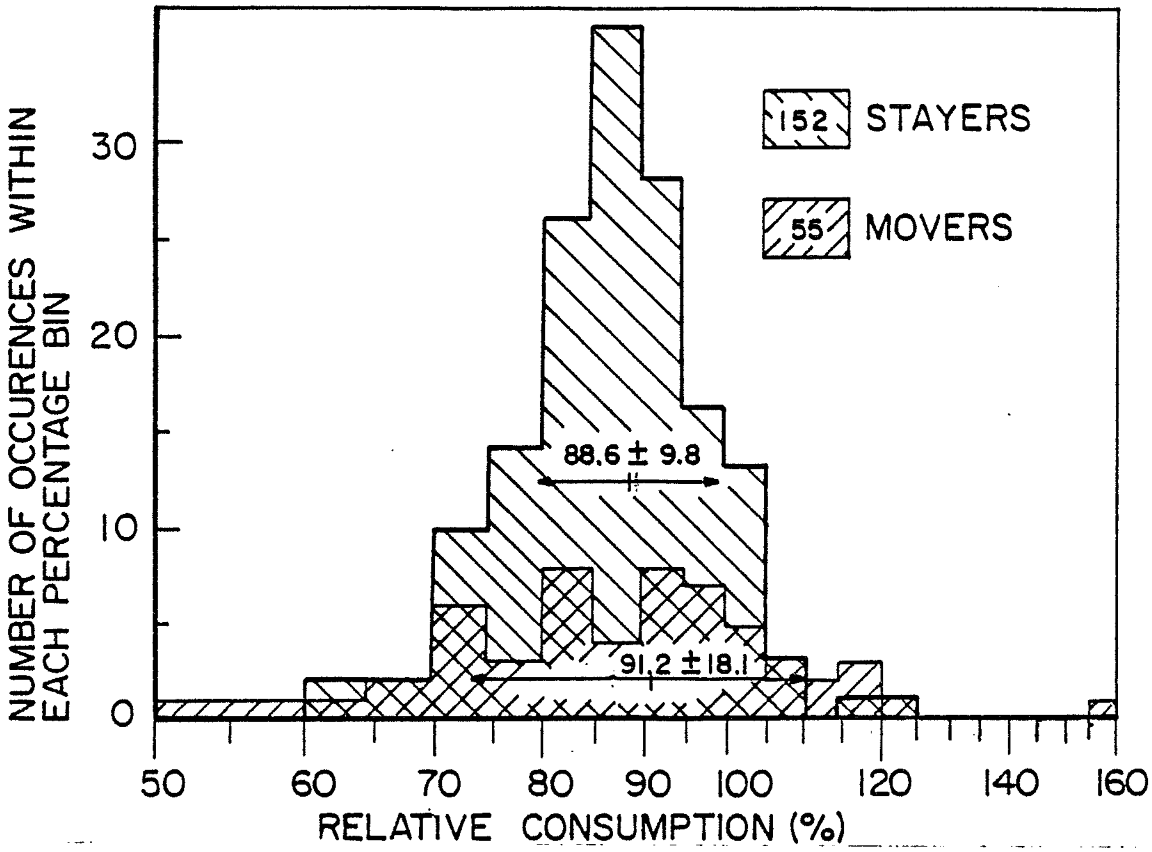
differences between first and second floor are insignificant because heating is not provided by electricity. The effects of a sun high in the south in summertime are clearly present in the electric bills (which include air conditioning), with benefits incurred for facing north and for being on the ground floor.

The effects of compass orientation at Twin Rivers, where exactly the same structure is found facing north, east, south, and west, are certainly not limited to those appearing in our data analyses. One woman in a north-facing house said: "I love my kitchen: I can sit by the patio door in January and imagine I am in Miami." In another north-facing house, there was a vegetable garden in the back patio, and the owner pointed out that the neighbors across the street had their patios shaded by their houses and so couldn't grow anything: "They sit out in front of the house in the summer, practically in the parking lot." One wonders how many of the impacts of orientation on living patterns are in the minds of the architects and builders who decide to put identical structures in all compass orientations.

D. Behavior-induced variation: the effect of moves.

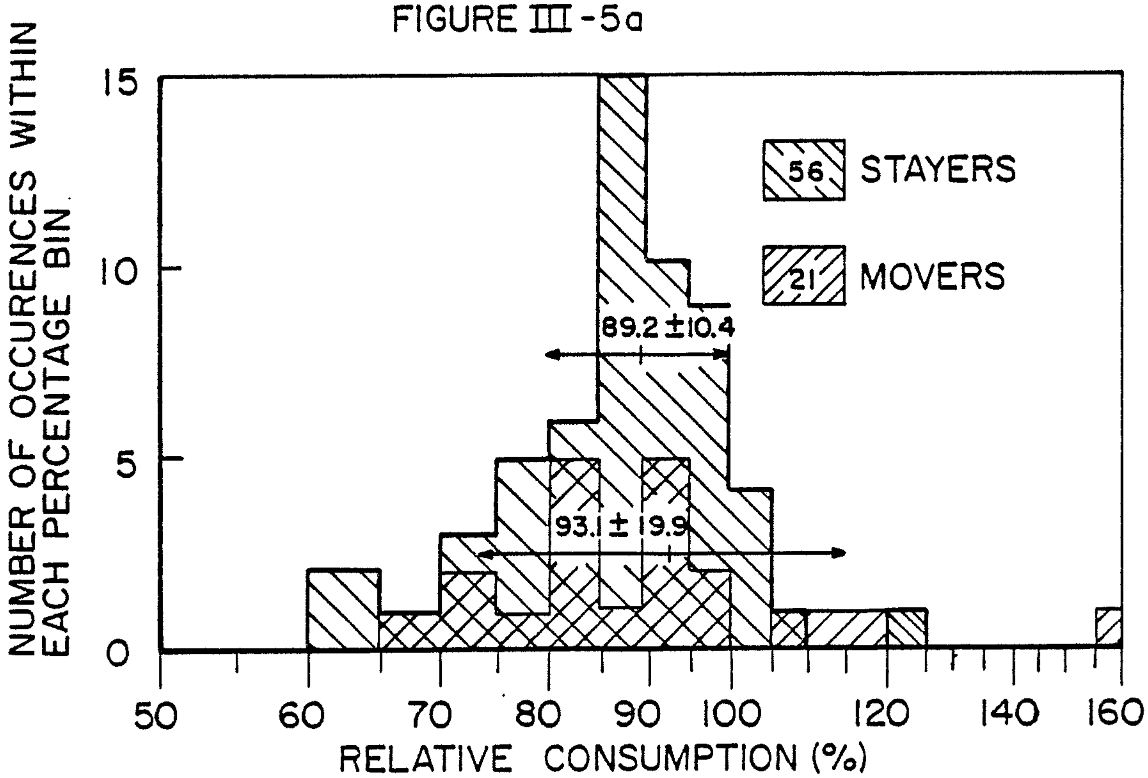
The relative significance of human behavior and building performance in the observed variability at Twin Rivers has been an endless source of discussion; as a rule, those who inquire want a particular answer, depending on their background and allegiances. Yet the separation is not a clear one. We have seen evidence of a new owner moving into a townhouse and overhauling it, such that it switches from one of the highest to one of the lowest of the users of gas. Is this shift a matter of structure or behavior? The significance of interior temperature is large, for a $1^{o}F$ change in interior temperature setting will reduce the average winter heat losses through the shell by between 3 and 4 percent and should lead to a similar reduction in gas consumption. There is direct evidence from our instrumented townhouses that the higher users tend to have higher thermostat settings, but there is also evidence that interior temperature setting is not the whole story.

Figure III-5 compares the gas consumption in 1974 and in 1972 in townhouses which still had the same resident (stayers) and in those in which there had been a change of owner (movers). The ratio of the two values of gas consumption is plotted for both the full townhouse sample and the subset of 3-bedroom interior units, as a histogram. The mean value of the ratio, for both the movers and the stayers, is down by about 10 percent, reflecting the response to the energy crisis which is the subject of Chapter V. The standard deviation for the movers, however, is clearly larger than for the stayers. The stayers vary, on the average, by 10 percent about their mean, implying a random walk averaging 7 percent a year, by every household and its house, relative to the year before. Recall that uncorrelated random effects "add" as the sum of the squares of their standard deviations, yielding the square of the standard deviation of the combined effect. Where the household is changed, the standard deviation of the ratio of consumption two years apart is about 18 percent, when the whole sample is examined,



HISTOGRAM OF WINTER 73/74 GAS CONSUMPTION RELATIVE TO WINTER 71/72 GAS CONSUMPTION FOR QUAD II TOWNHOUSES. (100 = NO CHANGE IN CONSUMPTION)

FIGURE III-5a



HISTOGRAM OF WINTER 73/74 GAS CONSUMPTION RELATIVE TO WINTER 71/72 GAS CONSUMPTION FOR QUAD II 3-BEDROOM INTERIOR TOWNHOUSES (100 = NO CHANGE IN CONSUMPTION)

FIGURE III-5b

and situations where the house is clearly not occupied are eliminated. An independent 15 percent random effect ($10^2 + 15^2 = 18^2$) introduced by changing owners would explain the extra spread in the population of movers. Assuming that the people newly moved to Twin Rivers are a subset of the same population originally attracted by the Town (in Quad II, the first families moved in in 1970), then the effect of replacing old owners with new ones is conceptually identical to performing a random presentation of owners within the house subsample called "movers."

Under this assumption (identity of subpopulations), the random variation of 15% in gas consumption introduced by a new family in 1974 with respect to the previous family in 1972 is statistically indistinguishable from an equal variation between two different families using different amounts of gas at the same time. Recall that in the small sample in Figure III-1, 14% is all the variability we actually see in structurally identical townhouses. Thus, there does not have to be any further role for structure. The consistency of the results for both the full sample (Figure III-5a) and the subset of 3-bedroom interior units (Figure III-5b) is a valid check for the advantage of taking relative consumption, which automatically eliminates the "obvious" variations stemming from differences in size and other house-related parameters.

Our list of ways people can alter the thermal performance of their houses grows steadily longer, as we begin to understand how the house works. The thermostat temperature setting receives appropriate emphasis, and open windows and doors are clearly important too. What types of drapes and when they are drawn, whether there is furniture blocking the ducts, whether the interior doors are open or closed, all appear to matter as well. If all the variation is assigned to behavior, it must be added that much of that behavior is unconscious and proceeds in a vacuum of information about how the structure works. And that, in a way, puts the blame for the variation back on the structure, too sensitive for the natural differences between its human users.

IV. VARIATIONS WITH OUTSIDE TEMPERATURE

A. A two-parameter deterministic model of average gas consumption of a set of houses

Winter gas consumption is strongly predicted by a linear relation involving one 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 IV-1 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

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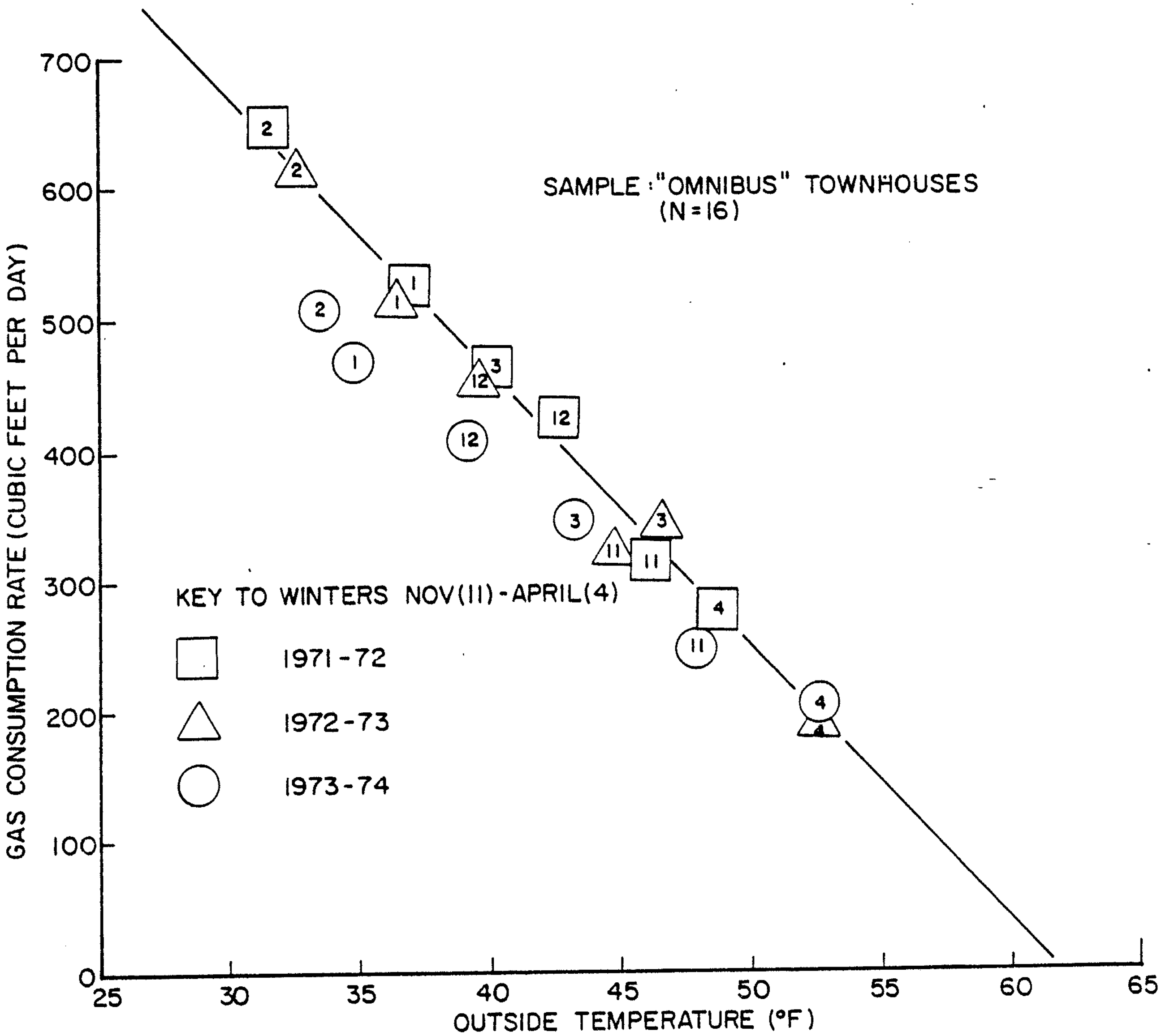
*Throughout this report, the "1972 winter" is the winter containing January 1972, etc.



MEAN GAS CONSUMPTION OVER WINTER MONTHS

FIGURE IV-1

daily low exceeded 65°F are 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 IV-1 are our first set of "Omnibus" houses, where we are carrying out a series of designed experiments to study the effect of retrofits. The Omnibus sample is somewhat enriched in houses with very high and very low rates of gas consumption; it is otherwise typical, and it will be used frequently in this report.

The data in Figure IV-1 show a clear pattern: one line passes neatly through the data of the 1972 and 1973 winters (its $R^2 = 0.99$), 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, and that story is the subject of the next chapter. Here, we concentrate on the first two winters. The model postulated to fit the data is:

$$G = B(R-T) \qquad \text{(IV.1)}$$

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

*The 65°F exclusion rule is unimportant, as far as any quantitative results here are concerned, because there are only a very few days in November and April where the rule comes into effect, and there usually because of an average of daily high and daily low between 65°F and 70°F.

of a retrofit program, for example, may be tracked with considerable accuracy. A convenient unit of measurement, used consistently throughout this report, is cubic feet per degree day, (cubic feet of natural gas, with 1025 btu per cubic foot; Fahrenheit degree days). B is the slope of the line drawn in Figure IV-1.

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 proportional, not just linearly related, to degree days. R is the temperature intercept of the line drawn in Figure IV-1.

The result of a least squares fit of the model to the twelve data points from the 1972 and 1973 winters is

$$G = 21(62° - T) \qquad \text{(IV.2)}$$

To what can we relate the system performance index B, here 21 cubic feet per degree day, and the reference temperature, here 62°F? Thomas Schrader investigated in detail in his M.S.E. thesis the simple model expressed in Equation IV.3, the heat balance equation, expressing the conservation of energy:

$$e_g G + e_e E + e_s S = K(T_{in} - T) \qquad \text{(IV.3)}$$

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 an 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 IV.3 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 IV.3 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, as discussed in Chapter III.) 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. Equations (IV.1) and IV.3), can be "matched," <u>assuming that all quantities except G and T are constant over time</u>, to obtain:

$$B = K/e_g \tag{IV.4}$$

$$R = T_{in} - \frac{e_e E + e_s S}{K} \tag{IV.5}$$

Thus, B is a measure of the efficiency of the use of gas, with high B meaning low efficiency for a fixed structure (fixed K). Using the value of the heat loss rate, K = 600 btu/hr °F (or 14,400 btu/day °F, or 14 cubic feet/day°F), from Appendix A, we find

$$e_g = K/B = 14/21 = 0.67 \tag{IV.6}$$

Compare this result, an efficiency of 2/3 for the heating system, to the "efficiency" (97 percent) obtained in Chapter III; here, the important contributions of electricity and of the sun are included, to the extent that they may be regarded as being constant over time. The efficiency of the gas heating system, e_g, derived in (IV.6), is not conceptually separable from the heat load calculation that leads to

K; e_g is the combined efficiency of the furnace-house heating system, not of the furnace alone. As seen in Appendix A, there are numerous instances of arbitrariness in the calculation of the heat loss rate K; the subsequent measurement of the efficiency e_g, therefore, carries the same arbitrariness with it. Given that warning, it follows directly from Equation IV.6 that 2/3 of the heat lost through the shell (by conduction and air infiltration) is replaced via gas combustion and 1/3 by the other two (principal) heat sources: electric appliances and the sun.

The intercept, or reference temperature, R, is seen from equation IV.5 to be lower than the interior temperature because it also embodies the indirect heating by electricity and sunlight. An average interior temperature at Twin Rivers is 72°F. Thus, at Twin Rivers (in 1971-73), the best reference temperature for the degree day method was 10°F below the interior temperature. It was 3°F below the usual reference temperature used in the United States, 65°F, a reflection of the large number of appliances dumping heat into the house and large glass area capturing sunlight.*

Equation IV.5 also allows one to obtain the magnitude of the combined heating rate of electricity and sunlight. Using R = 62°F, T_{in} = 72°F, and K = 600 btu/hr °F, one finds:

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*Apparently, in no two European countries does the conventional reference temperature take the same value, but the value is almost invariably lower than 65°F. The European reference temperatures are lower than 65°F, because their houses are generally cooler, not because the indirect heating is large.

$$e_e E + e_s S = K(T_{in} - R) = 6000 \text{ btu/hr} = 1.8 \text{ kilowatts} \qquad \text{(IV.7)}$$

(Again, since this result uses a calculated value of K, it is only as accurate as K.) The average rate of consumption of electricity in winter in these Twin Rivers townhouses is:

$$E = 1.6 \text{ kilowatts} \qquad \text{(IV.8)}$$

so there must be a solar contribution to the heating. We will find in Chapter IX that e_e is about as large as e_g; then $e_e E = 1.1$ kilowatts, and electricity and sunlight contribute approximately 60 percent and 40 percent of the non-furnace heating. The total winter heating assignment, then, is divided: 67 percent furnace, 20 percent electric appliances, and 13 percent sunlight.

The percentage role for sunlight is small. Yet more heat falls on the structure's walls in winter than is required for all heating needs. Had the 160 square feet of glass used in the shell of the townhouse alone been better placed from the standpoint of solar heating (no glass on the north wall in north-south houses, avoidance of projections -- here, closets -- on a level with and south of the windows in east-west houses), the solar role might well have doubled.

An alternative form of equation (IV.7) is:

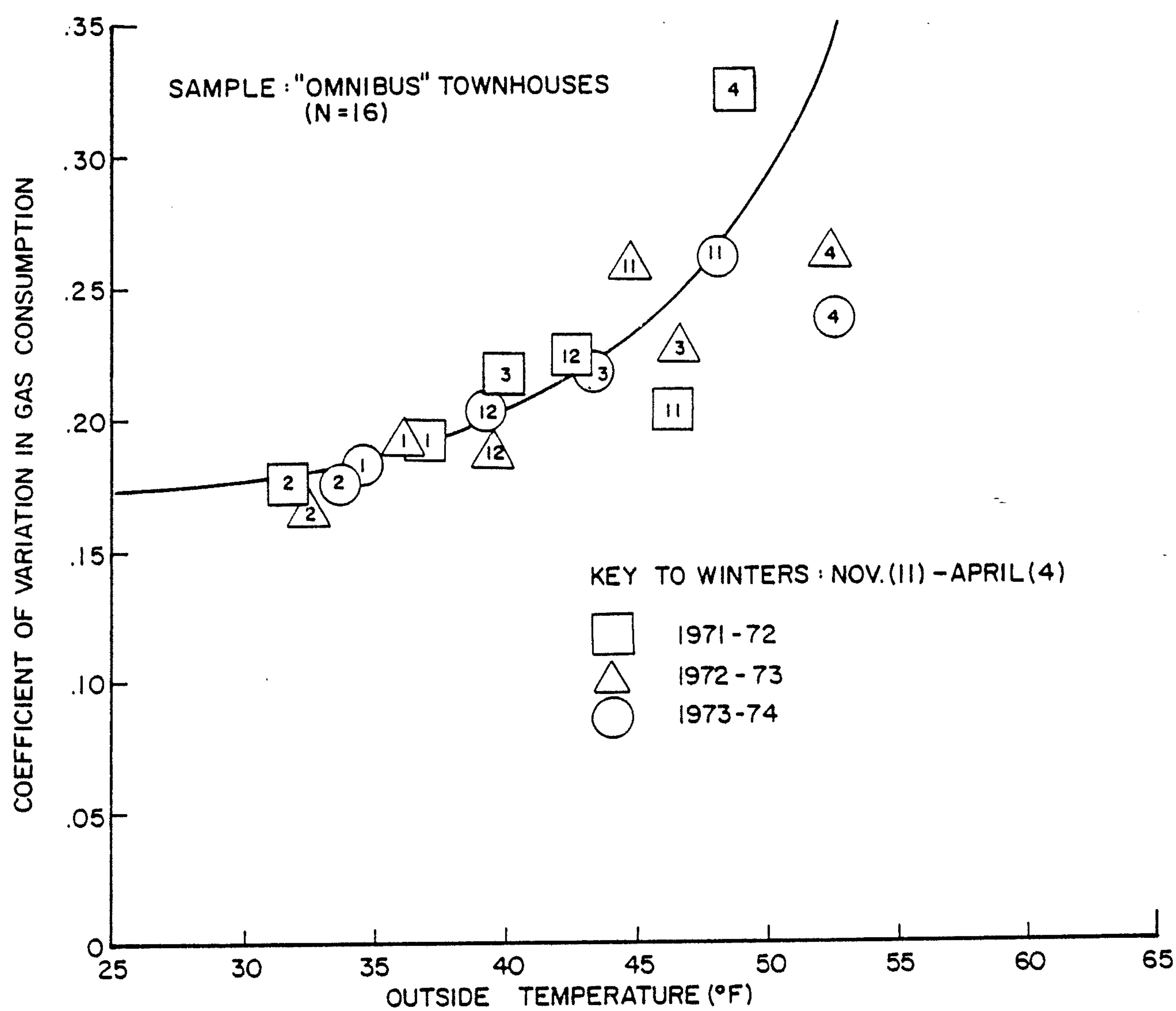
$$\begin{aligned}(e_e/e_g)E + (e_s/e_g)S &= B(T_{in} - R) \\ &= 210 \text{ cubic feet per day} \\ &= 2.6 \text{ kilowatts} \qquad \text{(IV.9)}\end{aligned}$$

The coefficients multiplying the energy inputs from electricity and sunlight are now <u>relative</u> efficiencies; in this form, one has shucked the heat load calculation, and the equation involves only measurable quantities.

Recall that all of these deviations require the quantities other than G and T to be constant over the 1972 and 1973 winter months. The residuals of the line drawn through the points in Figure IV-1 are too small to be explored with profit, and that is in part because the average wind speed and the average level of cloudiness vary little over months at Twin Rivers (see Appendix B). There is a subtle solar effect which displaces houses facing east and west from houses facing north and south, (it increases the slope and decreases the intercept of the former set with respect to the latter) to be discussed below in Section C; the line whose parameters have been explored in this section has averaged that effect, for about equal numbers of Quad-II townhouses face each direction.

B. A two-variable probabilistic model of the gas consumption for a set of houses

The standard deviation of the gas consumption over houses in a given month is found to be a decreasing fraction of the mean value as the weather gets colder. This is reasonable, since in cold weather, variations in indoor temperatures across houses make a smaller percentage difference, heat losses being driven by the indoor minus outdoor temperature. Figure IV-2 shows the coefficient of variation (the standard deviation divided by the mean) of the gas consumption, C(G), versus the average outside temperature, (T), for the same sample of 16 Omnibus houses and the same 18 winter months as in Figure IV-1. The ratio falls from about 0.25 in mild weather to 0.18 in cold weather; there is considerable scatter in the data, but the trend is clear. Moreover, the ratio is not perceptibly different in the



COEFFICIENT OF VARIATION (STANDARD DEVIATION DIVIDED BY MEAN) OVER WINTER MONTHS

FIGURE IV- 2

winter following the energy crisis.

To try to fit the data of Figure IV-2, we postulate a probabilistic version of Equation (IV.1):

$$\underline{G} = \underline{B}(\underline{R} - T), \qquad \text{(IV.10)}$$

where $\underline{B}$ and $\underline{R}$ are now random variables over houses, and we assume that they are uncorrelated. It follows that $\underline{G}$ is a random variable (T, of course, is not a variable over houses; all houses see the same outside temperature), and that

$$[C(\underline{G})]^2 = [C(\underline{B})]^2 + [C(\underline{R} - T]^2 \qquad \text{(IV.11)}$$

where $C(\underline{X})$ is the coefficient of variation of $\underline{X}$. Moreover, since T is not a variable over houses,

$$C(\underline{R} - T) = \frac{\sigma(\underline{R})}{\mu(\underline{R})-T} \qquad \text{(IV.12)}$$

where $\sigma(\underline{R})$ and $\mu(\underline{R})$ are the standard deviation and mean of the "intercept", or "reference temperature," over houses. The mean of the intercepts was found from Figure IV-1 to be 62°F, leaving us with a two-parameter model for the data in Figure IV-2:

$$C(\underline{G}) = \sqrt{a + \frac{b}{(62°-T)}} \quad , \qquad \text{(IV.13)}$$

where

$$a = [C(\underline{B})]^2 \qquad \text{(IV.14)}$$

and

$$b = [\,\sigma(\underline{R})]^2 \qquad \text{(IV.15)}$$

In Figure IV-2, the line generated by $a = (0.15)^2$, $b = (3°F)^2$ is seen to fit the data quite well. Thus, our earlier numerical model (IV.2) is now embellished:

$$GC = (21 \pm 3) * (62° \pm 3° - T) \qquad \text{(IV.16)}$$

Equation (IV.16) displays at a glance the relative significance of variability in slope and variability in intercept in determining the spread in gas consumption.

The standard deviation of the performance index, $\pm$ 3 cubic feet per degree day, translates into a coefficient of variation of 15 percent in the value of K/e_g, or, postulating that K is constant over houses, into a standard deviation of 10 percentage points (around a mean of 67 percent) in the efficiency of the heating system. (Again, a spread in the shell quality and a spread in the efficiencies of the heating systems cannot be distinguished.)

The standard deviation of the reference temperature, $\pm$ 3°F, embodies the consequences of variations, across houses, in interior temperatures <u>and</u> in indirect heating from electricity and sunlight. Both standard deviations would be somewhat smaller if the differential effect over months of solar heating of east-west and north-south houses had been controlled for.

It is our tentative proposition that the probabilistic model (IV.16) contains about as much detail as the data warrant. Such four-parameter descriptions of the energy consumption for space heating of a population of houses may be useful general summaries for many purposes, including the monitoring of the accomplishments of any campaign to bring about changes in building performance.

C. Temperature models for individual houses

One good reason why one might well be advised to proceed with caution, once one has obtained a probabilistic description of a population of townhouses equivalent to Equation IV.16, is that the next logical step in the analysis, a house by house exploration of slopes and intercepts, has some pitfalls. Figure IV-3 shows the results of a house-by-house fit of daily rate of gas consumption versus average outside temperature, for the 16 Omnibus townhouses. The gas consumption for each of the houses for each of the twelve months of the 1972 and 1973 winters was the data base; in four cases, less than twelve months of data were available. Figure IV-3 is a cross plot of slope versus intercept (performance index versus reference temperature). Attached to each data point is the quality of the fit to the data from that house. Two factors related to each house are flagged in Figure IV.3:
1) Was the house one of the eight highest users of gas (clear symbol) or one of the eight lowest users of gas (shaded symbol), and 2) Was the fit to the data one of the best nine fits (round symbol; nine, not eight, because of a tie) or one of the worst seven fits (triangular symbol). We observe:

a) Those nine houses which fit the linear model best ($R^2 \geq 0.94$) have uncorrelated slopes and intercepts. (The correlation coefficient for the nine pairs of slopes and intercepts is 0.02).

b) High and low users, in these nine houses, are clearly separated.

c) Those seven houses which fit the linear model worst ($R^2 < 0.94$) show a strong negative correlation between slope and intercept.

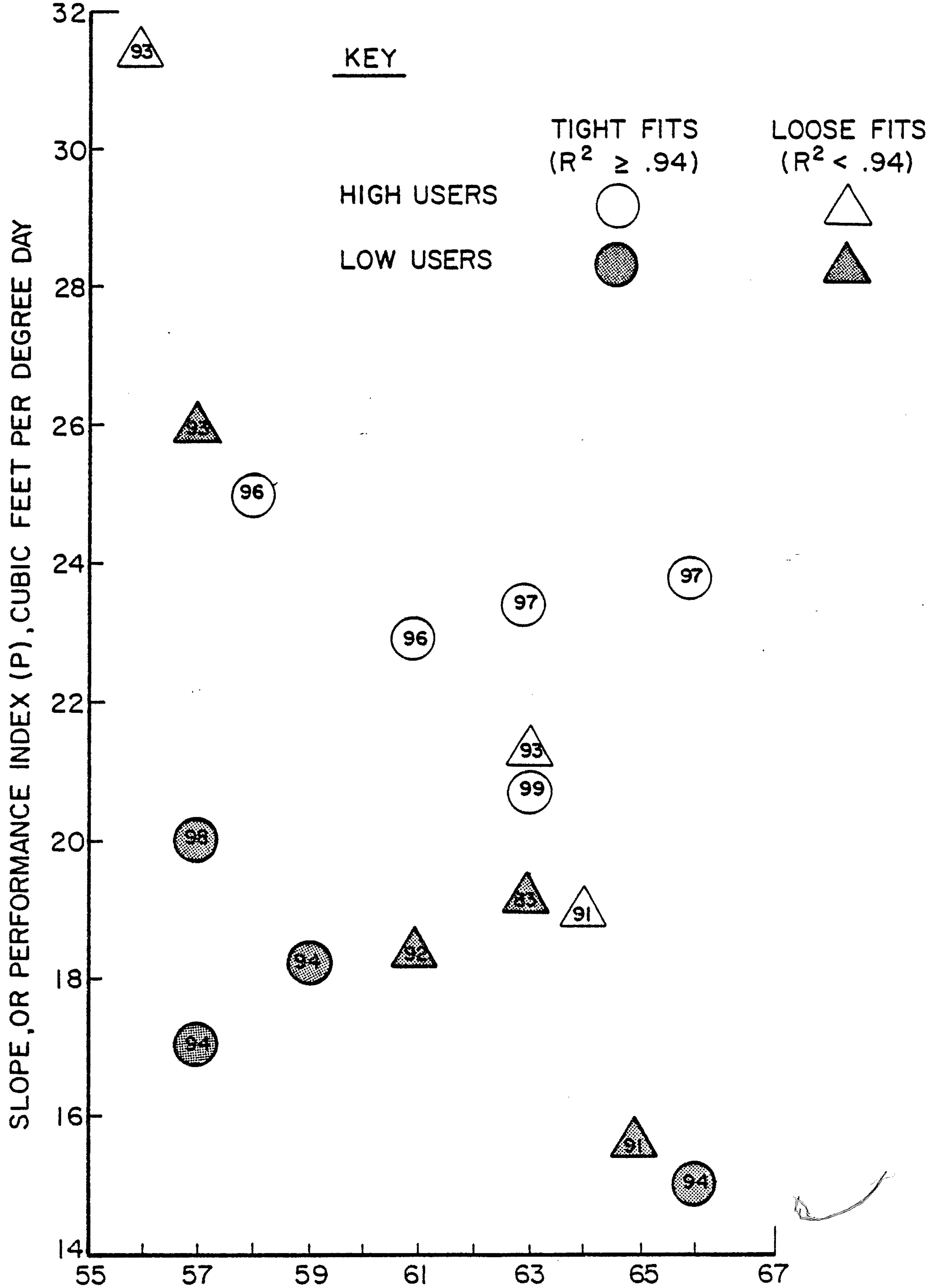

KEY
TIGHT FITS ($R^2 \geq .94$)
LOOSE FITS ($R^2 < .94$)
HIGH USERS
LOW USERS
SLOPE, OR PERFORMANCE INDEX (P), CUBIC FEET PER DEGREE DAY
INTERCEPT, OR REFERENCE TEMPERATURE, °F
93
93
96
97
97
96
93
99
98
95
91
94
92
94
91
94
32
30
28
26
24
22
20
18
16
14
55
57
59
61
63
65
67

FIGURE IV-3

(The correlation coefficient for the seven pairs of slopes and intercepts is -0.92).

d) High and low users, in these seven houses, are interspersed. The linear fits to the data, when the data fits are poor, are introducing spurious effects. Linear fits to sets of two-variable (x,y) data with random error and the same center of mass ($\mu(x)$, $\mu(y)$), will generally yield negative correlations between slopes and intercepts, as the least squares line wiggles about the center of mass. The degree of negative correlation between slope and intercept is a warning that these artifacts are present. They warn us not to look for physical meaning in the small reference temperature associated with the high user at the upper end of the scale.*

These conclusions about house-level analysis are tentative. They are being checked, with a much larger sample of houses, and placing special emphasis on houses where there has been a change of owner, in the masters' thesis research of Thomas Schrader. Schrader finds that the performance index B_i, of the ith house, can itself be made the dependent variable in a regression analysis completely parallel to the regression analysis of gas consumption presented in

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*Nonetheless, it is probably significant that the standard deviations of the slopes and intercepts shown in Fig. IV.3 are respectively 3.3 cubic feet per degree day and 3.3°F, if the top left point is regarded as an outlier (4.2 cubic feet per degree day and 3.4°F if the point is included). These values are indeed close to the standard deviations, 3.0 cubic feet per degree day and 3.0°F that were used to generate the theoretical curve shown in Figure IV-2. (See the discussion in Section B.)

Chapter III. He obtains

$$B = \underset{(2.9)}{22.2} - \underset{(0.5)}{5.3}*D2 + \underset{(0.5)}{2.8}*END + \underset{(0.6)}{3.1}*D4$$

$$- \underset{(0.5)}{2.4}*DS - \underset{(0.5)}{2.0}*DN - \underset{(0.2)}{0.7}*INS \qquad (IV.17)$$

$$R^2 = 0.58$$

Here B is the performance index in cubic feet per degree day; D2, END, D4, DS, and DN are (0-1) dummy variables taking the value 1 for two-bedroom, end, four-bedroom, south-facing, and north-facing units respectively; and INS is the number of hundred square feet of double glass. All except DN and DS entered the earlier regression analysis for gas consumption. Equation IV.17 should be compared to equation III.1. If the performance parameter B indeed isolates the system response to cold from the effects of interior temperature, electricity, and sun, then Equation IV.17 should give a cleaner estimate of structural variations than did Equation III.1. We find, indeed, that the t-values (standard deviations divided by the estimated coefficient) of the regression coefficients are larger in Equation IV.17, and so is their statistical significance. The constant term, 22.2 cubic feet per degree day, gives the value of the performance parameter for the three-bedroom, interior, east-facing townhouse with single-pane glass. Other coefficients may be turned into percents of 22.2. Table IV.1 gives the percent penalties and savings associated with the four terms both equations have in common, and repeats the physical estimates, derived from the heat load calculation, already presented in Chapter III. We see that the two-bedroom anomaly is now considerably less pronounced, and we associate this with the fact that part of the two-

Table IV.1

Structural Effects: A Comparison of Estimates from Regression Coefficients and from Heat Load Calculations (Percentages of Reference Case: Three-Bedroom Interior Unit with Single-Pane Glass)

Effect	Estimate: from Equation III.1	from Equation IV.17	from Heat Load Calculation
Two-bedroom Unit	-26 ± 2	-24 ± 2	-20
End Unit	$+13\pm2$	$+13\pm2$	$+19$
Four-bedroom Unit	$+9\pm3$	$+14\pm3$	$+17$
Unit with 100 sq.ft of double-pane glass	-2 ± 1	-3 ± 1	-6

bedroom anomaly was associated with interior temperature and is now loaded on the reference temperature. The other comparisons are qualitatively the same as in Chapter III, except that the arguments can be drawn more sharply because the estimates are now tighter.

The terms DN and DS in Equation IV.17 indicate an apparent ten percent reduction in the performance coefficient for north-south townhouses. This effect should not be the result of a greater average solar load on north-south houses -- that effect should load onto the reference temperature (recall equation IV.5). The north-south "savings" is partly accounted for by the prevailing westerly winds, which make east- and west-facing houses effectively leakier, but we do not believe that cause alone could give a ten percent effect. Rather, we believe the artifact of the varying solar elevation over the months of the winter: the solar load on a north or south facing house is largest when it is coldest, and thus reduces the gas consumption preferentially in the coldest months; the solar load on an east- or west-facing house increases in mild weather. The net result is to decrease the slope (and increase the intercept) in the best fit through north-south houses relative to east-west houses.*

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*A similar effect operates when regression models are used to predict daily gas consumption. Here, too, north-south houses have their slopes depressed and their intercepts increased. However, the reason in this case is that the very coldest days at Twin Rivers (and in many other places) are also the clearest ones, and so the larger solar gain in north-south houses does more flattening to their "line" of gas consumption versus outside temperature, relative to the "line" for east-west houses.

D. Variations of electricity consumption

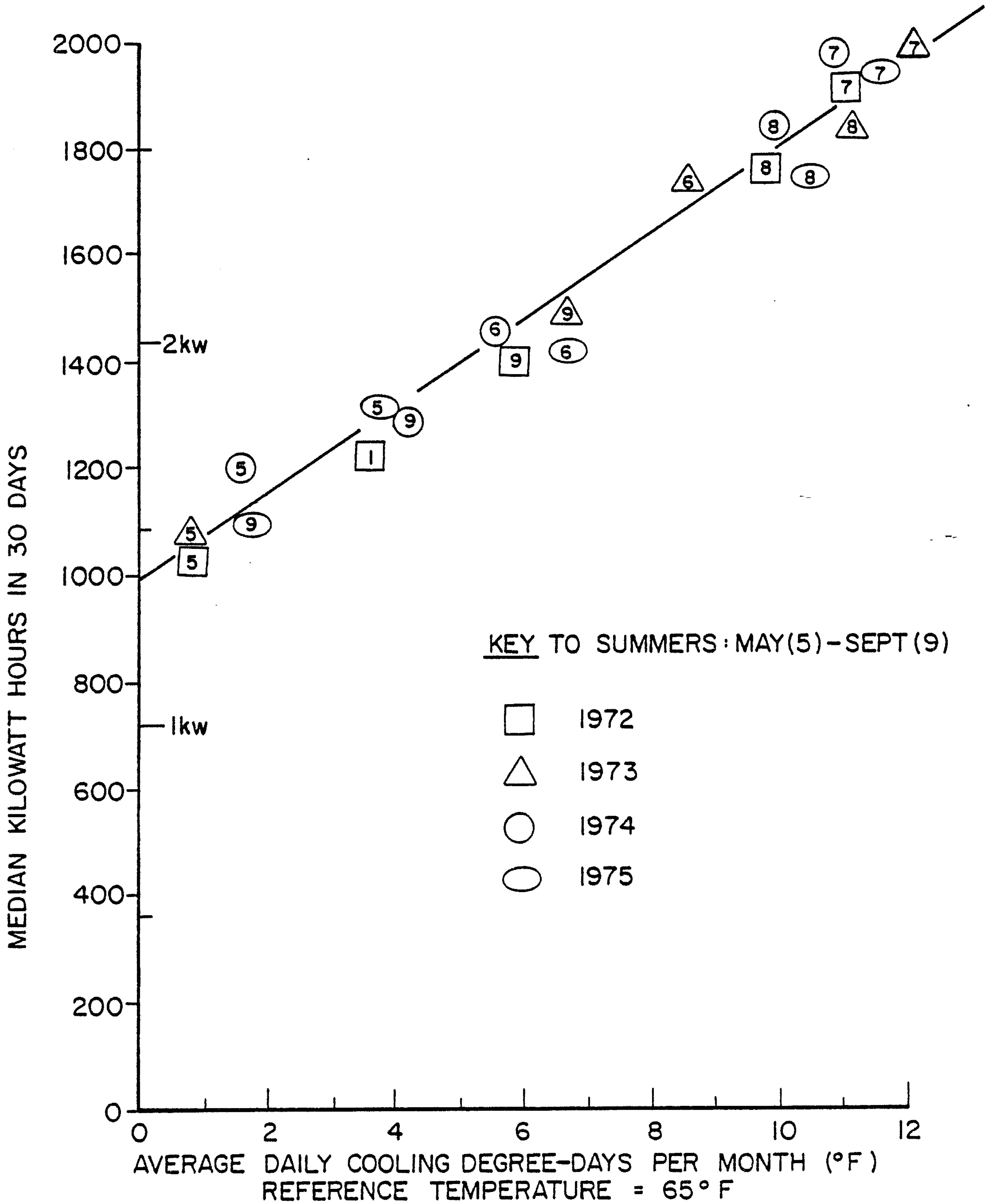
There is a small systematic trend in winter electricity consumption, visible in Figure II-2, toward smaller values in the spring and fall and larger values in the winter. The winter peak is a result both of larger amounts of lighting when the nights are longest (peaking in December 21) and larger amounts of furnace fan operation when the weather is coldest (peaking around February 1). The former effect dominates.

The summer electricity consumption shows an "air conditioning peak" which one might hope to correlate with average outside temperature, and, indeed, this can be done with some success. Indeed, the variations in median summer electricity consumption over the months of the summer are almost as well described by a model linear in an effective outside temperature as are the variations in average monthly winter gas consumption discussed above.

Figure IV-4 plots median summer electricity consumption (E) for a sample of 150 Quad-II townhouses, for each of five "months" (defined by the dates of the meter readings by the electric utilities) of four summers. The independent variable (T) is the average number of cooling degree days per day (in °F), which, exactly as with heating degree days, is defined as:

$$T = \text{the larger of } \left(\frac{T_{max} + T_{min}}{2} - 65°F,\ 0\right) \qquad \text{(IV.18)}$$

Thus a day whose high temperature was 80 and whose low was 66 has 8 cooling degree days; one with a high of 80 and a low of 50 has no cooling degree days. The warmest of the 20 months (July 1973) averaged 12 degree days per day.



MEDIAN KILOWATT HOURS IN 30 DAYS
2000
1800
1600
1400
1200
1000
800
600
400
200
0
2kw
1kw
0
2
4
6
8
10
12
AVERAGE DAILY COOLING DEGREE-DAYS PER MONTH (°F)
REFERENCE TEMPERATURE = 65° F
KEY TO SUMMERS: MAY(5)-SEPT(9)
1972
1973
1974
1975

FIGURE IV-4

The best linear fit through the 20 data points in Figure IV.4 (with $R^2 = 0.97$) is:

$$E = 975 + 82T \qquad \text{(IV.19A)}$$

where E is measured in kilowatt-hours per 30-day month, or

$$E = 1.35 + 0.114T \qquad \text{(IV.19B)}$$

when E is measured in kilowatts. The intercept in Equation IV.19 is 15 to 20 percent smaller than our estimate of an average winter electric load in three-bedroom townhouses (1180 kw-hrs per 30 day month, in 1.64 kw); reasons for the difference include: 1) the 470 watt indoor fan which circulates the air conditioned air appears in the slope parameter, not the intercept, and 2) the summer sample of units contains many two-bedroom units. Direct measurements of the non-air conditioning portion of the electricity use in three-bedroom townhouses have shown average summer use to be about as large as average winter use.

The slope parameter in Equation IV.19 can be re-expressed by making use of the fact that the air conditioner (including its indoor fan) draws electricity at a rate of about 3.6 kilowatts. A rate of use of 0.114 kilowatts by the air conditioner then represents usage 3 percent of the time, or 45 minutes each day. Thus, for each increase of 1°F in the average daily temperature (above 65°F), the air conditioner will be run 45 additional minutes, and will consume an additional 2.7 kilowatt-hours a day. For the average 12 degree-day-per-24-hours day this means over 9 hours of air conditioner use, or 32.8 kilowatt hours, an enormous value that was confirmed by extended independent field measurements.

The heat gains by a house in summer are not as completely dominated by conduction and convection as are the heat losses in winter, because the heat gain due to electricity and the sun is a larger fraction of the total and because New Jersey humidity plays an important role. The strong linearity of the data in Figure IV-4 is, therefore, somewhat surprising. It emboldens us to make the further hypothesis (a good one in winter) that if the temperature is increased by 1°F indoors (by a shift of thermostat, for example), that is essentially equivalent to lowering the temperature 1°F outdoors, and the total power usage by the house will drop by 0.114 kilowatts. From Figure IV-4, it is evident that we should probably not include May in the calculation, since the month barely averages 1°F in daily cooling degree days, but over the other 120 days, the savings will be

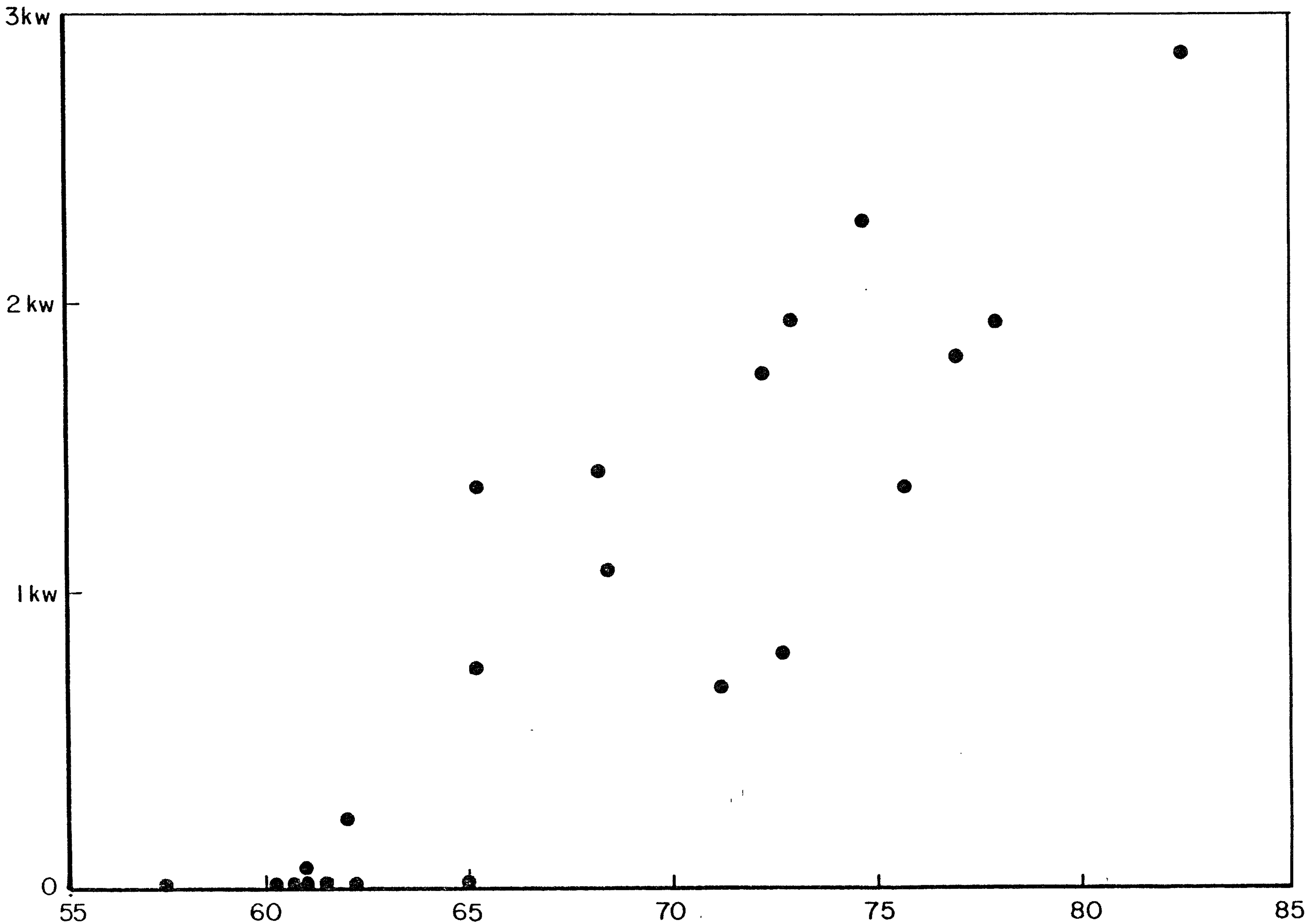
$$(0.114)(24)(120) = 330 \text{ kilowatt-hours.}$$

The saving of 120 cooling degree days, out of a total of 1000 for the summer, is a saving of 12 percent of the total energy use for air conditioning. Thus the first 1°F change in average indoor temperature in summer carries high percentage dividends, approximately three times larger than the corresponding percentage changes in winter: effectively, 200 heating degree days are avoided when the house is 1°F colder over a 200-day winter, and for a 5000 degree-day winter, as at Twin Rivers, this comes to a savings of 200/5000 = 4 percent of the heating costs per degree Fahrenheit change in interior temperature. Using the 1976 marginal prices at Twin Rivers, the annual summer and winter savings for 1°F changes in interior temperature are approximately 16 dollars and 10 dollars respectively. Of course, the <u>penalties</u> for a 1°F decrease in interior summer temperature or a 1°F increase in interior winter temperature are numerically identical to the corresponding savings.

The interior temperatures, to be sure, are not identical across houses. Those households which have set their thermostats higher will have a smaller bill for air conditioning; a 1°F change in their thermostat setting in summer will make a smaller absolute difference but a larger percentage difference, relative to the average user. (Eventually, one encounters the household which uses the air conditioner only on the hottest day, and which, by a 1°F change in thermostat setting, would eliminate its use entirely.) Such non-users actually have been encountered by our researchers in the field. The variations in temperatures within houses in <u>winter</u> make much less difference; a savings of about 4 percent per °F change in average winter indoor temperature applies to nearly every house, because temperature variations within houses are small when compared to the difference between the temperature indoors and out.

The above calculations have been coarse in two respects. First, the Quad II air conditioner is sized small enough so that it essentially runs continuously on the very hottest days, and the temperature indoors climbs in spite of its efforts. Increasing the thermostat setting in such a situation may result in no savings at all (until evening). Second, we have arbitrarily assumed a 65°F reference temperature for the calculation of cooling degree days, and the calculation of the relationship between air conditioner use and outside temperature turns out to be sensitive to that assumption. The monthly data for median electricity consumption appear almost as linear when plotted against cooling degree days based on a reference temperature of 71°F, for example, and yet the slope is twice as steep: the air conditioning consumption is assigned to many fewer days (only the hottest ones), with a greater effect of each 1°F change in outside temperature once consumption for air conditioning sets in. It appears to us, after looking closely at the record of daily temperatures within each month, that 65°F is a close estimate of the best reference temperature; assigning 10°F to the indirect heating load from sun and electric appliances, as in winter, corresponds to an average summer interior temperature of 75°F.

Preliminary modeling of monthly data on a house by house basis has revealed that the scatter across months in some houses is considerable. A linear model of electricity use versus average outside temperature, identical to that leading to Equation IV.19 above, was applied to 61 townhouses, using data for 10 summer months. The distribution of R^2 values of the fits was: 23 below 0.8, 19 between 0.8 and 0.9, and 19 above 0.9. Allowing the model an extra term, proportional to average outside humidity (quantified in various ways) made no appreciable improvement, especially in its predictive value for subsequent periods of time, in spite of the additional free parameter and in spite of the physical reality, where the latent heat load is often one-half of the total air conditioning load. What happens when we look at the air conditioner consumption on a daily level for a single house (here, HIT 2), is shown in Figure IV-5. Although the scatter in the data is considerably more pronounced than in Figure IV-4, the general "macro" pattern is reproduced on a "micro" level, with an additional kilowatt



DAILY AVERAGE RATE OF AIR CONDITIONER ELECTRICITY USED IN HOUSE 2
FIGURE IV-5

consumption for about every 9°F of outside temperature, versus one kilowatt every 8.8°F in Figure IV-4. Neglecting the zero-consumption points at the bottom left because of the undue distortion introduced by them (imagine another few (physically possible) zero kilowatt points at temperatures below 55°F, that cannot possibly fit on a straight line with the others), the intercept is estimated about at 63°F.

More detailed field investigations of summer air conditioning are in progress during the 1976 summer. These investigations should help pin down the best reference temperature (and the spread about the mean), the detailed role of sun (via orientation effects), the significance of internal electric loads, the significance of "undersized" units, and the reasons why some individual houses depart so strongly from a linear pattern.

V. VARIATION ACROSS YEARS: CONSERVATION

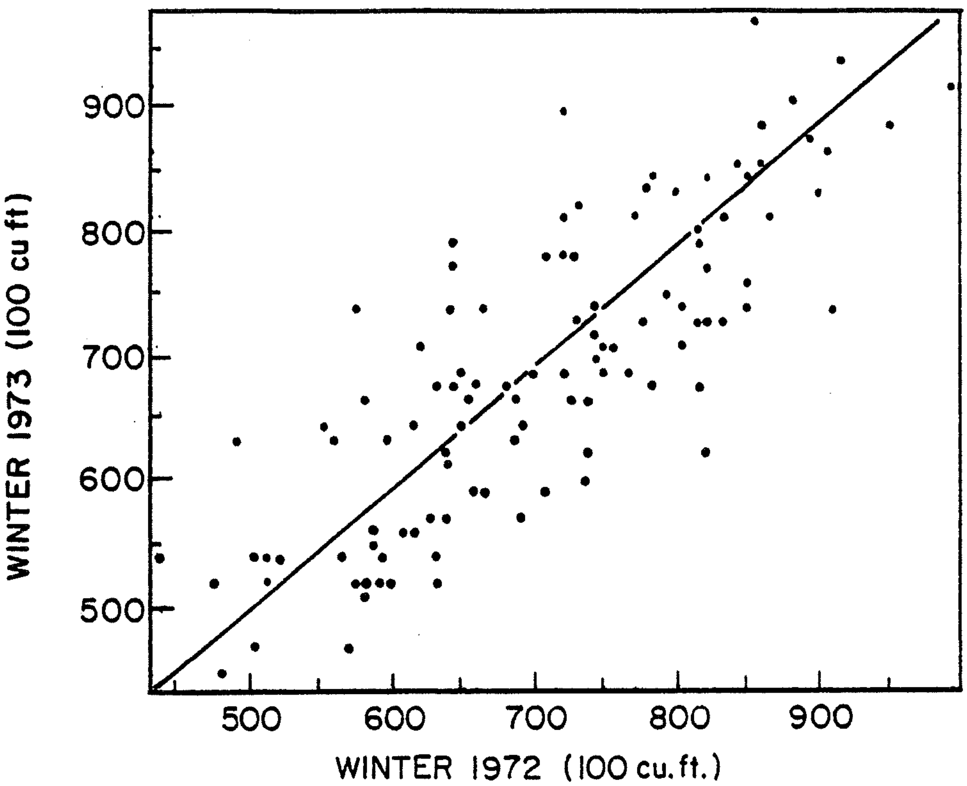
A. Conservation in the 1973-74 winter

The winter 1973-74 was a time of salience for energy. Twin Rivers residents were confronted with hour-long lines at gas stations and, although they were spared the dire warnings to those whose homes were heated by oil that the supplies might not last through the winters, they were deluged with pleas to conserve, in particular, to turn down their thermostat. Our data show the response in gas consumption, that winter, to have been by far the largest of any response, in either gas or electric consumption, over the five years (1971-76) since the town began.

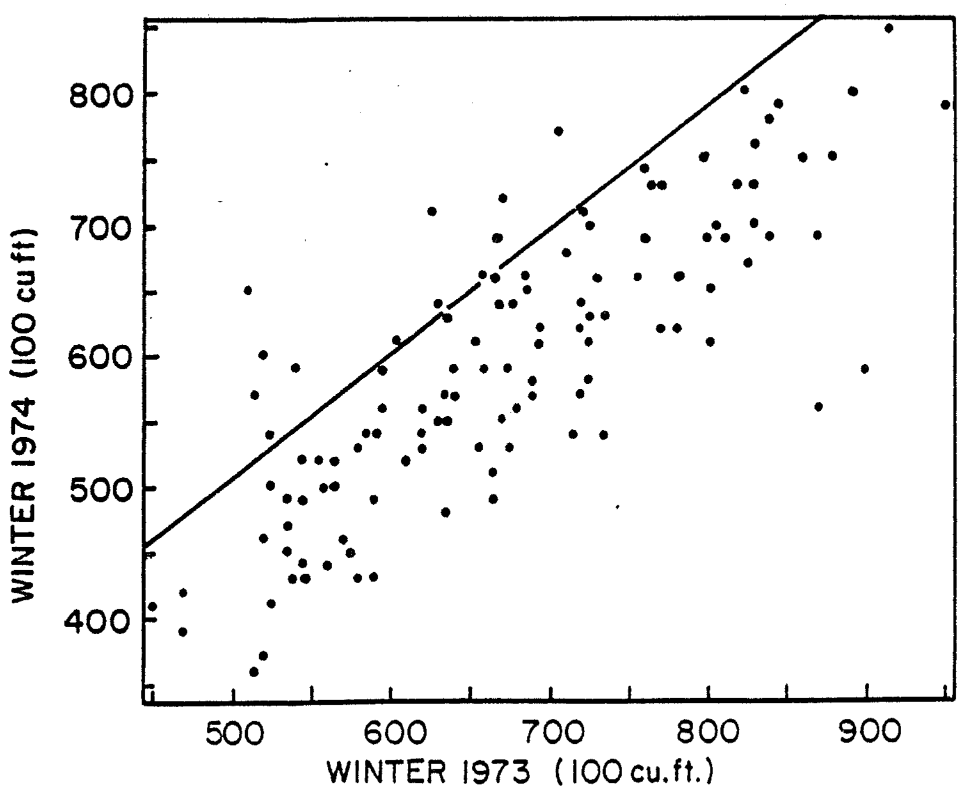
Consider the total winter gas consumption in the thirteen "Omnibus" townhouses for which data are complete, for the 1972, 1973, 1974, and 1975 winters. There were no changes of owners in those houses in that period. Three houses reduced their winter energy consumption by more than 10 percent between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

As was seen in Figure IV-1, 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. As was seen in Figure IV-2, 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 we control for outside temperature.

The pattern of conservation across houses is rendered in a striking fashion in the crossplots in Figure V-1. Here gas consumption over the four-month winters 1972, 1973, and 1974 are 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 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 and the pattern is well balanced below the line of equal consumption for the second pair of winters. The lower graph clearly shows 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 from where one started. The pattern in Figure V-1 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,



WINTER 1972 VS WINTER 1973 GAS CONSUMPTION



WINTER 1973 VS WINTER 1974 CONSUMPTION

FIGURE V-1

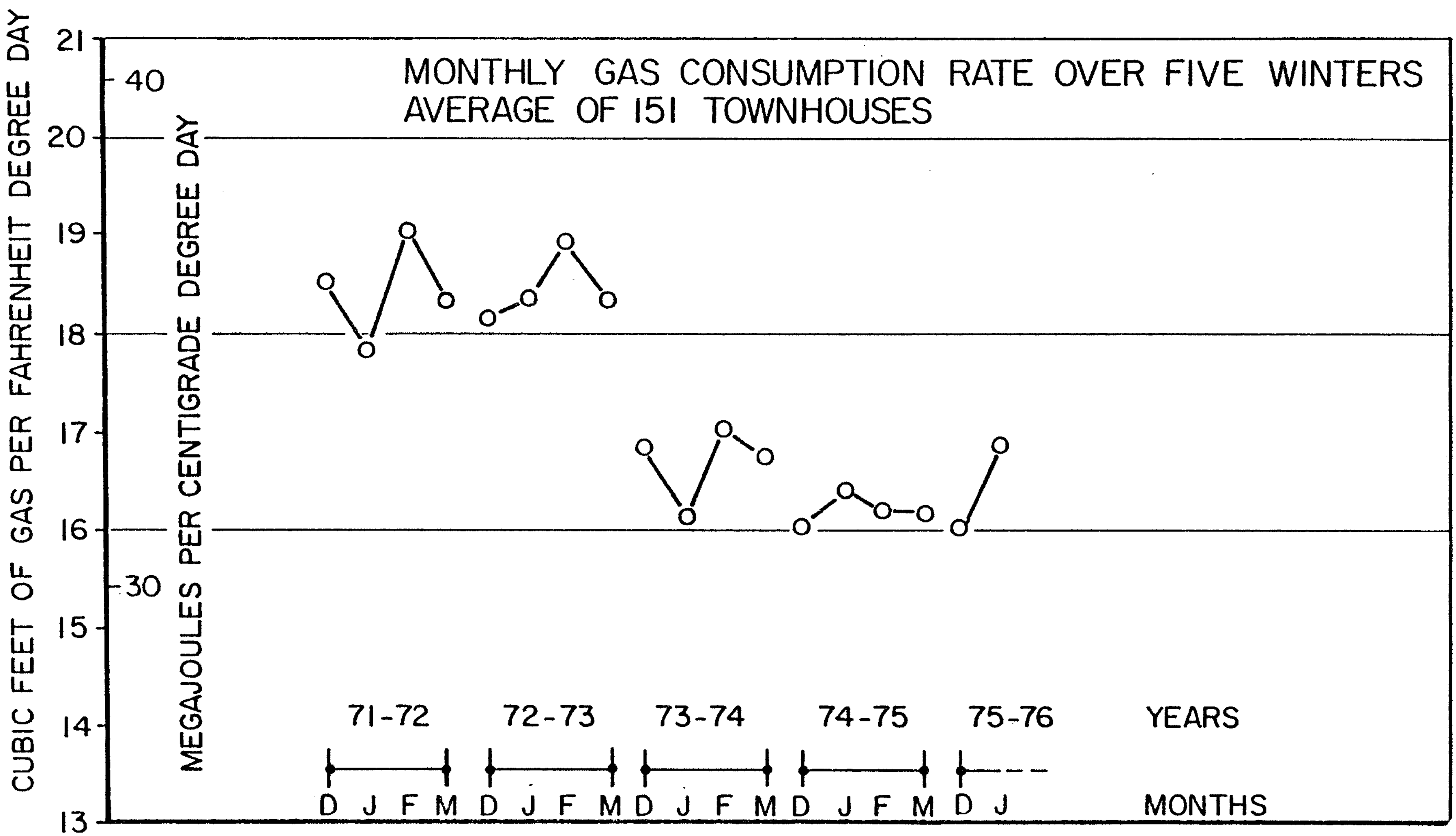
another for shift in temperature. The behavioral scientist appears now to have a second factor to explain: not only who is high and who is low but also who is responsive and who is not. The two factors appear to be nearly independent.

B. 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 V-2. This figure extends the data of Figure IV-1 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 was used; this is nearly always the form of easily available data.

However, the intercept in Figure IV-1 is 62°F. The effect of using a reference temperature higher than the intercept turns data which appear linear when plotted as in Figure IV-1 into data which do not lie on a horizontal line when plotted as in Figure V-2. 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:



MONTHLY GAS CONSUMPTION RATE OVER FIVE WINTERS
AVERAGE OF 151 TOWNHOUSES
CUBIC FEET OF GAS PER FAHRENHEIT DEGREE DAY
MEGAJOULES PER CENTIGRADE DEGREE DAY
21
20
19
18
17
16
15
14
13
40
30
71-72
72-73
73-74
74-75
75-76
YEARS
D J F M D J F M D J F M D J F M D J
MONTHS

FIGURE V-2

$$f(T_1,T_2,R,R_o) = \frac{(T_1-T_2)(R_o-R)}{1/2[(R-T_1)(R_o-T_2) + (R-T_2)(R_o-T_1)} \qquad (V.1)$$

of their own value.

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

For example, if $T_1 = 30$, $T_2 = 32$, $R = 62$, and $R_o = 65$, the value of the ratio in (V.1) is f = 0.006, or a little more than one-half percent. When the ratio in (V.1) 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. IV.1 are preferable to plots like Fig. V.2.

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 "score" of the performance of a house. Indeed, the voluntary conservation portrayed in Figure V-2 can be summed up tidily: "The gas consumption index of the average house hovered between 18 and 19 for the 1972 and 1973 winters, but dropped to a new level, between 16 and 17, 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 of the kind captured in Equation V.1: 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.*

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*A 40-year history of the local average annual temperature (which is not quite the same thing as the average winter temperature but probably shows comparable variability) is found in Appendix B.

The annual scores for the five winters are 17.8, 17.7, 16.4, 15.9, and 15.7 cubic feet per degree 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. Recall that median values of summer electricity consumption were displayed in Figure IV-4. They deserve a second look. There is no evidence of conservation.

As will be discussed below, 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.

We are not sure whether there was 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 effect. An analysis of median consumption indicated a 6 percent reduction in winter consumption in 1974. A close examination of the distributions should clarify the discrepancy; in spite of the efforts of the group, errors in meter readings and "outliers" reflecting empty houses may still be lurking in our data set.

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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.

C. <u>Price and price response</u>

The price of energy has been rising at Twin Rivers. The marginal prices of both electricity and gas approximately doubled between 1971 and 1976, as seen in Figure V-3* and V-4. 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 combined data of Figure IV-4 and Figure V-4 are a testament to the apparent absence of any demand elasticity at all for summer electricity, including summer air conditioning.

Annual data for gas consumption per degree day and marginal price are combined in Figure V-5; a robust regression on these data, with no correction for inflation (see below), tested the model (C = consumer per degree day, P = marginal price):

$$\ln C = \ \ln P + (\text{const}), \tag{V.2}$$

and yielded the five year average elasticity:

$$= -0.24 \pm 0.04 \tag{V.3}$$

The R^2 of the fit was 0.91.

The data in Figure V-5 clearly tell a more complicated story than is captured by a constant elasticity, however: first, consumption went down, then price went up. There is no way in which our data can refute the economist who says "Ah ha, price anticipation!" or the sociologist

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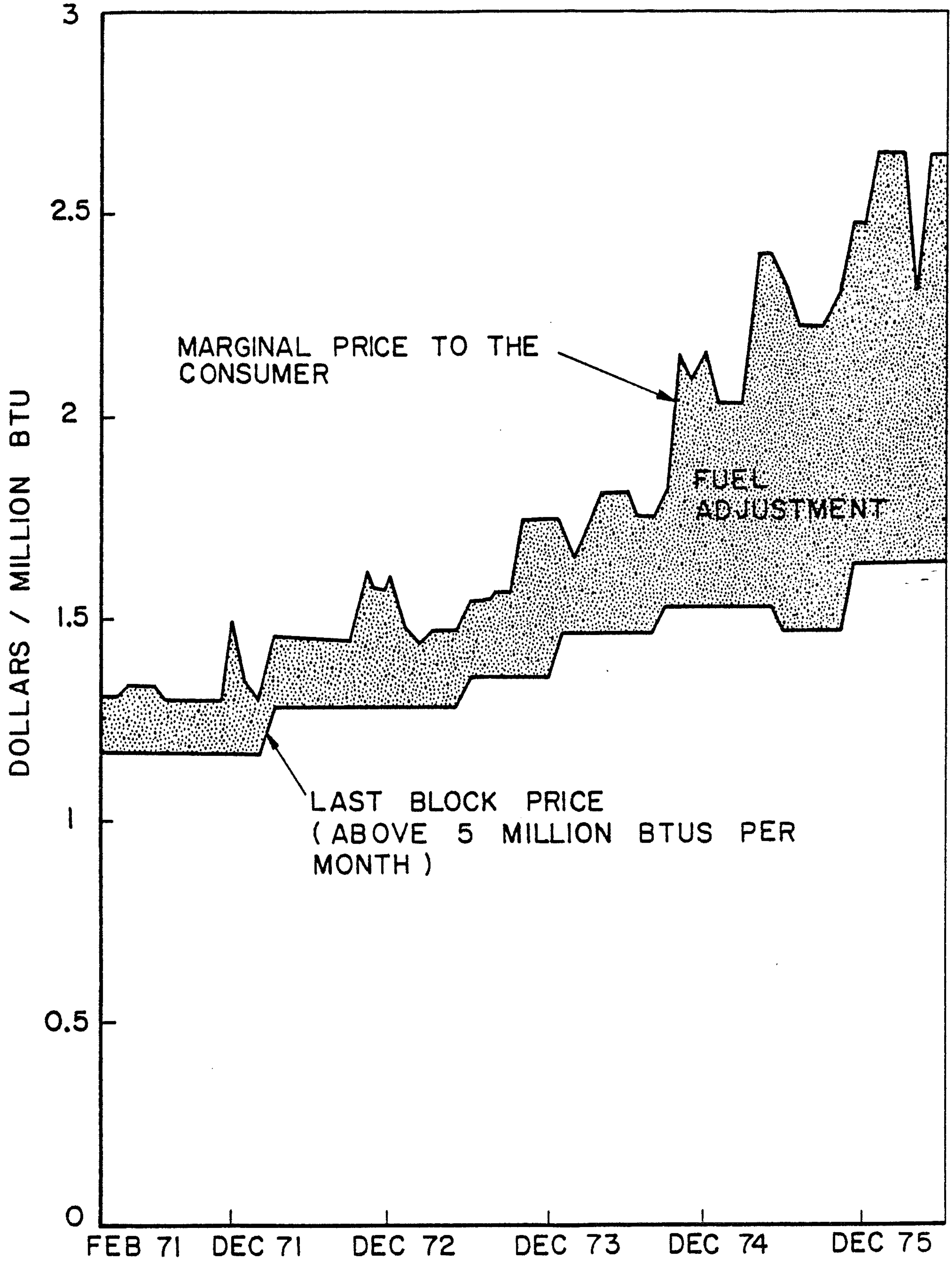
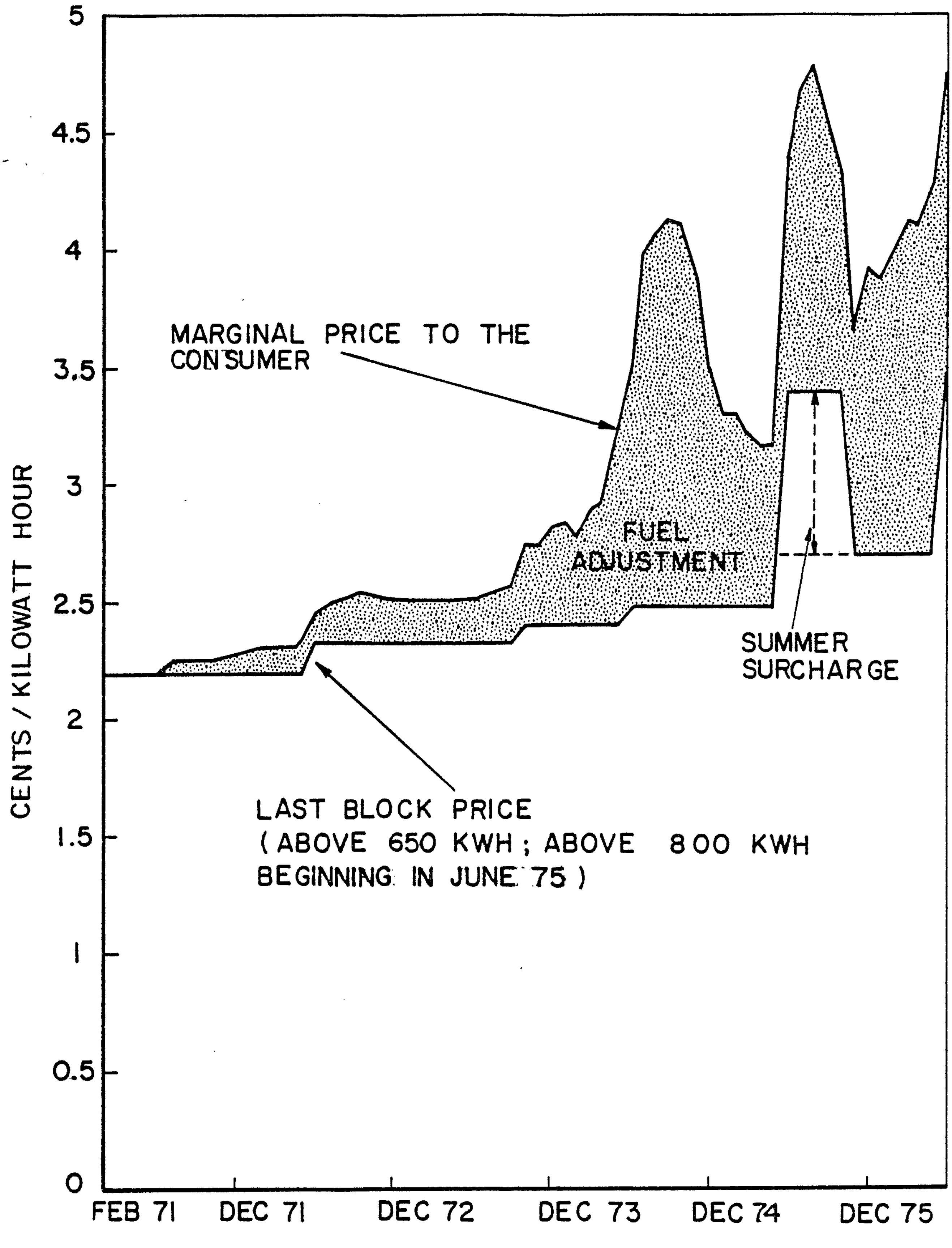
*The block structure of price and the various surcharges and discounts are discussed in Appendix C.



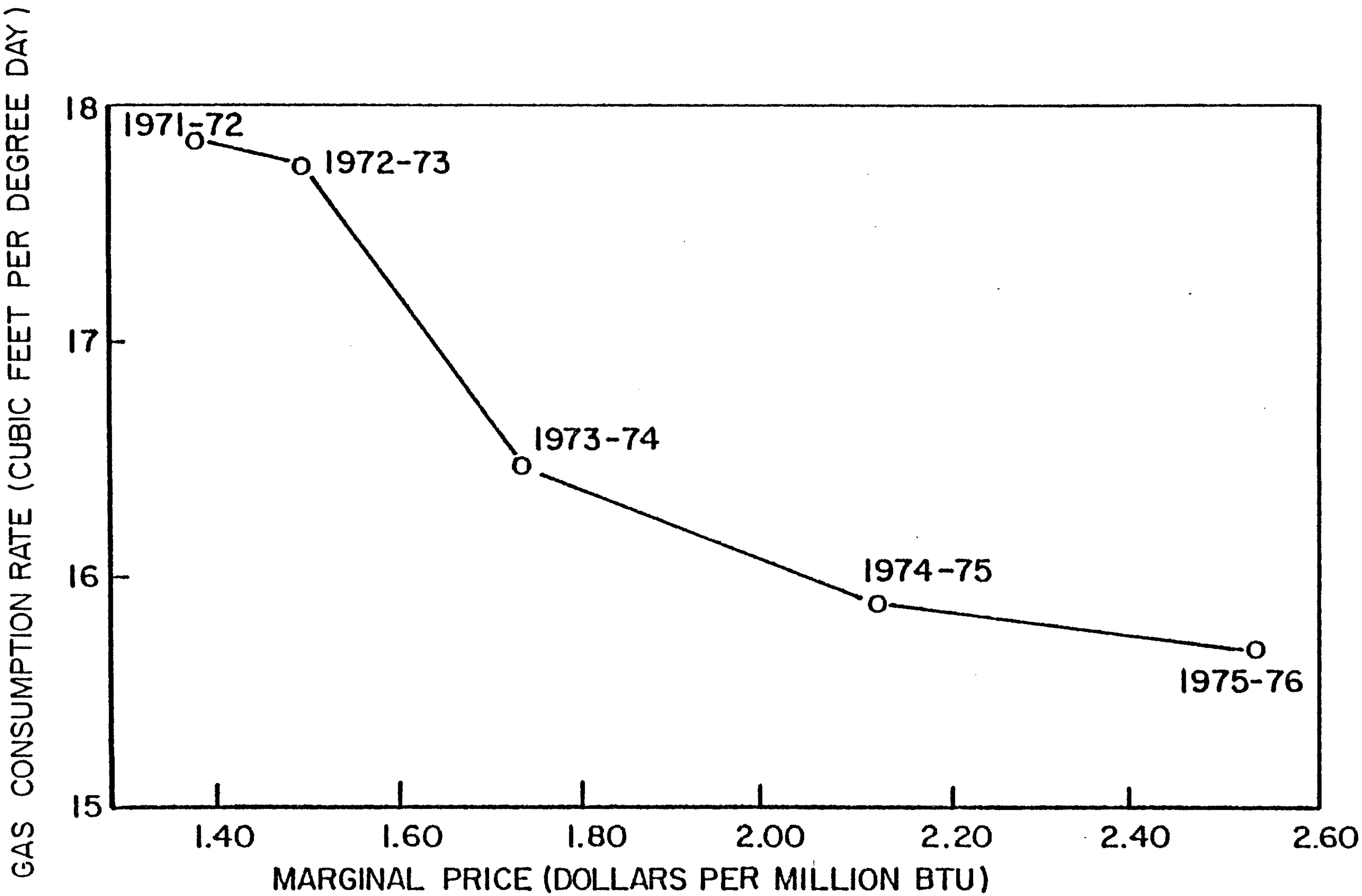
MARGINAL PRICE OF RESIDENTIAL NATURAL GAS, IN DOLLARS PER MILLION BTU.

FIGURE V-3



MARGINAL PRICE OF RESIDENTIAL ELECTRICITY, IN CENTS PER KWH

FIGURE V-4



PRICE VS. RATE OF CONSUMPTION OF GAS

FIGURE V-5

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.

Marginal prices change every month, because of the variable fuel adjustments. It would be remarkable if any gas consumption index would reflect such short-term influences, given the delays and obfuscation that attend the transmission of price information from the public utility to the consumer. A vigorous search for a consumer response to short-term variations (less than one year) in the price of natural gas has been conducted by Cindy Horowitz, and it has yielded the expected negative result.

The marginal price of natural gas, used in all these estimates, is the price for the last block of gas in the residential rate structure. It is exceeded by the average price because the rate structure is composed of declining block rates. We can work out which consumers see this block price as their marginal price, and when. The last block begins at 5 million btu's per month (50 "therms", where 1 therm = 100,000 btu); at 1025 btu per cubic foot, this is about 4900 cubic feet in about 30 days, or about 160 cubic feet per day. A gas heated house using 20 cubic feet per degree day will face a marginal price equal to the price of the last block, for all months whose average outside temperature is more than 160/20 = 8°F below the best reference temperature for that house.* Looking back to Figure IV-1, we see that all six

*For a house with a best reference temperature of 62°F, that means a month averaging at least 11°F below 65°F, or about 330 conventional degree days per month.

winter months, November to April, are that cold. In the remaining months of the year, for those houses having no other gas appliances, the occasional use of gas is considerably more costly per cubic foot. The summer furnace pilot produces a meter change of, typically, 600 cubic feet per month, or 0.6 million btu per month. At the current rates, this gas costs the resident about 5 dollars each month, or eight dollars per million btu, three times the current marginal price; one is really just paying billing costs.* There ought to be a strong economic incentive to shut off the pilot in summer, but it is not felt.

The <u>average</u> price of natural gas in winter is not only higher than the marginal price, but it has also been climbing more slowly, as the residential rate structure has been made flatter. The average monthly bill for winter heating has been computed by Ms. Horowitz, using the rates in effect, the average metered gas consumption (for 151 houses), and the number of degree days (conventional base temperature, 65°F). The costs expressed in cents per degree day, and they are plotted in Figures V-6, V-7, and V-8. To understand the ballpark of the vertical scale, observe that 1) gas costs (1976) about 3 dollars per million btu, or 3 dollars per thousand cubic feet; 2) consumers use 16 cubic feet per degree day; so that 3) gas costs 3 dollars for about 60 degree days of heating, <u>or a nickel per degree day</u>, in current money.

Figure V-6 plots the yearly average cost (for a six month winter) and Figure V-7 plots the monthly costs for 27 consecutive winter months

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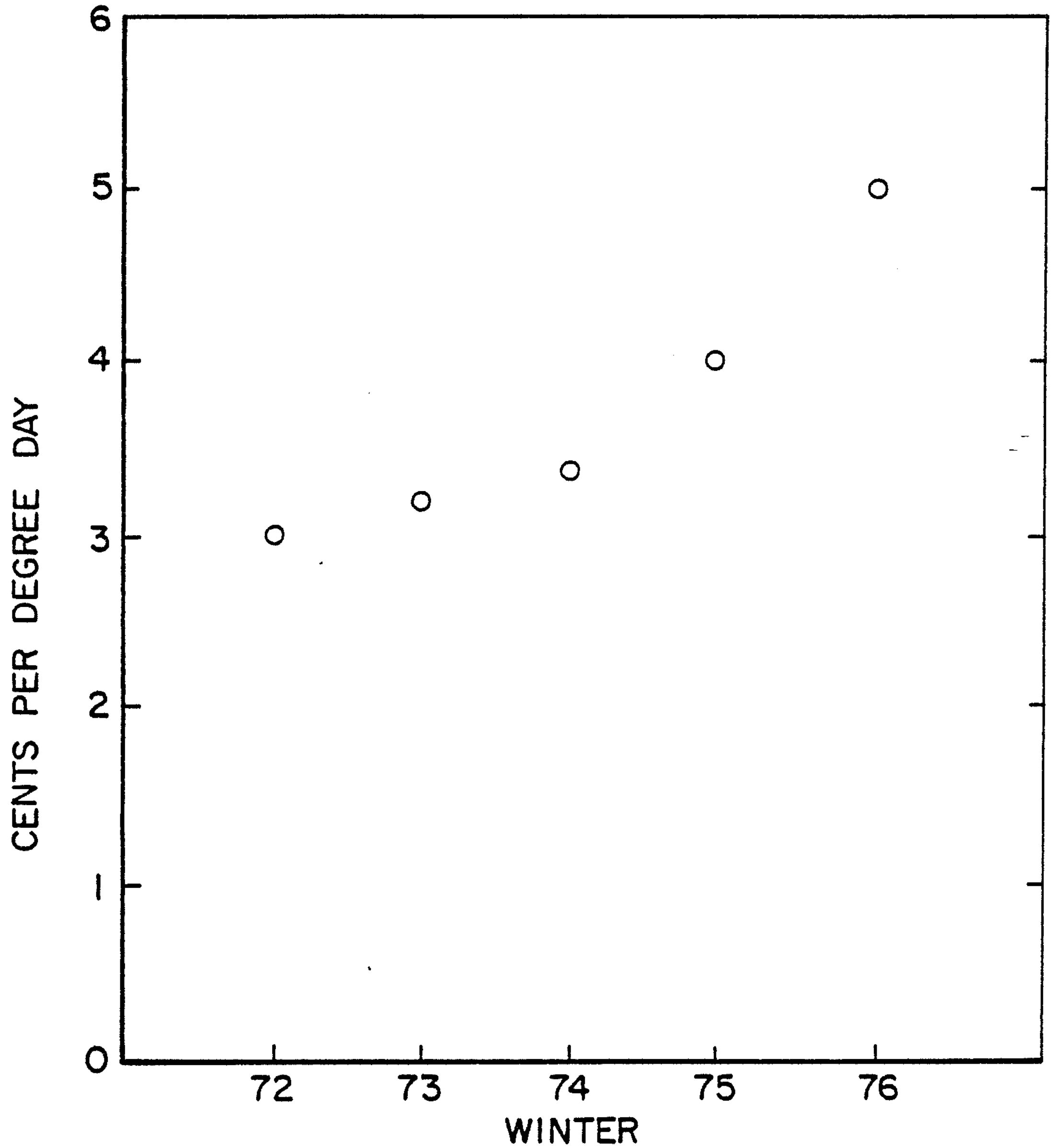
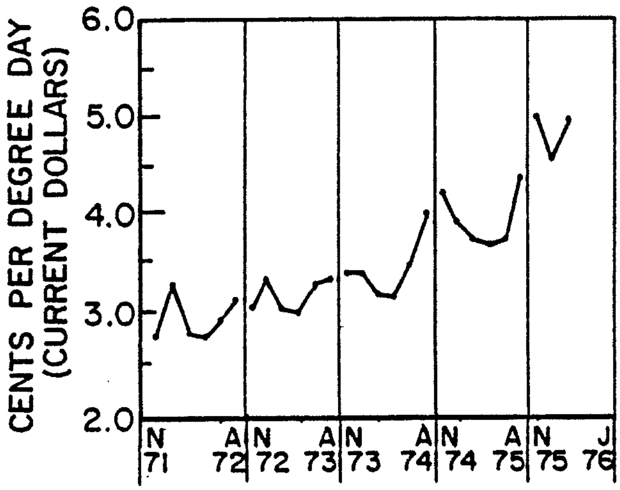
*This does not include the cost of the electrical energy to remove the pilot light energy, which adds about 3 dollars each month, assuming the flame does not remove most of its own heat by inducing a net flow up the flue.



AVERAGE ANNUAL COST OF WINTER GAS HEATING
FIGURE V-6



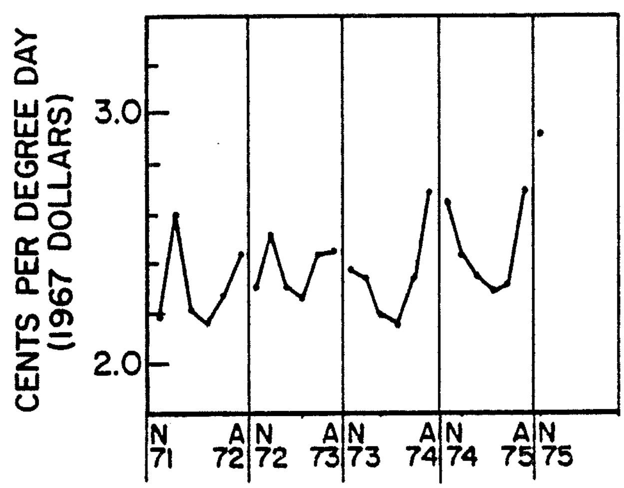
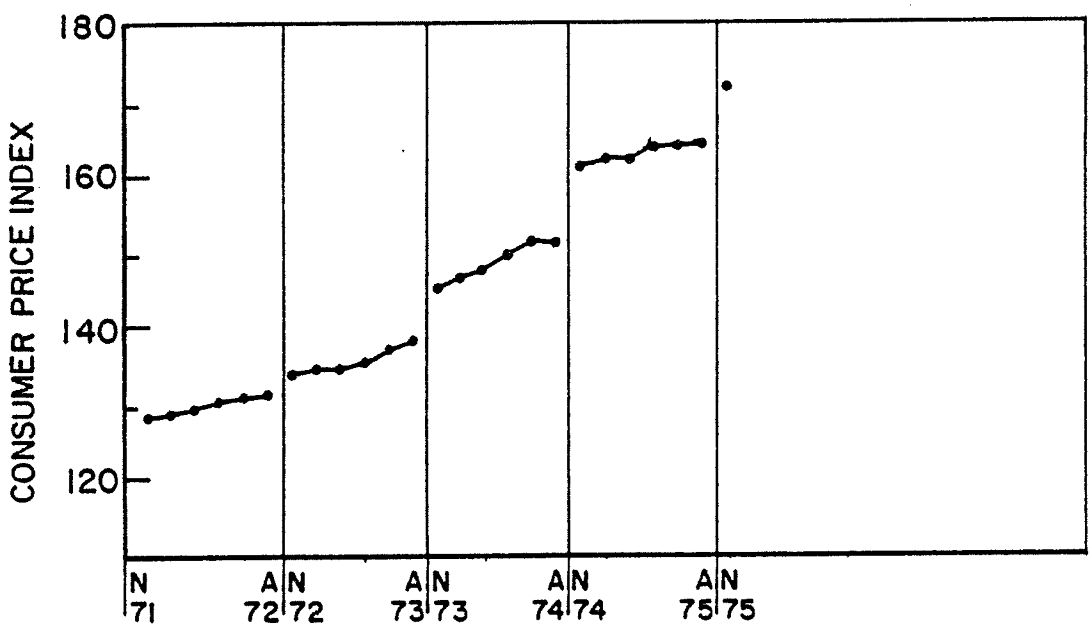


FIGURE V-7

FIGURE V-8

AVERAGE MONTHLY COST OF WINTER GAS HEATING (LEFT)UNCORRECTED, AND(RIGHT) CORRECTED FOR INFLATION. (N=NOVEMBER, A=APRIL)



CONSUMER PRICE INDEX VS. TIME (month)

FIGURE V-9

(November 1971-January 1976). Figure V-8 shows the monthly costs when deflated by a regional consumer price index, and the index itself is shown in Figure V-9. The index used here is the Consumer Price Index -- City Average, as reported in the Monthly Labor Review, a monthly index covering New York City and northeastern New Jersey, for which 1967 = 100. The index climbed from 128 to 170, or 33 percent, between November 1971 and November 1975 (the latest date available to Ms. Horowitz).

Figure V-8 is the first curve over time that has looked at all flat. To review, three factors are conspiring to keep the constant dollar cost per degree day from climbing at anything like the rate of climb of the marginal price for residential gas: 1) a flattening rate structure, 2) the general inflation of the economy, and 3) the efforts at conservation.

VI. CONSUMPTION BEFORE AND AFTER RETROFITS

A systematic program of retrofits was launched at Twin Rivers during the 1976 winter. 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 providing comfort at minimum energy cost.* The retrofits we chose to introduce this past winter, and the schedule of placement in the townhouses, may be found in Appendix F. Photographs and discussion of the defects in the houses being addressed by retrofits are found throughout this report, but especially in Chapter VII. Here, we present some summary results concerning the savings in natural gas which resulted from the retrofits. There are two objectives here. The first is to emphasize the "bottom line": <u>The full retrofit package reduced average winter gas consumption by 25 percent</u>. The second is to exercise the techniques developed, especially in Chapters IV and V, to demonstrate the high level of confidence with which this claim can be asserted.

This chapter makes us attempt to reveal the richness in the data we have obtained by monitoring temperatures and electric and gas consumption, hourly, in the periods both before and after retrofit. The houses not only reduced their energy consumption, but they also became more comfortable, with less temperature difference between upstairs

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*In space-age fashion, retrofit is used as a noun, adjective, and verb.

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 generally. Such detailed analyses are currently in progress and will be discussed in subsequent reports.

The retrofits were implemented in two batches, 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 batch of retrofits was visible almost instantly in the data obtained by daily monitoring of the gas and electric meters.* Figure VI-1 shows

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*Located against the outside wall in the back patio, these meters provided back-up for our instrumentation within the houses, and all data in this Chapter are drawn from those readings.

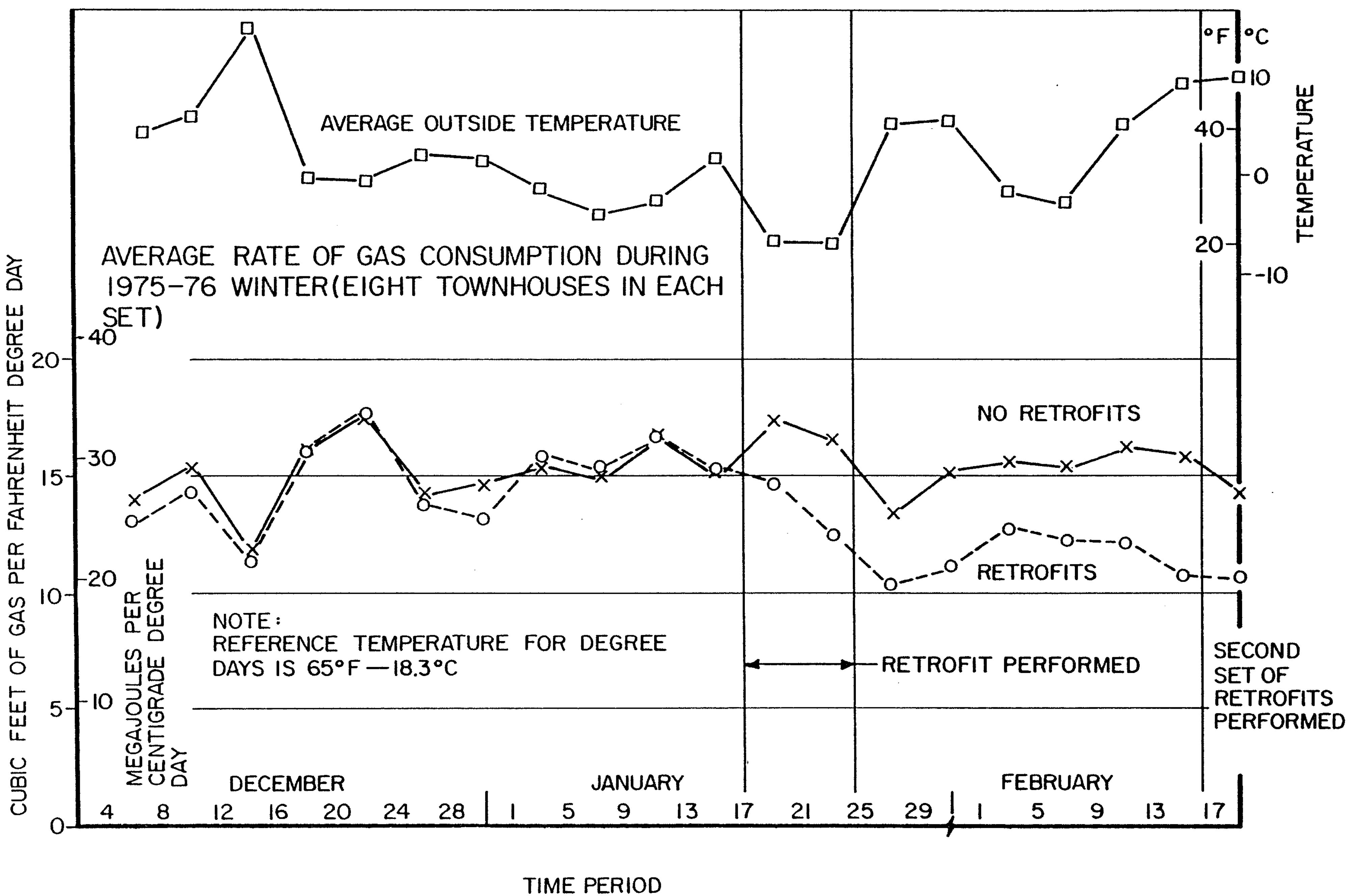
AVERAGE OUTSIDE TEMPERATURE
AVERAGE RATE OF GAS CONSUMPTION DURING 1975-76 WINTER (EIGHT TOWNHOUSES IN EACH SET)
NO RETROFITS
RETROFITS
NOTE:
REFERENCE TEMPERATURE FOR DEGREE DAYS IS 65°F — 18.3°C
RETROFIT PERFORMED
SECOND SET OF RETROFITS PERFORMED
°F
°C
TEMPERATURE
CUBIC FEET OF GAS PER FAHRENHEIT DEGREE DAY
MEGAJOULES PER CENTIGRADE DEGREE DAY
DECEMBER
JANUARY
FEBRUARY
TIME PERIOD

FIGURE VI-I

two average rates of gas consumption, one for the eight townhouses which were retrofitted in the first batch, one for the other eight "control" houses. Averages were computed every four days, and variations in weather were crudely incorporated by dividing by the degree days reported at Trenton, based on a 65°F reference temperature. The two lines had nearly lain upon one another before the retrofits were performed (the selection of the "first eight" was made in part to accomplish this) and separated immediately into one "score" averaging just above 15 cubic feet per degree day and another score averaging around 12.*

Neither before nor after retrofit were the average gas consumption rates flat over time. Figure VI-1 gives a clue about the source of the wriggling 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, as was seen in the plot of monthly data in Figure IV-1. In Figure VI-1 it is clear that this correction alone cannot account for all the wriggles: 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 "score" cubic feet per degree day does seem to be to adjust for a lower intercept, and this is done for the rest of

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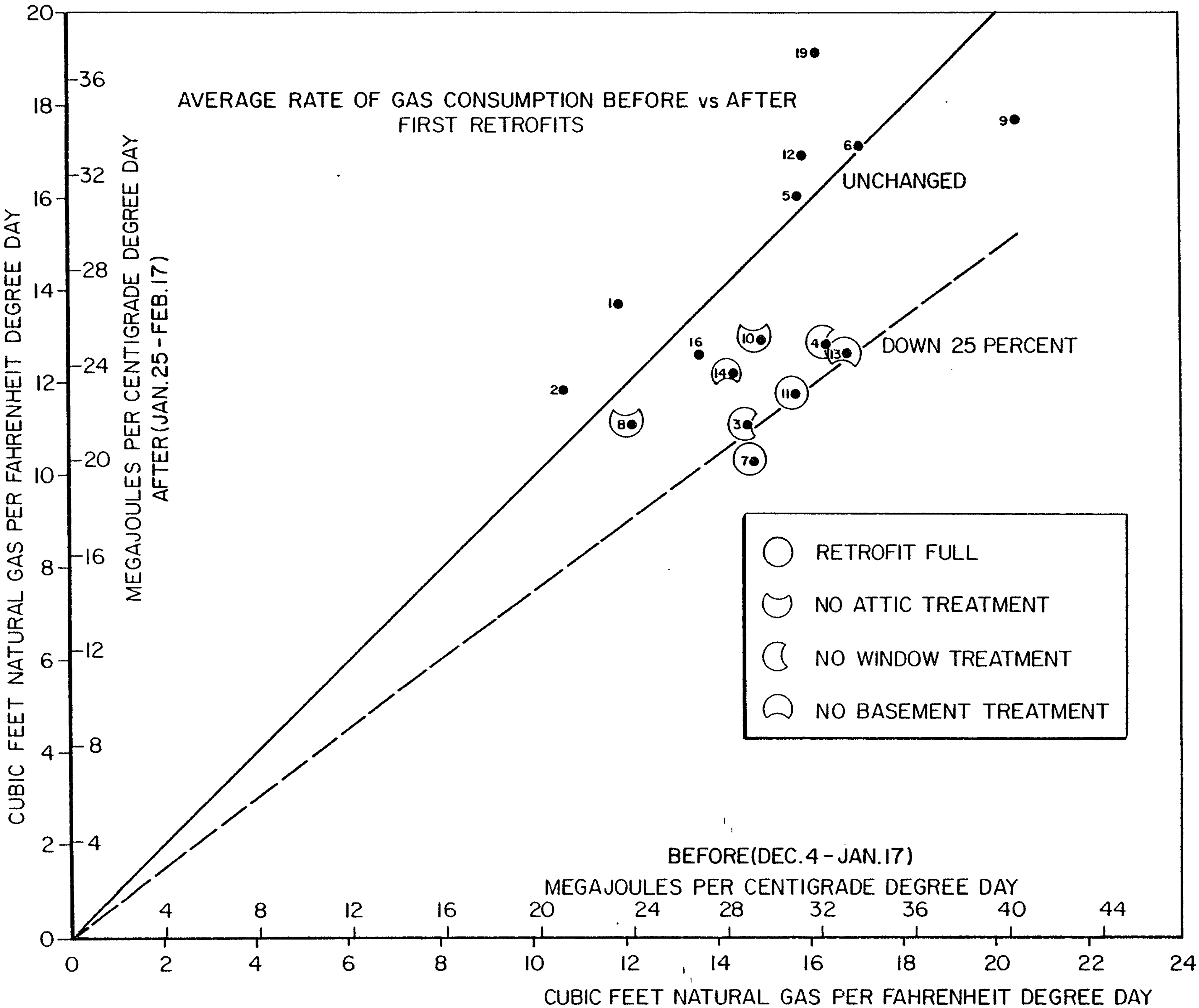
*The Figures in this chapter also show the "score" in what seems likely to be the most reasonable metric unit: megajoules per Centigrade Degree Day. The conversion, assuming 1025 btu/cu.ft. for natural gas, is almost exactly 2 to 1; 1 cu. ft/°F-day = 1.946 Mjl°C-day.

this chapter, following the method embodied in Equation V.1 of the previous chapter (with R set equal to 62°F), whenever a comparison is made between scores for periods differing appreciably in average outside temperature.

Figure VI-2 and VI-3 give a house-by-house snapshot of the effects of the retrofits, averaging over the longest available time periods. Figure VI-2 shows that all eight retrofitted houses showed the effects of treatment, and strongly suggests an ordering of the retrofits in order of decreased significance of the associated savings: A (attic insulation), B (sealing and caulking of windows, doors and party walls, abbreviated as "windows") and C (duct insulation, abbreviated as "basement"). All eight houses received the D retrofit (sealing of the flue shaft).

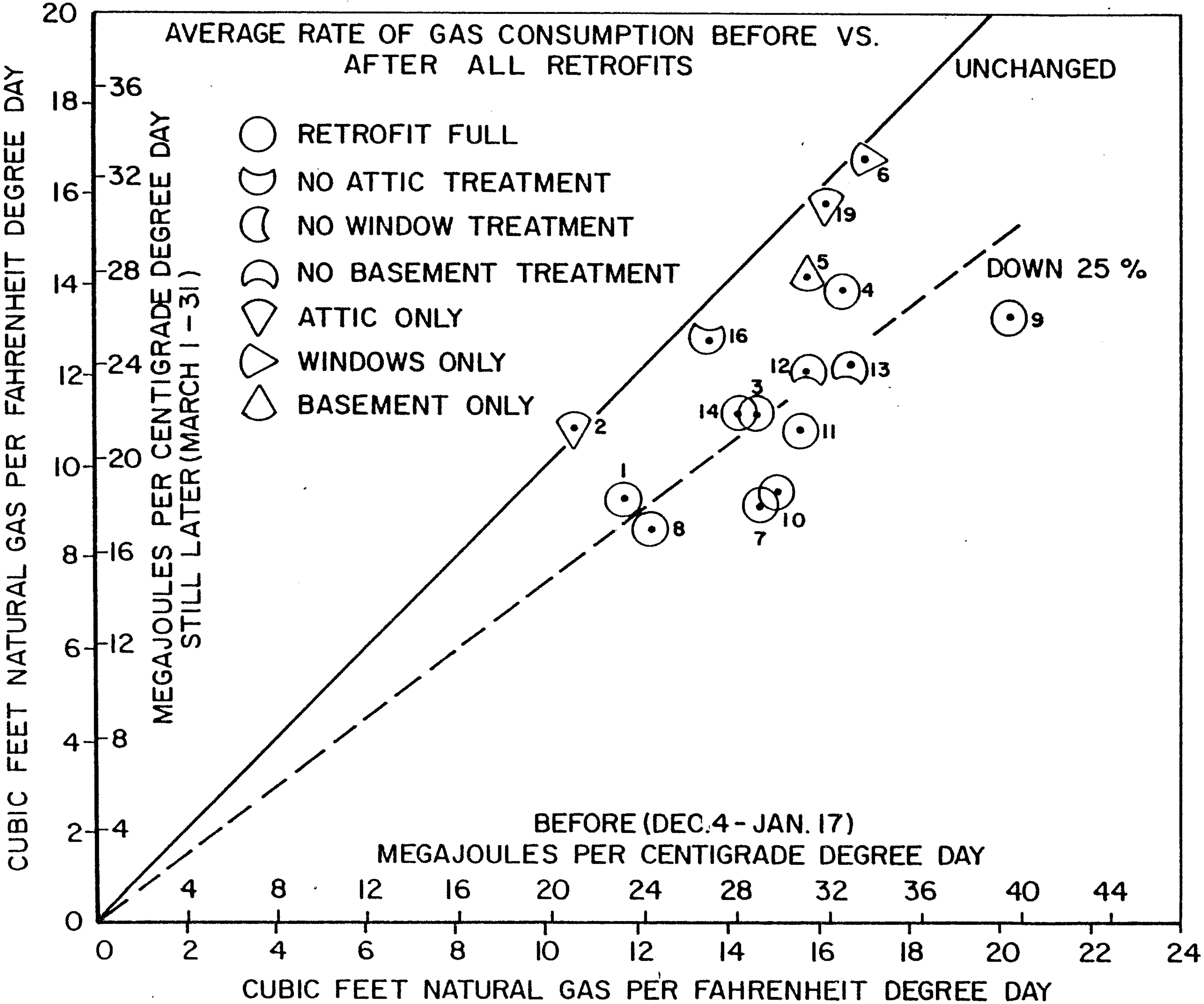
House Number 9 is actually a contaminated member of the control group, for the residents became aware of anomalously large gas consumption, called for help, and allowed our technicians to replace their thermostat, to reset a furnace control (fan-off at lower temperature) and to reconnect two sections of a heating duct that had come apart. Whether the residents also modified their behavior (e.g., thermostat settings) should become clear on close examination of our field data. The reason why the control houses generally scatter above the line of unchanged rate of gas consumption is currently unclear. Excluding House 9, the average increase is 8 percent, and only 1 percent can be accounted for by the fact that the period after retrofit was slightly warmer.*

*The average outside temperature was 34.5°F before and 36.7°F after; then $f = 0.009$ if $R = 62°F$ and $R_o = 65°F$ are used in equation V.1.



AVERAGE RATE OF GAS CONSUMPTION BEFORE vs AFTER FIRST RETROFITS
UNCHANGED
DOWN 25 PERCENT
RETROFIT FULL
NO ATTIC TREATMENT
NO WINDOW TREATMENT
NO BASEMENT TREATMENT
CUBIC FEET NATURAL GAS PER FAHRENHEIT DEGREE DAY
MEGAJOULES PER CENTIGRADE DEGREE DAY
AFTER (JAN.25 - FEB.17)
BEFORE (DEC.4 - JAN.17)
MEGAJOULES PER CENTIGRADE DEGREE DAY
CUBIC FEET NATURAL GAS PER FAHRENHEIT DEGREE DAY

FIGURE VI - 2



AVERAGE RATE OF GAS CONSUMPTION BEFORE VS. AFTER ALL RETROFITS
UNCHANGED
DOWN 25 %
RETROFIT FULL
NO ATTIC TREATMENT
NO WINDOW TREATMENT
NO BASEMENT TREATMENT
ATTIC ONLY
WINDOWS ONLY
BASEMENT ONLY
CUBIC FEET NATURAL GAS PER FAHRENHEIT DEGREE DAY
MEGAJOULES PER CENTIGRADE DEGREE DAY
STILL LATER (MARCH 1 - 31)
BEFORE (DEC. 4 - JAN. 17)
MEGAJOULES PER CENTIGRADE DEGREE DAY
CUBIC FEET NATURAL GAS PER FAHRENHEIT DEGREE DAY

FIGURE VI - 3

If the seven-house control group is used to establish the norm, and the temperature correction is made, the dashed line reading "down 25 percent" would become "down 32 percent."

In Figure VI-3, only two of the seven houses which have less than the full complement of retrofits are found among the nine "ABCD" houses: House 12 and House 13. Both are effectively "finished," because their basement has a drop ceiling and a C retrofit will be foregone. Retrofit A (Attic) for House 12 was carried out only in mid-March, so its consumption per degree day will presumably drop somewhat more. House #7 had a change of owner in the midst of February, and the previous occupants were notorious low users. This might have offset the effect of the attic retrofit to the point where the consumption remained almost constant. During the period shown in Figure VI-3, the D retrofit was not in place in houses where the A retrofit had not been done (Houses 5, 6, and 16). The performance indices in Figure VI-3 for March 1-31 have been adjusted (upward by 6 percent) to take the milder weather into account: the average outside temperature was 45.3°F.* Even after making this adjustment, the savings exceed 25 percent in five of the nine fully retrofitted townhouses.

The nine fully retrofitted (ABCD) houses become a fascinating subset for further study. Table VI.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

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*f(34.5, 45.3, 62, 65) = 0.062 in the notation of Equation V.1.

Table VI.1

Rate of Gas Consumption by ABCD Houses (cu. ft/°F-day)
(corrected for outside temperature difference)

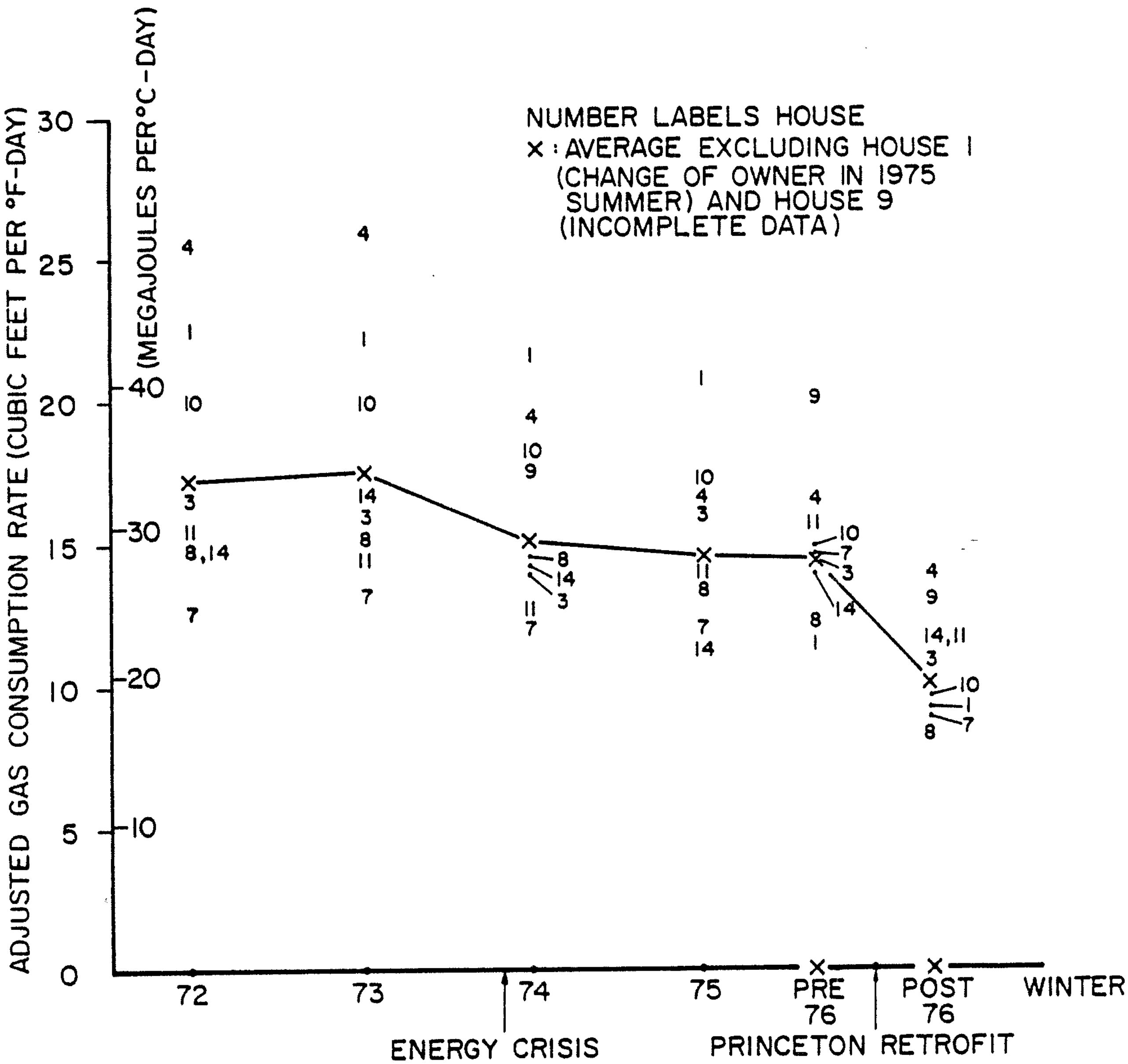
House #	Pre-Retrofit (Dec. 4 - Jan. 17) Rate	Pre-Retrofit Number of S.D. from mean	Post-Retrofit (March 1-31) Rate	Post-Retrofit Number of S.D. from mean
1	11.8	-1.3	9.4	-0.8
8	12.0	-1.2	8.5	-1.3
14	14.2	-0.3	11.2	+0.2
3	14.5	-0.2	10.7	+0.2
7	14.6	-0.1	9.3	-0.8
10	14.8	+0.0	9.6	-0.6
11	15.5	+0.3	11.0	+0.1
4	16.2	+0.5	13.7	+1.6
9	20.2	+2.1	13.2	+1.3
Mean	14.9		10.7	
Standard Deviation (SD)		2.5		1.8
S.D./Mean	.17		.17	

Correlation pre-post retrofit rates 0.81

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 16 percent of the mean.

These results can only be accounted for in one of two ways: either the reasons for variation are structural, but lie in areas untouched by our retrofits (such as in the workings of the furnaces) or they are behavioral. As discussed in Chapter III, this cannot be a sharp line, for people must express their behavior by doing <u>something</u> 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 be the result of variations in behavior within the houses that are <u>not</u> related to gross defects in structure nor to interior temperature settings (even though both of the latter are important), and to which both the building professionals and the residents are oblivious. Examples of such behavior are whether interior doors are left open or closed and whether drapes are drawn or not. The tightening of the knot that explains variability across houses still lies in the future.

Figure VI-4 looks back over the five year period for the nine ABCD houses. For House 9, the public utility's data are incomplete, but the others can be tracked in full. The relative standing of House 1 plummets from highest to lowest across the 1975 summer, with a change of owner! The mean of the other seven houses is traced by the solid line: the scores (corrected for outside temperature) dropped from



5 YEAR HISTORY OF NINE OMNIBUS HOUSES FULLY RETROFITTED BY PRINCETON IN WINTER 76

FIGURE VI-4

17.2 and 17.4 in the period before the "energy crisis," to 15.1 and 14.4 in the two following winters, to 14.6 before retrofit and 10.6 after retrofit. The savings from retrofits, were 4.0 out of 14.6, or 27 percent. Whether they started out high or low, down they came, and they sorted themselves out at the end as at the beginning.

We are inevitably asked about the payback period for the savings observed. The A, D and C retrofits were done by contractors, each at $150 per house. The B retrofit was done by our technicians; per house, the materials cost approximately 25 dollars, but the labor would have cost at least another $75 (although many households would have accomplished the same task during their "spare" time). At $400 per house, 3 dollars per milltion btu, 80 million btu (800 hundred cubic feet) per winter, and 25 percent savings, the payback period considering <u>only winter savings</u> comes to 7 years.

There are at least four reasons why this is a high estimate of the payback period: 1) Savings in summer and in winter electricity are not included; they are currently being documented and are estimated to reduce the payback period to less than 3 years. 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; for example, if the attic retrofit alone saved 15 percent, its payback period would be 4 years; and the insulation wrapped around the hot water heater pays for itself in a few minutes. 4) No price is put on improved comfort and the higher propensity to night setbacks that could result from it. Furthermore, in some circumstances, neighbors and entire communities, bargaining collectively, will obtain better prices than we did.

It will be interesting to see whether other Twin Rivers residents pursue any of these retrofits with their own money and on their own time. Who will and who won't? Does it matter what Princeton says, and how? These are yet another set of questions waiting for testing in the Twin Rivers laboratory.

Part Two

What Else You Can Learn by Going Inside the House

To gain any further understanding of what determines the energy balance in the townhouse we have to go beyond the mere analysis of monthly utility meter readings and must cross the threshold of the house.

Chapter VII defines the townhouse as a heat transfer problem and presents the inefficiencies caused by some construction details, the heating system and the residents themselves. Chapter VIII continues the discussion of the previous chapter by examining the transients caused by the pulsed operation of the furnace, by the weather and by thermostat setbacks. Chapter IX highlights the results of the automatized experiments (as opposed to the controlled experiments described in chapters VII and VIII) performed in a variety of townhouses, focusing on the statistical models and the experimental results of furnace gas consumption, attic temperature and air infiltration. Chapter X concludes this report with a discussion of the load profiles of the main appliances over the hours of a day and over the months of a year.

VII. A CLOSER LOOK AT THE TOWNHOUSE: STATICS

A. Introduction

Different people look at a house in rather diverse ways: while the occupant likes to think of it as his shelter and security, the carpenter will see primarily the wooden frames and doors and the painter the quality of the surface coatings. "Our" part of the house, its energy performance, is somewhat more abstract. Instead of materials, we have to look at temperatures, heat sources, and their interactions, all invisible, and only the first easily measurable.

In this chapter we will attempt to define the heat transfer problem associated with a house: we could look at it as a one zone system (one temperature inside the house) with uniformly distributed internal heat sources (furnace, people, appliances, sunshine entering through the windows) and given outside boundary conditions (outside temperature, wind and sun, next door neighbors' house temperature in the case of attached townhouses, and ground temperature). What is the equilibrium temperature of this system and what is the heat flux between indoors and out? The next few sections will first simplify, and then add to the complexity and to the accuracy of this initial model. In Section B we will define more clearly the conditions of the simple one-zone box model. Section C through E will move closer to the real world, discussing the natural vertical zoning of the temperature in a house, emphasizing the peculiarities caused by the (inhomogeneous) furnace heat distribution and the design deficiencies and discussing how they have been corrected by retrofits. Section F concludes with the energy inefficiencies introduced indirectly by the residents, and their diagnosis by the trained house-doctor.

B. Inside and outside boundary conditions of the one-zone model

The inside boundary conditions are all heat sources, best characterized by their heat output per unit time, rather than by some temperature. The furnace primarily produces heat at the rate of 80,000 btu/hr (23.4 kilowatt) when it is running, and essentially nothing when it idles. The fraction which passes usefully through the house is called furnace efficiency.* The electric appliances that come as standard equipment in a Twin Rivers house are also best described in terms of their heat output, as obtained from their electricity labels. Table VII-1 lists the power ratings of the standard set of appliances that come with each house, some of them, like the refrigerator, of optional size and type. Also listed are the furnace, the air conditioner, the furnace blower fan, and the set of appliances most commonly purchased by the residents themselves, with an estimated average of their power rating. The combined power consumed, if the entire standard set of appliances in Quad II townhouses is running full blast, taking an average where an option exists, is 79,000 btu/hr or 23 kilowatt, almost equal to the furnace rating. Adding the lights and the most conspicuous extra appliances commonly

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*The furnace efficiency is here defined as the ratio of the total heat output from gas combustion minus the unused heat escaping through the flue, divided by the total heat output from gas combustion.

Table VII.1

Power Rating of Standard Set of Electric Appliances in a Twin Rivers Townhouse in Quad II

Item	Rated Power Btu/hr	Rated Power kilowatt
Furnace (gas powered)	80,000	23.4
Air Conditioner (output)	24,000	7.0
Air Conditioner (input)	10,900	3.2
Blower Fan (heating mode)*	1,200	0.34
Blower Fan (cooling and manual mode)*	1,600	0.47
Hot Water Heater	15,400	4.5
Refrigerator (12 cu. ft.)*	500	0.14
Refrigerator (15 cu. ft.)*	1,200	0.35
Refrigerator (18 cu. ft.)*	1,800	0.54
Dishwasher*	3,400	1.0 (0.5 kwh per load)
Range and Stove (regular)	35,100	10.3
Range and Stove (self-cleaning)	40,900	12.0
Clothes Washer*	1,000	0.3 (0.2 kwh per load)
Clothes Dryer*(cold)	700	0.2
Clothes Dryer (warm)	9,900	2.9
Clothes Dryer (hot)	19,100	5.6
3 Bathroom Fans	1,000	0.3
Most Common Appliances Moved in with Owner:		
Lighting (about 30 lamps)	7,700	2.25
2 TV sets	1,700	0.5
Humidifier	400	0.12
Stereo	700	0.2
Freezer	1,000	0.3

*Actual consumption; includes power factor of 0.6 (see Chapter X) belonging to the household yields a total of approximately 91,000 btu/hr or 27 kilowatt. Of course most of these appliances are left on for only a fraction of the time, often at partial load, so the average rate of appliance heat generation, obtained from data presented in Chapter II, is only about 5,500 btu/hr or 1.61 kilowatt (excluding the outside air conditioner compressor unit), or about 6% of the maximum possible consumption. The occupants themselves are heat sources of about 400 btu/hr or 100 watts per person. On an average $35^{\circ}F$ ($1.7^{\circ}C$) winter day, a party of forty people would need no furnace at all. This result is based on the degree-day model of Chapter 3, using a slope of 21 cu. ft./degree-day, a reference temperature of $62^{\circ}F$ and a 67% furnace efficiency.

The solar flux entering the house through the windows (with an optical transmission of 75% for double glass, assuming the drapes are completely open), can be similarly described as a heat source with a sunny December 21 (12:40 EST) yearly peak of 17,000 btu/hr (5 kilowatts) for a house with the most favorable orientation, and a year-round, all-orientation, weather average of 1500 btu/hr or 0.44 kilowatts. The solar load on the roof and the outside walls will be treated as one of the outside boundary conditions.

Just as the internal heat sources are best characterized by their heat production, the outside 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. Solar flux striking the walls and the roof and the infrared radiation exchange between the house surface and the sky can be combined with the prevailing air temperature to determine "sol-air temperature,"[*] that can be treated as the new outside temperature, different for the 2 outside walls and the roof. On a

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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. The energy balance then requires:

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

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

I_d varies between 30 and 300 btu/(hr sq. ft.)

$\frac{\alpha}{h}$ varies between 0.15 and 0.30 ($^{\circ}$F hr sq. ft.)/btu

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

sunny summer day, the sol-air temperature for a wall facing the sun may exceed the air temperature typically by 20-70^{o}F (11-39^{o}C).

Wind enters our house heat transfer problem in two ways: high wind speeds both increase the shell's outside film coefficient and the air infiltration, augmenting 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.

In conclusion, 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

$$T_{in} = \frac{\sum_j Q_j + \sum_i U_i A_i T_i}{\Sigma_i U_i A_i} \qquad \text{VII.1}$$

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

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

A_i = the corresponding area,

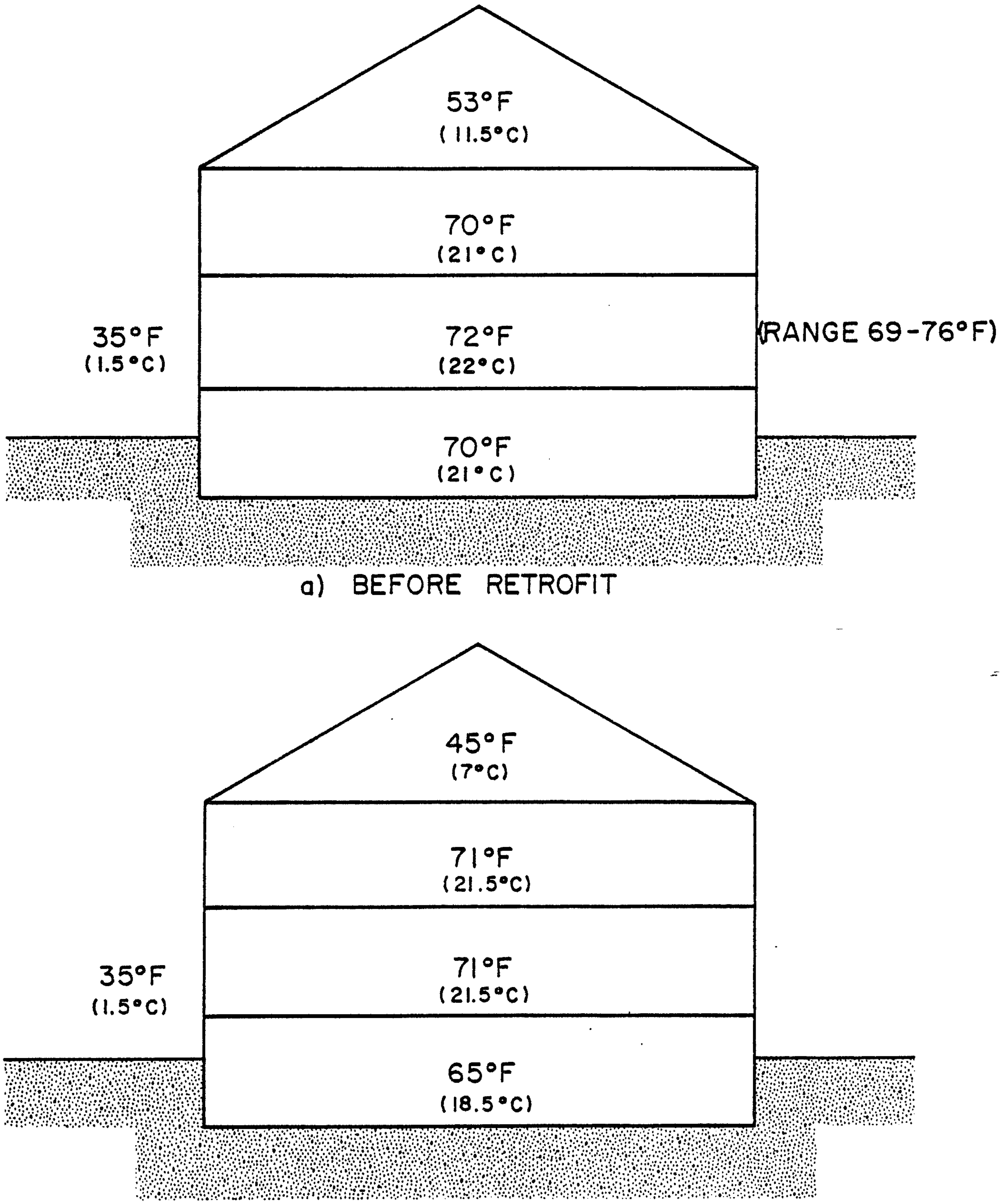
T_i = the corresponding temperature i.e. sol-air, ground, or next-door neighbor temperature.

*We will revert in Chapter VIII to the question of time lags and thermal storage.

Air infiltration has been assigned to one of the $U_i A_i$ products, for the sake of simplicity. 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.

C. The vertically zoned real house

There are several differences between the simple mode of operation of the ideal box described in the last section and the actual life of a typical house in the field. In a real house, first of all, there is no uniquely determined house temperature, T_{in}, and the internal heat sources are not distributed homogeneously inside the house. At the next level of complexity, the house is subdivided into zones of relatively constant temperature, each of which satisfies its own heat balance: e.g. a basement, a first floor ("downstairs"), a second floor ("upstairs"), and an attic. In Figure VII-1 typical zone temperatures are given for Twin Rivers houses on a 35°F (1.7°C) winter day. The initiated reader might already notice the relatively high temperature in the seldom used (except for the houses where the basement was finished after purchase) basement and the attic, totally outside the living area. These temperatures, together with the upstairs temperature consistently colder than the downstairs, are the key indicators for some energy inefficiencies of a Twin Rivers townhouse that will be discussed in this chapter. In the winter of 1975/76 our research group has addressed the most predominant among those inefficiencies, and performed a series of retrofits, whose details are discussed in



TOWNHOUSE TEMPERATURES

note: ALL TEMPERATURES MEASURED 1FT. FROM CEILING
(FLOOR TEMPERATURES ~5°F LESS)

FIGURE VII-1

Appendix F, and whose repercussions on the energy consumption of the houses are documented in Chapter VI.

The task before us in the following actions is to explain <u>why</u> the 4 zone temperatures are what they are, which leads us to a discussion of the design of the house and its shortcomings as seen by the energy people. Let us then start in the basement with the furnace and gradually work our way upstairs from there.

D. <u>The furnace and its duct system</u>

All townhouses in Quad II operate on a 80,000 btu/hr (23.4 kilowatts) hot air furnace. Laboratory and field measurements under varying conditions have determined a heat exchange efficiency, on the average, between 75 and 80 percent. This means that 20-25% of the heat, or up to 20,000 btu/hr (5.9 kilowatts) are exhausted directly to the outdoors by means of hot combustion gases through the flue, and are essentially lost, although some uncertainty exists on the magnitude of additional heat recovery along the flue path. The house's 60,000 btu/hr (17.5 kilowatts) of "disposable energy income" at the furnace plenum are distributed by means of forced convection of heated air through a network of ducts, branching off the plenum and leading to a total of nine individual registers located next to the outside wall in each room. Practically the entire length of the five ducts feeding the downstairs run along the basement ceiling, while the upstairs ducts are embedded in the interior walls and above the first floor ceiling for about 2/3 of their length. A layout of the duct network at the basement level is shown in Fig. A-3 in Appendix A. Out of the entire duct length of 246* feet (excluding the return duct), 86 feet (or 35%) run inside the wall and ceiling structure, the remaining 160 feet (65%) run along the basement ceiling, usually between two 2 x 8 joists supporting the downstairs floor.

Two out of the three ducts leading to the living room pass through a poorly insulated overhang, which can be seen, together with the two ducts in question along the basement ceiling, in Photo Page 5.

Although there is usually no built-in provision to heat the basement, the presence of the furnace and its leaking, uninsulated ducts provides more than enough heat to keep the basement at room temperature, causing needless heat transfer to the surrounding ground and the outside air. The ducts are composed of sections and elbows loosely fit together, often without duct tape, and leak accordingly.

E. Where the furnace heat goes: heating system efficiency and house deficiency.

The amount of heat leaving the duct registers per unit time has been experimentally measured to be about 50% of the heat flow at the furnace plenum; the remaining 50% dissipates from the ducts by means of air leakage and conduction/convection. This assessment was

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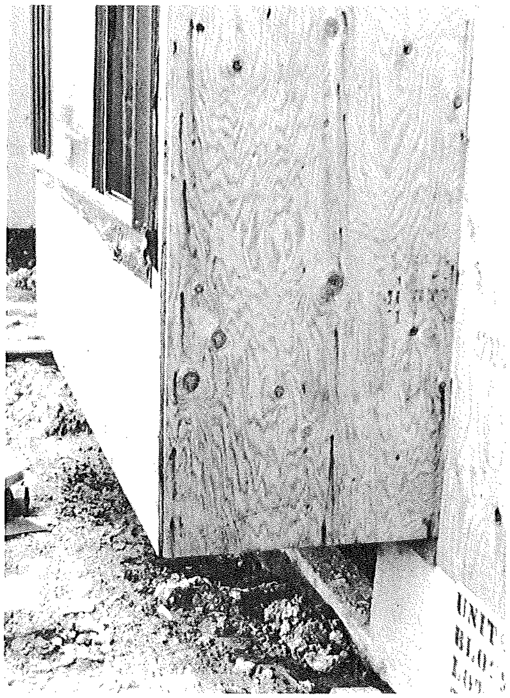
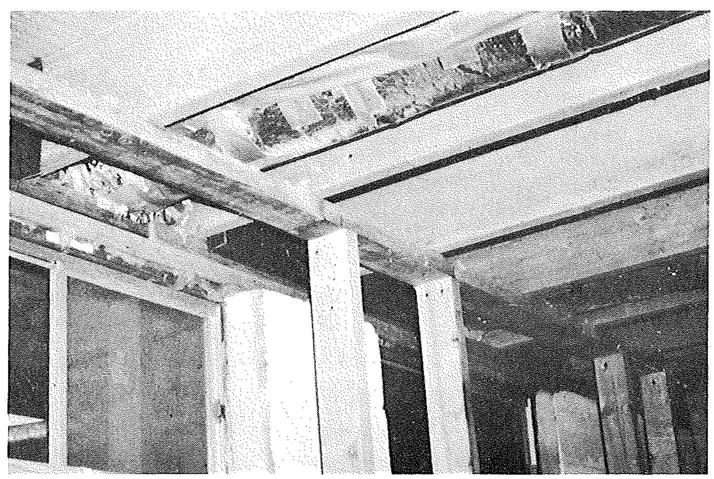
*The thicker supply ducts and the furnace plenum have been included in this calculation, multiplying their physical length by the ratio between their respective perimeters and the perimeter of the 5-inch diameter room ducts, in order to keep their (heat transfer) surface constant.



LIVING ROOM OVERHANG AT TIME OF CONSTRUCTION.

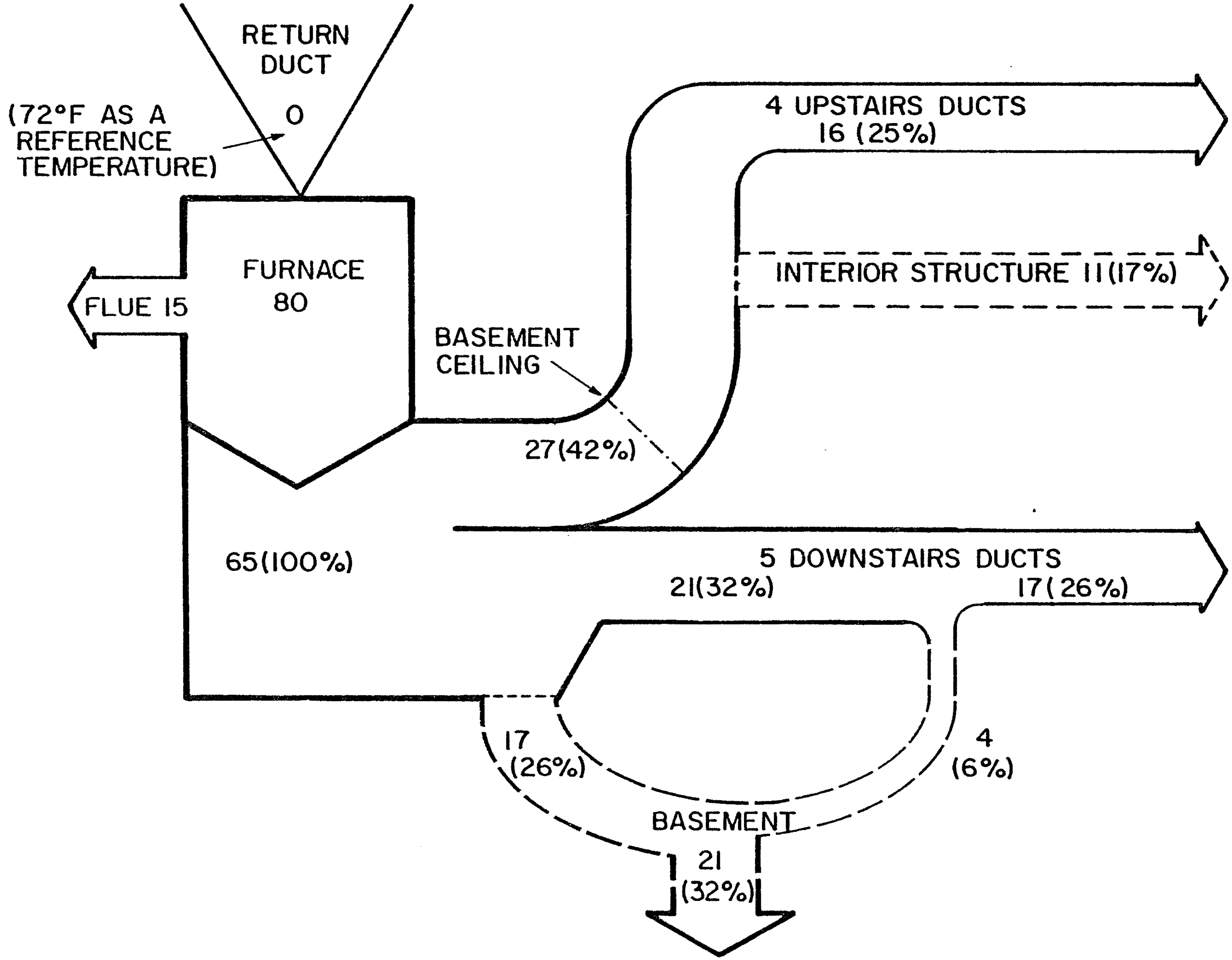
DUCTS PASSING INTO LIVING ROOM OVERHANG, CASUALLY INSULATED.



INSULATION OF DUCT AND OVERHANG, PART OF PRINCETON RETROFIT PACKAGE C.

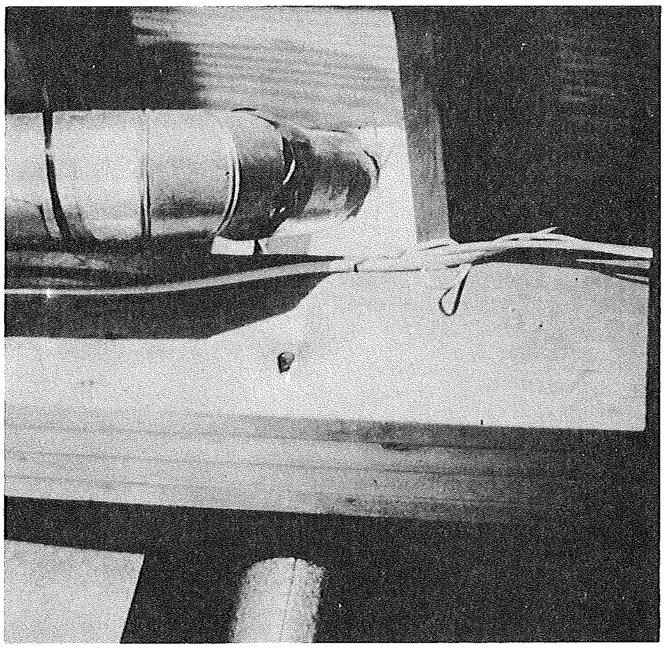
made by recording air flows and temperature at 3 points in each duct and calculating the heat flow using the return duct temperature as a reference, and is graphically displayed in Fig. VII-2. About one-third of the total heat flow recorded at the plenum heats the basement, and one-sixth heats the wall structure. The relative magnitude of interior structure versus basement heating compares well with the relative amount of duct work in the two locations. This indicates a constant duct surface heat leakage per unit length, although theoretically one would expect an exponentially decreasing heat leakage as we proceed along the duct axis, away from the furnace. The 1/6 of the plenum heat flow heating the interior walls and the first floor ceiling is as good a way of heating as the "design" way through the registers, maybe even better, when we think of the location of the registers next to cold exterior walls and windows, and the ensuing higher losses.* What happens to the one-third heating the basement is less obvious. If the basement were very well insulated, all of the heat leaking through the ducts would eventually benefit the house, by heating the downstairs floor. Yet, in a townhouse without basement insulation, of the one-third of the heat leaked to the basement, about another third, or 10% of the total heat flow at the plenum, is lost by conduction through the basement walls and floor to the outside and the ground. Only about 1 kBtu/hr is conducted through the basement

*This arrangement was meant to improve creature comfort through shielding of "cold radiation" from the outside.

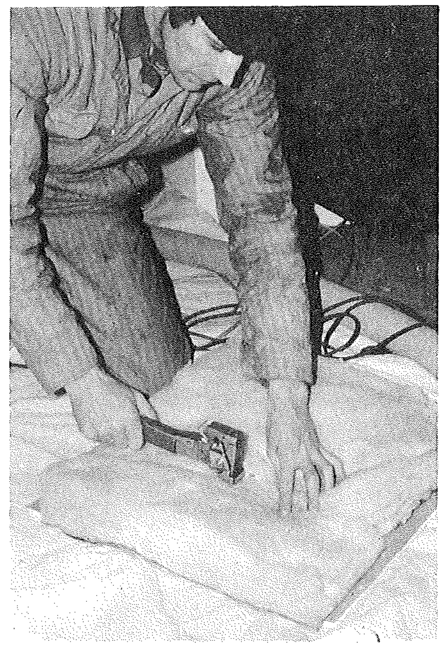


SCHEMATIC FURNACE HEAT FLOW (KILO BTU/HR) IN A 3-BEDROOM TOWNHOUSE
DOWNSTAIRS DUCTS PARTIALLY CLOSED
FIGURE VII-2

ceiling into the first floor, after the 5^{o}F stratification within the first floor room air is taken into account, resulting in 70 - (72-5) = 3^{o}F temperature difference. Another 3kBtu/hr are lost for every air exchange per hour of basement air, replaced with outside air. Assuming a basement air exchange rate of 1.5, bringing the total basement losses to 17%, about 9.5 kBtu/hr (2.8 kilowatt) or almost 15% of the plenum heat, must be heating the attic, by direct air flow through a wooden shaft with a 1 square foot cross section built around the flue and through the space between the bricks of the fire walls and the interior gypsum board structure. Both passages are displayed schematically in Figure VII-3 and photographically in PhotoPages 6 and 7. While the open-ended shaft is a design feature of the house, the gap between floor joists and firewall occurs through settling of the structure and may vary from house to house anywhere between 0 and 1/4 inch generating up to 8 square feet of additional flow path cross section between basement and attic. The consequence of direct heat flow from basement to attic (and of inefficient ceiling insulation) is an abnormally high attic temperature recorded in every house we have examined. The drop in attic temperature following Retrofit A, indicating the reduction in the heat loss through the ceiling and the air paths, is documented in Fig. VII-1b. Considerable statistical modeling of the attic energy performance has been undertaken and will be discussed in detail in Chapter IX, Section C.



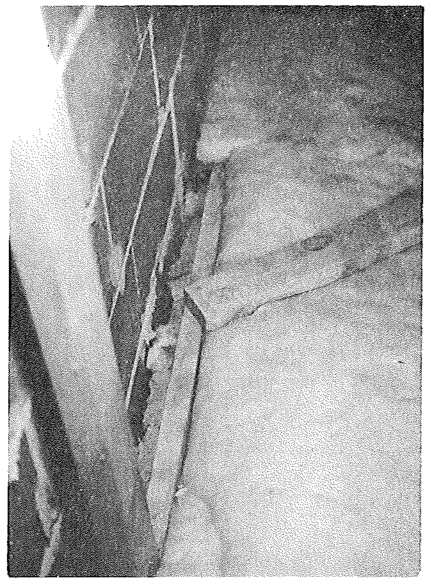
VIEW OF OPEN SHAFT AROUND FURNACE FLUE FROM BASEMENT TO ATTIC. IN FOREGROUND DUCT TO UPSTAIRS BEDROOM PASSING THROUGH FIRST PART OF SHAFT. ATTIC END OF SHAFT (NOT VISIBLE) WILL BE SEALED, AS PART OF PRINCETON RETROFIT PACKAGE D.



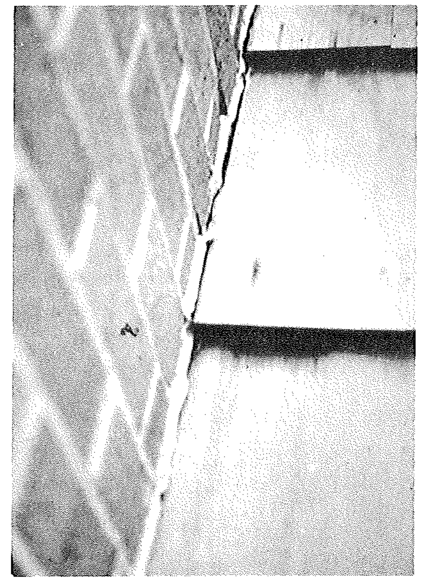
INSULATION BATT BEING STAPLED ONTO ATTIC FLOOR TRAP DOOR, PART OF PRINCETON RETROFIT PACKAGE A.

FOUR VIEWS OF GAPS BETWEEN WALL FRAMING AND MASONRY FIREWALL.

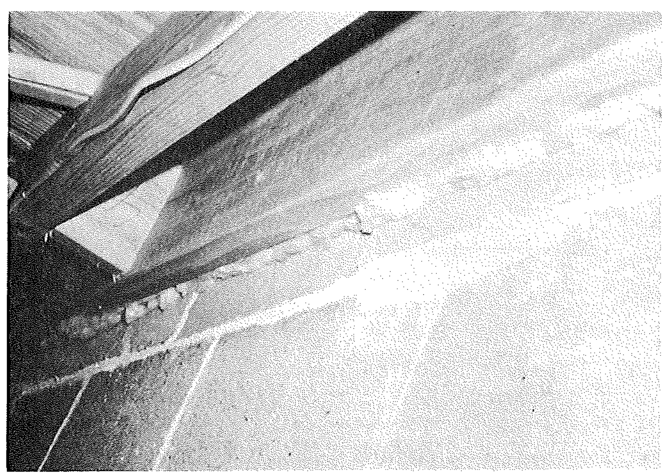
SEEN AT TIME OF CONSTRUCTION, DOWNSTAIRS.



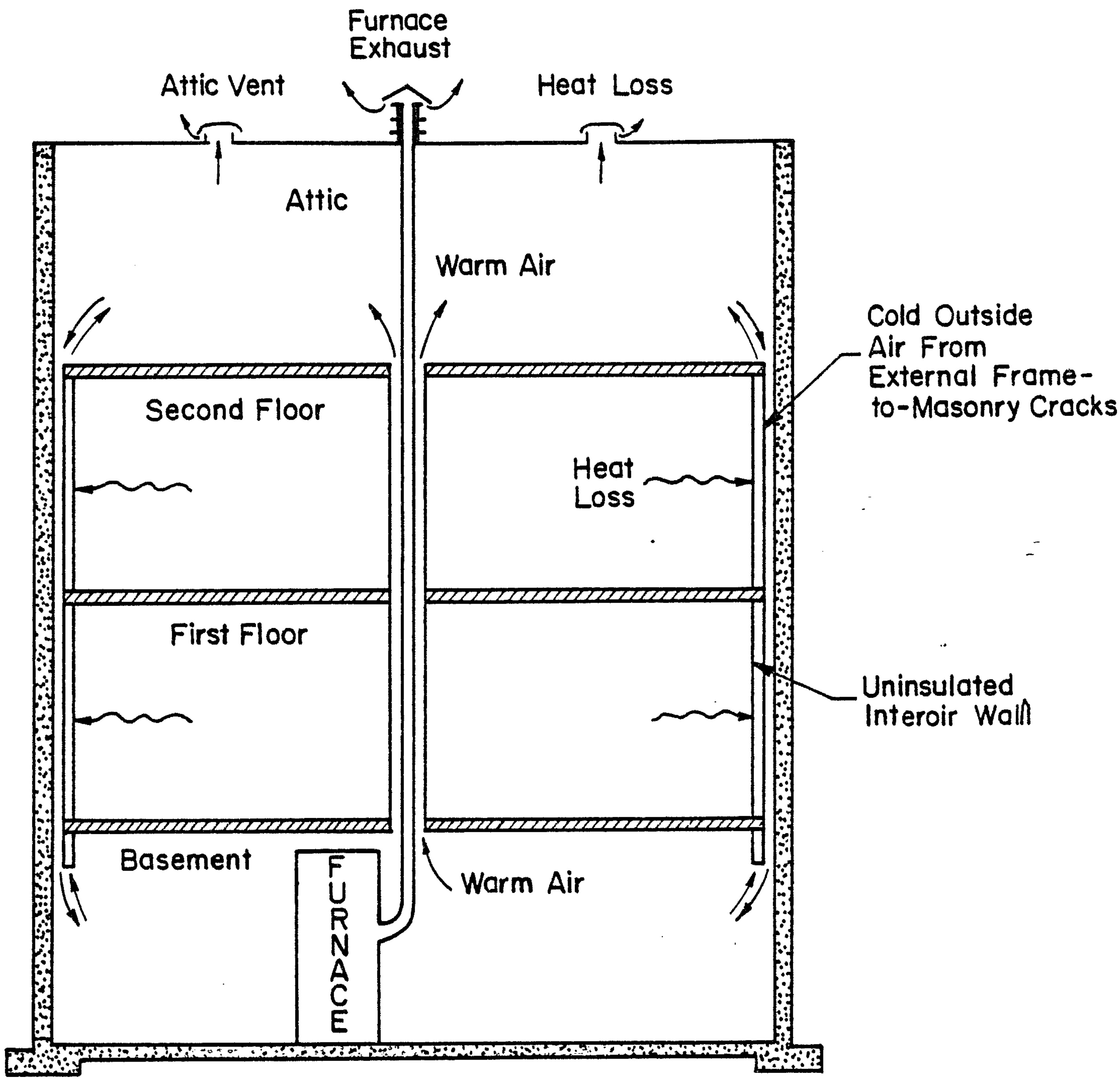
GAPS AT ATTIC FLOOR



VIEW FROM OUTDOORS. CAULKING COMES AWAY AT WOOD-MASONRY JOINT.



PLUG OF GAP FROM BASEMENT BY FIBERGLASS, PART OF PRINCETON RETROFIT PACKAGE B.



Cross-Section of Townhouse
Showing Air Flow Pattern

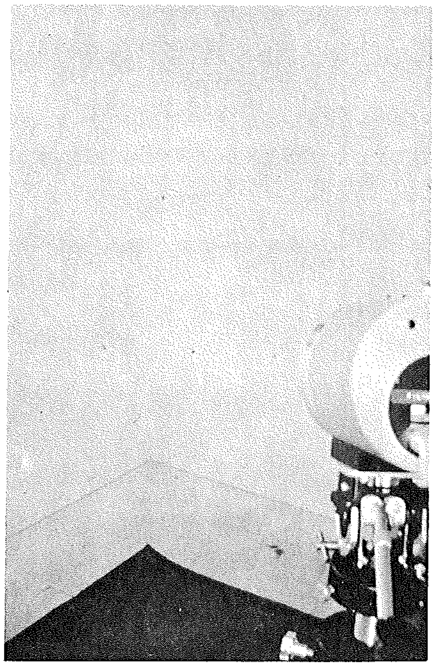
Figure VII-3

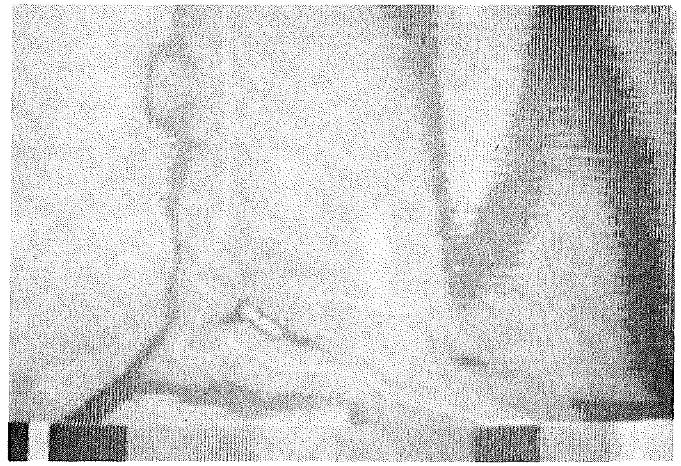
To complicate matters, the caulking material sealing the joints between front and back walls dries out and cracks when the structure settles, opening an additional air path from the outside to the fire wall cavity, and thus to the basement and the attic. Photo Page 6 shows a basement view of the shaft and the attic floor, initially insulated to R-7. Photo Page 7 shows the fire wall air passages and their sealing, part of retrofit package B. The heat flow induced by this series of short circuits is a function of the difference in temperature between indoors and out, of the vertical stratification in the house (buoyancy forces drive air from basement to attic), of the wind velocity and direction (Pitot tube effect on the attic vent, air infiltration through cracked fire wall joint) and, most prominently, of the house itself. Like the air leaks along the window frames and the mood of the construction worker while installing insulation in the walls, the final rest position of the house structure and the resulting cracks are unpredictable, introducing a random element into the supposedly uniform construction quality across houses. Such construction deficiencies (to be distinguished from design deficiencies identical across houses, like the shaft, and the duct registers placed along the outside walls) play a significant role in the variation of the gas consumption across houses, or, which is equivalent, in the performance coefficient B discussed in Chapter IV.

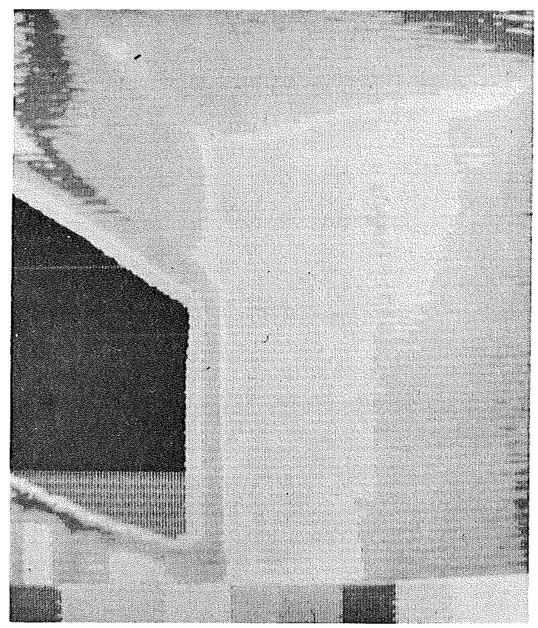
F. House diagnostics and resident-induced inefficiencies.

Getting to know your house can be more than just a matter of recording temperatures. In collaboration with Richard Grot of the National Bureau of Standards, the diagnostic possibilities of an infrared TV camera have been assessed in a multitude of houses. Window perimeters, room edges and corners and front doors have been unmasked as the prime culprits in leaking heat to the outside, in a fashion unforeseen by every existing heat load model. Photo Page 8 highlights a visit by the thermovision-equipped "housedoctor."

Basement, attic and fire wall heat losses are diseases invisible to the homeowner, while they manifest themselves to the "housedoctor" through a high temperature here or a dark patch on the screen there. This is not true for the cold upstairs, strongly perceived as discomfort by the residents. All houses we have monitored have consistently shown a temperature drop of at least $2^{o}F$ ($1^{o}C$), as we go from downstairs to the second floor in winter, and a temperature increase of similar magnitude in summer. While to us this is just another indication of high heat loss to the attic and little furnace heat reaching the upstairs through the leaky ducts, the homeowner usually tries to eliminate the inconvenience by manipulating duct valves in such fashion as to direct proportionately more warm furnace air to the upstairs. Doing so, he inadvertently increases the back pressure in the ducts, and so their leakage into basement and structure. It may be speculated that a naturally cold upstairs leads to higher thermostat settings and discourages







TOP LEFT: INFRARED CAMERA SCANS A CORNER, WITH OUTSIDE WALL TO LEFT, WALL FRONTING A FIRE WALL TO RIGHT.

TOP RIGHT: INFRARED PHOTO OF SAME CORNER REVEALS INTERIOR WALL TO BE SEVERAL DEGREES COLDER. DIP IN THE PATTERN IS FIRST VERTICAL STUD, SEPARATING TWO POCKETS OF COLD AIR.

BOTTOM: CHARACTERISTIC CORNER PATTERN: COLD AIR FLOWS FROM OUTSIDE THROUGH SPACE BETWEEN FIRE WALL MASONRY AND SHEET ROCK PANELS AND MERGES WITH WARM AIR FROM BASEMENT.

nightly thermostat setbacks; the lack of the latter has been certified by a multitude of data. Both hypotheses can be tested against post retrofit data, that are currently being analyzed. At this point it has been ascertained that retrofit A brought the upstairs temperature to the downstairs level; and the post-retrofit enthusiasm of several homeowners, asking whether they could reset the valve settings on their duct system to a more equilibrated level has kept alive the interest in this particular interference between behavior and construction.

VIII. TRANSIENT HEATING: THE HEARTBEAT OF THE HOUSE

A. Time-dependent, coupled phenomena

In Chapter VII the house has been treated as a box with given boundary temperatures and internal heat sources. The question of how this box responds to a change in any of these parameters has been carefully avoided by considering only steady state situations, where the set of boundary temperatures and internal heat sources were kept constant over long periods of time.

When we go to the real world, all of the inner and outer boundary conditions of the house change continuously over time, even the house heat transfer properties themselves change, mainly by opening or closing windows and doors, drawing drapes, and by the variation in wind speed. Meanwhile the furnace fires and shuts off at the rate of twice or three times an hour depending on the weather, appliance usage peaks about twice a day, as discussed in Chapter X, and the weather itself changes daily, with a fundamental cycle of 24 hours.

How dare we speak of steady state in Chapter VII with such a wealth of changes? The answer lies in the definition of short and long times, or fast and slow changes. Just as our senses are unable to perceive the 24 times a second on/off flickering of a movie image or the aging process of our nearest relatives over the years, because the former is too fast for us to pick up and the latter so slow that it appears to us as a steady state, there is a "too slow" and "too fast" for almost every time dependent process in nature, including the thermal response process of a house and of individual parts of it, like the furnace, the duct work, and the air in the rooms. For a house, the change in monthly average temperature from one month to the next is so slow, that we can speak of a steady state and draw all the conclusions in the first seven chapters. Is this still true when we consider the outside temperature change from one day to the next, from one hour to the next? Is the 20-60 minute cycle of the furnace too fast to be picked up by the house structure? These are some of the questions that will be discussed in the following sections, where the natural time frames of all principal actors in the thermal life of a house and their mutual interactions are examined. Whenever the time frames of two such actors overlap, there will be a place for unsteady or <u>transient</u> phenomena. Instead of a time frame, which is hard to define properly, it is easier to talk of a natural time constant * that is related to the time required for a block of some substance to cool (or heat) to the surrounding temperature. The more mass is present, the slower the process, and the longer the time constant. Changes occurring over times much shorter than this time constant will be termed "too fast" to be picked up by this particular actor; if they occur over time periods much longer than this time constant they will be termed "too slow" or essentially steady state.

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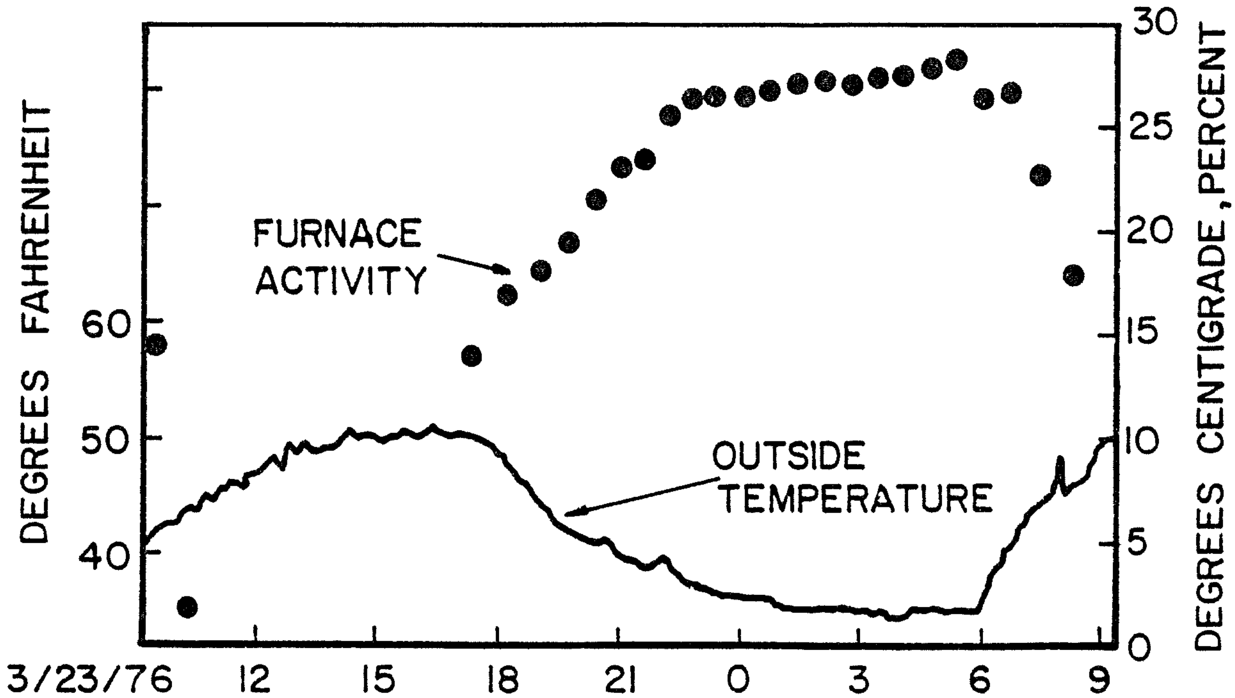
*A time constant τ henceforth will be defined as the time constant of a negative exponential decay. I.e., τ is the time after which a temperature dropping from an initial value T_o to a final value T_∞, has dropped to 1/e of $(T_o - T_\infty)$. This behavior can be mathematically stated as $T(t) = T_\infty + (T_o - T_\infty)\, e^{-\frac{t}{\tau}}$. A negative exponential rise is defined analogously, with $T_\infty > T_o$.

B. The natural time scale of a house

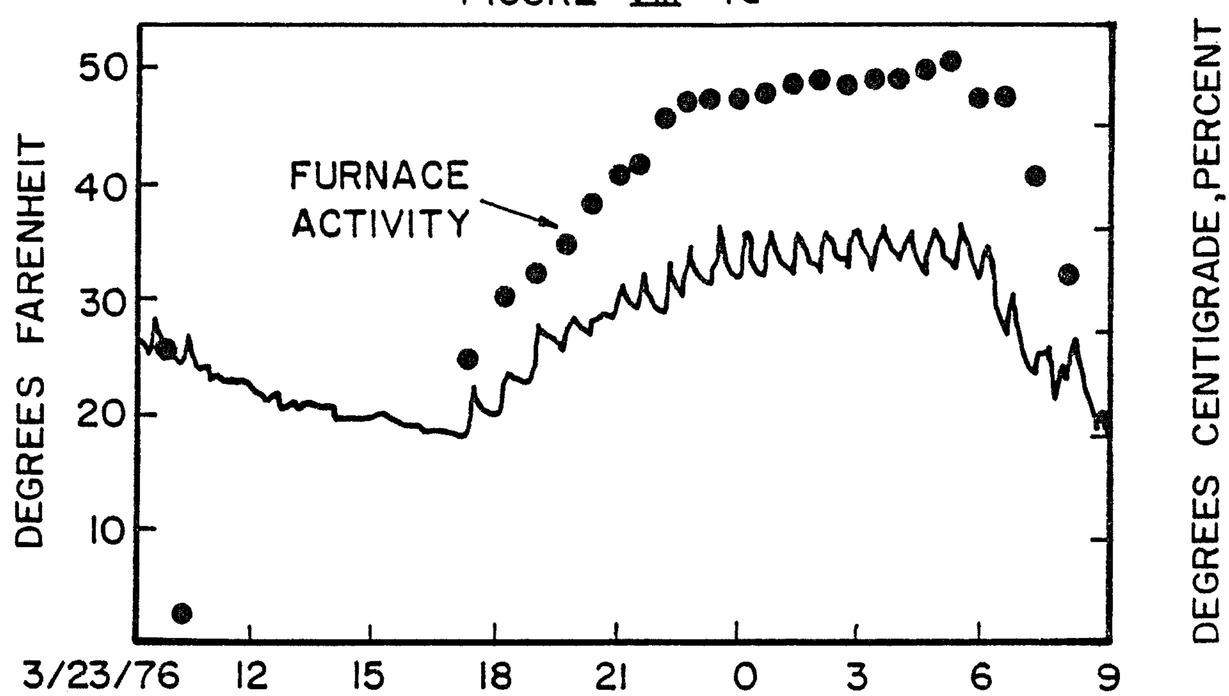
In analyzing the thermal behavior of a house we have to distinguish between the solid structure (the wood, gypsum board, insulation and cinder blocks in the walls and floors) and the room air contained within the house. While the first exchanges heat with its surroundings with a characteristic time constant of about 13 to 18 hours,* the latter adjusts much faster to temperature changes, with a time constant of about 5 minutes. Thus, the once to twice an hour firing of the furnace primarily affects the room air temperature that goes through rapid oscillations of about ±1.5°F (±0.8°C) amplitude during furnace cycles, while the temperature of the house structure itself remains almost constant. In other words, the structure "can't tell the difference" between a continuous, slowly varying stream of heat from a sophisticated variable - output furnace and the actual on-off heat pulsing of the furnaces installed in Twin Rivers. The changes in outside weather, in turn, are usually slow enough to be quite closely tracked by the structure of a Twin Rivers townhouse, as shown in Fig. VIII-1a. Here, the "furnace activity" (the fraction of firing time in total elapsed time for each furnace cycle) is plotted, along with the outside temperature, for 20 hours centered on a winter night. The same furnace activity is plotted with the difference between the average downstairs room temperature and the outside temperature in Fig. VIII-1b. The furnace activity, a "heartbeat" of sorts of the house, increases as it gets colder outside, reproducing even the midnight flattening of the outside temperature and its sharp sunrise "corner." The

*See Appendix A for more details.



FURNACE ACTIVITY (IN PERCENT ON-TIME) AND OUTSIDE TEMPERATURE

FIGURE VIII - 1a



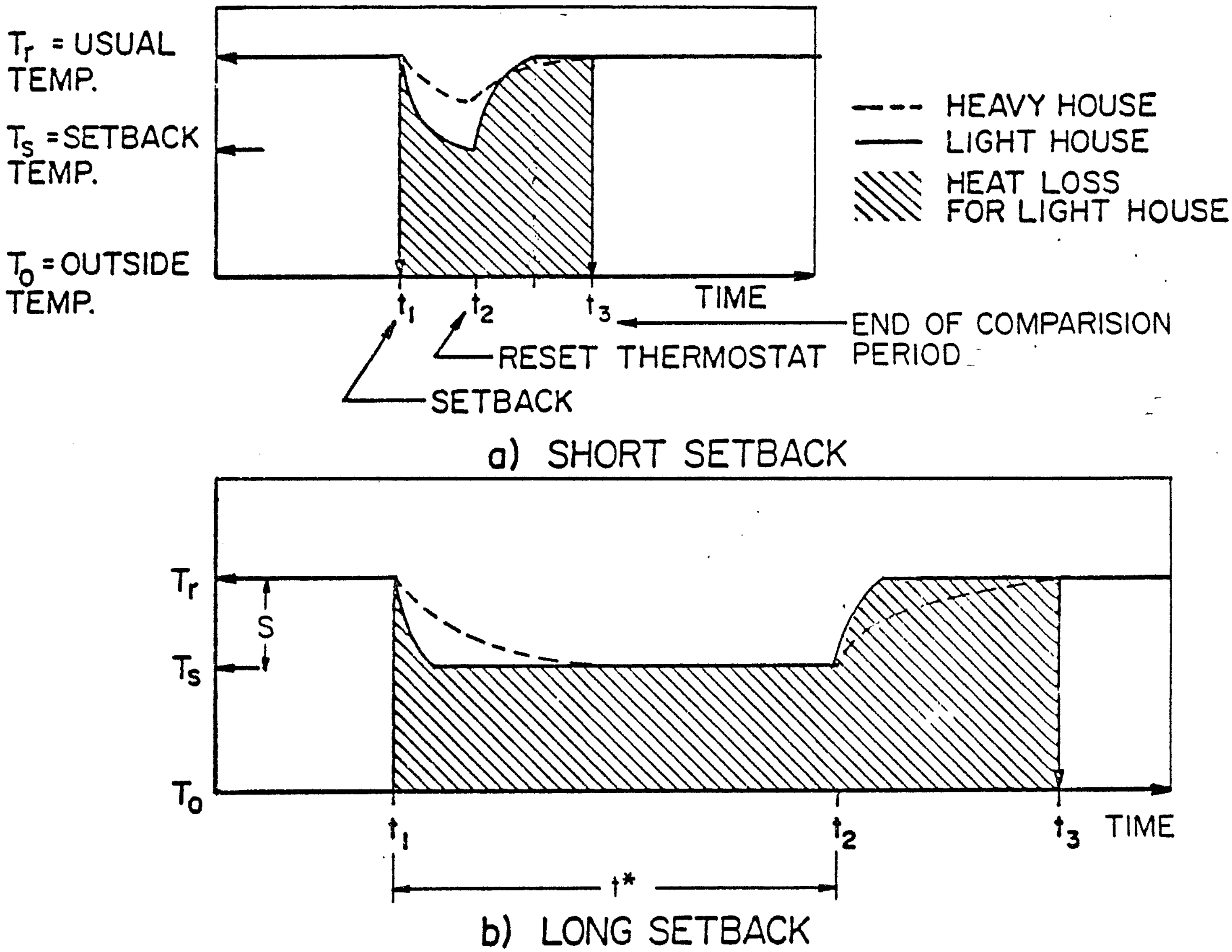
FURNACE ACTIVITY (IN PERCENT ON-TIME) AND INDOORS-OUTDOORS TEMPERATURE DIFFERENCE

FIGURE VIII - 1b

bottom figure shows also the "pulse rate" with which the furnace heats the room air. The natural time constant of the house structure is intimately related to the concept of its heat capacity, which, for most building materials, is roughly proportional to the weight of the house. The heavier a house (the larger its heat capacity), the larger its thermal time constant. On the other hand, the greater its overall thermal leakiness (i.e. the heat loss per unit time and unit temperature difference) the more the effect of heat capacity is offset. To a very rough approximation, the natural heat transfer time constant is proportional to the total heat capacity divided by the heat loss constant, or "weight over leakiness."

C. Thermostat setbacks

The time constant of the house is most important when we talk about thermostat setbacks over certain periods of the day. The purpose of a thermostat setback is to reduce the magnitude of the inside-outside temperature difference (so in summer, when the outside is warmer than the inside, a setback is really a "setup"). The smaller inside-outside temperature difference will cause a smaller heat transfer between inside and outside and will therefore save on furnace or air conditioner operation. Yet, if the house is heavy and well insulated, the inside temperature drops slowly, to the point where it may never reach the setback level before this thermostat is reset to normal. This situation is shown by the dashed line in Fig. VIII-2a. The same would happen for a light,



THERMOSTAT SETBACK IN LIGHT AND HEAVY CONSTRUCTION TYPE HOUSES

FIGURE VIII-2

less insulated house, if the setback period were correspondingly shorter. This behavior is undesirable from the standpoint of energy conservation, because it does not allow for taking full advantage of a thermostat setback. Whether the setback period is "too short" or "long enough," depends again on the natural time scale (or the "weight over leakiness") of the house and the magnitude of the setback. The qualitative difference between long and short setbacks of equal magnitude for heavy and light houses is shown in Fig. VIII-2b. The areas under the curves represent the heat loss in energy units for each house, assuming that both have the same heat loss constant, but different capacities. The comparison period spans the time between t_1, when the setback begins, and t_3, when the furnace resumes its normal "pulse rate," after a period of increased activity following the resetting of the thermostat at t_2. The advantage of a light house is qualitatively obvious in Fig. VIII-2a, where the heavy house (dashed line) never really gets a chance to fully benefit from the potential setback savings, as the light house does. In the long setback situation, sketched in Fig. VIII-2b, the initial advantage of the light house is essentially wiped out after t_2, when the heavy house takes longer to reestablish its original temperature and loses accordingly less heat than the light one during that time span. Thus, the setback period $(t_2 - t_1)$ for the heavier house has to be longer than t^* hours, depending on the magnitude of the setback, in order to be as energy saving as the same setback performed in a light house. Following is a derivation of the time and magnitude constraints on a setback:

If the thermostat is set back by S degrees from an initial setting T_o, at time $t = 0$, the house temperature will drop roughly like

$$T(t) = T_o e^{-\frac{t}{\tau}} \qquad \text{(VIII.1)}$$

where τ is the natural time constant of the house structure. The temperature approached asympotically after a very long time, if $S > T_o$, has been assumed here to be zero, without any loss of generality. This asymptotic limit is approximately equal to the outside temperature plus about 10^oF (5^oC), representing the "free" heat from internal heat gains, like appliances, people, etc., as discussed in Chapter IV. Thus, the time required by the house to drop by S degrees below the initial level is calculated from

$$T(t) = T_o - S = T_o e^{-\frac{t^*}{\tau}} \qquad \text{(VIII.2)}$$

or

$$t^* = \tau \ln \frac{T_o}{T_o - S}$$

For small setbacks, where $S \ll T_o$, this formula can be simplified to

$$t^* = \tau \frac{S}{T_o} \qquad \text{(VIII.3)}$$

On a cold winter night, with an outside temperature of 20^oF (-6.7^oC) and an inside temperature of 70^oF (21.1^oC), a Twin Rivers townhouse with a time constant of 15 hours takes about 4 hours and 20 minutes after a setback of 10^oF (5.6^oC) to reach the new thermostat setting of 60^oF (15.6^oC). This follows from

$$t^* = 15 \text{ hrs} * \ln \left[\frac{70^o - (20^o + 10^o)}{70^o - (20^o + 10^o) - 10^o}\right] = 4.3 \text{ hrs.}$$

Equation VIII.2 can also be used to compute the maximum meaningful magnitude of a setback that can be performed in a house over a fixed period ($t_2 - t_1$). If we assume the latter to be 8 hours, the maximum meaningful setback magnitude in a Twin Rivers townhouse is estimated to be roughly 59% of T_o, or 23.5^oF (13^oC) with the same corrected indoor outdoor temperature difference $T_o = 70^o - (20^o + 10^o) = 40^oF$.

D. <u>The furnace operating mode and its time characteristics</u>

Unlike the heating and cooling systems used in some commercial buildings, most residential furnaces (and air conditioners) work on an "on-off" or "full blast-nothing" basis. During the off-mode while the room temperature is cooling, a temperature sensing coil inside the thermostat contracts to a preset point, corresponding to the, say, 68^oF (20^oC) setting dialed by the occupant, where it triggers the furnace to fire. After 1 to 2 minutes, the blower fan, triggered by another thermostat located in the furnace plenum, will start circulating hot air through the heating ducts. After the house air temperature has rapidly increased by about 3^oF (1.7^oC), the "throttling range" of the thermostat, the same element in the thermostat breaks the circuit and turns the furnace off. Again, the fan goes off after a delay of 1 to 2 minutes. The cycle recurs, after the room temperature has cooled again by $3^{o}F$, and the furnace fires anew. There are two degrees of freedom associated with the furnace cycle. One is the proportion of on-time to total elapsed time ("furnace activity"), the other is the length in minutes of each on-time and the (strongly correlated) length of the subsequent off-time.

The first characteristic, on-time divided by total cycle time,* when multiplied by the power rating of the furnace (80,000 btu/hr, or about 23.4 kilowatt), indicates the average rate of heat output from the furnace per unit time within that cycle. This "furnace activity" is almost completely controlled by the difference between inside and outside temperature, as shown in Fig. VIII-1, and is proportional to the heat load discussed in various parts of this report.

The second characteristic, the time length of each on and off time, should be controlled, in principle, by the speed at which the house heats up and the throttling range of the thermostat. In reality, the fast heating rate (initially about $0.5^{o}F$/minute, or $0.3^{o}C$/minute) caused by the oversized furnace and worsened by the accumulation under the ceilings of the hot air exiting from the registers, does not give the thermostat a chance to properly sense the temperature increase in a useful time. Therefore, the furnace would now fire continuously for 20-40 minutes, depending on the outside temperature, causing an undesirably large temperature rise of about $10^{o}F$ ($5^{o}C$).

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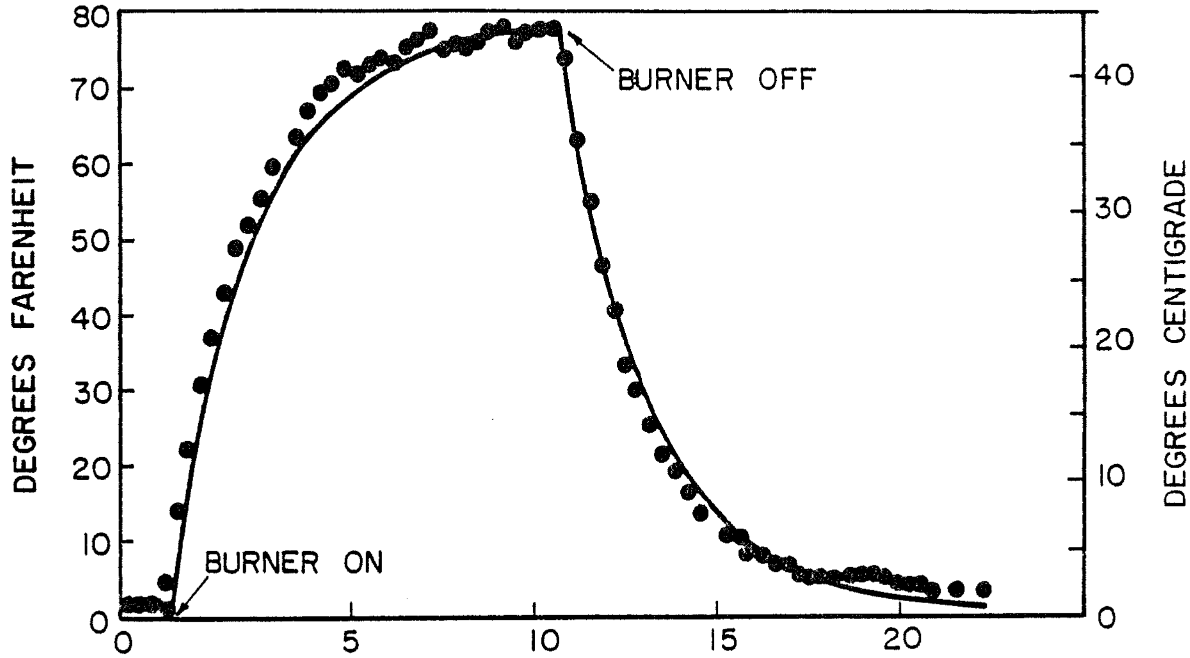
*Cycle time is defined as the time elapsed between two subsequent furnace firings.

To correct for this fact, a small resistor, called an anticipator, acting as a tiny heater, is usually installed under the temperature sensing element, and is activated at the same time a furnace firing is triggered. The heating by the anticipator causes the temperature sensing coil in the thermostat to expand faster, thus shutting off the furnace (and the anticipator) after a mere 3-10 minutes, depending on the outside weather and on the anticipator setting, which can be easily changed by lifting off the thermostat cover. At constant anticipator setting (in fact, most lay-residents don't even know it's there, let alone what it is for), cold weather increases the furnace on-time (the net heating of the house, resulting from the heating imparted by the furnace minus the cooling from the cold weather, is slower) and decreases the subsequent furnace off-time (the house cools down faster in cold weather). The nature of this relationship is displayed in Fig. VIII-3b, where furnace on-time (y-axis) is plotted versus subsequent furnace off-time (x-axis) for two different anticipator settings and naturally variable weather conditions. Further work interpreting the parameters that determine this curve is in progress.

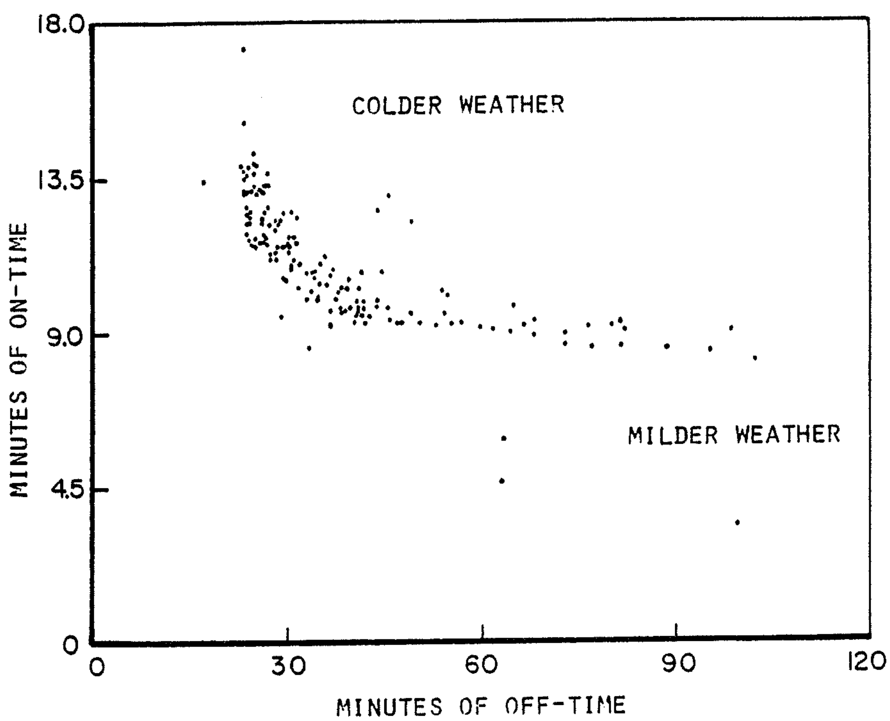
E. Is furnace oversizing bad?

In this section the question of the often cited possible energy inefficiencies from an oversizing of the furnace is discussed, in relation to the duct time constant and the degree of communication between the basement and the outdoors. A simple model predicting the



DUCT TEMPERATURE MINUS RETURN DUCT TEMPERATURE VERSUS TIME AND EXPONENTIAL CURVE FITTED TO DATA

FIGURE VIII - 3a



FURNACE ON-TIME VERSUS SUBSEQUENT OFF-TIME OVER A PERIOD OF 7 DAYS

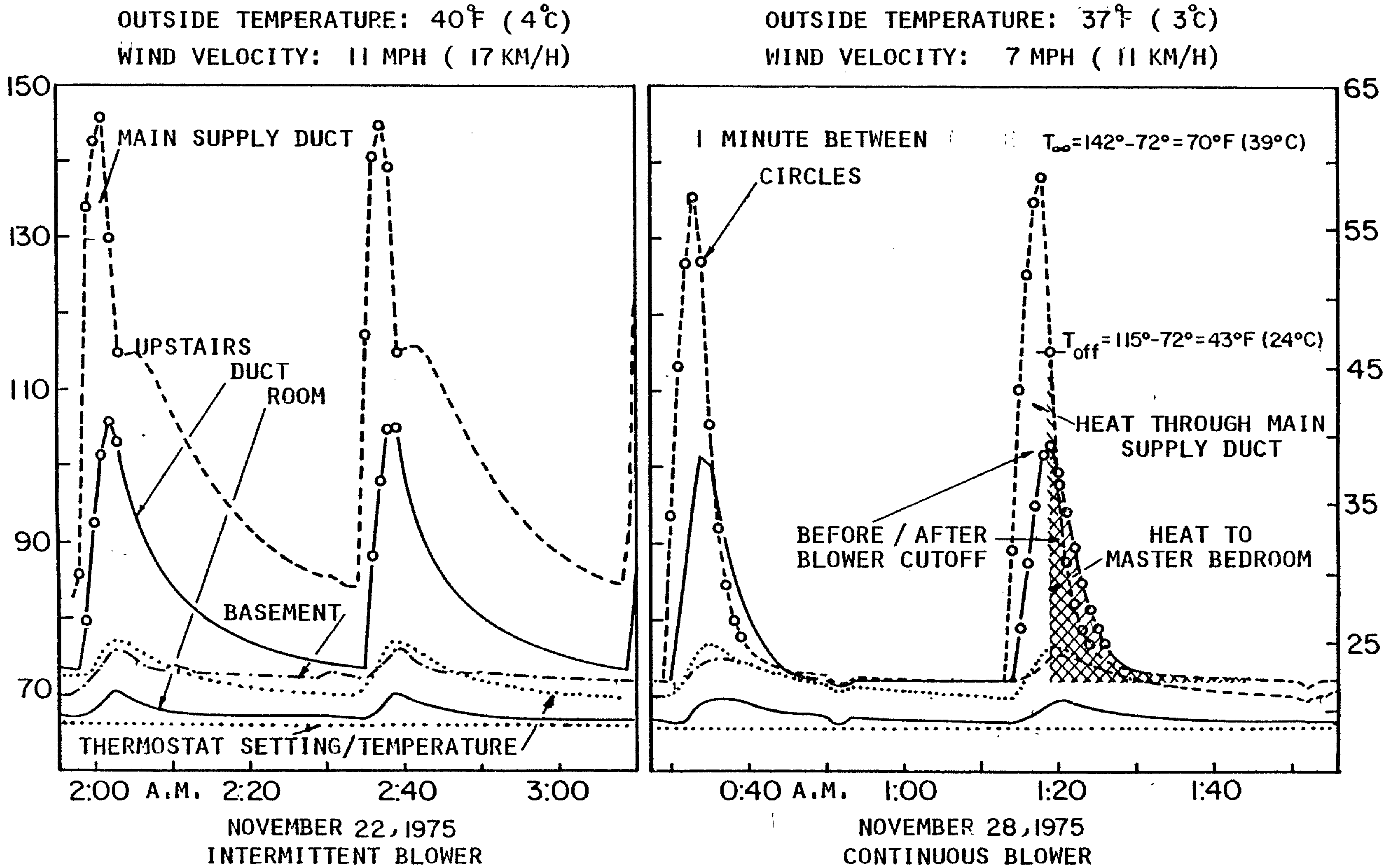
FIGURE VIII - 3b

residual heat in the ductwork under transient conditions is derived and checked against actual data. This residual heat is the candidate for possible heat losses directly to the outside, via the basement, causing possible furnace inefficiencies. The need for an anticipator, as discussed in the previous section, arises from the fact that the furnace time scale (a few minutes) is not matched to the time scale of the house (10-15 hours) or, which is equivalent, that the furnace is oversized. The 80,000 btu/hr (23.4 kw) furnace in a Twin Rivers 3-bedroom townhouse is oversized by 50% when compared to the design conditions occurring in this latitude, that is, an outside temperature of $5^{o}F$ ($-12.8^{o}C$) and an inside temperature of $75^{o}F$ 923.$9^{o}C$), with a 15 mph wind (24.5 km/h) and 0.75 exchanges per hour of air infiltration, in the absence of sun and the "free" heat from the electric appliances in the house.

The inefficiencies related to this oversizing are not immediately apparent. What difference does it make whether a fixed quantity of energy is delivered at a high rate over a short time, or at a slower rate during a correspondingly longer time? The difference lies in the relative importance of the two ways through which the furnace heats the house: in a hot air system like the one found in all Twin Rivers houses, the "design" way of heat delivery is the forced convection through a network of ducts, while the alternate way is the combination of radiation, conduction and natural convection through the duct walls and the house structure, as discussed in Section D of Chapter VII.

During a furnace firing, right after the blower fan has switched on, the air heated by the furnace, circulating through the ducts, heats them up as well as the room's air. This duct heating process has a time constant of about 2 minutes, and is essentially completed after 5 minutes, as seen in Fig. VIII-3a. Beyond this time, the heat leaving through the duct registers per unit time approaches 50% of the heat flow recorded at the plenum, as discussed in Section D of Chapter VII. The other 50% radiates and convects through the duct walls directly to the inner walls and the structure. A detailed breakdown of the different heating shares in steady state was displayed in Figure VII-2.

Yet, the anticipator in a Twin Rivers townhouse is set in such a way as to cause the furnace to typically stay on for 3 to 8 minutes with the fan blowing only 2 to 6 minutes during firing. This means that the steady state point in the heat transfer from hot air to surrounding ducts is not yet reached after completion of firing, i.e., the ducts are never given a chance to warm up completely, as made obvious in Fig. VIII-4a or b where the duct air temperature in two different locations for two subsequent furnace cycles are portrayed. The temperature in both ducts, one near the furnace plenum, the other at the master bedroom right register in the second floor, have not reached their "plateau" yet (about 70°F above the "rest" temperature, for the supply duct). Moreover, the blower fan stops after the duct temperatures have dropped by only about half their original rise.



ROOM AND DUCT TEMPERATURES AT TWO DIFFERENT FURNACE BLOWER MODES

FIGURE VIII-4a FIGURE VIII-4b

The heat carried by a stream of hot air through a duct is proportional to the area under the temperature curve during blower operation as indicated schematically in Fig. VIII-5. The temperature rise and decay curves near the plenum have been shown by Mark Nowotarski to be both negative exponential curves with equal time constants of about 2 minutes:

The temperature rise is described by:

$$T = T_\infty (1 - e^{\frac{-t}{\tau}}) \qquad \text{(VIII.1)}$$

where t is the time elapsed since the blower fan switched on.

T_∞ is the temperature reached for $t = \infty$ (approximated to within 1% after $t = 4.6 \times \tau$)

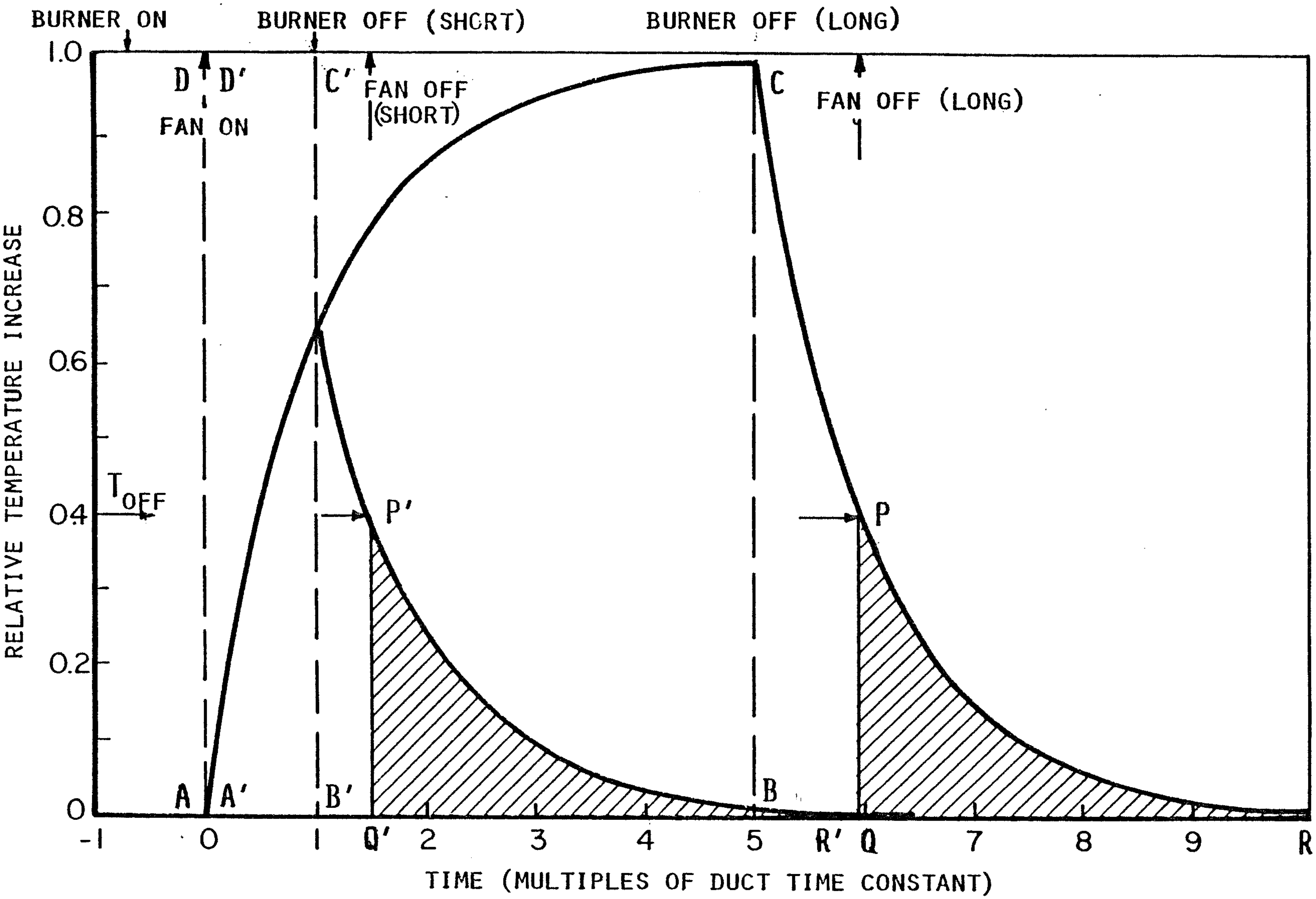
τ is the duct time constant measured to be $\sim$ 2 minutes.

Note: the initial temperature is assumed to be zero.

The temperature decay after the burner switches off and before fan cutoff is

$$T = T_\infty (1 - e^{-t_{on}/\tau}) e^{-t/\tau} \qquad \text{(VIII.2)}$$

If the blower fan were left on for a "very long" time after the firing stops ($t_{off} > 5 * \tau$), the heat convected through the ducts would be proportional to the area under the temperature curve in Figure



TEMPERATURE AND HEAT CONVECTION IN A DUCT FOR DIFFERENT BURNER ON-TIMES

FIGURE VIII-5

VIII-5 and can be shown analytically (from VIII.1 and VIII.2) to be equal to $T_\infty \times t_{on}$, symbolized by ABCD and A'B'C'D' in Figure VII-5 for a long and a short burner on-time.

In reality, the blower fan switches off sooner, at a cutoff temperature T_{off} set by a duct air thermostat located in the plenum. The heat that remains trapped in the ducts after blower cutoff is computed from VIII.2 to be $T_{off} \times \tau$, and is represented by PQR and P'Q'R' for long and short t_{on} - times in Figure VIII-5. It is obvious, both graphically and mathematically, that the amount of residual heat remaining in the duct is dependent only on the cutoff temperature, not on the amount of time the furnace was on. Therefore, the <u>fraction</u> R of residual duct heat in total convected heat decreases as the furnace is left firing for longer times:

$$R = \frac{T_{off} \times \tau}{T_\infty \times t_{on}} \qquad \text{(VIII.3)}$$

Making a heavier duct system or insulating the duct walls (smaller τ) as well as leaving the blower fan on for a long time after burner cutoff (lowering T_{off}) all tend to decrease R, bringing it closer to 0, or, equivalently, bringing the heat <u>convected</u> through the ducts closer to its steady state value of 50% of the heat flow at the plenum.

A furnace size increase would call for a blower speed increase in order to keep the maximum temperature T_∞ within a reasonable comfort range. But this would lead to shorter burner on-times (t_{on}) during blower operation, making R larger.

The heat retained by the ducts after burner cutoff can be measured by an indirect method displayed in Figure VIII-4. The figure to the left (a) shows, together with a few room temperatures for a comparison of orders of magnitudes, the temperature in a supply duct near the furnace and in an upstairs duct register far removed from the furnace. The temperature curves start rising at the onset of the blower fan (the initial burner firing is not "felt") and reach their peak at the end of firing, dropping smoothly until fan cutoff at 115°F (in the supply duct) about 2 minutes later. increase in the supply duct temperature and the much slower decay in both ducts, after fan cutoff, are an indication of the heat retained in the ducts. Figure VIII-4b shows the same temperatures for a day with comparable weather, but with the blower fan "locked on." The shaded areas under the duct temperature curves in the second cycle displayed in (b) indicate the amount of heat per cycle that would have remained trapped in the ducts if the blower fan had stopped operating at 115°F, as usual (compare to PQR and shaded P'Q'R' in Figure VIII-5). The area under the supply curve was measured to be 29% of the total area for the same cycle. Using VIII.3 with T_{off}= 115 - 72= 43°F, T_∞= 70°F (70°F is the rated temperature rise of the furnace) τ= 2 minutes and t_{on}= 5 minutes (each point in the curve represents data one minute apart), we obtain

$R = \frac{43 \times 2}{70 \times 5} = 0.25$, compared to 0.29 measured experimentally.

Looking back at Figure VIII-4a, it would appear unfair to say that, under normal (intermittent) fan operation, 25 - 29% of the maximum possible heat convected through the supply duct is left in the duct walls after blower fan cutoff, because under normal fan operation, the average duct temperature (and so the reference temperature T_o) is higher (T_o= 84°F instead of 72°F), making the relative cutoff temperature (constant at 115°F in "absolute units") T_{off}= 115 - 84= 31°F smaller. Still, using VIII.3 with the appropriate parameters, we obtain $R = \frac{31 \times 2}{70 \times 3.5} = 0.25$ as before. The smaller relative cutoff temperature has been offset by a shorter temperature curve rise time, 3.5 minutes instead of 5 minutes, as seen in Figure VIII-4a (3.5 minutes was taken as an average between the two cycles shown).

This brings us to the further interesting observation that, under comparable weather conditions and virtually identical thermostat settings, the furnace fires more often, but less per cycle, in normal fan operation mode, compared to a continuous fan mode. More quantitatively, the furnace fires once every 71 minutes in (a), and convects 55.7 arbitrary units of heat before fan cutoff, while the corresponding values in (b) are 85 minutes and 66.5 of the same arbitrary units (minutes - height). The rate of heat delivery turns out to be 0.78 (arbitrary heat units per minute) in (somewhat fortuitously) both cases, which makes physical sense (equal "furnace activity").

Why the furnace fires less often under continuous fan operation is not entirely clear. A possible explanation is that with more heat delivered to the room air under continuous furnace operation, and less to the structure, it takes longer for the room air-structure system to equilibrate (or the heat exchange rates to reach a steady state), or, longer for the room air to drop from the (higher) peak temperature after burner shut-off to its low, right before a new firing occurs.

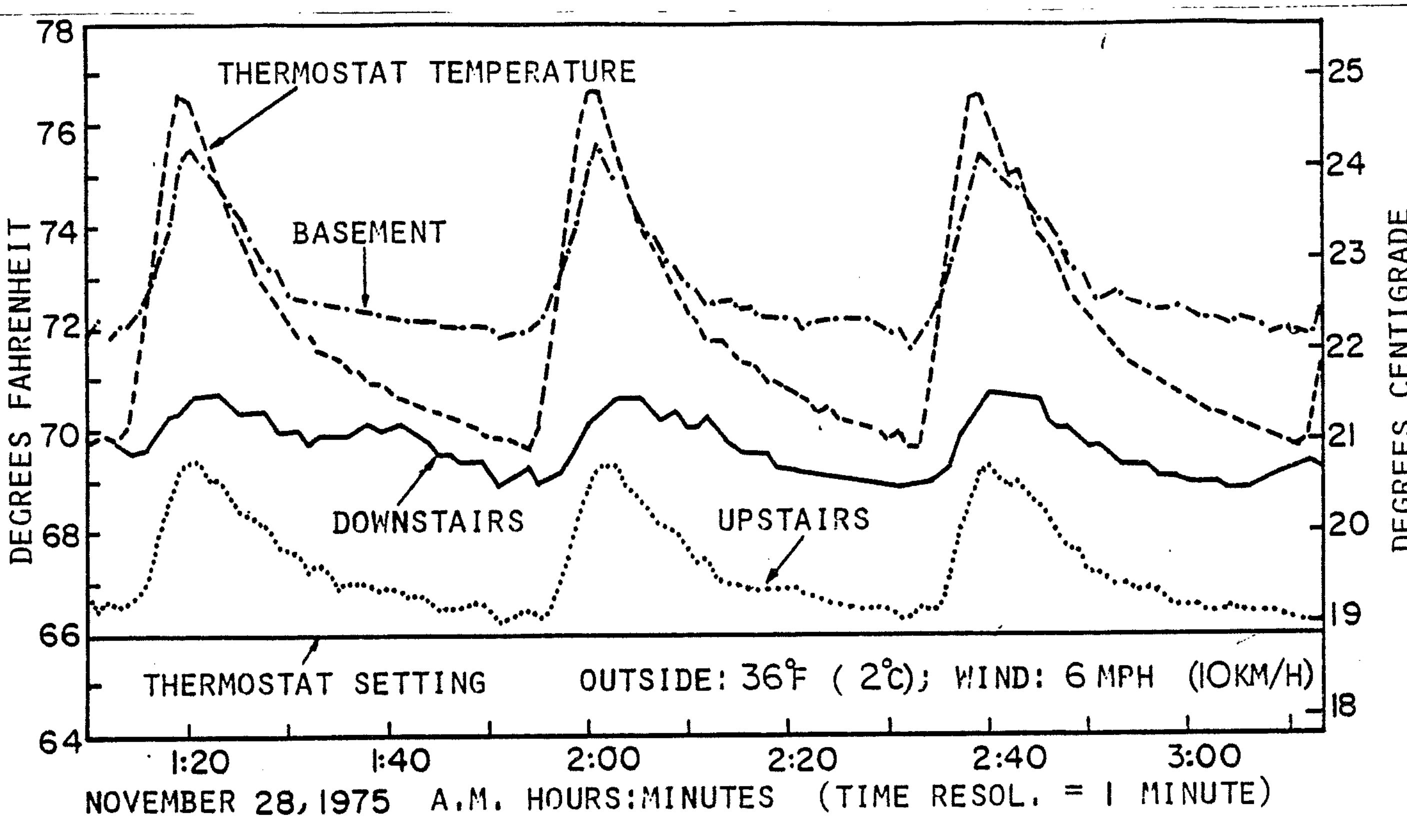
The Master Bedroom duct, heating and cooling at a slower rate, displays quite a different behavior. It is the heat stored in the duct length upstream (very small for the supply duct that sits right on top of the furnace) that causes this effect. A mathematical analysis of the physical phenomena is beyond the scope of this report. Suffice it to say that R, the fractional amount of heat retained by the ducts after blower cutoff, is larger than the value calculated from VIII.3 the further away one goes from the furnace. For the Master Bedroom duct in Figure VIII-4b, the shaded area is 61% of the total, versus a prediction of 40%, using $T_\infty \simeq T_{off} = 34°F$. Of the roughly 40% average for the entire house, a large fraction will benefit the downstairs, in whose walls most of the residual duct heat remains stored, the rest will heat the upstairs floor or the basement; the consequences have been discussed in Chapter VII, Section D.

The assignments for the combined steady state and transient heat transfer from the furnace to the house under normal (intermittent) fan operation will thus result to:

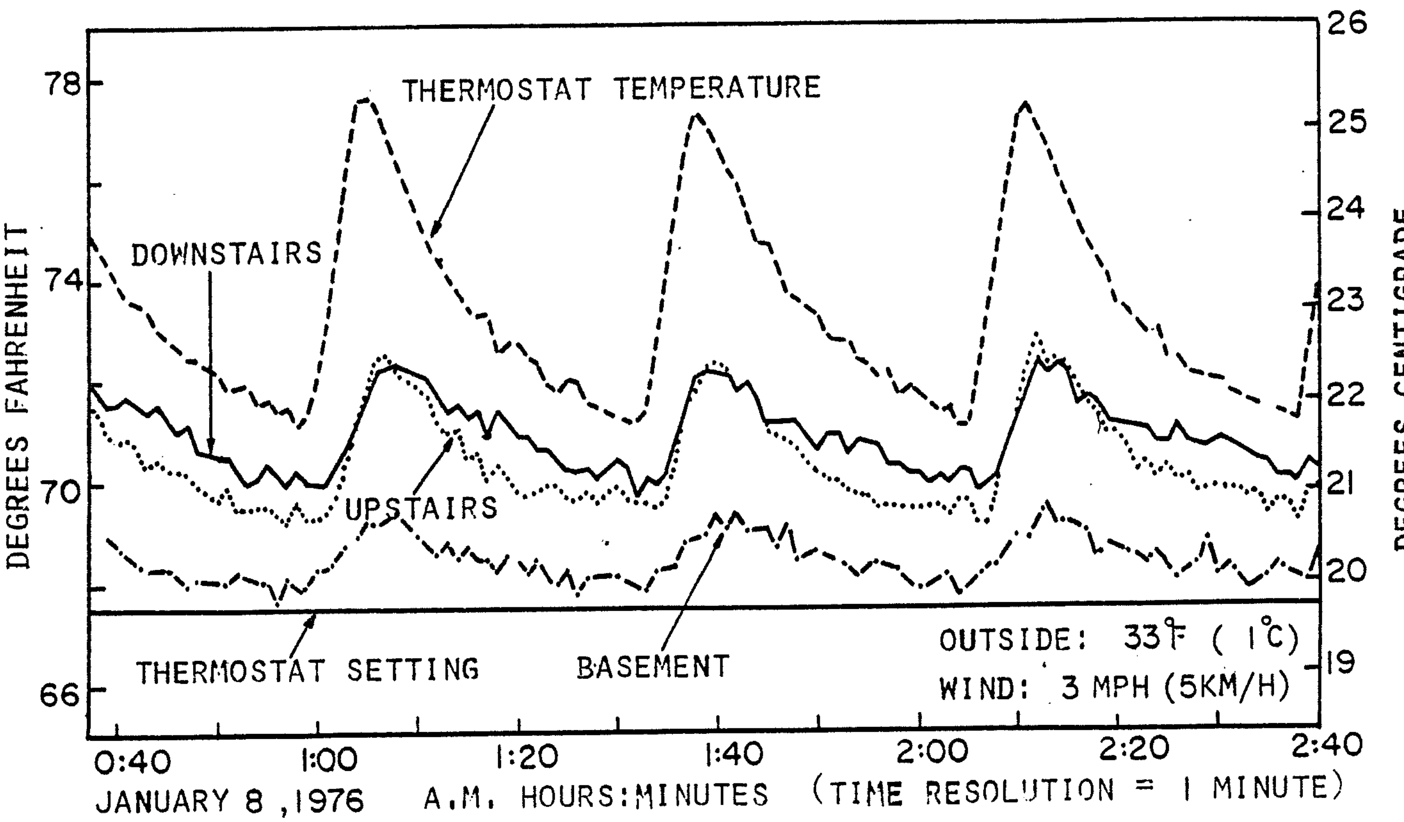
50% * 60% =	30%	(forced convection through ducts)
50%+ 50% * 40% =	70%	(heat transfer to structure and basement)
	100%	(heat flow at furnace plenum)

Under continuous fan operation, the different assignments are essentially equal to the steady state shares in Figure VII-2, and are split in even fashion between forced convection through the ducts and direct heat transfer to the structure and the basement. Considering the losses from the basement to the outside discussed in Chapter VII, it would appear profitable to lower the blower cutoff temperature considerably, to approximate the (more costly) continuous operating mode. Yet, in view of the negative result from the comparison of the two figures in VIII-4 (in both situations, the furnace fired at the same rate, with comparable weather conditions), the claim made above merits further investigation.

The conclusion then, best represented by Equation VIII.3, is that virtually all alterations of the furnace-duct system, including furnace resizing, fan operation mode changes, duct insulation, etc., affect primarily the relative shares of heat distribution through the registers and through the structure and the basement. It is by examining the consequences of such a shift in heating shares that the additional (in)efficiencies generated by the alterations listed above have to be evaluated: they are nil if the basement is perfectly insulated, and of increasing importance, as the short circuits in the heat flow between basement and outdoors are included.



(a) ROOM AND BASEMENT TEMPERATURES BEFORE RETROFIT



(b) ROOM AND BASEMENT TEMPERATURES AFTER RETROFIT

FIGURE VIII-6

Recall that the basement receives about one-third of the heat flow through the plenum (which is 75 - 80% of the heat generated by gas combustion); the prize at stake is high enough to be coveted. A first move in this direction was Princeton Retrofit package C, discussed in Chapter VI; it will be complemented in the next heating season by a lowering of the fan cutoff temperature and by a reduction of the furnace size by decreasing its orifice diameter.

F. The room temperature cycle

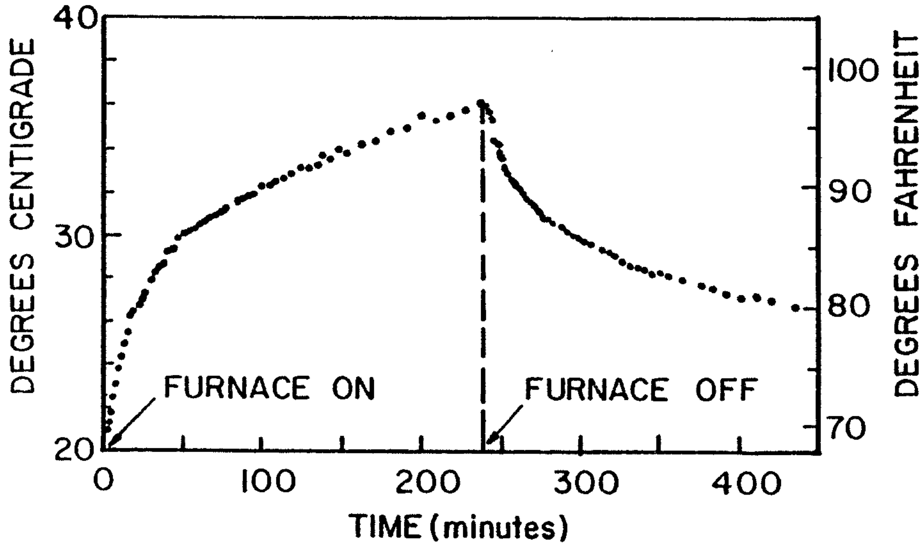
Looked at with a sufficiently small time resolution, the rooms show temperature cycles similar to those found in the ducts, driven by the "heartbeat" of the house, the furnace. Two such cycles recorded at about 2 a.m. of two different nights are shown in Figure VIII-6 both before and after retrofit. Again, we find the by now familiar shape in the basement, in a downstairs and an upstairs room, and in the thermostat itself. The nominal thermostat setting is also shown. Immediately noticeable is the high basement temperature of this house (because of a very leaky duct system), figuratively plunging into the basement. Notice that the upstairs and downstairs temperatures are rendered about equal by the retrofits during furnace firing time. Still, the upstairs cools slightly faster, after the furnace stops firing, presumably because of the additional exposure to the weather through the ceiling. The larger amplitude of the downstairs temperature oscillation after retrofit is an indication that the residents reset the duct dampers to obtain a more equilibrated heat distribution. The thermostat temperature has a deceptively large amplitude: recall the anticipator located within the thermostat, that "cooks" the thermostat element while the furnace is on.

The data in Figure VIII-4 and 6 were observed with a data acquisition system belonging to the National Bureau of Standards (dubbed "Rapidscan" by our group) and capable of far faster data handling than any of our own equipment. For nearly a year, Rapidscan sat alongside our own system in the basement of one of the highly instrumented townhouses (HIT 2), and when it was running it sampled precisely the same data channels for that house.

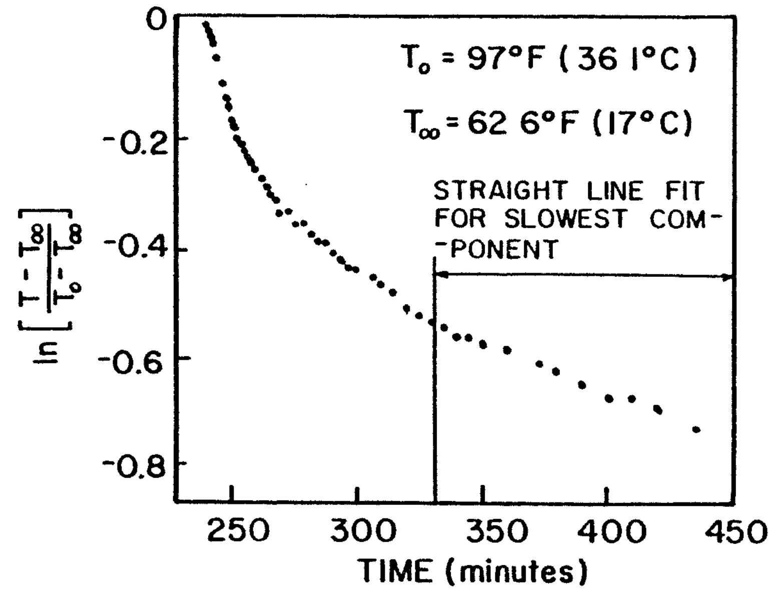
The room temperature cycle has been tested for much longer firing and off periods in our rented townhouse, "toasted" during 4 hours of continuous furnace firing up to a temperature of 77°F (36°C), and then cooled for another 3 1/2 hours; the cooling continued beyond the end of the experiment.

The hall temperature measured during this experiment is shown in Figure VIII-7. Because of the laws of heat transfer, the temperature cycle is expected to go through a similar kind of exponential rise and decay, just like the duct temperatures (see Equations VIII.1 and VIII.2). But the room temperature curves decay into a sum of three exponentials, rather than one. That is, we observe three distinct time constants both for the temperature rise and its subsequent decay.

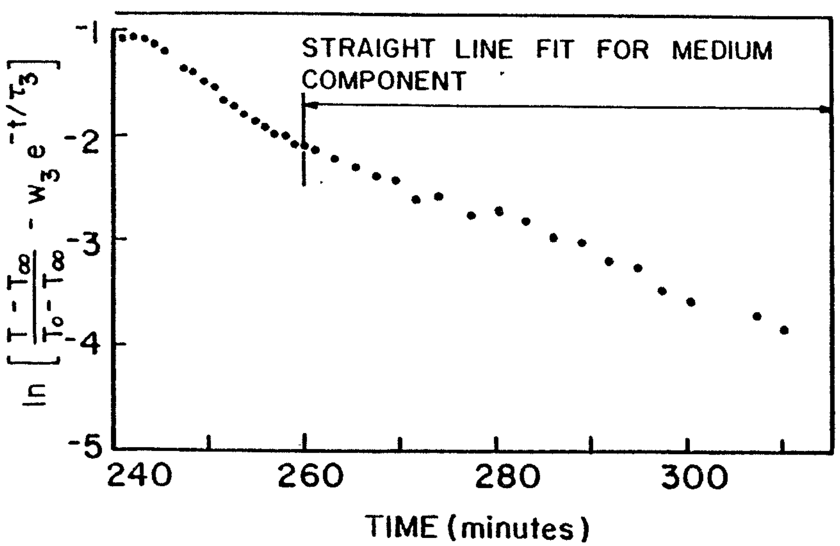
$$\frac{T - T_\infty}{T_o - T_\infty} = w_1 e^{-t/\tau_1} + w_2 e^{-t/\tau_2} + w_3 e^{-t/\tau_3} \quad \text{(VIII.4)}$$



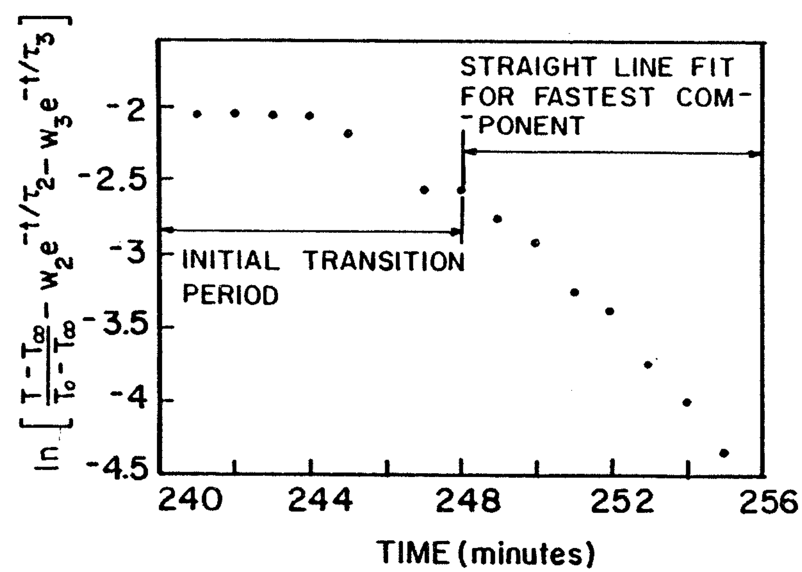
(a) HALL TEMPERATURE VERSUS TIME



(b) LOGARITHMIC PLOT OF $\frac{T - T_\infty}{T_o - T_\infty}$



(c) LOG PLOT OF DECAY CURVE MINUS SLOWEST EXPONENTIAL COMPONENT



(d) LOG PLOT OF DECAY CURVE MI-NUS SLOWEST AND MEDIUM EX-PONENTIAL COMPONENTS

FIGURE VIII-7

A certain ambiguity in the determination of the longest time constant stems from the necessity of estimating a temperature at infinity for both rise and decay. The goodness of the fit to the slowest exponential (a straight line on a logarithmic plot as seen in Figure VIII-7b) was used to estimate the "best" temperature at infinity, rather than a temperature calculated by physics, because, once the house heats above 80°F, second order effects like free heat supplied to the neighbors and the ground water, increased film coefficients along the warm walls and the four hours worth of furnace heat that can be stored in the cinder blocks of the firewalls (at a temperature increase of 30°F), tend to become important. After the longest time constant τ_3 and the weight w_3 of "its" exponential have been so determined, $w_3 \times e^{-t/\tau_3}$ is subtracted from the original temperature curve and the remaining curve

$$\frac{T - T_\infty}{T_0 - T_\infty} = w_1 e^{-t/\tau_1} + w_2 e^{-t/\tau_2} \qquad \text{(VIII.5)}$$

is again plotted logarithmically, as shown in Figure VIII-7c, to obtain w_2 and τ_2. The process is repeated for w_1 and τ_1 and, in fact, would reveal further (shorter) time constants as well, if there were any. Using this method, the three time constants were found to be of the order of 4-5 minutes, 30 minutes, and 9 hours for both the temperature rise and the decay. The slowest exponential accounts for about 70 - 75% of the total temperature excursion, the two shorter ones for 20 - 25%. An initial temperature rise of 2°F that does not obey an exponential law, has been eliminated from the analysis.

The time constants and the relative magnitudes of each exponential component are displayed in Table VIII.1, for a choice of two "temperatures at infinity" for both rise and decay, representing the range of the possible variation and still maintaining a good fit of the slowest exponential.

Table VIII.1

Exponential Components of the Hall Temperature Versus Time

		Rise (T_o = 22.8°C*)		Fall (T_o = 34.1°C*)	
		T_∞ = 45°C	T_∞ = 50°C	T_∞ = 20°C	T_∞ = 17°C
Percentage of total* increase	F	10.0	8.6	10.5	8.7
	M	15.4	13.3	21.6	18.5
	S	74.6	78.1	67.9	72.8
Time constants (minutes)	F	5.6	5.9	4.0	4.0
	M	26.0	28.7	29.5	30.1
	S	398.0	580.0	433.0	618.0

F= Fastest
M= Medium
S= Slowest

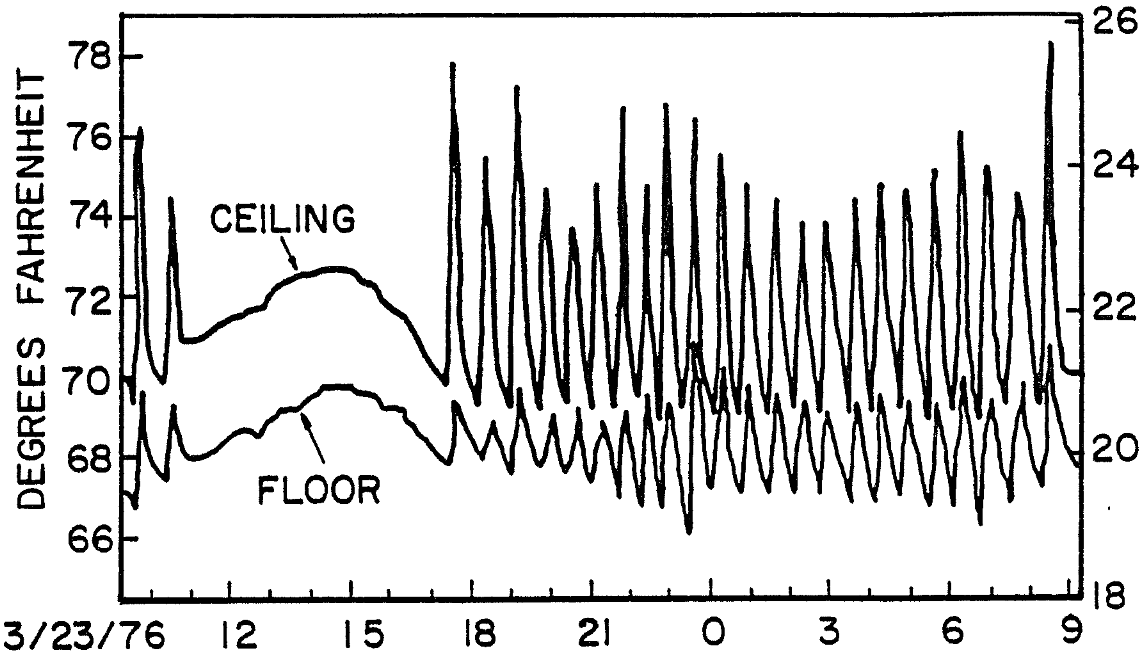
*Only the temperature curve after an initial non-exponential transition period of 1.9°F (Rise) and 2.0°F (Fall) has been examined. Both initial temperature T_o and "total" temperature increase refer to this residual curve.

Notice how the two sets of time constants and relative weights are compatible for the heating and cooling mode and how little the choice of T_∞ affects the two shorter exponentials. Only the fastest time constant is somewhat smaller than its counterpart for the temperature rise. Several physical phenomena could be searched for answers; this task lies ahead of us. The longest time constant can be thought of as representing the heat exchange between "the solid structure" of the house and the outdoors. It is shorter than the 13 - 18 hours mentioned at the beginning of this chapter, because of the second order effects (mentioned above) that increase the heat loss constant H and thus make the ratio $\tau = \frac{C}{H}$ smaller. The shortest time constant is presumably an indication of the mixing within the air itself, while the middle time constant stands for the air-to-wall heat transfer. In the language of Chapter IX, these time constants and coefficients are promising candidates for the "signature" of a house.

The initial transition period, during which the temperature rises by 1.9°F (or falls by 2.0°F), deserves some discussion also. For the temperature rise, it lasts for 5 minutes after the furnace starts firing, and 8 minutes after it stops, and indicates the buildup and breakdown of stratification at the beginning and the end of a furnace firing period (see the next section). In fact, the temperature cycle analyzed in Figure VIII-7 was recorded next to the ceiling of the downstairs hall. Further research as to the physical meaning of these parameters and the question of structure storage in general is in progress.

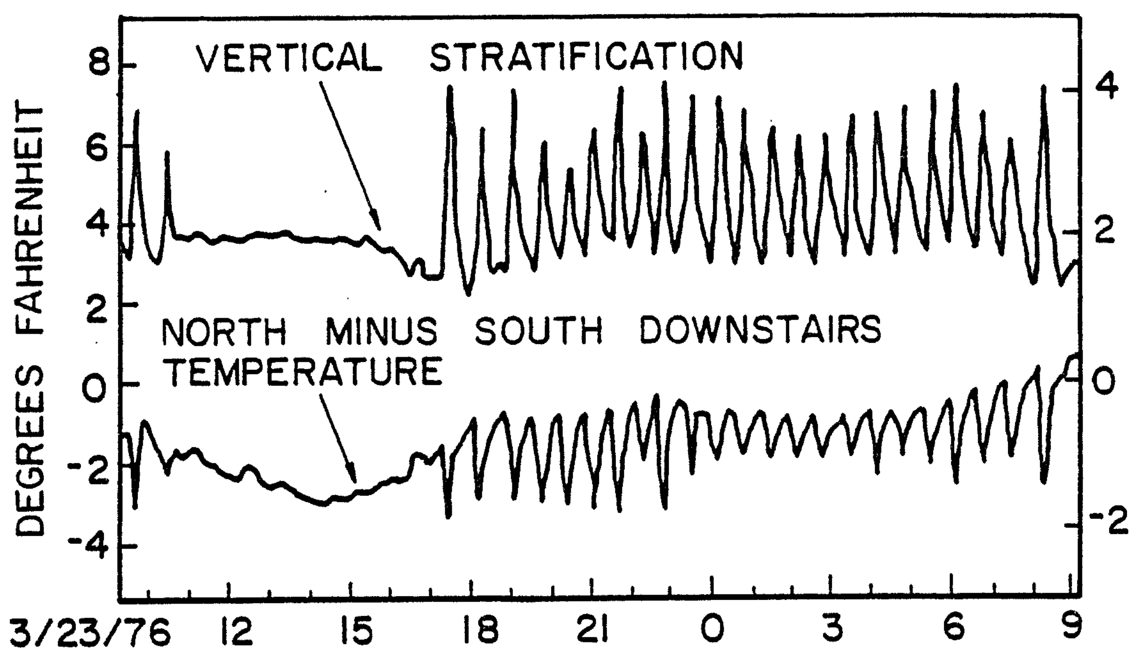
G. Vertical and horizontal temperature gradients in a zone: an effect of furnace and solar heating

A typical plot of the ceiling and floor temperatures (each measured in the Living Room at about 1 foot from the surface) in the first floor of a townhouse is shown in Figure VIII-8a, over a period of 24 hours. Figure VIII-8b displays the horizontal temperature differences across the North-South axis of the downstairs, and the average vertical temperature stratification. Two typical situations arise: During the day, the sun heats the south side of the house, increasing its temperature with respect to the north side by as much as 3°F (1.7°C) during a sunny day. At the same time, in the absence of furnace operation during the daylight portion of this day, with the outside temperature at an average 46°F (8°C), the vertical temperature stratification hovers in the range of 3.5°F (2°C). At night, the situation changes radically: both the vertical and the horizontal temperature differences pulsate rhythmically with the furnace. The vertical stratification oscillates between the "rest value" of about 3.5°F (2°C) and a high of about 7°F (4°C) that is reached shortly after the blower fan starts operating. The horizontal pulsating should not be overemphasized; it is mostly an indication of the different rates at which heat is delivered to the northern and the southern part of the house, a function of the particular duct damper settings.



LIVING ROOM CEILING AND FLOOR TEMPERATURES

FIGURE VIII - 8a



FIRST FLOOR VERTICAL AND HORIZONTAL TEM-
-PERATURE DIFFERENCES

FIGURE VIII - 8b

Looking back at the solar heating of the (southern) Living Room, the reader will observe that the furnace completely stopped operating during that time, although the outside temperature was below 50°F (10°C). This happened because the thermostat is placed in the south facing Living Room, and, if the drapes are open on a sunny day, "thinks" it is warm enough, while the northern half of the house structure cools down. The apparent saving in gas consumption is greater than the influx of solar energy, and the difference is "paid back" in the early evening hours, when the furnace resumes its cycles at a faster pace than required by the outside temperature only (see also Figure VIII-1). Therefore, the sun has to be thought of as the combined effect of a little heater and a thermostat setback over the sunlight period of the day.

H. Conclusions

This chapter was directed to the transient heat transfers occuring in a townhouse. Quite a few of the discussed physical behaviors can be generalized, if the relevant parameters are changed according to the requirements of a different house. Considering the numerous conventional heat load models that completely neglect transient effects and the (few) large computer programs that treat some of them with voluminous sophistication at the expense of transparency, this chapter attempted a simpler approach, focusing on the areas where our experiments have shown transients to be important.

IX. ASTRONOMY IN THE TOWNHOUSE: DATA FROM PASSIVE EXPERIMENTS

A. Constraints on measurements in other people's homes.

Our field experience in this research program has left us wishing to tell others two things above all: First, that houses are different enough from one another to require some on-site observation before sensible advice can be given; this point was emphasized in Chapter VII. Second, that the use of automated instrumentation to diagnose a house is in its infancy, requiring much more development. In this chapter, we will describe a few analyses of data obtained by our group from instrumentation left behind in houses where the residents continued to go about their business. Some details about the instrumentation will be found in Appendix E.

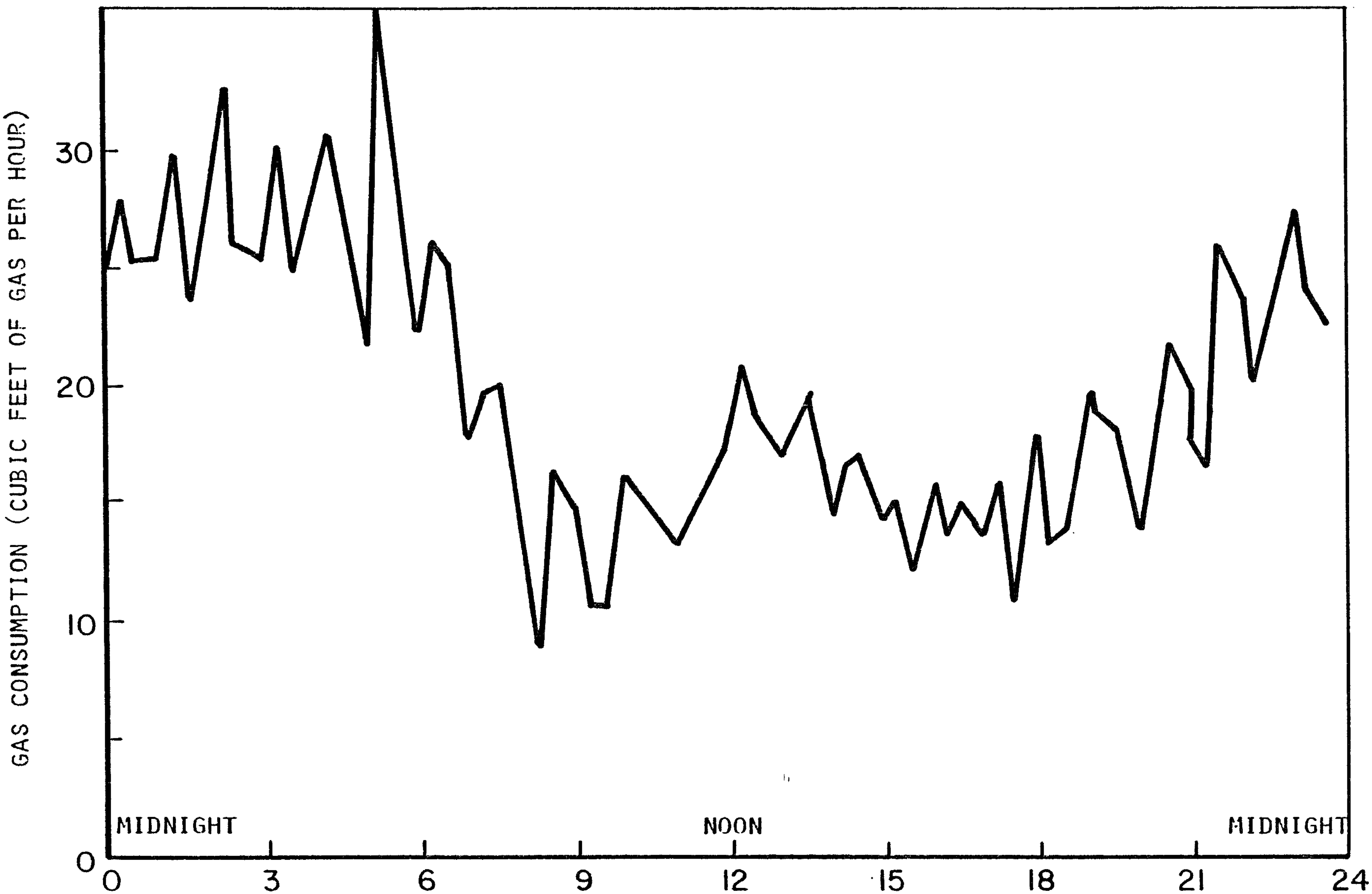
Research in occupied houses is different from research in controlled houses in ways not unlike the ways that astronomy is different from physics. In controlled houses, intervention is essentially unlimited. Intrusions can occur to almost any level; the "toasting" of our rented house described in Chapter VIII is a case in point. Intrusions can also occur at almost any time, so one tends to plan experiments in detail, then (often) wait for appropriate weather. By contrast, intrusion into the lives of the families who have permitted us into their homes has been perceived from the start of this program as a quantity to be minimized, wherever possible. Initially, we were worried about perturbing the system being studied. This has not turned out to be a serious problem, as the behavior being exhibited by the residents has power to be highly resistant to influence. The principal reasons for minimizing intrusion have centered on common decency, or, in the practical world of our research, on not being asked to get out once we are in. The record of the group working under David Harrje has been a remarkable one; no home in which we have worked has ever asked us to terminate our research, and houses have been instrumented for a total (as of July, 1976) of roughly 34 house-years.

The distortions of research brought about by the constraint of minimum intrusion are unfamiliar ones. There is a large constraint on going in and out, strongly inhibiting routine check-out and leading to a corresponding emphasis on the reliability of components. Thermistors, for example, have been the workhorses of our program, not only because they are so precise, but also because they are so rugged. There are subsidiary constraints that the instrumentation be quiet, safe, and inconspicuous; these have led to the replacement of squeaky metal bearings by plastic ones, to the use of tracer gases only in minute quantities, and to the color coding of thermistors and lead wires to match the walls. These same constraints were responsible for our failing to document the significant vertical temperature gradients within rooms until experiments were done in our controlled townhouse: initially, virtually all thermistors were placed just below the ceiling, where no one could walk into them.

It follows, also, that there is almost no constraint on the quality of data obtained from a single house -- in particular, on the frequency with which any particular data channel is sampled. In order to overcome a particular ambiguity in our instrumentation, readings were taken at twenty-minute intervals, instead of hourly, in the second winter in the highly instrumented townhouses, at almost no increase in cost. From a technical standpoint, this freedom to choose the sampling interval is helpful, for one wants quite different sampling intervals depending on the question being addressed. Optimum frequency of data acquisition has to be matched to the characteristic time constants of the problem.

B. Statistical models of gas consumption.

There has been a determined effort in our group to quantify the effects, in addition to outside temperature, that determine gas consumption. Whereas monthly data, as seen in Chapter IV, wash out nearly entirely any signals from changes in thermostat setting, from wind, from appliance use, and from the sun, it has been our hope that these signals could be deciphered in the more frequent data obtained from our own instrumentation. Among the signals requiring explanation are sharp variations across hours of the day, the most distinctive of which is the sharp 8 a.m. drop in gas consumption in House 1, seen in the furnace profile over hours in Figure IX-1. Is that effect due to the sun shining in the east window, or the heavy use of appliances in the morning? Using methods discussed in this section, Thomas Woteki has concluded that both contribute, and that appliances are more important.



LOAD PROFILE OF FURNACE (HOUSE 1, 1975 WINTER)

FIGURE IX-1

The group's approach has been to model the relevant physical effects using linear models, and to fit the parameters using multiple regression analysis. This approach turns out to require a stout heart. Although the signs of the effects generally are physically sensible (extra gas consumption when it is windy, reduced gas consumption when appliances are running and when the sun is shining -- always relative to what a straight-temperature model would predict), we have not yet confirmed that the magnitudes of the coefficients are reproducible as the weather or usage patterns vary. We have hoped that a set of coefficients derived from such a model could be considered a "signature" of the house, capturing enough of its physical properties to serve as the point of departure for the ranking of alternative retrofits. For this to be possible, the models must be quite close representations of physical reality.

Consider the leakiness of a house, for example. Will that property be captured in a regression coefficient expressing the additional gas consumption on a windy day? With how much subtlety will the windiness have to be modeled? We have tried to include a simple term in the heat balance: V* DT, where V is the average wind speed (usually over an hour) and DT is the temperature that hour between indoors and out. Nearly always, the inclusion of such a term improves the fit of gas consumption versus (various) weather variables, relative to the fit of a model with no mention of wind velocity. But regression methods are not well suited to distinguishing one <u>form</u> of term from another, because alternative formulations (here, of the wind effect) tend to be highly correlated with one another (V, V^2, and the component of V normal to the windows, for example). One knows one is on the right track largely by finding that the coefficients of the model are reproducible in a variety of situations, and that takes a great deal of detailed investigation.

There is always the possibility that one can measure directly exactly what one is interested in. In the case of the leakiness of a house, there have been repeated measurements in a single house (HIT-1) over most seasons of the year. Nicholas Malik, who has focused on air infiltration in his graduate work, found direct confirmation of the additive model of heat loss (conduction plus convection) and in the process obtained what is probably a robust pair of coefficients for that house. Specifically, he obtained the following equation in fitting data on gas consumption and air infiltration over 26 nights:

$$G = -450 + [(18 \pm 2) + (11 \pm 1)\,\overline{AI}]\ DT \qquad \text{(IX.1)}$$

Here, G is the average rate of gas consumption (in cubic feet per day), $\overline{AI}$ is the average air exchange rate (in exchanges of the house's volume of air per hour) and DT is the temperature difference between inside and outside (in °F). The value of R^2 (the square of the multiple correlation coefficient) was 0.96, and the standard error was 80 cubic feet per day. The best fit to the data obtainable from a model of the form G= -S + B* DT (that is, a model without air infiltration taken into account explicitly), had an R^2 of 0.78 and a standard error of 180 cubic feet per day.* To be more specific, there were two nights, February 1-2, 1975, and April 3-4, 1975, during both of which the temperature out of doors was between 25°F and 30°F, but the first night was calm and the second had a severe storm. The furnace ran 30 percent of the time the first night (600 cubic feet per day) and 80 percent of the time the second night (1500 cubic feet per day). The air infiltration rate was measured to average 0.5 exchanges per hour the first night and 1.9 exchanges per hour the second night. Clearly, something had to be in the equations to allow for that huge difference.

Ordinarily, the air infiltration rate will not be measured directly. Models in which the air infiltration rate becomes the dependent variable and one tries to predict it in terms of weather and house parameters become desired substitutes for actual measurements. Our work in progress toward that objective is reviewed briefly in Section D of this chapter.

As always, there is a lot of physical information in the regression coefficients. Regarding Equation IX.1, the performance index, B, of Chapter IV** has evidently been split into a conductive and a convective part

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* Moreover, that model, G= -660 + (32 + 4) DT, has too large a slope and too small an intercept, the characteristic reaction to scatter in data discussed in Chapter IV.

** Most of the B- coefficients obtained in this chapter are higher than the all house-average 21 cubic feet per degree-day, of Chapter IV, because HIT 1 is a rather high user.

$$B = (18 \pm 2) + (11 \pm 1)\ \overline{AI}, \qquad (IX.2)$$

with B carrying the units of cubic feet per degree day. The naive heat load calculations for those townhouses give ratios very close to 2:1 for air infiltration rates of 3/4 exchanges per hour; the ratio here, 18:8.75, is in excellent agreement: Equation IX.2 allows one to appreciate why it is that the conventional design basis day is poorly chosen: The design basis day is a day of 5°F outside temperature in New Jersey, with a 15 miles per hour (24 km/h) wind. Yet the day on which the furnace runs the longest is a very windy day,conceivably much milder. In fact, the furnace in the HIT-1 townhouse never has run as often as it did during that April storm, during all of the period we have monitored, a period including many much colder evenings. The peak wind speeds in the April storm were over 40 miles per hour, high for New Jersey but not for many other locations where (presumably) the design basis day is also determined by considerations of temperature alone.

Both the constant term (which works out to 5.6 kw) and the slope (25 cubic feet per degree day at an average exchange rate) are quite similar to what has been seen for the same house in fits to other data, as will be seen forthwith,

The models used to "explain" gas consumption, in the absence of direct measurements of air infiltration have been of a limited, nested sort. Specifically, under Thomas Woteki's management, we have incorporated some or all of the following variables:

a) Outside temperature, (T). It is measured hourly by our weather station approximately one quarter mile from the townhouses. (Units: °F)

b) Interior temperature, (T_{in}). Usually, the hall temperature is chosen (see Figure I-2), for it has proven to be a representative average interior temperature. The interior temperature ordinarily varies so little, relative to the other independent variables, that it could be set equal to a constant, its average value, with little effect. However, we consistently incorporate the interior temperature into the models through the temperature difference:

$$DT = T_{in} - T \qquad \text{(Units °F).}$$

c) Average wind speed (V). The weather station measures the instantaneous speed and direction hourly and also the average hourly speed. In models of gas consumption, we have used the average speed, incorporated into the models through the product:

$$V * DT$$

In air infiltration models (Section D of this chapter), effects of wind direction have also been explored. (Units: mph - °F)

d) Appliance use (E), the sum of the hot water use (HW) and all other electricity use (LARA, an acronym for lights, appliances, and range). A small contribution from the drier has not been modeled. We have yet to find a situation where HW gives a statistically significant signal, implying that the time-varying portion of hot water use has failed to play a significant role in the heat balance. (Units: kw, or, to match the units of G, cubic feet of natural gas equivalent per day. One kw= 79.9 cf/day.)

e) Solar flux, incident either on a horizontal surface (H) or on a surface parallel to the front and back walls (W). H is measured at our weather station, and W is calculated either by trigonometry or with the help of ASHRAE tables. Trigonometry is not adequate when the sun is near the horizon. (Units: btu/hr ft^2, btu/day ft^2, or, to match the units of G, cubic feet of natural gas equivalent per day per ft^2; 1cf= 1025 btu.)

Hourly data from ten cold days in the 1975 winter (10 a.m., February 7, to 9 a.m., February 17) have been modeled in considerable detail to explore the consistency of regression coefficients and the significance ~~of the~~ time period over which data are averaged.

Four basic models were tested:

$$G2 = -S + B^* \, DT$$

$$G3 = -S + B_D^*(1 + V/V_o) \, {}^*DT$$

$$G4 = -(S_4 + k_e LARA) + B_o^*(1 + V/V_o) \, {}^*DT$$

$$G5 = -(S_5 + aw + k_e LARA) + B_o^*(1 + V/V_o) \, {}^*DT$$

The number following G is the number of measured independent variables incorporated into the model. The parameter names are meant to be suggestive, and all should take only positive values if the models are sensible:

S: The rate at which sources of energy other than gas contribute to the thermal energy balance (Units: kw or cu.ft./day).

$S_{4,5}$: The same as S, except that heating by electric appliances and sun are separated out (Units: kw or cu.ft./day).

B: The same performance coefficient as in Chapter IV (Units: cubic feet/°F-day).

B_o: Performance coefficient at zero wind speed (Units: cf/°F-day).

v_o: The wind velocity at which the performance of the shell deteriorates by a factor of two, i.e. at which the coefficient of DT doubles (Units: mph).

k_e: Thermal efficiency of appliances relative to gas; in Chapter IV notation, $k_e = e_e/e_g$ (Units: dimensionless, and, directly, the relative efficiency when G and LARA are measured in the same units).

a: The relative efficiency of solar energy collection compared to furnace gas combustion, with the units of an area (square feet). Put differently, the coefficient a indicates the area of a hypothetical solar collector with the same collection efficiency as the furnace combustion efficiency placed on the vertical walls of an otherwise 100% reflective house that would collect the same amount of solar energy as observed in the data.

The 240 sets of hourly data were used in the models in one of five ways, either intact, or collapsing into one of the following: 80 3-hour intervals, 40 6-hour intervals, 20 12-hour intervals, or 10 24-hour intervals. All four models are evaluated at once when terms are forced to enter sequentially in SPSS, the statistical computer package used for most of the research on these models. The basic data were available for three townhouses, and thus four models times five time intervals times three houses, or 60 multiple regressions, were run. Several patterns have emerged:

The R^2 of the fits increased and the standard errors of the regressions decreased as more terms entered the regression (inevitably) and as the data set was collapsed into fewer data points (largely because the noise of high frequency furnace cycling became increasingly invisible). Table IX.1 gives the R^2 of the twenty regression analyses for House 1. The wind effect (which is added going from G2 to G3) is

Table IX.1
R^2 Table for House 1 (in percent)

	Hours averaged over				
Model	1	3	6	12	24
G2	36	51	66	70	76
G3	39	57	77	81	88
G4	44	63	79	86	91
G5	44	63	79	87	96

seen to make a larger incremental difference when longer time periods are used, and the effect of electric appliances (which is added between G3 and G4) is seen to make a larger incremental difference when shorter time periods are used. In fact, following the incorporation of DT into the regression, LARA would enter next, if the choice were made on the basis of an F-test, for 1-hour and 3-hour decks, and V*DT would enter next for the decks using 6-hour periods or longer. What is happening in the physics is that variations in electric consumption are being smoothed over, whereas variations in windiness affect the house over a longer characteristic time period only and are becoming more prominent. We have found throughout our research that, whenever we use data based on daily averages, the single physical variable most able to explain the residuals remaining after the effects of outside temperature are controlled for is wind speed, in particular, much more than sunniness. The Twin Rivers townhouse is much more aware that it is windy than that it is sunny.

The standard errors on individual coefficients usually increased as the number of points in the data set decreased. Compare the G4 models for House 1 from one-hour and six-hour decks:

One-hour data (240 sets) $R^2 = 0.44$, s.e. = 210:

$$G4 = -250 + \underset{(2)}{22}\,(1 + V/\underset{(30)}{100})DT - \underset{(0.3)}{1.4}\,LARA \qquad (IX.3)$$

Six-hour data (40 sets) $R^2 = 0.79$, s.e. = 90:

$$G4 = -220 + \underset{(2)}{20}\,(1 + V/\underset{(20)}{60})DT - \underset{(0.5)}{1.1}\,LARA \qquad (IX.4)$$

Here G4, the constant term, and LARA are all in cubic feet per day; V is in mph. Standard errors are written below the coefficients. The loss of detail on the individual coefficients as the R^2 value increases suggests that one try to use moving averages instead, to smooth the data without reducing the number of data points.

The coefficient of DT in Equations IX.3 and IX.4 should be compared with the B coefficient in equation IX.2. They are fairly consistent: taking average values of V = 10 mph and $\overline{AI}$ = 0.75 exchanges per hour, the B coefficient is 27 and the two DT coefficients are 24 and 23, in cubic feet per degree day.

Equations IX.3 and IX.4 demonstrate a number of trends which run consistently through the output. Regression coefficients generally are consistent from one level of collapse of the data to another. The exception is the wind effect, which appears steadily larger (V_o decreases) as the time period of data averaging increases; Table IX.2 gives several of the V_o coefficients for House 1. The 24-hour

Table IX-2

Wind Coefficient, V_o, for House 1 (mph)

Model	Hours Averaged Over		
	1	6	24
G3	100$\pm$30	60$\pm$20	40$\pm$20
G4	100$\pm$30	60$\pm$20	40$\pm$20
G5	70$\pm$20	(models are not sensible)	

value is seen to be three standard deviations from the central value obtained from the hourly data. It is just such anomalies in the behavior of coefficients that must be closely investigated: a retrofit program to tighten a house might be expected to increase the value of V_o. The G4 models gave values of V_o of 160 and 170 mph in the one-hour models and 140 and 120 mph in the six-hour models, for houses 2 and 3 respectively, both believed by our group to be tighter houses on the basis of direct inspection.

The coefficient of LARA gives the efficiency of lights and appliances relative to gas, in heating the house. The coefficients fall in the same range in all three houses, as seen in Table IX.3. Moreover,

Table IX.3

Relative Efficiency of Electric Appliances and Gas as Sources of Winter Heat
(k_e coefficient)

Model	Hours Averaged Over: 1	6
House 1:G4	1.4 ± 0.3	1.1 ± 0.5
G5	1.4 ± 0.3	1.1 ± 0.5
House 2:G4	1.0 ± 0.2	1.2 ± 0.4
G5	1.0 ± 0.2	1.2 ± 0.4
House 3:G4	1.0 ± 0.4	1.4 ± 0.7
G5	0.8 ± 0.3	0.9 ± 0.6

the coefficients are stable, even when the sun is included in G5 models. From Equation IX.3, lights and appliances are 1.4 ± 0.3 times more efficient than gas in heating the house. The heat they give off is delivered directly to the living area, so this result seems quite reasonable. Since no efficiency can exceed 100 percent, the LARA coefficient sets an upper limit on the efficiency by which the furnace adds heat to the house, here, roughly 70 ± 20 percent; the coefficient checks well with the 2/3 found in Chapter IV, and is well worth pursuing.

The models cited here have not allowed for the effects of electric consumption by the hot water. No statistically significant effect of this kind has yet been seen by us. In part, there are irregular time delays between electric consumption and hot water use which disguise the effect (and we have not measured hot water flow). In part, the nearly constant heat loss through the sides of the hot water heater gets embedded in the constant term of the regression. In part, the hot water indeed goes down the drain without doing any heating. The Twin Rivers hot water heater uses electricity at a rate of 0.9 kw. Assigning 0.3 kw to standby losses and assuming that the remaining 0.6 kw goes down the drain without heating the house, one finds that over 15 percent of the natural gas consumption over a winter could have been avoided if the hot water had substituted its energy for gas with the same relative efficiency as the lights and appliances.* Hot water heat recovery within the house would appear to have substantial payoff.

The solar flux is the fifth independent variable, and, not surprisingly, the model goes haywire when it is tried on the day-averaged data, which has only 10 sets of points. The solar coefficient acquires the wrong sign in several cases, and the standard errors are large. In the hourly data, however, the solar signal is more reasonable. Table IX.4 shows the A coefficient, in square feet, both for the G5 model

*0.6 kw for 200 days is the energy equivalent of 96 hundred cubic feet of natural gas. Multiply by 1.4 (relative efficiency) and compare with an average winter use of 80,000 cubic feet.

and for a variant in which hourly solar flux on a horizontal surface (H) is used, instead of the flux on the walls (W). All three houses

Table IX.4

Areas Intercepted by Sunlight (a coefficient)

G5 model: a x Flux on E-W walls
G5'model: a x Flux on a horizontal surface

Hourly Data. a in ft^2

	Horizontal area	E-W area
House 1	6 ± 13	31 ± 7
2	-5 ± 8	5 ± 5
3	65 ± 15	49 ± 16

are seen to be different: House 1 shows much larger response to W than to H. The sharp drop in gas consumption at 8 A.M. in that (east-facing) house, seen in Figure IX-1, is modeled in part by giving W a large coefficient, as W peaks in morning and late afternoon. House 2 shows no statistically significant solar effect. House 3 shows large and comparable effects no matter whether H or W is used; as House 3 is an end unit with a south wall, this is not completely unexpected. As for the numerical values of the coefficients, they could in principle be turned into "efficiencies for solar heating" by dividing by some appropriate "solar capture area;" one choice might be the average window area per side, 80 square feet. At the present time, the dramatic difference between houses 1 and 2, interior units along one another, remains unexplained, but large differences among the solar signatures of various houses have led us to focus greater attention on "capture efficiency," for example, as it might be affected by the color of drapes and their operation.

What we have hardly done yet is to take a batch of data like the 240 hours discussed above, partition it according to the value of some physical variable, and then model each portion separately. A good model will give consistent coefficients in both portions (or, at least, coefficients which differ in a consistent and well understood manner). Partitions into periods which are sunny and cloudy, dry and wet, windy and calm, or cold and warm, may give insights into house dynamics.* So, especially, we suspect, will partitions by time of day: Models of data confined to night hours tend to be simpler, and a separate analysis of effects in each six-hour quarter of the day, in the larger set of "Omnibus" townhouses, is currently in progress.

The 10-day period in February 1975, of course, has not been the only period modeled in detail. Using daily averages, we have looked at large stretches of both the 1974 and the 1975 winter for the three highly instrumented townhouses, and at the 1976 winter in those houses and the Omnibus houses. The qualitative conclusions discussed earlier in this section largely prevail in those analyses as well. The critical task for the coming year will be to establish which formulations of

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*A partition of daily data into cold and warm periods was tried once with daily data by Gautam Dutt, using a G3 model for House 1, and gave substantially different coefficients of DT, implying that the house used more extra gas per degree day in cold weather than in mild weather.

various physical effects produce robust parameters, so that before and after statements about retrofits can be made with confidence.

Figure IX-2 shows daily averaged data for House 1 over 62 days of the 1974 winter. The scatter of points should be compared with Figure IV-1, which showed monthly data, averaged over 16 houses and Figure IV-5, depicting daily averages of air conditioner consumption for House 2. Regression analyses were done for these data and for the corresponding data from the 1975 winter, a period including the 10-day stretch discussed above. The following G4 models emerged for House 1:

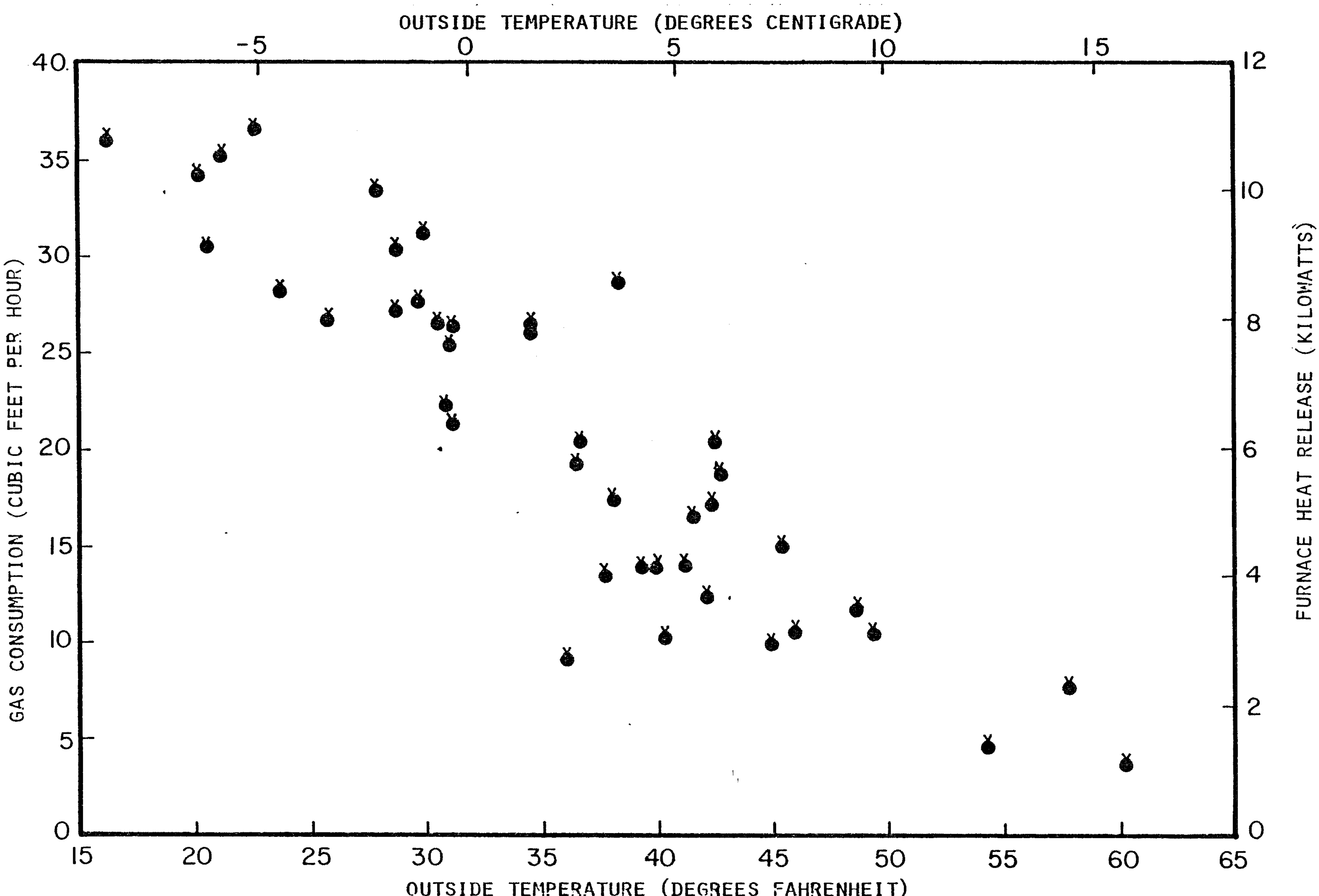
1974 winter days: $R^2 = 0.94$, s.e. = 60:

$$G4 = -60 + \underset{(1)}{15}\,(1 + V/\underset{(4)}{40})DT - \underset{(0.6)}{1.9}\,LARA \qquad (IX.5)$$

1975 winter days: $R^2 = 0.93$, s.e. = 67:

$$G4 = -230 + \underset{(1)}{21}(1 + V/\underset{(8)}{60})DT - \underset{(0.5)}{2.0}\,LARA \qquad (IX.6)$$

All notation is exactly as in the discussion earlier in this Section. Comparing the coefficients in IX.6 with Equations IX.1 and IX.2 above, we conclude that the representation of the 1975 winter is remarkably consistent, whether one looks at 10 days in detail or 62 days coarsely. The coefficients for the winter of 1974, however, differ substantially: there has been a shift from slope to intercept, implying that the house in 1974 used less gas in cold weather and more gas in mild



FURNACE GAS CONSUMPTION VERSUS OUTSIDE TEMPERATURE FOR HOUSE I

FIGURE IX-2

weather. Examination of the monthly meter readings shows that the effect is spurious, but reveals other peculiarities in the pattern of 1975 winter consumption that merit further investigation. Comparing Equations IX.5 and IX.6, the constancy of both the wind chill and the appliance warming across winters is heartening.

To review briefly, Chapter IV proposed a linear model for gas consumption appropriate to the situation where the only measured independent variable is gas consumption. In the language of this chapter, these are G1 models. The two parameters that result, a slope and an intercept, are identifiable with, respectively, heat losses through the shell and internal heat gains, as long as several strong assumptions hold: the interior temperature and the internal heat gains need to be constant over time, and the heat losses need to be proportional to DT. These assumptions have a better chance of being reasonable, the longer the time period being averaged over, but it appears that methods of statistical averaging such as linear regression permit G1 models to be used even when the time periods are shorter. And some examples were given in Chapter IV where slopes and intercepts had their physical identifications intertwined. This happens, for example, when there is a pattern of raising the thermostat in very cold weather or a pattern where very cold days are sunny.

The inclusion of inside temperature (G2 models) allows the furnace-on temperature (intercept) of the Chapter IV models to be broken apart, and provides a direct measurement of the effective/magnitude of the non-gas energy sources. These can be further disaggregated into electric and solar sources (G4 and G5 models). The separation of the performance index (slope) of Chapter IV into its conductive and convective parts can be done most clearly when air infiltration is measured directly, as in Equation IX.2, but the use of a term of the form V*DT (G3 models) is a promising surrogate.

The entire task of getting a neat hold on the effects subordinate to outside temperature is still largely untested. Simple models of the energy balance in a residence will have to be tried in a wide variety of buildings and for a wide range of climates. Certainly, the models in Chapter IV are an improvement on degree-day models with fixed reference temperature. But it must be possible to advance the state of the art further, while sacrificing only a little of the simplicity and economy of the current models. It remains our conviction that the way to further progress is not by the back door of elaborate, costly, and highly deterministic computer models drawn from the world of office buildings with fixed usage patterns, that track the weather hour by hour through the year. Rather, it may well lie in the direction of identifying those few parameters that capture the gross features of the energy balance of a house (its "signature") and then finding simple field approaches to measure their numerical values.

C. Models of Attic Temperature.

Multiple linear regression models have been applied to several dependent variables other than gas consumption in the Princeton research program. Section D of this chapter will describe the modeling of what may be the most complex physical effect in the house, air infiltration. Here, we report briefly on models of what is probably the most straightforward physical system, the system determining the temperature in the attic.

The most natural point of departure for attic modeling is the "two-resistance" model, where the attic temperature is established at a value that is a constant fraction of the "distance" between outside temperature and inside temperature. That fraction is given by

$$h = \frac{T_a - T}{T_{in} - T} = \frac{R_r}{R_r + R_f} \qquad \text{(IX.7)}$$

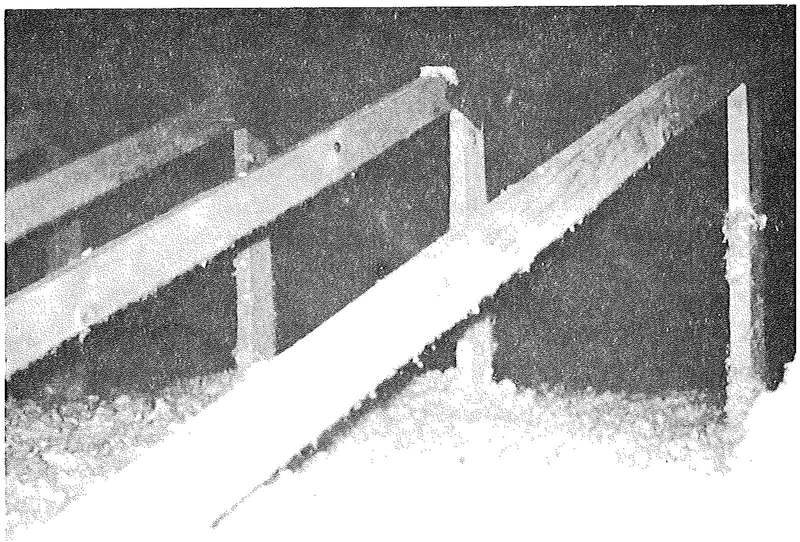
Here T_a, T_{in}, and T are the attic temperature, the inside temperature (typically, an upstairs temperature) and the outside temperature; R_r and R_f are the thermal resistances of the attic's roof and floor, divided by their surface, respectively. When the attic insulation is in the roof, R_r is much larger than R_f, and the attic temperature should be close to the temperature in the house. When, as at Twin Rivers, the attic insulation is in the floor, the attic temperature should be close to the temperature of the outside air.

Chapter VII has hinted at the Twin Rivers attic anomaly: the temperature of the attic (before any retrofit) is midway. The ratio, h, in Equation IX.7 runs from 0.4 to 0.7, in spite of R-11 insulation in the attic floor and an uninsulated (R-2) roof. This unexpectedly high value can be traced in part to a series of short circuits of the insulation in the attic floor, connecting attic and basement, related to an open shaft around the flue and to open passages along the party walls. Following retrofit (to a floor insulation of R-30), the ratio drops to about 0.3, still higher than expected, but this time the role of sideways heating from the warmer attics of neighbors needs to be taken into account, and may account for the observed ratio.

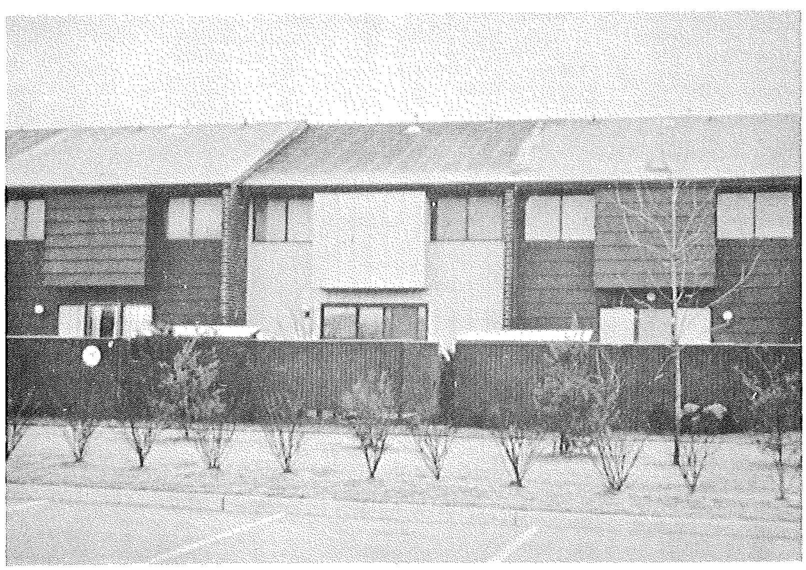
All reference above is to nighttime values of the ratio, <u>h</u>. The sun raises the attic temperature considerably and its effect on <u>h</u> is not taken into account in the two resistance model. Nor are the effects of wind, which lowers the ratio in Equation IX.17, both by scooping the air out of the attic and by alterning the outside boundary layer at the roof. The latter effect is particularly important in determining the amount of daytime heating of the attic by the sun, and a wind-sun interaction term has been found to be helpful in daytime attic models.

The effects of the sun on an attic are of fairly limited interest, however, especially once the attic floor is insulated. If one wants to heat a house by solar energy through the roof, one will have to turn to skylights. The nighttime models get directly at a quantity likely to be of general interest, the rate of vertical heat flow out of the house.

Nighttime attic models were developed, by Alison Pollack, beginning with data from the same ten days of February 1975 as were the workhorses in the discussion in Section B of this chapter. The temperature in these attics for the night of December 23, 1975, were then "predicted" and compared with the temperatures actually observed. Two of the attics had been retrofitted with added insulation five days earlier (refer to Photo Page 10), the attic of the third (House 1) had



BLOWN FIBERGLASS R-30 INSULATION LIES ON TOP OF EXISTING BATT INSULATION ON ATTIC FLOOR, PART OF PRINCETON RETROFIT PACKAGE A.



EARLY MORNING VIEW OF FROST PATTERN ON BACK SLOPES OF ATTICS OF THE THREE HIGHLY INSTRUMENTED TOWNHOUSES, AT A TIME WHEN THE MIDDLE ONE HAS NOT YET RECEIVED RETROFIT PACKAGE A. DARK COLOR INDICATES GREATER HEAT FLOW THROUGH ROOF AND LESS FROST FORMATION.

been left alone. The results are shown in Figure IX-3. The temperature in House 1 was predicted to within 1°F. The temperature in the other two attics was much lower than "predicted." The change in the h ratio of Equation IX.7 is a measure of the improvements brought about by the attic retrofit, and Figure IX-3 shows an equivalent graphical ratio, based on the assumption that the properties of the attic roof are unchanged.

The attic models used in Alison Pollack's work take the form

$$T_a = aT + bT_{in} - cV + D \qquad \text{(IX.8)}$$

the modeling of wind effects (V being the hourly average wind speed) being particularly crude. Eighty hours of data (over 10 nights) were used. The four derived coefficients were then regrouped to emphasize the close connection of Equations IX.7 and IX.8:

$$T_a = (1-h)T + hT_{in} - cV + k(T_{in} - T_o) \qquad \text{(IX.9)}$$

Thus, h, k, and T_o replace a, b, and c. If Equation IX.7 is close to the physical situation, the last term in Equation IX.9 will be small.

Table IX.5 gives the numerical values of the four constants for

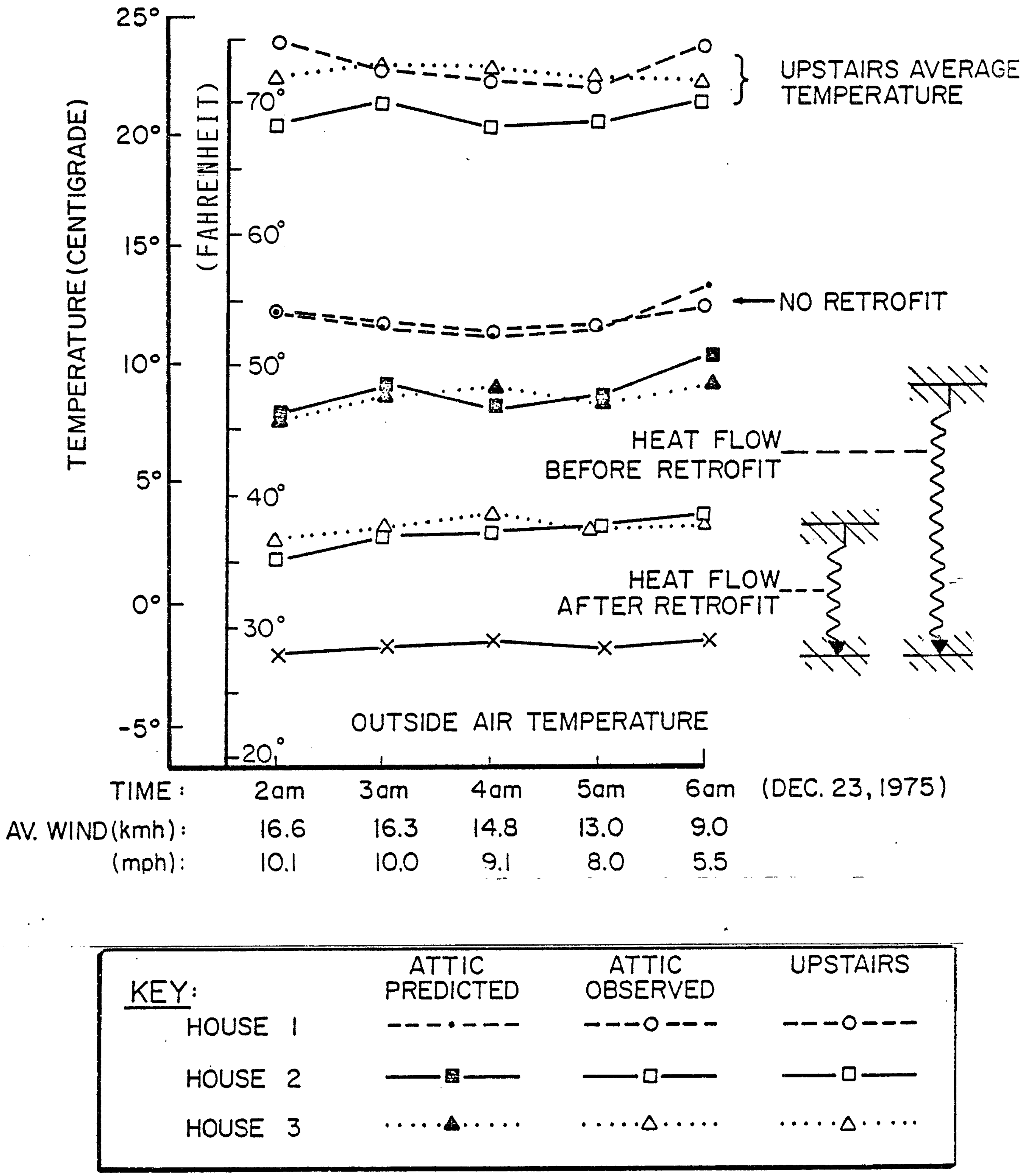
Table IX.5

Coefficients in the Nighttime Attic Model

	f	c(°F/mph)	d'	T_o(°F)	R^2
House 1	.66±.02	.37±.04	.20	73.5	.90
House 2	.58±.03	.27±.07	.50	71.4	.86
House 3*	.48±.02	.51±.05	.83	68.9	.90

*End unit. (The larger value of the wind-related coefficient, c, is probably related to that attic's greater exposure.)

Adapted from Table 5. "Attic Models, Nighttime Hours" of Pollack(76).



EFFECT OF ATTIC RETROFIT ON ATTIC TEMPERATURE

FIGURE IX-3

the three houses, before retrofit. The dimensionless constant, h, in particular, is seen to be remarkably high for houses that had indeed complied with the minimum property standards of the time by putting 3 1/2 inches of fiberglass batt insulation (R-11) on the attic floor. Calculations using standard ASHRAE procedures predict U-values for attic floor and attic ceiling of 0.080 and 0.581 btu/hr ft^2°F, respectively. After correcting for the relative areas, the attic temperature is still expected to be seven times closer to outdoor than to indoor temperature (h = 1/8 = 0.125). The differences in the values of h among the three houses, although statistically significant, are far less striking than the differences in all three houses between nominal and actual effectiveness of the attic insulation. Poor design and construction have reduced the effectiveness of the attic insulation by a factor of 5 to 10! Photo page 10 shows, on top, the blown R-30 fiberglas insulation in an attic, after receiving retrofit package A. The bottom picture was taken early on a January morning. The houses with frost on the roof (HIT 2 and HIT 3) had already received the attic retrofit, the house in the middle (HIT 1) had not, melting the frost away from the roof of its warm attic.

There appears to be justification in recommending a fairly simple exercise to nearly all the residents of houses with insulated attics. On a cold night with low wind, take a thermometer into your attic and take its temperature. Also read the temperatures outdoors and in and compute the ratio in Equation IX.7. If it is 0.4 or above, and there is insulation in your attic floor, you have some variant on the Twin Rivers attic disease -- one or more short circuits perforating the thermal cap on your house.

D. Air infiltration.

Direct measurements of air infiltration rates have been made in several townhouses, using a versatile device developed jointly by the National Bureau of Standards and Princeton. Up to a week of data are obtained in a single run, with output recorded every fifteen minutes or even more often. About 10 cc 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 exchanges per hour.

Exchanges of what 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, within well-defined boundaries. In that case, the answer to the question is well defined. 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

$$AI = F/\hat{V} \qquad (IX.10)$$

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

$$\begin{pmatrix}\text{Heat loss from air}\\ \text{infiltration}\end{pmatrix} = \rho C_\rho F*DT = \rho C_\rho \hat{V}*AI*DT \qquad (IX.11)$$

where ρ and C_ρ are the density and specific heat of air at room temperature. The product ρC_ρ is approximately 0.018 btu/ft^3°F. Taking V to be 11,000 cubic feet (the upstairs volume at Twin Rivers) gives

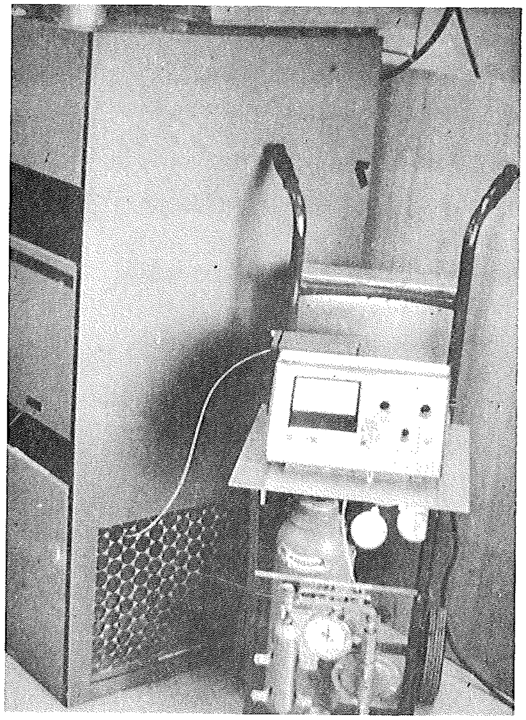
$$\rho C_\rho \hat{V} \simeq 200 \text{ vtu/°F}. \qquad (IX.12)$$

Equation IX.11 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 humidification from natural sources and from a humidifier was found to be about 10 percent of the annual gas consumption in tests at Twin Rivers; there would not necessarily be an immediate savings of energy if the house were made tighter, because the humidifier is typically undersized for the nominal job of raising the relative humidity indoors to 40 percent. The humidifier was found by direct measurement to provide about half of the water vapor added to the interior, the other half coming from showering, watering of plants, and breathing. A theoretical calculation suggested that at least three fourths of the net water vapor flow to the outside is carried along with the exfiltrating air, the remainder finding its way out of the house by diffusion; the calculation depends critically on estimates of the effectiveness of the vapor barriers installed in most of the shell of the house. Attempts to obtain a daily water vapor balance for the interior of the house revealed the large role of the structure of the house as a storage system for water vapor, and influxes and effluxes from that storage system could be associated with rainy and sunny weather. The conclusion holds strongly that the more the emphasis on humidification in a residence at the smallest possible energy costs, the greater the attendant significance of tightness of the structure.

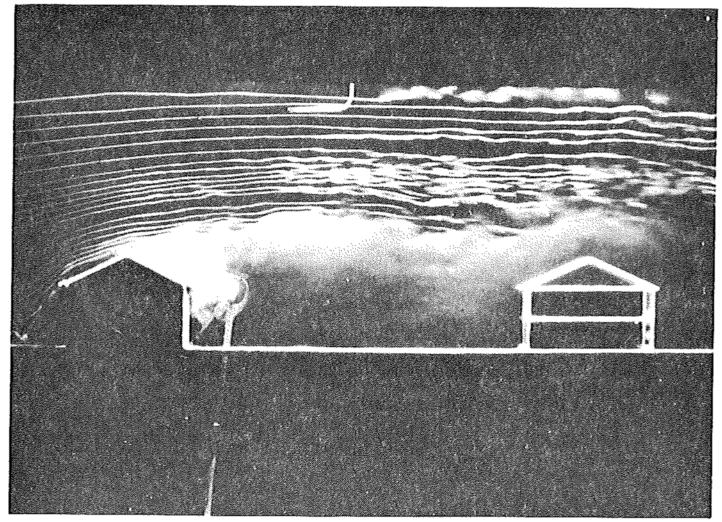
Direct measurements of concentration have revealed that the approximation of a single well-stirred volume is a reasonable one in many situations, the basement being the most frequent complication. With the basement door closed, interior doors open, and windows and doors closed, the first and second floor usually act like a single "zone," and the basement acts like a second zone. On a cold day, as both zones exchange air with the outside, heat is lost through both zones. With the basement door open, the two zones exchange air with one another as well as with outside; it is not obvious which way the air flows through the open door. In general, the measurements to be discussed in this Section are more nearly measurements of the exchange rate in the upper zone. A refined method of measurement and analysis starting from a two-zone model of the house has just begun to be pursued.

Photo page 9 gives four views of our wide-ranging investigation of air infiltration. The photo at the top left shows the air infiltration device alongside the Twin Rivers furnace. The small

FOUR ASPECTS OF PRINCETON'S AIR INFILTRATION RESEARCH.

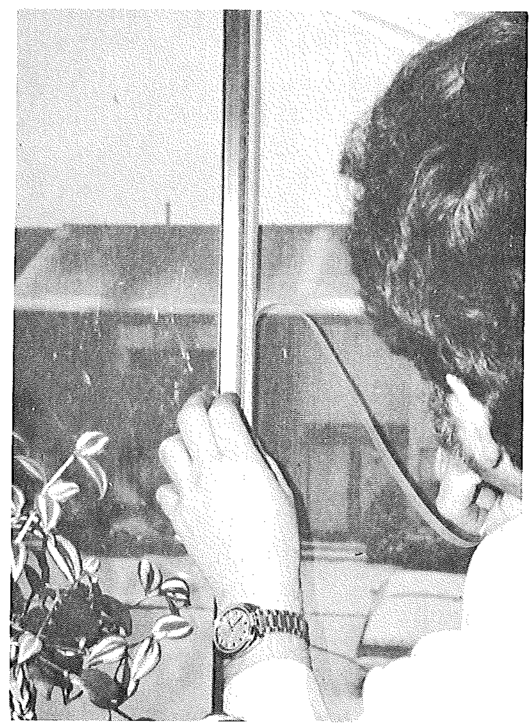


AIR INFILTRATION MEASUREMENT DEVICE, ALONGSIDE GAS FURNACE.



WIND TUNNEL SMOKE TEST WITH SCALE MODELS REVEALS SHELTERING OF ONE HOUSE BY ANOTHER.

WINDBREAK OF TREES INSTALLED BEHIND HIGHLY INSTRUMENTED TOWNHOUSES, IN COLLABORATION WITH U.S. FOREST SERVICE.



KENNETH GADSBY INSTALLS WEATHERSTRIPPING IN SLIDING PANEL OF PATIO DOOR, PART OF PRINCETON RETROFIT PACKAGE B.

gas cylinder contains SF_6 and the large cylinder contains argon. (The flow of argon establishes a reference condition of zero electron absorption; SF_6 is detected by its absorption of electrons emitted at a constant rate by a tritium foil.) The device is shown in an early version, when output was put on a chart recorder; a later version puts the output in digital form onto a tape casette. At top right, a smoke test of a scale model of the townhouses reveals the way houses can shelter one another. George Mattingly conducted those tests, and went on to install a windbreak of Virginia white pine, seen in the lower left, on the windward (back) side of the three highly instrumented townhouses, in a satellite program conducted with the U.S. Forest Service. In the lower right, Kenneth Gadsby performs a portion of retrofit B to tighten the fit of the windows (see Appendix F for details). Evaluation of air infiltration data before and after the tree experiment and before and after retrofit is still continuing.

Statistical analysis of the air infiltration data has proceeded in an exploratory spirit similar to that which has motivated the analyses of gas consumption and attic temperature, the subject of the previous two sections of this chapter. Three basic causes of air infiltration have been partially separated from one another: wind, buoyancy, and furnace combustion. Wind tends to lead to horizontal movements of air through the house, but it also leads to a flow up the flue as it passes over the roof. Buoyant effects are largely vertical: the hotter, less dense indoor air tries to pop out through the roof. Furnace combustion air has to be replaced from somewhere, but the rate of air infiltration associated with combustion is inevitably several times the rate at which air is actually required for combustion: exhaust gases entrain additional indoor air as they pass up the flue.

A recurrent feature of our data analysis has been a difficulty in obtaining good linear models when buoyancy effects and wind effects are both present. In general, air exchange increases smoothly with increasing values of DT (the temperature difference between indoors and outdoors) if the wind speed (V) is small, and it also increases smoothly with V if DT is small. But when both are large, the scatter in the data increases and the modeling becomes less accurate and less reproducible. Frank Sinden has been investigating the wind-temperature interaction on theoretical grounds, and he is able to prove from quite general assumptions that the interaction is "sub-additive," effectively, like destructive interference: the combined effect of buoyant forces and wind driven forces should be <u>less</u> than the sum of the effects of each acting alone. In general, that prediction is confirmed by our data.

The effects of buoyancy and of wind are comparable. The pressure difference associated with incident wind is roughly $1/2\,\rho V^2$ and the pressure difference associated with buoyant forces is (DT/T) gh, where T is the outside temperature on the absolute temperature scale, ρ is the density of air, g the acceleration of gravity, and h the vertical distance over which the buoyant force operates. The two effects are then of approximately the same magnitude when

$$(DT/T)gh = 1/2V^2 \qquad \text{(IX.13)}$$

Taking DT = 50°F makes DT/T = 0.1. Also taking h = 15 feet (with g =

32 ft/sec^2), Equation IX.13 balances when V = 10 mph.

A detailed discussion of the results of regression analyses of air infiltration data may be found in the M.S.E. thesis of Nicholas Malik. Here only a few typical sets of coefficients will be cited. At low wind speeds (V less than 6 mph), a typical model of the air infiltration rate (AI) with one independent variable, of the form AI = a + b*DT, takes the approximate numerical form:

$$AI = 0.2 + .008*DT \qquad (IX.14)$$

where DT is measured in °F and AI in exchanges per hour. (In three separate data sets, b was found to be .008, .010, and .007.) Thus, a 50°F temperature difference leads to an extra 0.4 exchanges per hour, even in the absence of any wind. The b coefficient contains both buoyancy effects and combustion effects (the latter because the combustion rate is roughly proportional to DT).

The DT coefficient of the air infiltration rate, b is a reasonable candidate for inclusion in the set of coefficients making up the house "signature" discussed in Section B. It should, in principle, reappear as the coefficient of a term proportional to the square of DT in regression analyses of the gas combustion rate. However, in practice, the strong collinearity of DT and (DT)^2 in winter data appears to preclude the isolation of a b coefficient in any regression model of the gas consumption rate.

The addition of further independent variables to a regression analysis of air infiltration at low wind speeds is unexpectedly productive of further insights. Malik finds the following regression equation, encompassing five independent variables:

$$AI = .19 + \underset{(1)}{.005}*DT + \underset{(3)}{.012}*V*\cos(\theta - \theta_o) + \underset{(1)}{.003}*G + \underset{(3)}{.002}*B + \underset{(2)}{.009}*F \qquad (IX.15)$$

Here θ is the angle of incidence of the wind, θ_o is normal to the back of the house (280° north at Twin Rivers); G is the gas consumption rate, in cubic feet per hour; and B and F are the fractions of the time during which the basement door and the front door, respectively, are open, in minutes per hour. Standard errors of the estimates of the regression coefficients are written below the coefficients. The inclusion of the additional terms has raised the R^2 of the regression from 0.23 to 0.49, and reduced the standard error from .086 to .071 exchanges per hour. The data set has 242 air exchange rates, in all of which the wind is below 6 mph and comes from the back half of the house. From direct measurements, we know that windows were closed throughout.

The coefficient of DT is reduced in Equation IX.15, relative to the earlier regression equation, IX.14. The reason is that the furnace effect has been separated out. At Twin Rivers about 0.8 cu ft/hr of additional gas consumption are associated with every degree Fahrenheit of additional temperature difference (a performance index of 0.8 x 24 = 19 cubic feet per degree day). Then the coefficient of G in Equation IX.15, .003 exchanges per cubic foot, can be approximately restated as .0024 exchanges per hour per °F, and thereby compared with the coefficient of DT, .005 exchanges per hour per °F.

Thus, one-third of the DT effect observed in Equation IX.14 turns out to be combustion-related.

The value of the G coefficient can be compared with what would occur if the effect were caused exclusively by the air required for combustion. In stoichiometric combustion, 10 volumes of air combine with one volume of methane (natural gas). The volume of the Twin Rivers house is roughly 10,000 cubic feet. Therefore stoichiometric combustion requires 0.001 exchanges per cubic foot. The G coefficient is three times larger.

Everyone has always assumed that air infiltration increases when the front door is open. Not surprisingly, keeping the door open a full hour leads to about a half of one exchange of outside air ($0.009 \times 60 = 0.54$). What was unexpected, at least to us, was that an effect proportional to the length of time the <u>basement</u> door was open would give a statistically significant signal. Having the basement door open 4 minutes is equivalent to having the front door open one minute (at least as far as air exchange in the upstairs zone is concerned), yet the basement door opens into the downstairs hallway! We will have more to say about interior doors below.

The directional effects in the wind velocity term are not large, since V is restricted to values below 6 mph, but it is interesting that already at low wind speeds a statistically significant enhancement can be observed for winds blowing normal to the outside walls of the townhouse, relative to winds blowing down the townhouse row parallel to the outside walls. The inclusion of a term proportional to V instead of $V*\cos(\theta - \theta_o)$ in the multiple regression analysis explains less of the observed variation.

At high wind speeds ($\underline{V}$ greater than 6 mph) a typical model with one independent variable, of the form AI = r + s*$\underline{V}$, takes the approximate numerical form:

$$AI = 0.2 + 0.06*V \qquad (IX.16)$$

where V is measured in miles per hour and AI in exchanges per hour. The value of the constant term is not sensitive to the temperature difference, a sign that models linear in wind and temperature are in for trouble (trouble with physical origins).

We can associate the $\underline{V}$ coefficient in Equation IX.16 with the coefficient of V*DT in the regression analyses of gas consumption, using Equations IX.11 and IX.12 to relate the air infiltration rate to the heat loss rate, and incorporating a furnace system efficiency, e_g, to go from heat loss to gas consumed. Thus, if, from modeling of the furnace we isolate the term

$$G = \ldots + B*(V/V_o)*DT + \ldots ,$$

and from modeling of air infiltration we isolate the term

$$G = \ldots + (1/e_g)*(\rho*C_\rho*V_e)*(\ldots + s*V + \ldots)$$

we can make the identification

$$B/V_o = \rho*C_\rho*\hat{V}*s/e_g \qquad (IX.17)$$

Taking $\rho C_\rho V$ = 200 btu/hr°F from Equation IX.12, s = 0.06 exchanges per hour per mph from Equation IX.16, and e_g = 0.6 (dimensionless), B = 18 cf/°F-day = 800 btu per °F-hour as typical values from Section B of this chapter, we obtain V_o = 40 mph, which is within the range of values cited in Table IX.2 above. Thus the modeling of air infiltration and gas consumption can proceed in close association: the given term gives a signal in one, DT times that term, in principle, should give a signal in the other, and the coefficients should be relatable by a relation like Equation IX.17.

As with the low-wind-speed temperature models, it again becomes possible to incorporate several further physical effects in a multiple linear regression and still pass relatively strong tests of statistical significance. Malik found the following regression equation for high wind data and a narrow range of outside temperatures (DT ≃ 40°F):

$$\begin{aligned} AI = -.14 + \underset{(7)}{.011{*}DT} + \underset{(5)}{.044{*}V{*}\cos(\theta - \theta_1)} \\ + \underset{(2)}{.010{*}G} + \underset{(2)}{.004{*}B} - \underset{(7)}{.007{*}V} \end{aligned} \qquad (IX.18)$$

All notation is as in Equation IX.15.

A negative constant appears in virtually all our linear models built from the structure AI = c_1 + c_2*DT + c_3*V, and expresses the subadditivity of the wind-temperature interaction discussed above. The wind coefficient is much stronger in Equation IX.18 than in Equation IX.15, because we are in a domain where wind effects dominate. The reference angle, θ_1, is 20 degrees higher than the earlier angle θ_o; for some reason, the data is skewed, with substantial enhancements of air infiltration rates when the wind is hitting the house somewhat north of straight on. If such a directional effect is not an artifact of our data, it could be the result of overhangs, fences, and other obstacles asymmetrically located with respect to the back wall of the house; conceivably such an effect could be illuminated by scale model tests in a wind tunnel.

The wind-temperature interaction is actually substantially more complicated than Equation IX.18 suggests. In general, directional effects are enhanced when both V and DT are large, and the data are substantially simplified when the wind moves close to the axis of the houses. Malik finds that more than 90 percent of the variation in an entire data set can be explained by the remarkable equation:

$$AI = .31 + \underset{(4)}{.042}*(DT/40)*V*\cos(\theta - \theta_1) + \underset{(1)}{.007}*G \qquad (IX.19)$$

where the wind speed, the wind direction, and the inside-outside temperature difference are all rolled together in one product term.

As for the remaining coefficients in Equation IX.18, the basement door effect is consistent with its magnitude in Equation IX.15, and the absence of a front door effect in the high wind data only reflects an absence of data points rather than an absence of an effect. However, the large enhancement of the G coefficient in the high wind data is physically reasonable: at high wind speeds, greater volumes of air accompany the combustion products up the flue. Recalling the estimate above, a coefficient of 0.010 exchanges per cubic foot is about 10 times stoichiometric! The argument for sealed combustion furnaces, where there would be no entrained air, may well be a compelling one.

Field studies have shown that the position of not only the basement door but of virtually every interior door plays some role in determining the air infiltration rate. When the wind tries to blow air laterally through a house, it finds cracks in the shell, whose resistance determines the rate of flow, but when the interior doors are closed, these contribute to the total resistance and reduce the flow. Similarly, when the air exchange is driven by vertical buoyancy forces, closed interior doors can inhibit the flow between floors. The positioning of interior doors, perhaps even more than the positioning of drapes, is an example of inadvertent behavior inside the house that has consequences for gas consumption and that may contribute to variations of the rate of consumption in "identical" dwellings. Yet we are not ready to recommend that every household keep its interior doors closed whenever possible as an energy conservation measure. Particularly when there is a forced air heating system and just one intake for return air per floor (as in Twin Rivers townhouses) the possibility that temperature imbalances could be created if the circulation of air through the duct system is impeded, and that these imbalances would have compensating penalties in overall energy use, was discussed in Chapter VII. An energy conserving house might well have many zones, thermally insulated from one another, capable of being ventilated separately, and (if the distribution system uses forced air) each with its own return duct -- the whole presenting a substantially larger resistance to the entry of outside air than the shell itself would provide.

No energy-conserving house can be formulated in very much detail before the designer comes up against the question: when does a house become too tight? The reasons for desiring ventilation are numerous. They are rooted in concerns about fresh versus stale air and dry versus humid air, apparently culture-dependent in part; in concerns about the buildup of the concentration of pathogens (like common cold viruses) and odiferous molecules (like those emitted by frying onions); and in concerns about the safety of the furnace combustion system. In some instances, as with germs and odors, the optimal response is probably intermittent, short ventilation.. Sealed combusion furnaces, using outside air for combustion, may obviate the concern for proper performance of the furnace. For questions of staleness and humidity, however, there certainly can be no technical fix at least until some careful quantification of what poeple mean by "stale" and "stuffy" has occurred. As houses become better insulated, air infiltration, now typically responsible for one-third of the heat loss, will dominate the heat load. As tightening of houses leads to air exchange rates averaging below about 0.5 exchanges per hour, issues of comfort and safety will loom large and will have to be addressed. The pursuit of energy conservation in houses could founder rather quickly if the pitfalls of overtight houses are not perceived in advance and solutions of design and technology are not made ready.

X. APPLIANCE USE -- PROFILES ACROSS HOURS

A. Introduction

During which hours of the day do appliances draw electric current, and how much? Among those interested in the answers to this question are virtually all those concerned with meeting or diverting peak demand, including the professionals in the utility industries, first of all, but also the designers of solar energy and fuel cell systems for the home, and, rather soon, the residents who will confront peak power pricing and will want to try to do something in response.

Dr. Lawrence Mayer of our group conceived the idea of generating "hour decks" from a stretch of hourly data running over several days, by averaging over days for each hour of the day. For each data channel and each house, a 24-point sample results, which represents an average day's profile. In this section, we present such profiles, for the hot water heater, the air conditioner, the refrigerator, the range, and the total electric load.

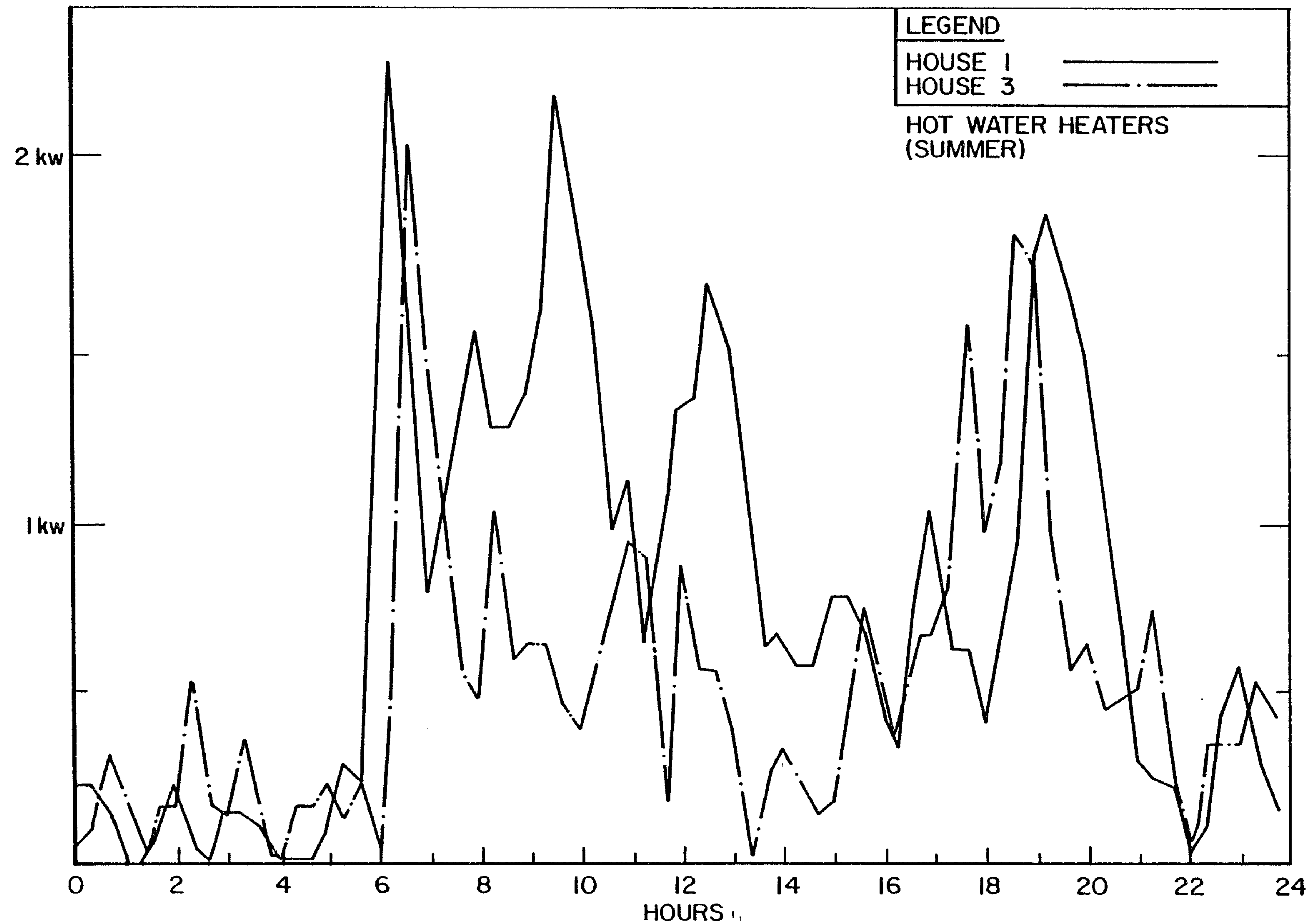
Actually, the figures below have 72 points, because data were transmitted at 20-minute intervals instead of hourly. The profiles have a bit more detail as a result.

Each figure was generated from one of two sets of data: 1) a 22-day summer set (with a gap), running from Saturday, August 24th through Thursday, September 19, 1974, and 2) a 97 day winter set (with a gap) running from January 20 to April 30, 1975.

B. Hot Water Heater

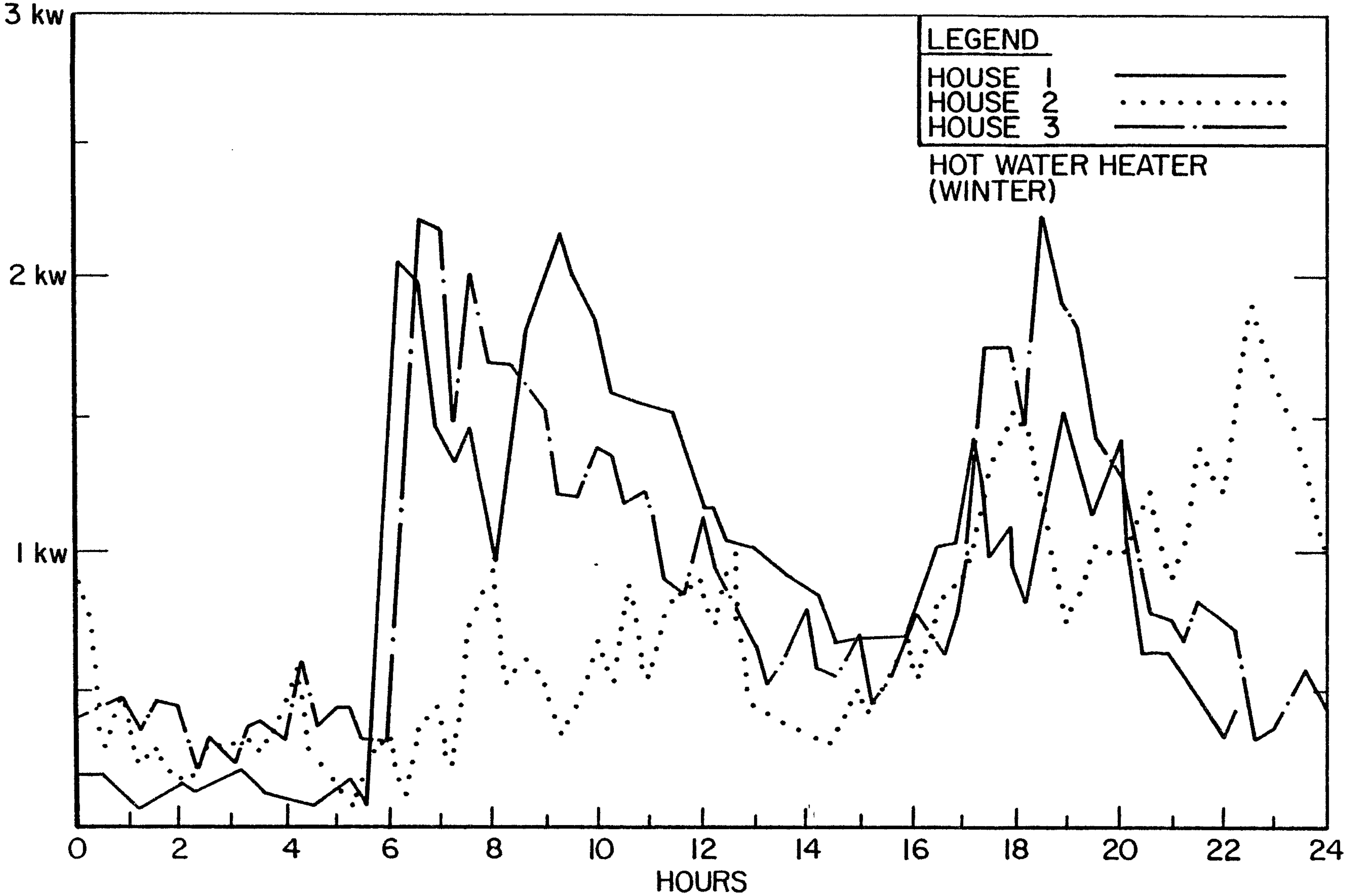
The patterns are remarkably consistent from one set to the other, as seen in Figures X-1 and X-2, which show the two patterns for the hot water heater. Both patterns show a double peak in the morning in House 1, each peak at an average rate of 2 kilowatts, one at 6 a.m. and one at 9 a.m. House 3 shows its own double-peaked structure, a morning peak just after the one in House 1 (the alarm must go off about 20 minutes later) and an evening peak at 6 p.m. Unfortunately, there were no summer data from the hot water heater in House 2; at least in winter, it uses much less energy than the other two. The average winter consumption rates are 870 watts, 690 watts, and 900 watts, respectively. Peaks to troughs in Figure X-1 and X-2 represent more than 10 to 1 ratios. The consumption during the night, when power is cheapest to generate, is virtually nil. Yet all three water heaters have 80 gallon tanks (678 pounds of water, with abundant storage capacity of over 55000 Btu, heated to 145°F from the 60°F (16°C) water temperature in slightly more than 3 hours by one of the two 4.5 kw heating elements.

This past winter, a large amount of further data on the hot water heater has been collected, in 19 additional homes, both before and after the retrofit to reduce standby losses depicted in Photo Page 3. Preliminary examination of the data partially listed in Table X.1 indicates a) that the average power use is about 900 watts, b) that about 300 watts represents standby losses, and c) that the standby lossess are approximately halved by the retrofit. A report



LOAD PROFILE – HOT WATER HEATER (SUMMER)

FIGURE X-1



LOAD PROFILE - HOT WATER HEATER (WINTER)

FIGURE X-2

giving detailed results will be prepared.

Table X.1

Hot Water Heater Electricity Consumption

6 Omnibus Houses

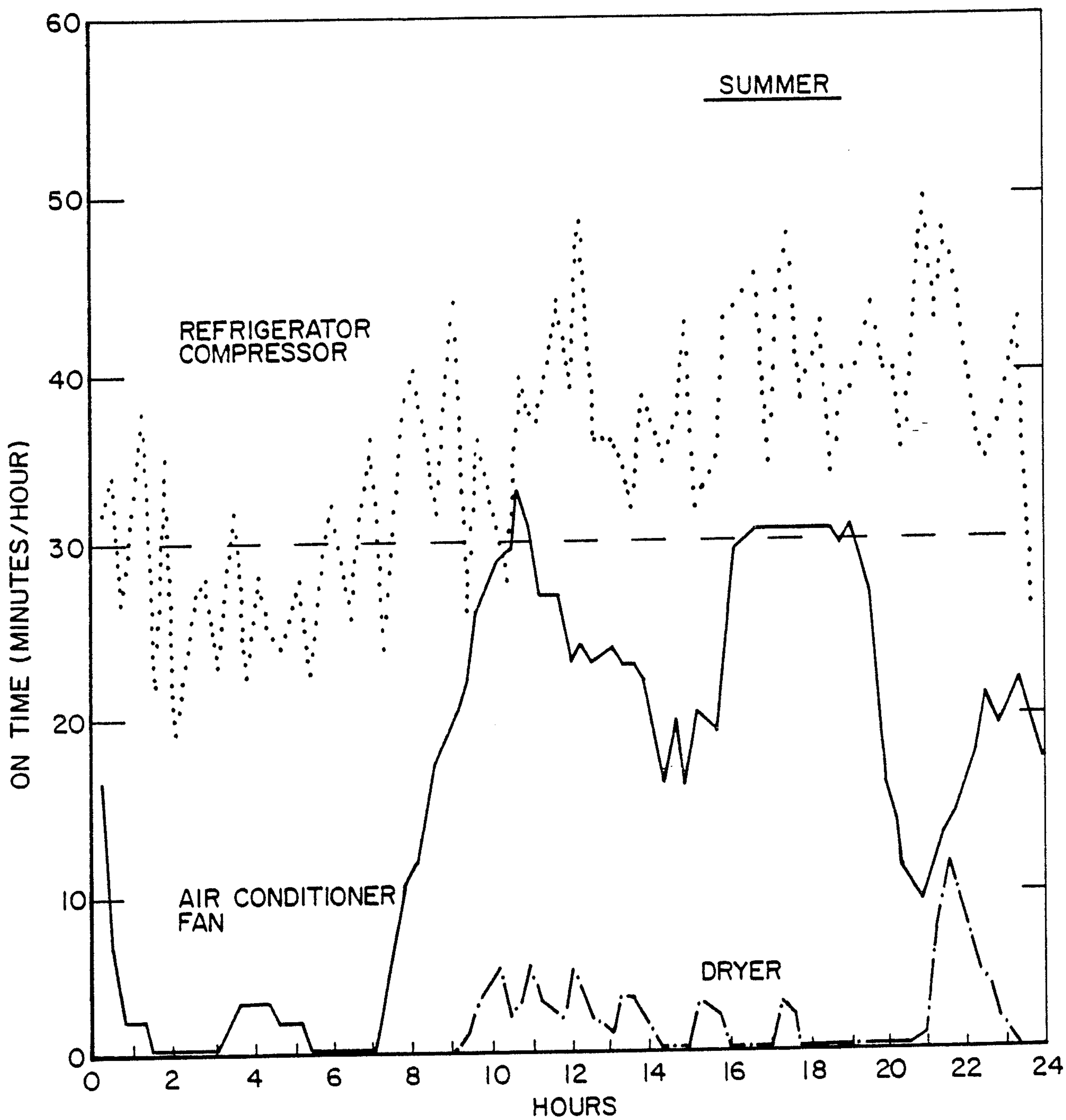
November 20 - December 18, 1975

Number of House	Minutes/Hour	Kilowatt
1	14.4	1.18
4	12.7	0.95
7	16.6	1.24
11	8.7	0.65
16	11.7	0.88
19	13.3	1.00
Average	12.9	0/97 bw

At 900 watts average power, a hot water heater will use 650 kilowatt-hours in a month, or 8000 kilowatt hours in a year. At current marginal rates, which are in excess of 4 cents per kilowatt hour most of the year, it costs about 300 dollars a year to run the hot water heater, as much as the total year's bill for space heating.

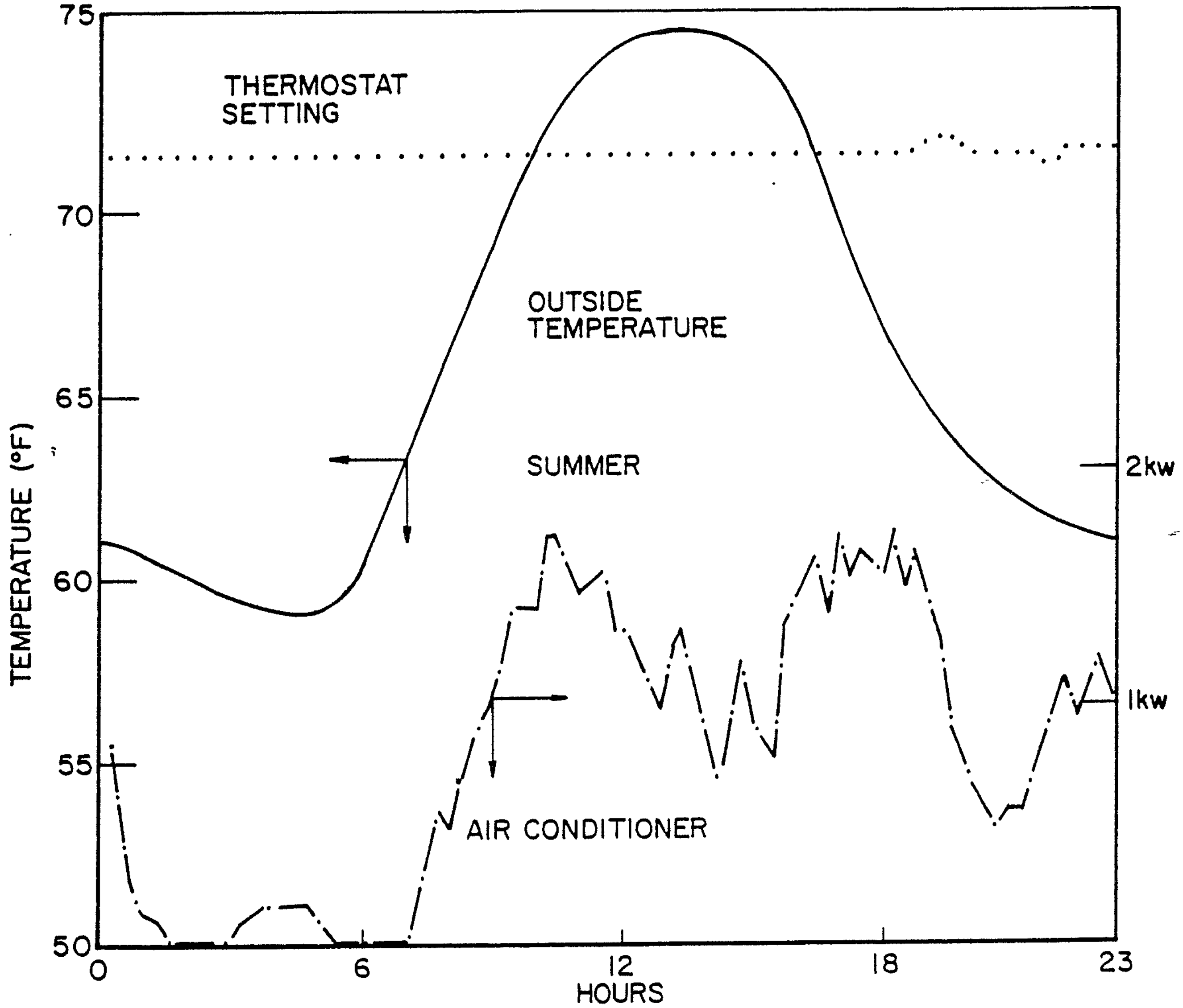
C. The Air Conditioner, the Refrigerator and the Dryer

Figures X-3 through X-5 give profiles over the day for the other



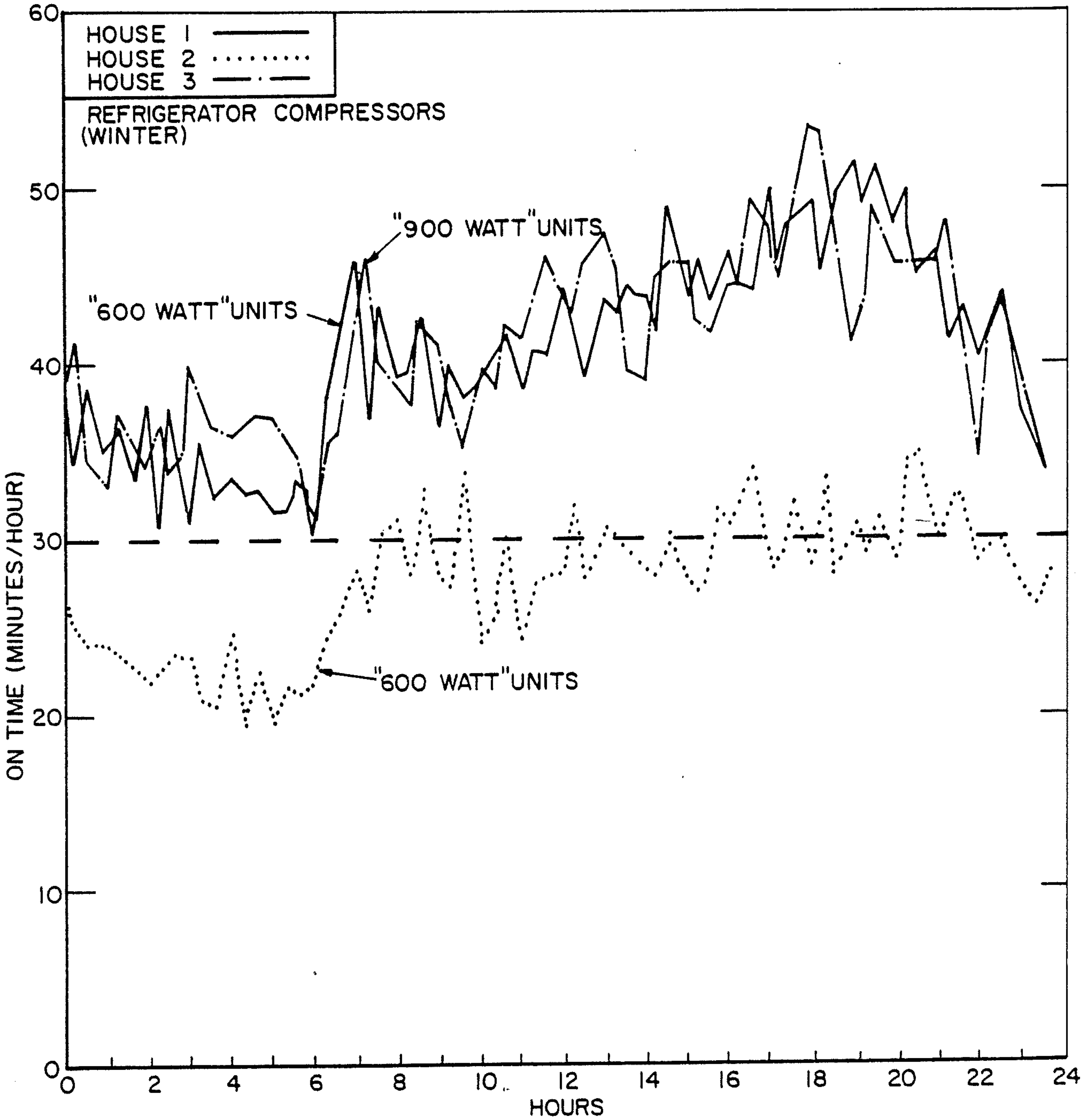
LOAD PROFILE - AIR CONDITIONER FAN, REFRIGERATOR, DRYER (HOUSE 2)

FIGURE X-3



LOAD PROFILE — AIR CONDITIONER (HOUSE 2) AND HOURLY AVERAGE TEMPERATURE

FIGURE X-4



LOAD PROFILE - REFRIGERATOR (WINTER)

FIGURE X-5

two big electric users: the central air conditioner and the refrigerator; each uses about 2500 kilowatt-hours a year. The dryer pattern is also shown. The three show totally different patterns over time. The air conditioner uses about 800 kilowatt hours per month in July and August and 400 kilowatt hours per month in June and September, nearly all in the daylight hours. The refrigerator uses about 200 kilowatt hours per month right through the year, and the load is nearly steady over the day. The dryer is used for about one-half hour, once a day; the height of the curve in Figure X-3 is deceptive, for the power output, 5.6 kw on the "hot"-setting is about 20 times that of the refrigerator.

The profile of central air conditioner use in House 2, shown in Figure X-3, manifests a W-shape during the day, which we believe to be a solar effect. These townhouses are oriented with the front door facing 10° south of east. They have equal window areas in front and in the back. And the sun passes directly over the roof at about 1 p.m.

The temperature averaged over the 22 summer days was well below 70°F (21°C), and in the evenings it was never hot as seen in Figure X-4. The evening peak in air conditioner use is avoidable by opening the windows, something many residents, not just those in House 2, do not do.

The air conditioners are two-ton (24,000 btu/hour) units, whose compressors and outdoor fans combined draw between 3.0 and 3.5 kilowatts (and hence have energy efficiency ratings of 7 to 8, or COP's of 2.0 to 2.4). The fan which circulates the air within the house draws 470 watts, hence adding about 15 percent to the total consumption for air conditioning (this power is not included in the metered power consumption shown in Figure X-4). Some people run the fan without the air conditioner; what confort they achieve comes at one-eighth the cost.

The 600 watt nominal refrigerator compressor in House 2, seen in summer in Figure X-3 and in winter in Figure X-5, operates a bit more than half of the time in summer and a bit less than half of the time in winter, as expected from the higher room temperature. The other two refrigerators in winter (and in summer, not shown) operate even more often (the fractions of time on, in winter, are 0.66, 0.47 and 0.67 in Houses 1, 2, and 3, respectively). The pattern over hours is relatively flat, remaining above 20 minutes of operation per hour even in the early morning hours, indicating that usage adds a small perturbation on the basic heat losses through the refrigerator walls. The energy consumption of the refrigerators is overestimated by multiplying nominal compressor wattage by "time on"; a "power factor" of about 0.6 is required for the calculation, related to the impedance of the alternating current circuit.* Data for an "average" Quad II user are also given in Table X.2.

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*Simultaneous data on energy consumption and refrigerator on-time are currently being taken at Twin Rivers by Richard Grot of the National Bureau of Standards

Table X.2

Components of Winter Electric Load
(watts)

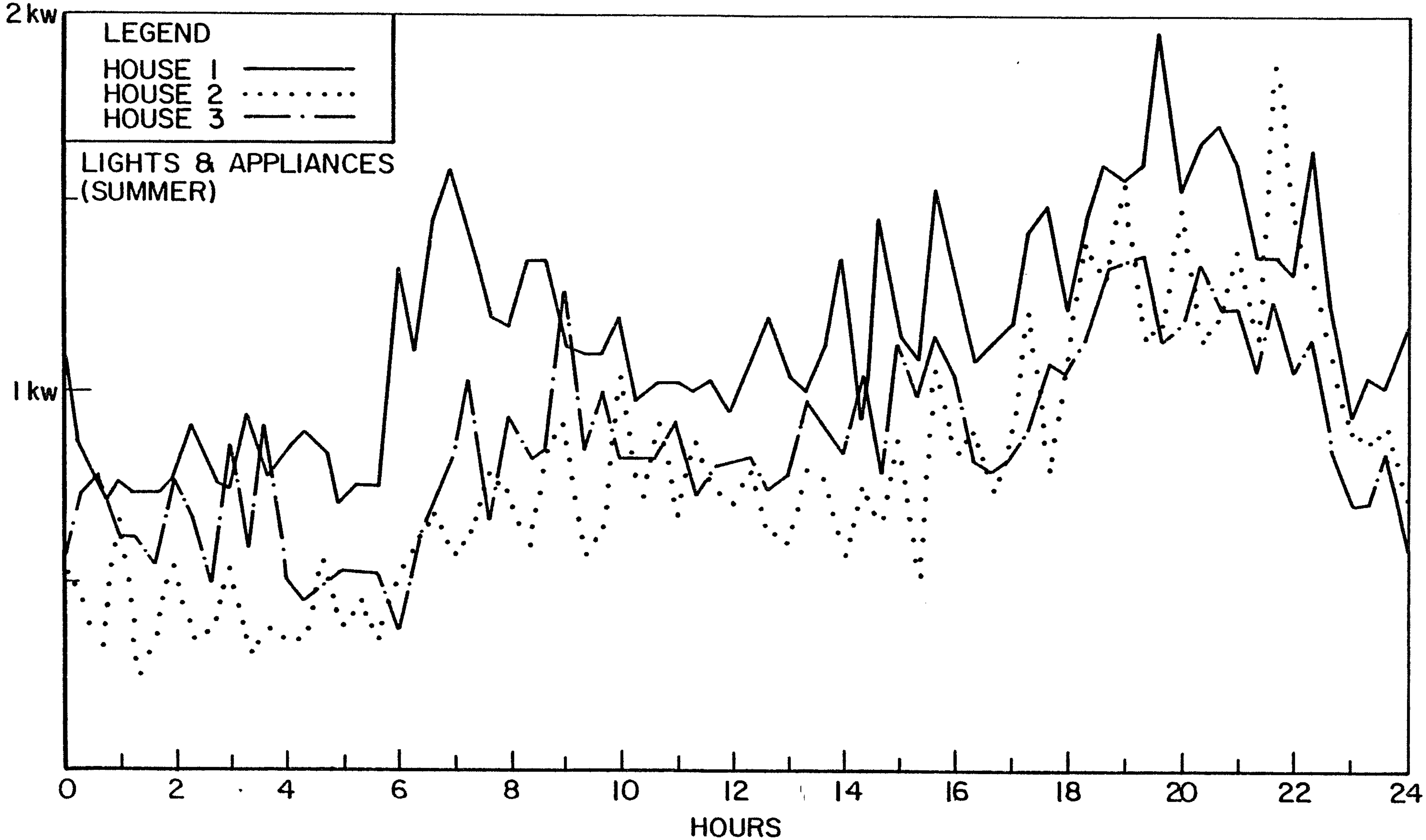
	House 1	House 2	House 3	Average three-bedroom Q-II Townhouse
Hot Water Heater (HW)	870	690	900	900
Range (R)	120	60	80	80
Dryer (D)*	150	100	40	60
Refrigerator*	240*	170*	360*	200
Furnace Fan	90	80	80	80
Princeton Equipment	300	100	100	--
All other appliances	390**	380**	320**	300
Lights and appliances, exclusive of HW, R, D	1020	730	860	580
TOTAL	2160	1580	1880	1640

* Including power factor of 0.6

** Obtained by subtraction of Refrigerator, Furnace Fan, and Princeton Equipment from "Lights and Appliances," measured accordingly.

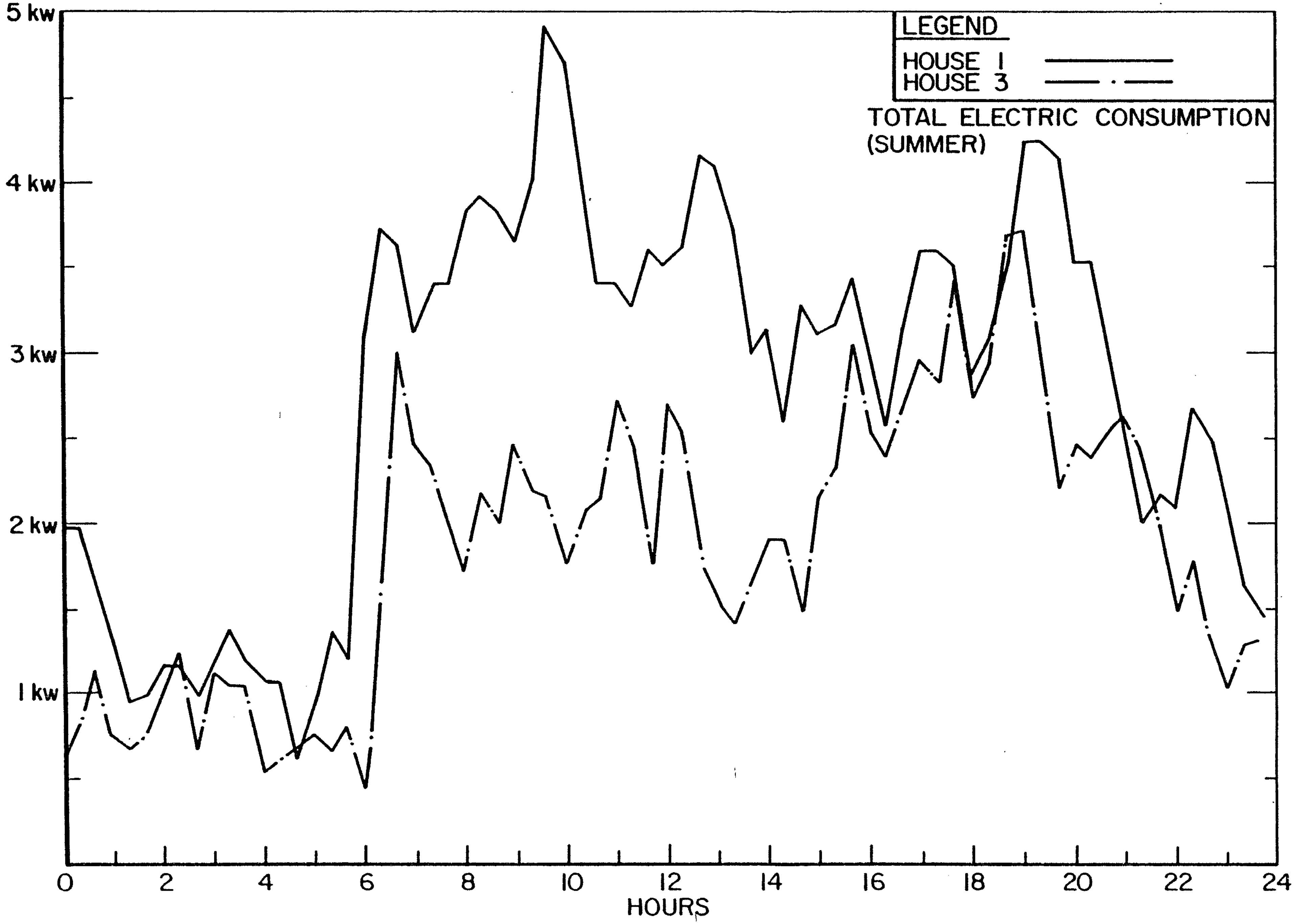
D. Other Appliances

As Table X.2 shows, the furnace fan is a small fraction of the total winter load. The fan draws 340 watts in winter (it is on a lower power setting than when the air conditioner is in use or when the fan is put in the constant-on mode), and, since the furnace runs approximately 1000 hours a year, the fan costs about 15 dollars a year to run, adding about 5 percent to the heating costs embodied in the gas bill. In our instrumentation, all the uses of the 110-volt circuits were combined in a single data channel (that is, all uses other than the air conditioner, the hot water heater, dryer, and range). The resulting load, labeled "Lights and Appliances," is relatively constant over the day and over the year, in large part because the refrigerator is included and accounts for about half of the total; also included are washer, dishwasher, TVs (at least two in each house), freezer (not always running), and all lights. The summer "hour deck" for this data channel is shown in Figure X-6, and the "grand total" summer profile in Figure X-7 (with House 2 omitted because the hot water heater had not been recorded). The adventurous reader can try to pick out peaks due to dryer, air conditioner, and hot water heater.



LOAD PROFILE-LIGHTS AND APPLIANCES (TOTAL EXCEPT HOT WATER HEATER, DRYER, RANGE)

FIGURE X-6



LOAD PROFILE–ALL USES OF ELECTRICITY
FIGURE X-7

E. Independent Appliance Data

While the final version of this report was being typed, a personal communication of the first results of an independent study on appliance usage by Richard Grot from the National Bureau of Standards reached this group. Table X.3 shows the average electric power consumed by the appliances monitored in four houses in Quad II, at the beginning of Summer 1976, two of which, House I and House II, are identical with two houses of our Omnibus set (#10 and #9, respectively). Also presented are simultaneous data for the water used by the Hot Water Heater, the Dishwasher and the Clothes Washer. The data are averaged over a 64 day stretch, for Houses I and III, and 28 days for Houses II and IV.

Houses I and II have retrofitted Hot Water Heaters (wrapped in R-7 insulation), the other two have no extra insulation. Houses I and III are low users of hot water (and of their appliances in general), Houses II and IV are on the high side, when compared with the 970 watt average in Table X.1. The average of electricity use over the four houses generally confirms our own data, where available.

It is interesting to observe how the combined water use of Dishwasher and Clothes Washer constitute a share of the total, constant across the four houses. Observing that the electricity consumed by these two appliances themselves is negligible compared to the Hot Water Heater, it follows that the electricity used by the dishwasher and the clothes washer together, including the required hot water heating, averages one quarter of the power used by the Hot Water Heater to heat water only (not including the stand-by losses). This one quarter share appears to be

Table X.3

Average Appliance Electricity and Water Use in 4 Homes
(From NBS Data)

a. Electricity usage (watts)

Appliance	House I (Omnibus 10)	House II (Omnibus 9)	House III	House IV
Hot Water Heater	501	1,012	565	1,031
Dishwasher	5	16	11	23
Clothes Washer	4	10	4	6
Dryer	55	80	93	80
Refrigerator	195	208	179	313
Range	84	120	59	83
Total (Average=1,184)	844	1,448	910	1,536

b. Water usage (gallons/day)

Appliance	House I	House II	House III	House IV
Hot Water Heater*	44.7	98.1	44.0	79.0
Dishwasher	4.6(10%)	12.5(13%)	4.6(10%)	10.8(14%)
Clothes Washer	6.7(15%)	10.5(11%)	5.1(12%)	8.5(11%)
Share of Hot Water Heater (24% average)	25%	24%	22%	25%

c. Hot Water Heater Efficiency (based on $\Delta T=85°F$)

House I	House II	House III	House IV
0.77**	0.84	0.67	0.66

*Includes water for dishwasher and clothes washer

**ΔT may be smaller (increasing efficiency). Owner tampered with thermostat.

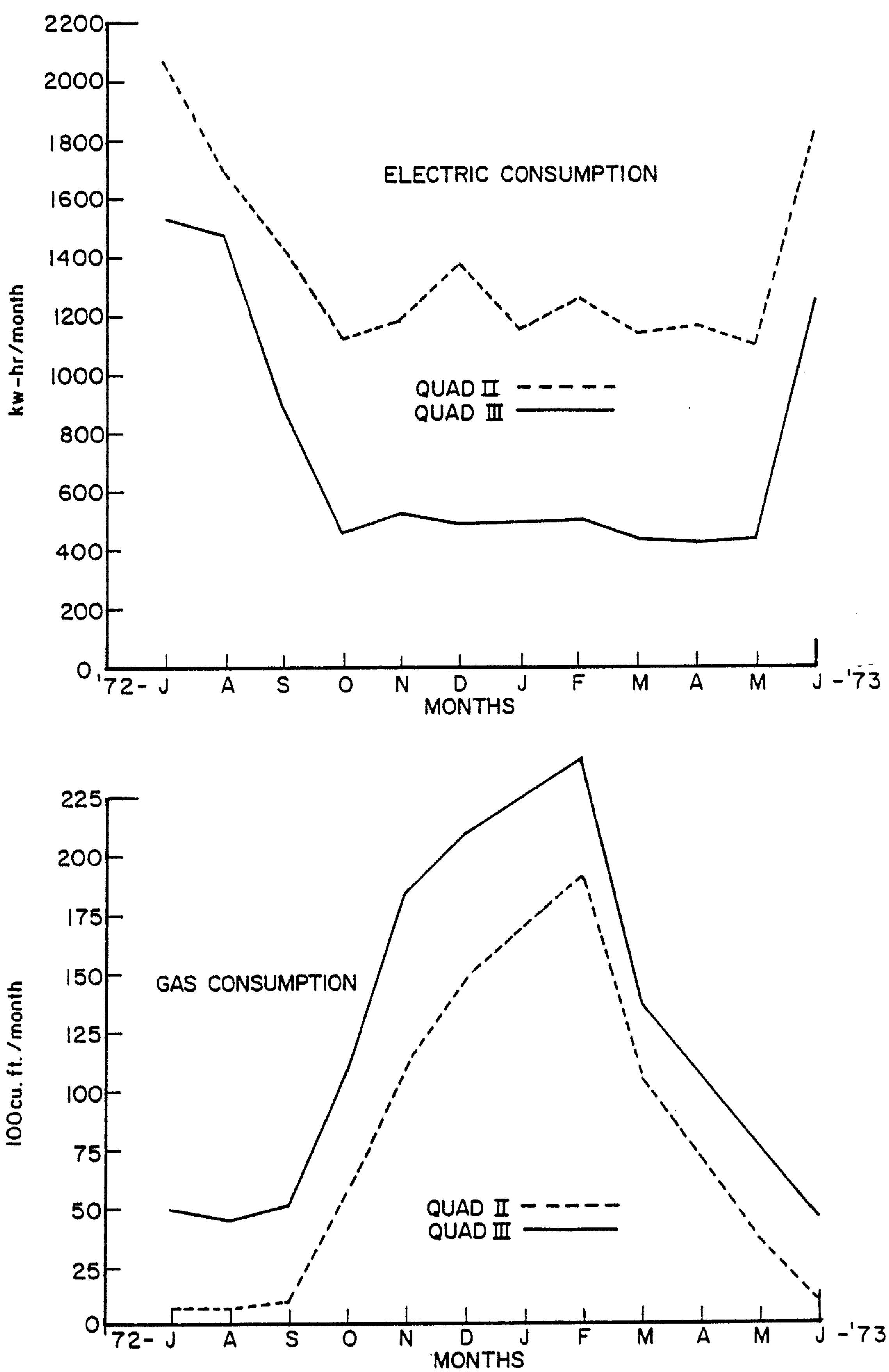
remarkably resistant against high and low usage and against hot water heater retrofit.

When dividing the energy needed to heat the influx of water from 60 to 145°F by the consumed electric power, we obtain the efficiency-in-use of water heating. While for the non-retrofitted Houses III and IV our earlier estimate of 2/3 is well replicated, the effect of the retrofit is not clear, when comparing Houses I and II, with 0.77 and 0.84 respectively. The difference could be caused by the low usage (inherently less efficient) of House I (but this effect then should be present also in Houses III and IV). Grot further indicated that the residents of House I had tampered with their Hot Water thermostat, possibly lowering its setting, which could explain the discrepancy. Unfortunately, the hot water temperature for that particular house is not yet available at this time.

We are now able to recognize another facet of the appliance usage microstructure: of the electricity consumed by the hot water heater (about half of the total electric power consumed in a house), one third is lost through the tank walls, one quarter of the remaining two thirds (or one sixth of the total) supplies the dishwasher and the clothes washer in about equal amounts, while the remaining half of the total is used for showering and odds and ends.

F. A Word on Gas and Electricity Powered Appliances

In Quad III at Twin Rivers, identical townhouses were built, but gas replaced electricity as the energy source for hot water heater, range, and dryer. Figure X-8 shows the average consumption in three



AVERAGE ENERGY CONSUMPTION IN IDENTICAL TOWNHOUSES:
QUAD II (ELECTRIC APPLIANCES) AND QUAD III (GAS APPLIANCES)

FIGURE X-8

bedroom townhouses, for gas and electricity for 138 Quad II and 146 Quad III townhouses. During the eight months from October through May, the differential electric consumption rate between the two Quads was relatively constant and averaged 710 kilowatt hours per month, or 1000 watts; we believe the electric hot water heater accounted for between 80 and 90 percent of that difference. In summer, the differential electric consumption between the two quads was sharply reduced, and the deviation increases with outside temperature. The Quad III air conditioner, apparently, used more energy than the Quad II air conditioner, predominantly to remove the heat generated by the less efficient gas appliances and their pilot lights to a smaller extent because the fans in those townhouses were resized by the builder, following initial installation, in response to complaints from some residents that their air conditioners were undersized. If we assume that the eight-month winter rate is accurate for non-airconditioning uses in the summer, then 3200 kilowatt hours and 2300 kilowatt hours, over the four months, were used by the air conditioners of Quad III and II, respectively.

The average differential rate of gas consumption over the year was 45 hcf/month. Presumably, this is a close estimate of the combined average consumption by the gas hot water heater, range, and dryer. There is a small phase difference between the two winter peaks, which results from meters being read six days apart (though the same day for all townhouses in a Quad). Comparing the average energy used by the Quad III gas appliances (45 hcf/month = 1,880 watts) to the 1000 watts used by their electrical counterparts in Quad II, and making the somewhat ad-hoc assumption that the residents in both Quads use their appliances equally often, we can deduce that the gas appliances seem to be only slightly more than half as efficient as the electric appliances.* The removal of the extra 880 watts in summer would require, with a COP of 2.2 (an average of what was recorded in the field), another 400 watts of air conditioning. Comparing this to the 310 watt differential in electric consumption over the four summer months, and recalling that the gas hot water heater is vented to the outside, we might find the discrepancy in air conditioner use satisfactorily explained.

The same effect, opposite in sign, cannot be seen in winter because although the additional heat released by the more wasteful gas appliances should decrease the load on the Quad III furnaces more than the electrical appliances do in Quad II, the savings in <u>gas</u> is bought by a waste in <u>gas</u> of equal amount** and our combined gas readings cannot discern the relative proportion going to the gas appliances and to the furnace.

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*We are using here our efficiency of <u>usage</u>, normalized on the energy at the <u>house</u>. If, as in Chapter II, we compare the efficiencies of the two appliance sets, using the consumed <u>fossil fuel</u> energy as a normalization, we would have to reverse the assessment, stating that the electrical appliances are only about 60% as efficient as the gas appliances.

**The implicit assumption is made that the gas appliances heat the house with the same <u>heating</u> efficiency (as opposed to usage efficiency) as the furnace (about 2/3), which was confirmed experimentally at least for the electrical appliances in Quad II.

At the risk of sounding too repetitive, we want to recall the attention of the reader one more time to the fact that the results from the data in Figure X-8, as well as all of the conclusions in the first five Chapters, have been derived from mere monthly meter readings obtained from the utility companies, and, occasionally, from a nearby weather station, without any interference with the lives of the residents themselves. To convey an appreciation of the power of such an analysis has been one of the main motives behind this report.

APPENDICES to

"The Twin Rivers Program on
Energy Conservation in Housing:
Four-Year Summary Report"

Robert H. Socolow

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Center for Environmental Studies

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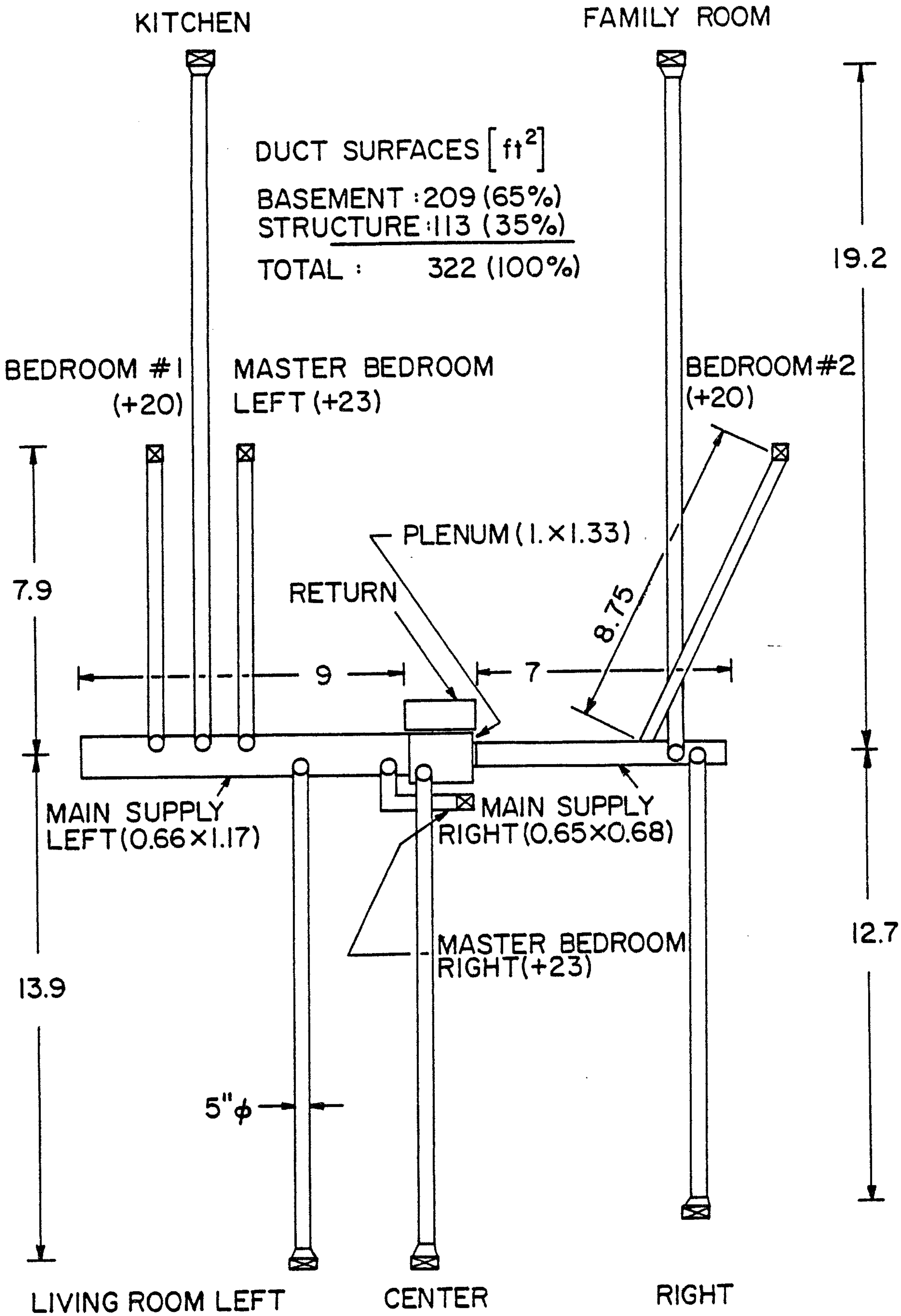
APPENDIX A: THE TWIN RIVERS TOWNHOUSE

1. Construction; special emphasis on the three-bedroom units

The Twin Rivers houses are made of standard wood-frame structure. The townhouses are arranged in rows of 5-10 two-story houses per block separated from each other by masonry fire walls; the end units have an additional exposed masonry wall and one more window in the upstairs hall.

The townhouses are divided into two stories, an attic and a basement. The layout of the basement and the two floors of a three-bedroom townhouse is displayed in Figure A-1; front and back views are shown in Figure A-2. At the time of purchase the basement had bare masonry walls and floor; an increasing number of residents have since "finished" it, by paneling the walls, by installing partitions with the intent of separating the clothes washing area and the furnace from the rest, by covering the floor with tiles and by installing a suspended ceiling that covers the duct work.

Heating and cooling are provided by an 80,000 btu/hr gas furnace integrated with a 24,000 btu/hr electrical air conditioner; both feed into a forced convection air duct system, whose layout at the basement ceiling level is displayed in Figure A-3. The blower fan has three speeds, of which only the medium and the fast one (providing 600 cubic feet per minute of flow at the furnace) are used: the medium speed operates during the automatic, intermittent fan mode when the furnace is firing, while the high speed is designed for manual, continuous operation or



LAYOUT OF HEATING DUCTS IN QUAD-II 3-BEDROOM TOWNHOUSE (DIMENSIONS IN FEET; NUMBERS NEXT TO UPSTAIRS DUCTS INDICATE DUCT LENGTH THROUGH STRUCTURE)

FIGURE A-3

in conjunction with the air conditioner use. The flow speed in each duct can be regulated by a damper in the basement section of the duct, and one at the room register at its end.

The downstairs is composed of a living room in the front part of the house, a dining area and a hall separated by a bathroom and a closet, and a kitchen-family room area in the rear part of the house. The front lawn can be seen through a 43 square foot window from the living room, while the fenced backyard is accessible through a 60 square foot glass patio door.

The upstairs is organized into a large master bedroom with a 34 square foot window above the living room and two smaller bedrooms with 23 sq. ft. windows in the rear of the house. The two bedroom areas are separated by two bathrooms, a walk-in closet and the upstairs hall. The attic is accessible through a trap door in the ceiling of the closet.

2. Thermal characteristics of the building materials.

Table A.1 shows some physical properties of the building materials used in the construction of the Twin Rivers townhouses. Listed are the density $\rho[\frac{\text{lbm}}{\text{cuft}}]$, the heat capacity per unit mass C_p $[\frac{\text{Btu}}{\text{lbm}^\circ\text{F}}]$, the conductivity k $[\frac{\text{Btu ft}}{\text{hr ft}^{2\circ}\text{F}}]$, the material thickness d in the direction of heat transfer, the resulting conductance $U = k/d$ $[\frac{\text{Btu}}{\text{hr ft}^{2\circ}\text{F}}]$ and capacitance (capacity per unit surface) $C_s = \rho C_\rho d$ $[\frac{\text{Btu}}{\text{ft}^{2\circ}\text{F}}]$. The ASHRAE 1972 "Handbook of Fundamentals" was consulted for most values; Baumeister & Marks' "Standard Handbook for Mechanical Engineers," 7th Edition, was used when the first source failed.

Table A.1

Physical Properties of Building Materials

Item	$\rho[\frac{lbm}{cu\,ft}]$	$C_p[\frac{Btu}{lbm\,°F}]$	$k[\frac{Btu}{hr\,ft\,°F}]$	d[in]	$U[\frac{Btu}{hr\,ft^2\,°F}]$	$C_s[\frac{Btu}{ft^2\,°F}]$
Plywood	34.	0.29	.0665	½	1.60	0.41
Wood Siding, lapped	32.	0.31	.0511	½	1.23	0.41
Studs and Joists*	32.	0.33	.068	3⅝	0.225	3.19
" " "	"	"	"	5⅝	0.145	4.95
" " "	"	"	"	7⅝	0.107	6.71
Gypsum Board	50.	0.26	.0936	½	2.25	0.54
Building Paper	—	—	—	—	16.70	—
Asphalt Shingles	70.	0.22**	.09***	½***	2.27	0.64***
Cinder Blocks	55.6	0.16	.387	8	0.581	5.93
Brick	120.	0.2	.417	8	0.63	16.0
Concrete	144.	0.16	.54	4	1.62	7.68
Stone Fill	95.	0.2	1.04	4	3.12	6.33
Linoleum Tile	50.***	0.30	.83***	½***	20.	0.63***
Rug (with fibrous pad)	50.***	0.48	.02	½	0.48	1.0***
Window Glass	161.	0.18	.59	⅛	56.6	0.30
Insulation, Batt R-7	0.9	0.18	.027	2¼	0.143	0.03
" " R-11	"	"	"	3½	0.091	0.05
" " R-19	"	"	"	6⅛	0.053	0.08
Earth (dry, stony)	120.	0.2	.5	—	—	—
Earth (wet)	120.	0.2	.3	—	—	—
Indoor film coeff.	0.075	0.24	—	—	1.46	(Vertical)
" " "	—	—	—	—	1.63	(Horizont.)
Attic film coeff.	—	—	—	—	2.20	—
Outdoor film coeff.****	—	—	—	—	6.0	(15 mph wind)
Air spaces	—	—	—	1-4	1.12	(Vertical)
" "	—	—	—	1	1.09	(Horizont.)
" "	—	—	—	4	0.91	(Horizont.)
" "	—	—	—	8	0.90	(Horizont.)

*One-dimensional heat transfer only

**Asphalt, pure

***Estimates

ρ = Density
C_p = Specific Heat Cap.
k = Conductivity
d = Thickness

****Approximate dependence on wind: $h[Btu/hr\text{-}ft^2\text{-}°F] = 1.8 + 0.28*V[mph]$

Conductance $U = \frac{k}{(d/12)}$ Capacitance (Capacity per unit area) $C_s = \rho * C_p * d/12$

3. Thermal characteristics of composite wall sections.

Using the conduction as U and the capacitance C_s of each layer listed in Table A.1, the U value and the capacitance of all composite N-layer surfaces are calculated:

$$U = \left(\sum_{i=1}^{N} 1/U_i\right)^{-1} = \left(\sum_{i=1}^{N} R_i\right)^{-1} \tag{A.1}$$

$$C = \sum_{i=1}^{N} C_{s_i} \tag{A.2}$$

The composition of each building section and the calculation steps of equations A.1 and A.2 are shown in Table A.2.

The way in which studs (or trusses) alternating with insulation batts (or air) are treated in this calculation, deserves some further attention. If the heat transfer were strictly one-dimensional, perpendicular to the wall surface, the different conductances of studs and insulation could be simply added, after being weighted by the fraction of wall area they occupy (a_{ins} and a_{stud}, where $a_{ins}+a_{stud}=1$), following ASHRAE.

$$U_i = a_{ins}*U_{ins} + a_{stud}*U_{stud} \tag{A.3}$$

For the case of a wall section, depicted in sketch(a), this is a relatively good assumption, because most of the stud sides are insulated by the insulation batt. Sketch(b) depicts the situation in the attic where a significant proportion of each floor joist acts as a fin of sorts, except for its conductance, smaller by an order of magnitude than the film coefficient. The heat flux in the joist portion marked by s will be two-dimensional, fanning out to the sides as well as flowing

Table A.2

Description, U-value, Resistance and Capacitance of

Composite Building Walls, Windows, Floors, Ceiling and Roof

	$U[\frac{Btu}{hr\ ft^2\ {}^\circ F}]$	R=1/U	$C_s[\frac{Btu}{ft^2\ {}^\circ F}]$
1. Outside Walls:			
Indoor film coefficient	1.46	0.68	0.
½" Gypsum Board	2.25	0.45	0.54
R-7 Insulation/2x4 Studs*	0.13	7.46	0.35
½" Plywood sheathing	1.60	0.62	0.41
15 lb. felt. (building paper)	16.70	0.06	0.
Wood siding (lapped)	1.23	0.81	0.41
Outdoor film coefficient (15 mph wind)	6.00	0.17	0.
		10.25	1.71
Composite U-Value	0.098		
1a. End Wall:			
Substitute Brick for outer 4 layers			
Composite U-value for end wall:	0.097		
2. Ceiling:			
Indoor film coefficient	1.63	0.61	0.
½" Gypsum Board	2.25	0.44	0.54
R-11 Insulation/2x6 Joists**	0.10	10.12	0.38
Attic film coefficient	2.20	0.46	0.
		11.63	0.92
Composite U-value	0.086		
3. Roof:			
Attic film coefficient	2.20	0.46	0.
½" Plywood/2x6 Joists***	1.50	0.67	0.75
15 lb. felt. (building paper)	16.70	0.06	0.
Asphalt Shingles	2.27	0.44	0.64
Outdoor film coefficient (15 mph wind)	6.00	0.17	0.
		1.80	1.39
Composite U-value	0.56		

*Composite values for R-7 Insulation plus 1" Air space in parallel with 2x4 Studs, 16" on center: see text and Sketch (a).

**Composite values for R-11 Insulation in parallel with 1⅝x5⅝ joists, 24" on center: see text and Sketch (b).

***Composite value for ½" Plywood sheathing in parallel with 1⅝x5⅝ joists, 24" on center, on top of Plywood: see text and Sketch (c)

Table A.2 (continued)

	$U[\frac{Btu}{hr\ ft^2\ °F}]$	R=1/U	$C_s[\frac{Btu}{ft^2\ °F}]$
4. Basement Walls:			
below grade only:			
Indoor film coefficient	1.46	0.68	0.
8" Cinder Blocks	0.58	1.72	5.93
		2.40	5.93
above grade, additionally:			
Outside film coefficient:	(6.00)	(0.17)	(0.)
		2.57	5.93
Composite U-value above grade:	0.39		
Composite U-value below grade*:	0.42		
5. Basement Floor:			
Indoor film coefficient	1.63	0.61	0.
4" Concrete floor	1.62	0.62	7.68
4" Stone fill	3.12	0.32	6.33
		1.55	14.01
Composite U-value*:	0.65		
6. Party Walls:			
Indoor film coefficient	1.46	0.68	0.
½" Gypsumboard	2.25	0.44	0.54
4" Air space/2x4 Studs**	1.03	0.97	0.33
		2.09	0.87
Composite U-value (wood frame alone):	0.48		
8" Cinder Block	0.58	1.72	5.93
Neighbor wood frame	0.48	2.09	0.87
		5.90	7.67
Composite U-value (wood+masonry):	0.17		
7. Downstairs Floor (carpet or tiles):			
Indoor film coefficient	1.63	0.61	0.
½" Plywood/2x8 Joists***	1.46	0.69	1.1
Carpet (fibrous pad)	0.48	2.08	1.0
alternate: Linoleum floor tiles	(20.00)	(0.05)	(0.63)
Indoor film coefficient	1.63	0.61	0.
		3.99	2.11
Composite U-value (carpet)	0.25		
Composite U-value (tiles)	0.51		

*Below grade Basement losses are evaluated without using this value.
**Composite values for 4" Air sp. in parallel with 1⅝x3⅝ studs 16" o.c.
***Composite values for ½" Plywood in parallel with 1⅝x5⅝ joists 16" o.c.

Table A.2 (continued)

	$U[\frac{Btu}{hr\ ft^2\ °F}]$	$R=1/U$	$C_s[\frac{Btu}{ft^2\ °F}]$
8. Upstairs Floor (carpet or tiles):			
Indoor film coefficient	1.63	0.61	0.
½" Gypsumboard	2.25	0.44	0.54
8" Air Space/2x8 trusses*	0.82	1.22	0.68
½" Plywood	1.60	0.62	0.41
Carpet (fibrous pad)	0.48	2.08	1.0
alternate: Linoleum floor tiles	(20.00)	(0.05)	(0.63)
Indoor film coefficient	1.63	0.61	0.
		5.58	2.63
Composite U-value (carpet):	0.18		
Composite U-value (tiles):	0.28		
9. Partition Walls:			
Indoor film coefficient	1.46	0.68	0.
½" Gypsumboard	2.25	0.44	0.54
4" Air space/2x4 Studs**	1.03	0.97	0.33
½" Gypsumboard	2.25	0.44	0.54
Indoor film coefficient	1.46	0.68	0.
		3.21	1.41
Composite U-value:	0.31		
10. Front Door:			
Composite U-value:	0.54		

11. Windows (80% glass area):

U-values, including film coefficients

Wind speed [mph]	0	5	10	15	
Single Pane	0.76	0.96	1.07	1.13	$[\frac{Btu}{hr\ ft^2\ °F}]$
Double Pane	0.58	0.70	0.75	0.78	

Capacitance 0.30 $Btu/ft^2\ °F$

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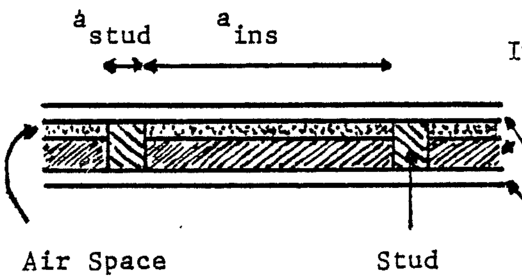
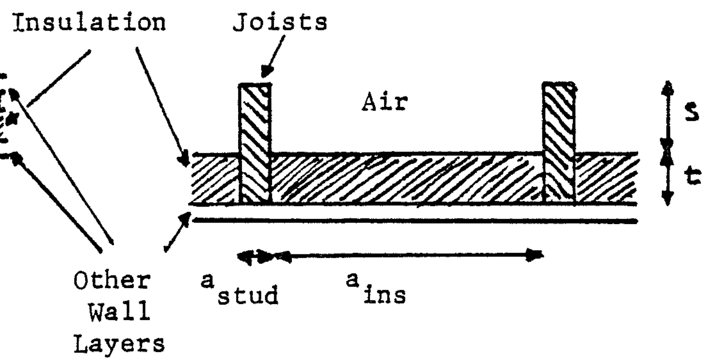
*Composite values of 8" Air space in parallel with 1⅝x7⅝ joists, 16" on center. See text and Sketch (a).

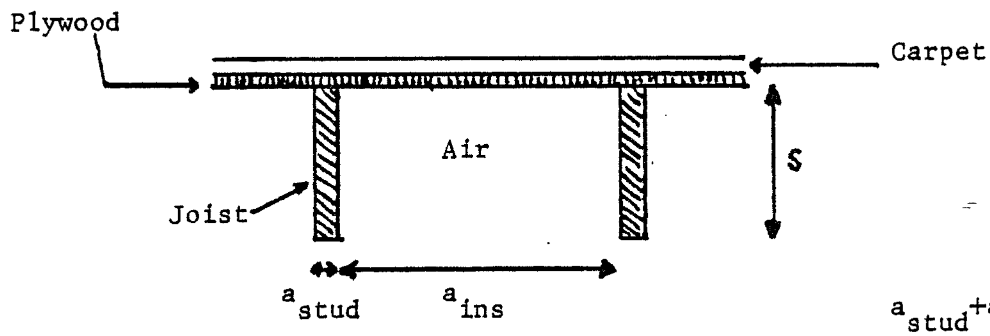
**Composite values of 4" Air space in parallel with 1⅝x3⅝ studs, 16" on center. See text and Sketch (a).



Sketch a: Wall Section



Sketch b: Attic Floor



Sketch c: Basement Ceiling

$a_{stud}+a_{ins}=1$
(in a, b & c)

to the top. To correct for this effect in the simplest possible way, the conductance for the joist is calculated using a depth of t + s/2, instead of t + s. After this corrected conductance is computed, the combined conductance of the joists and the insulation is evaluated using Equation A.3. For the same reasons of two-dimensionality of the heat flux, s/2 instead of s is used in the computation of the joist conductance in (c). This conductance, combined with the conductance of the plywood right on top of the joist (using A.1), is then aggregated with the conductance of the plywood between joists using A.3.

The joists enclosed between the downstairs ceiling and the upstairs floor are weighted with the air cavities simply by using Equation A.3. The same is true for the studs adjacent to the fire walls.

The capacitances for a wall layer combined of insulation (or air space) and a stud (or joist) are added, after accounting for the relative area fractions they occupy, in the same fashion as the conductances are computed in Equation A.3.

4. Heat loss constants and capacities.

After the tedious exercise in the past two sections, we are ready to harvest: multiplying the area of each wall or floor by the appropriate U-value from Table A.2, we obtain the heat loss constants [Btu/hr°F] for all sections of the house. The capacities [Btu/°F] are obtained analogously. Table A.3 shows how all these contributions are aggregated into several groups, representing the conduction through the outside shell, the basement and the attic. The mass transport-induced heat loss due to air infiltration is listed next, with a choice of values and volumes, discussed more extensively in Chapter IX. The heat loss constants and the capacities for the interior structure and the fire wall were also evaluated for further calculations involving secondary heat transfers involving the different zones or the fire walls.

5. Heat load calculations.

Table A.4 presents several ways of combining the different contributions to the total heat loss discussed in the previous section. The "design" way that follows ASHRAE guidelines assumes a 15 mph wind, an air infiltration rate of 0.75 air exchanges per hour, and an attic that

Table A.3

Heat Transfer Constants H and Heat Capacities C

for a Twin Rivers 3-Bedroom Townhouse

1) Outside Walls:	Table A.2#	Area[ft^2]	H[$\frac{Btu}{hr\,°F}$]	C[$\frac{Btu}{°F}$]
Front Walls	1	363	35.6	621
Back Walls	1	318	31.1	544
Front Door	10	20	10.8	34
Total Conduction and Capacity			77.5	1199
Extra End Unit Wall	1	545	52.9	9205
2) Windows:				
Front (single pane/double pane)	11	80	90.4 / 62.4	24
Back (single pane/double pane)	11	106	119.8 / 82.7	32
Total Conduction and Capacity			210.2/145.1	56
Extra End Unit Window	11	16	20.8 / 12.5	5
3) Basement:				
Windows (single pane)	11	8	9.0	2
Walls (above grade)	4	65	14.8	385
Walls (bel. gr.; Standard*/Sinden**)	4	246	18.5/23.7	1459
Floor (Standard*/Sinden**)	4	726	27.2/11.8	10171
Total Conduction and Capacity			60.5/50.3	12017
Extra End Unit Wall (above grade)	4	55	21.5	326
Extra End Unit Wall (below grade)	4	184	13.8/17.7	1091
Total Extra End Unit Wall			95.8/89.5	1417
4) Attic:				
Roof conduction	3	906	507.4	1259
Attic ventilation (0.5 cfm/sqft)	-	—	412.0	—
Total Roof Heat Loss Constant			919.4	
Ceiling	2	763	65.6	702
Extra End Unit Attic Wall	4	113	50.9	1808

*Recommended by ASHRAE, Handbook of Fundamentals, 1972; adapted for $\Delta T=40°F$.
**Frank Sinden, CES Note#4; two-dimensional exact solution.

Table A.3 (continued)

5) Air Infiltration:	Volume	H[$\frac{Btu}{hr\,°F}$]	AI[hr^{-1}]	H[..]	AI[..]
First and Second Floor only	11600	104	(0.5)	157	(0.75)
Above Grade Space	13500	122	(0.5)	182	(0.75)
First & Second Floor & Basement	17400	157	(0.5)	235	(0.75)
Both Floors, Basement and Attic	20000	180	(0.5)	270	(0.75)
Basement alone	5800	104	(1.0)	157	(1.50)

6) Party Walls (both):	Table A.2#	Area[ft^2]	H[$\frac{Btu}{hr\,°F}$]	C[$\frac{Btu}{°F}$]
Wood frame alone	6	1122	539	976
Wood frame & Masonry & Wood frame	6	1122	191	8606
7) Downstairs Floor:				
Floor with Carpet	7	451	113	952
Floor with Tiles	7	275	140	479
Total Conduction and Capacity			253	1431
8) Upstairs Floor:				
Floor with Carpet	8	588	106	1546
Floor with Tiles	8	138	39	312
Total Conduction and Capacity			145	1858
9) Partition Walls:				
Downstairs	9	549	—	774
Upstairs	9	736	—	1038
Total Capacity				1812

Table A.4

Heat Load Calculations for a 3-Bedroom Interior Townhouse

	Design Conditions ($15\ mph; 0.75\ hr^{-1}$)	Average conditions ($10\ mph; 0.5\ hr^{-1}$)		Post Retrofit ($10\ mph; 0.5\ hr^{-1}$)	
Walls & Door	78(13%)	78(12%)	78(9%)	78(17%)	78(12%)
Windows	210(36%)	199(32%)	199(22%)	199(44%)	199(31%)
Basement Conduction	55(9%)	55(9%)	55(6%)	55(12%)	55(9%)
Attic	61(10%)	33(5%)*	460(51%)**	19(4%)*	202(32%)**
Air Infiltration	182(31%)	104(17%)	104(12%)	104(23%)	104(16%)
Basement Air Inf.	0	157(25%)***	0	0	0
Total Heat Load $[\frac{Btu}{hr\ ^\circ F}]$	586(100%)	626(100%)	896(100%)	455(100%)	638(100%)

*Losses through Ceiling with a ΔT half the indoors-out temperature difference
**Losses through Roof & Attic Vents with half the indoors-out ΔT.
***Can be added to Attic losses, by means of air flow through flue shaft and air gaps along fire walls.

Table A.5

Design Heat Load Calculations for different House Sizes and Options

	End Unit	2-Bedroom	4-Bedroom	Double Pane W'dows
Walls & Door	131	57	77	78
Windows	231	174	269	145
Basement	92	45	61	55
Attic	61	49	69	61
Air Infiltration	182	145	207	182
Total Heat Load $[\frac{Btu}{hr\ ^\circ F}]$	697(+19%)	470(-20%)	683(+17%)	521(-11%)

Table A.6

Heat Capacity and Longest Time Constant of a 3-Bedroom Townhouse

Outside Walls	1255
Ceiling	702
½ Party Walls	4303
Partition Walls	1818
Floors	3289
	11367 $\frac{Btu}{^\circ F}$

Time Constant of the Living Space (1.&2. floor):

$\tau = 11367/626 = 18.2$ hours

If only Wood Frame of Party Walls included ($976 \frac{Btu}{^\circ F}$)

$\tau = 8040/626 = 12.8$ hours

performs as predicted by theory (see the section on the attic in Chapter IX). In column 2 of the same table we try to be more realistic by using an average winter wind speed (10 mph), affecting primarily the share of the windows, and incorporating what we know about the attic: as discussed in Chapter IX, its temperature is midway between indoors and out at night. With that knowledge, we can account for the attic either in terms of heat losses through the ceiling or through the roof, and they should be equal. In Column 2 of Table A.4 the heat loss constant for the ceiling is used, and a 1.5 exchanges per hour worth of basement infiltration is assumed to flow in its entirety into the attic, through the short circuits discussed in Chapter VII. Half an air exchange per hour of air infiltration is assumed for the living space. The third column in Table A.4 uses the roof U-value and 0.5 cfm per square foot of attic ventilation; the resulting roof heat loss is twice the previously calculated ceiling heat loss. The large discrepancy can be explained either by a failure of the ceiling insulation to match its handbook performance, or to the attic ventilation being virtually nil (this has been excluded by direct experiments). Comparing the total heat loss constants obtained in columns 2 and 3 to furnace data, column 2 seems closer to reality. Columns 4 and 5 in Table A.4 repeat the calculations of Columns 2 and 3 respectively, after implementation of all retrofits. The living space air infiltration after retrofit is not yet certain at this time and is left unchanged. The calculations for both the methods of accounting for the attics show between 25 and 30% of savings by the retrofits. Not included in this calculation are the effects of internal heat sources and the sun, both diminishing the required furnace input and the relative savings in heating.

Table A.5 lists the changes in the heat loss constant for end units, double pane windows and 2 and 4 bedroom units.

Finally, the total capacity of the two floors (the "living space") of a 3-bedroom townhouse is computed in Table A.6 with and without inclusion of the firewall masonry between the houses. The "longest time constant" (in the terminology of Chapter VIII) is estimated by dividing this capacity by the heat loss constant obtained from column 2 of Table A.4.

APPENDIX B: THE LOCAL WEATHER

Twin Rivers is located in central New Jersey at 40.3° North Latitude and 74.5° East Longitude. Although only 26 miles from the Atlantic Ocean, its climate is largely continental, mainly as a result of winds from the interior of North America. The temperature extremes lie at about 0°F (-18°C) (recorded about one winter in eight) and 100°F (38°C) (recorded about one summer in five). Summer relative humidty can be as high as 90% for a stretch of a few days, alternating with more comfortable periods.

The weather data for the Twin Rivers Project have been gathered both from our own weather station on top of the town's bank and the U.S. weather station located in Trenton, N.J., 14 miles west of Twin Rivers. Simultaneous observations from the two locations differ by an average of 1°F in temperatures and of about 1 m.p.h. in wind. The following four figures show Trenton data.

Figure B-1 displays the annual average temperature history for the past 40 years. The worldwide temperature peak during World War II is clearly visible. The heating trend of the past 12-13 years is probably a local heat island feature brought about by the increase in urban energy use.

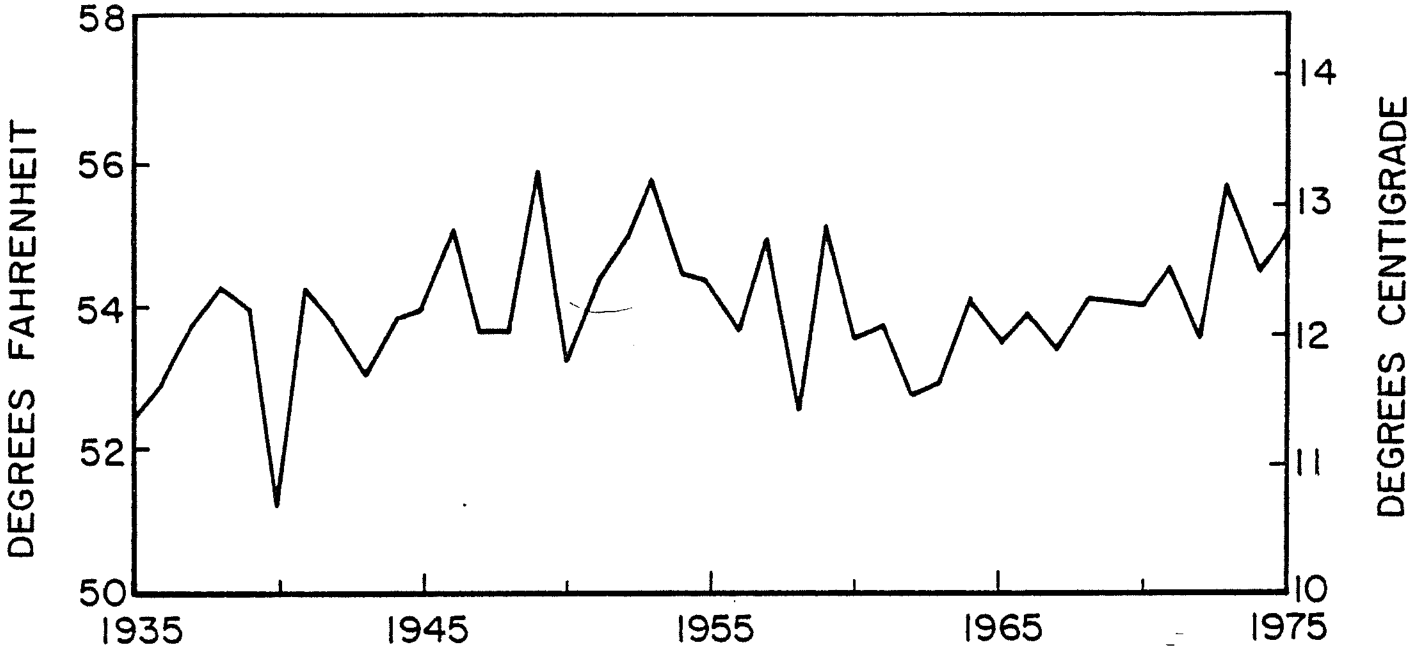
The monthly average temperatures shown in Figure B-2 were evaluated from data going back to 1893. The mean daily highs and lows for each month averaged over the same period are also drawn. Notice how the daily temperature excursions are larger in summer compared to winter.

Figure B-3 shows the average monthly behaviour of wind, sun and rain, the other three main weather parameters, averaged over 30 years and more. The wind goes through a rather smooth yearly cycle, peaking in March at 10.7 miles per hour and receding to a minimum of 7.6 miles per hour in August. The fraction of the maximum possible sunshine exhibits a similar yearly cycle peaking in July at 65% and diminishing to a mere 48% in December, with a yearly average of 59%.

The monthly averages of the maximum possible (clear sky) solar flux for Twin Rivers are given in Table B.1. With the exception of one block, all Twin Rivers Townhouses face one of the main four compass orientations, offset by 10°. That is, they face either 10° East from North, or 10°South from East, etc. The roofs are inclined by 22.6°, having a slope of $\frac{5}{12}$. The direct solar flux impinging upon a wall and a roof facing each of the above directions is given in Table B.1.

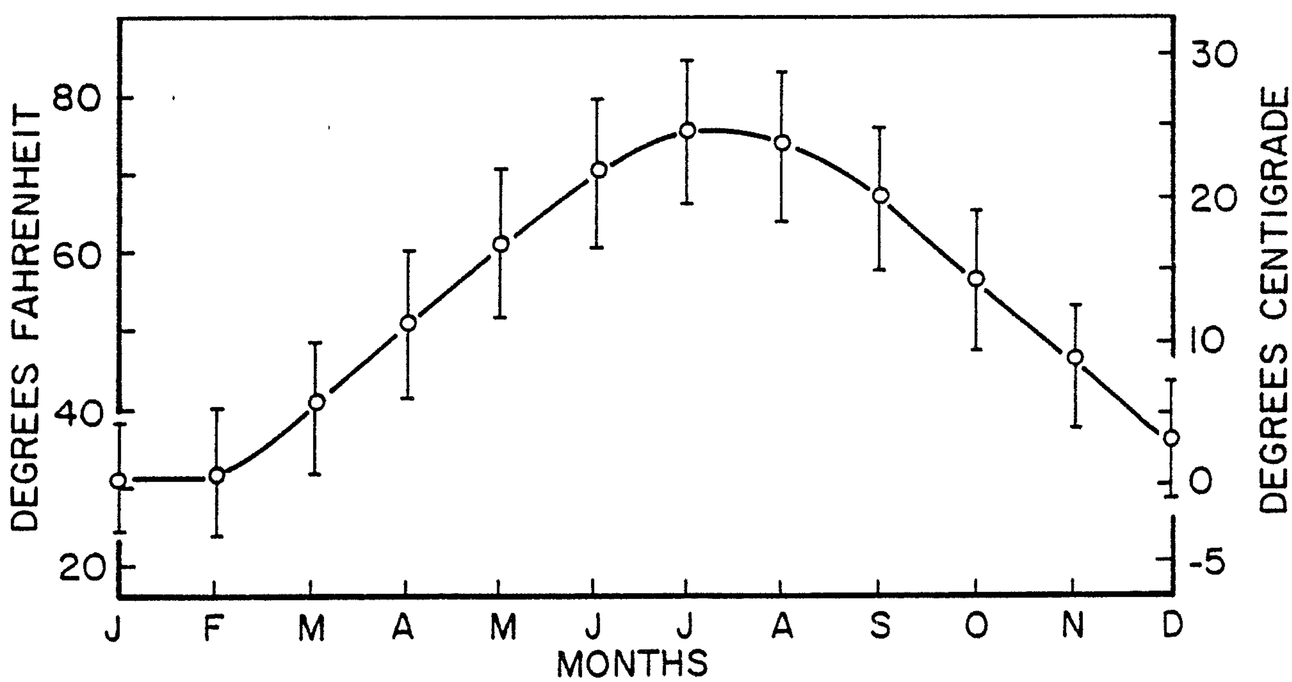
The direct radiation on a horizontal surface and the diffuse radiation are also given. The direct radiation on any surface has to be increased by the diffuse radiation, in order to obtain the total solar flux on that surface. The "weather averaged" solar radiation is obtained by multiplying the listed clear sky values by the weather factor C (plotted in Figure B-3) in the last column.

The average rainfall over a year is relatively constant at 3.4 inches per month except for July and August, when it increases to 4.6 and 5 inches, respectively.



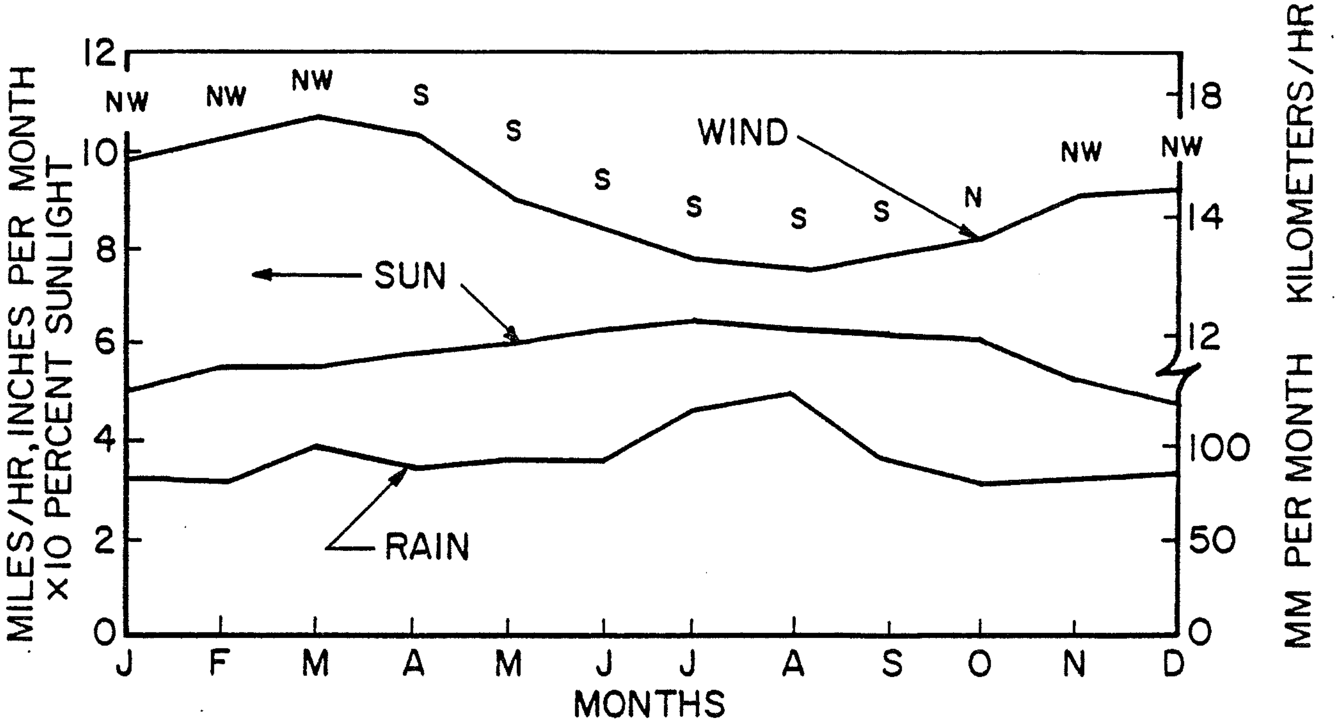
AVERAGE ANNUAL TEMPERATURE (1935 – 1975)

FIGURE B-1



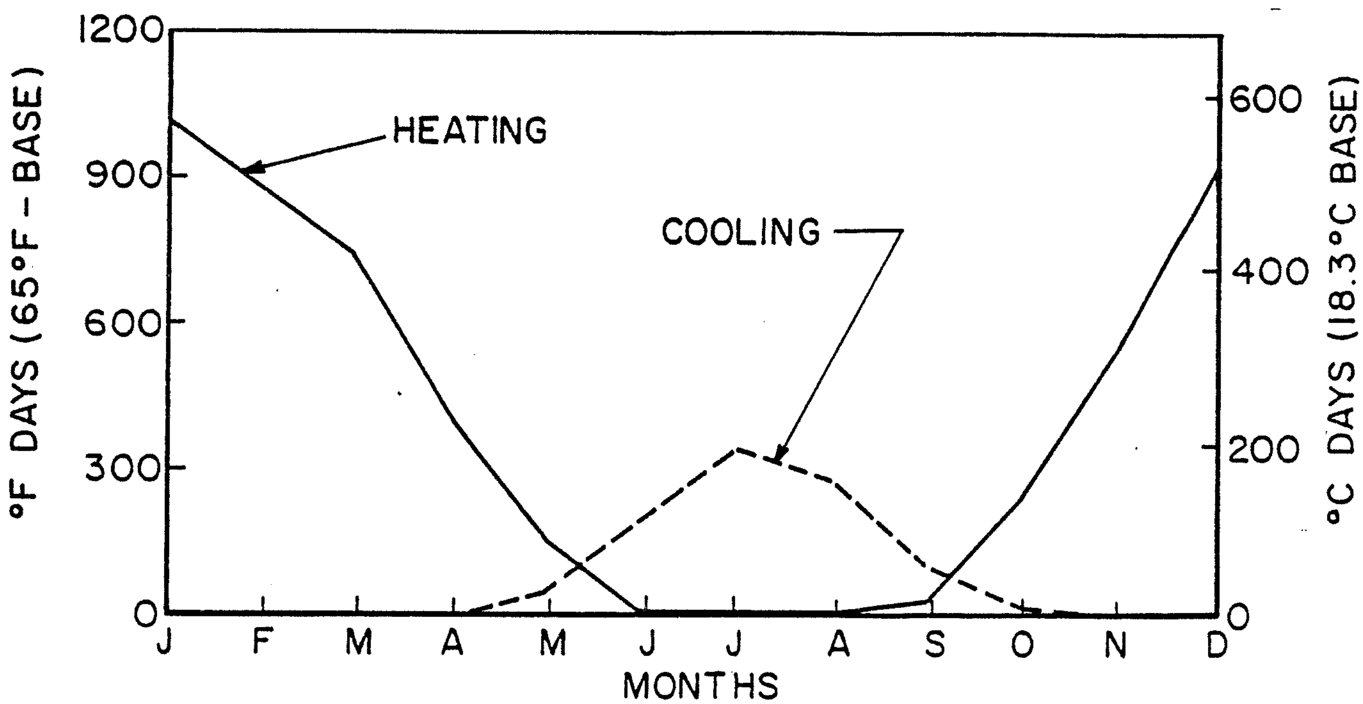
MONTHLY AVERAGE TEMPERATURE.
BARS INDICATE MEAN DAILY HIGHS AND LOWS.

FIGURE B-2



MONTHLY AVERAGE WINDSPEED, WIND DIRECTION, SUNLIGHT (% OF POSSIBLE), PRECIPITATION, BASED ON HISTORICAL RECORD

FIGURE B-3



MONTHLY AVERAGE HEATING AND COOLING DEGREE-DAYS, BASED ON 1941-1970 RECORD

FIGURE B-4

The average outside temperature for each day, subtracted from a reference temperature of 65°F, gives the number of degree-days for that day. Adding all positive differences over the days of the month, the number of heating degree-days for that month is calculated; the cooling degree-days are obtained as the (negative of the) sum of all negative differences. The average monthly heating and cooling degree-days for the past 21 and 6 years, respectively, are plotted in Figure B-4.

Table B.1

Average Clear Sky Solar Flux [Btu/day-ft^2] in Twin Rivers

	Diff.*	Horiz.	"E"**	"S"	"W"	"N"	"RE"	"RS"	"RW"	"RN"	C***
Jan	120	776	599	1607	316	0	841	1334	642	133	.51
Feb	148	1133	766	1644	477	0	1181	1678	975	425	.55
Mar	200	1553	905	1417	657	4	1560	1977	1377	891	.55
Apr	282	1919	963	988	797	48	1867	2133	1740	1410	.58
May	367	2135	954	626	868	141	2033	2160	1962	1784	.60
Jun	424	2214	930	453	889	215	2088	2139	2047	1952	.63
Jul	423	2141	916	507	858	178	2026	2107	1975	1850	.65
Aug	363	1925	904	783	779	75	1852	2050	1753	1504	.63
Sep	272	1602	866	1185	658	11	1585	1930	1431	1028	.62
Oct	191	1224	772	1514	507	0	1256	1708	1064	558	.61
Nov	138	864	632	1589	352	0	923	1408	767	209	.53
Dec	117	680	544	1547	271	0	746	1222	555	76	.48
Avg.	254	1514	813	1155	619	56	1497	1821	1357	985	.59

*Diffuse Radiation; to be added to direct radiation readings in other columns, in order to obtain the total solar radiation.

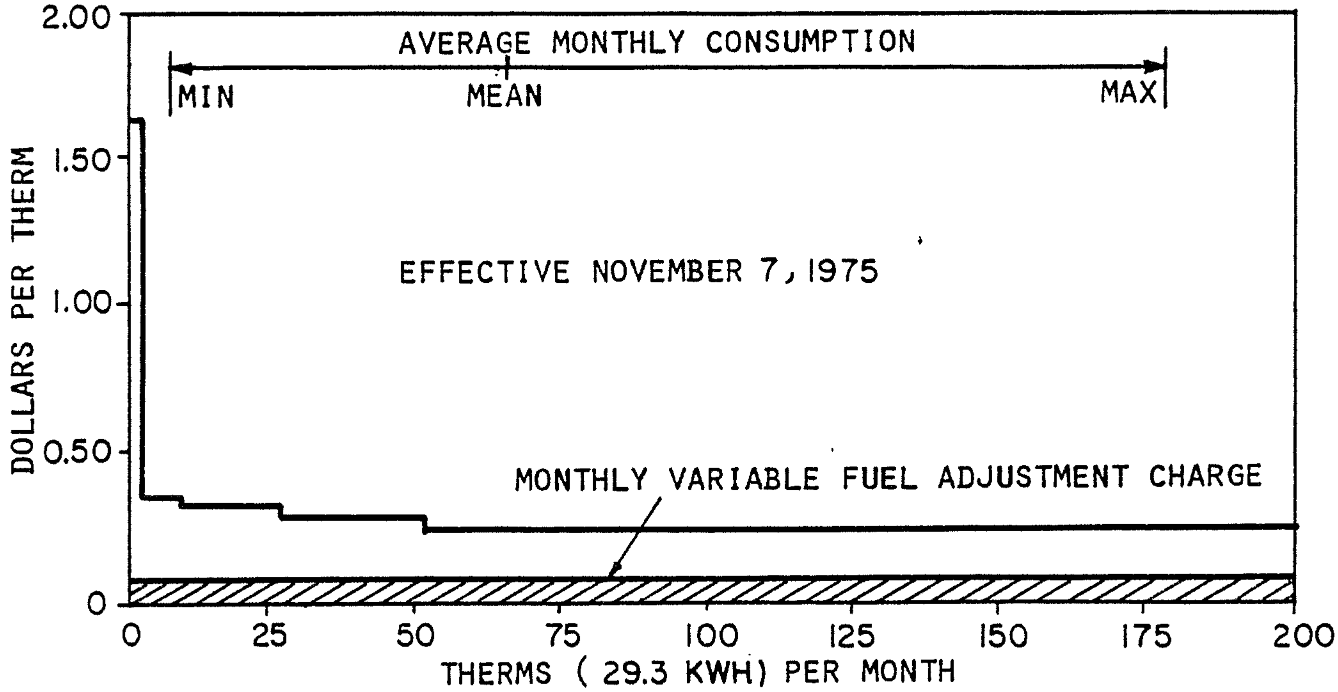
**"E": Solar flux striking a vertical wall oriented 10°South from East;
"S": Solar flux striking a vertical wall oriented 10°West of South; etc.
"RE": Solar flux impinging on a Roof surface (inclined by 22.6°) facing 10° South from East

***Monthly average fraction of the maximum possible sunshine for Central New Jersey.

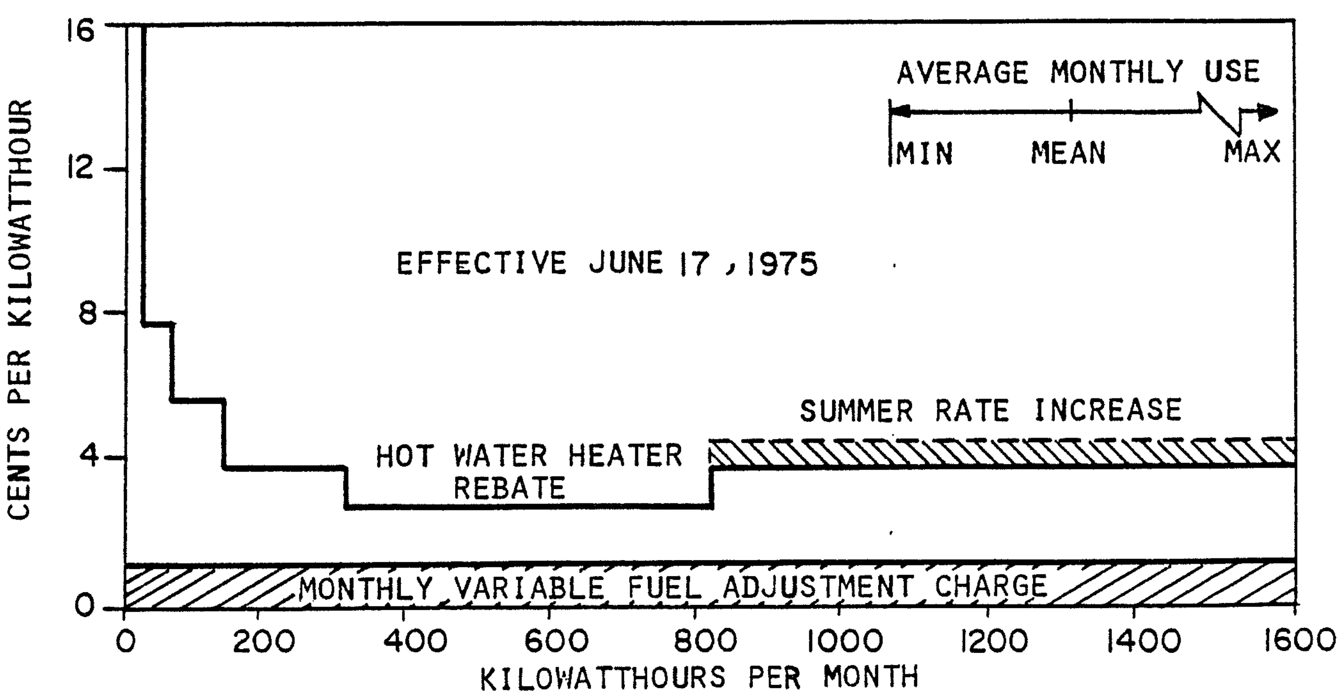
APPENDIX C: PRICES OF ENERGY

Energy in Twin Rivers is supplied in two forms: natural gas and electricity. In Quad II gas is used exclusively for space heating (and, sproadically, for an outdoor barbecue grill), while electricity powers all appliances and the air conditioner.

The price per unit energy charged every month by the utilities to their customers decreases stepwise as the quantity consumed increases, a normal fact of life in economics, but a bad incentive for energy conservation. A typical price schedule for natural gas is plotted in Figure C-1a: an initially high price of over a dollar per therm (the energy equivalent of 100 cubic feet of gas, or 29.3 kilowatt hours), essentially representing billing costs, rapidly decreases stepwise to something on the order of 15 cents per therm. The horizontal line at the bottom of the figure is the monthly variable fuel adjustment charge, an extra few cents per therm added to the regular price schedule, designed to allow the utilities to pass on fuel price changes to the customers without the need for negotiations with the government. Figure C-1a shows both fuel adjustment charges and regular price schedule. The plotted steps represent the sum of the two prices. The amount of the bill, sent every month to the customer, is represented by the surface delimited by the price line (steps), the left and bottom figure boundaries and a vertical line (not plotted) at the customer's consumption level. The monthly average consumption for Quad II is shown at the top of the figure together with the August minimum and the February maximum



GAS RATE SCHEDULE FOR TWIN RIVERS QUAD II TOWN-
-HOUSES
FIGURE C - 1a



ELECTRICITY RATE SCHEDULES FOR TWIN RIVERS QUAD II TOWNHOUSES
FIGURE C - 1b

(taken from Figure II-1).

Rate schedules change at an increasing pace, about once a year on the average. Table C.1 shows the recent history of the gas price faced by the Quad II residents.

Electricity is priced by a different utility company (Jersey Central Power and Light) in much the same way as gas is priced by Public Service Electric and Gas. Both the rate schedules and the monthly fuel adjustment charges over the past ten years are shown in Table C.2. At a closer look there are some differences between the way gas and electricity are priced. First, Quad II residents are eligible to a special hot water heater rebate as shown in Figure C-1b, because this appliance is electric. Thus at 800 kilowatt-hours a month one pays a lower average price than at 1300 kilowatt-hours a month. Second, a summer rate increase of $0.7 per kilowatt-hour during the months of June through October for consumption levels over 800 kilowatt-hours per month (to discourage the use of air conditioners) went into effect in summer 1975. It is interesting to observe how the average Twin Rivers Quad II townhouse uses more than 800 kilowatt-hours throughout the whole year, as displayed at the top of the figure and in Figure II-2.

Third, this utility company completely changed its pricing policy in July 1976 with a new uniform price of 3.3¢ per kilowatt-hour in winter and 4.0¢ in summer, plus a billing charge of $5.38. This might be considered as the first step in the change from a decreasing to an increasing marginal price for energy. This move would appear to be the easiest way to bring about energy conservation.

Table C.1

PUBLIC SERVICE ELECTRIC AND GAS RATE SCHEDULE FOR GAS

Rate per month	Flat fee in dollars plus rate in cents per therm, effective on 1/3/66	12/3/70	3/23/72	6/1/73	1/7/74	9/23/74	6/15/75	11/7/75
First 2 therms	$1.05	$1.08	$1.08	$1.14	$1.24	$1.30	$2.28	$3.15
Next 7 therms	¢21.40	¢21.90	¢22.50	¢23.72	¢25.83	¢27.00	¢25.89	¢27.83
Next 17 therms	¢18.50	¢18.90	¢19.50	¢20.53	¢22.38	¢23.38	¢22.45	¢24.19
Next 24 therms	¢14.50	¢14.80	¢15.50	¢16.34	¢17.78	¢18.57	¢17.78	¢19.52
Over 50 therms	¢11.40	¢11.66	¢12.80	¢13.50	¢14.69	¢15.35	¢14.69	¢16.43

RAW MATERIALS ADJUSTMENT (cents per therm)

Effective Date	1970	1971	1972	1973	1974	1975	1976	Effective Date
January	¢1.0200	¢1.4414	¢1.8190	¢1.9448	¢2.7608	¢4.9535	¢10.0785	January
February	¢1.0200	¢1.4414	¢1.3728	¢1.5787	¢1.8162	¢4.9535	¢10.0785	February
March	¢1.0200	¢1.4414	¢1.8190	¢1.9448	¢2.7685	¢4.9535	¢10.0785	March
April	¢1.0800	¢1.6817	¢1.7503	¢2.0020	¢3.4892	¢8.6578	¢06.6626	April
May	¢0.3000	¢1.6817	¢1.7503	¢2.0020	¢3.4892	¢8.6578	¢10.0785	May
June	¢1.0800	¢1.6817	¢1.7503	¢2.0020	¢3.4892	¢8.6578	¢10.0785	June
July	¢1.0800	¢1.3270	¢1.6474	¢2.0020	¢2.8714	¢7.5618	¢10.0785	July
August	¢1.0800	¢1.3270	¢1.6474	¢2.1850	¢2.8714	¢7.5618		August
September	¢1.0800	¢1.3270	¢1.6474	¢2.1850	¢2.8714	¢7.5618		September
October	¢1.0800	¢1.3270	¢3.3290	¢4.0498	¢6.1890	¢8.3039		October
November	¢1.0800	¢1.3270	¢3.0202	¢4.0498	¢5.6170	¢8.3039		November
December	¢2.2079	¢3.4206	¢3.3290	¢4.0498	¢6.1890	¢8.3039		December

Table C.2

JERSEY CENTRAL POWER AND LIGHT ELECTRIC RATE SCHEDULE

Service Classification 1: Residential Service - Apartments and Town Houses

Rate per month	Flat fee in \$ plus rate in ¢/kwh, effective 10/1/66	7/13/70	11/6/70	6/5/72	10/1/73	Rate per month	Effective 6/1/74	Rate per month	Rates effective on 6/17/75	7/19/76
First 14 kwh	\$1.00	\$1.06	\$1.09	\$1.15	\$1.20	First 20 kwh	\$2.00	First 20 kwh	\$3.00	\$5.38 bill.+
Next 46 kwh	¢5.60	¢5.98	¢6.13	¢6.50	¢6.70	Next 40 kwh	¢6.50	Next 40 kwh	¢6.70	¢3.30 (Winter)
Next 70 kwh	¢3.50	¢3.72	¢3.83	¢4.06	¢4.18	Next 70 kwh	¢4.40	Next 70 kwh	¢4.60	¢4.00 (Summer**)
Next 20 kwh	¢2.00	¢2.13	¢2.19	¢2.32	¢2.40	Next 20 kwh	¢2.48	Next 170 kwh	¢2.71	
Next 500 kwh*	¢1.30	¢1.38	¢1.42	¢1.50	¢1.55	Next 500 kwh*	¢1.59	Next 500 kwh*	¢1.60	
Over 650 kwh	¢2.00	¢2.13	¢2.19	¢2.32	¢2.40	Over 650 kwh	¢2.48	Over 800 kwh	¢2.71 (¢3.41 in Sum.)	

*Special Rate for customers with electric Hot Water Heaters.

**Summer = June through October

FUEL ADJUSTMENT (ENERGY ADJUSTMENT CLAUSE after October 1, 1973) PER KWH:

Effective Date	1971	1972	1973	1974	1975	1976	Effective Date
January	¢0.0	¢0.1189	¢0.1841	¢0.4486	¢0.8169	¢1.1649	January
February	¢0.0	¢0.1254	¢0.1941	¢0.3873	¢0.8365	¢1.3000	February
March	¢0.0	¢0.1299	¢0.1972	¢0.5055	¢0.7376	¢1.4258	March
April	¢0.0	¢0.1314	¢0.1926	¢0.5443	¢0.6783	¢1.3987	April
May	¢0.0	¢0.1417	¢0.2038	¢0.8257	¢0.7053	¢1.5421	May
June	¢0.0	¢0.1351	¢0.2112	¢1.0217	¢0.9403	¢1.3051	June
July	¢0.0589	¢0.1789	¢0.2296	¢1.4926	¢1.2751	¢1.2393	July
August	¢0.0589	¢0.2026	¢0.2478	¢1.6002	¢1.3891	¢0.9095	August
September	¢0.0589	¢0.2314	¢0.2608	¢1.6591	¢1.2098		September
October	¢0.0589	¢0.2232	¢0.3518	¢1.6242	¢0.9927		October
November	¢0.0752	¢0.1913	¢0.3368	¢1.4742	¢0.9320		November
December	¢0.0927	¢0.1933	¢0.4387	¢1.0261	¢1.2071		December

APPENDIX D: CHRONOLOGY OF THE BUILDING OF TWIN RIVERS AND LAND USE AT TWIN RIVERS*

Chronology

1963	Gerald Finn, a local developer, engaged the architectural firm of Whittlesey and Conklin to design a planned unit development for East Windsor Township, New Jersey. The target was 3000 residential units. The model was Reston, Virginia.
1964	Whittlesey and Conklin submitted regional analysis and proposed land use sketches.
1964-5	Finn acquired options on one farm of 415 acres; he acquired another 100 acres a few months later for additional commercial-industrial space.
1964-8	Finn met town officials throughout this period to convince them of desirability of PUD. They visited Reston, and attended discussions of PUD's by professionals. A model of Twin Rivers was displayed.
1967	Finn acquired additional 200 acres in response to pressures from town for additional industrial acreage.
May 1967	State Planned Unit Development Enabling Act passed.
Oct. 1967	East Windsor Zoning Ordinance Amendment, Planned Unit Development, passed.
1967	Herbert Kendall of Kendall Development Corporation, Princeton, became a co-venturer. He assumed the mortgage on the land.
Dec. 1967	Twin Rivers Holding Corporation established with Kendall as president.
1967	Finn and Kendall negotiated financing with American Standard.

*Taken from Appendix II of Report No. 6, H. Fraker, Jr., and E. Schorske (1973).

March 1968	Application made by Twin Rivers Holding Corporation for tentative approval of Township Planning Board, which held the public hearings prescribed by the PUD ordinance.
May 1968	East Windsor Planning Board gave tentative approval to Quad I.
1968	Sewer and water contract negotiated by developer with East Windsor Municipal Authority.
1968	Whittlesey, Conklin and Rossant, architects, N.Y.C., replaced by Robert J. Hillier, architect, Princeton, N.J.
1968	Twin Rivers Holding Corporation staff hired: Aaron Kenton, vice-president and James Lynch, vice-president for sales and marketing, Arthur Rothschild, vice-president and treasurer.
Feb. 1969	American Standard acquired Windsor Properties (Finn's corporation which had a 25% share in the development) and became financial backer and co-partner with Kendall Development Corporation.
March 1969	East Windsor Township issued construction permit for Quad I following local planning board approval.
April 1969	First model houses built.
Oct. 1969	Veterans Administration gave approval to Quad I, "a master certificate of reasonable value" issued.
Nov. 1969	Community Trust agreement signed with First Charter National Bank to manage resident payments for community services.
April 1970	State Department of Community Affairs issued approval of Quad I.
April 1970	First families moved in.
June 1970	East Windsor Township issued construction permit for Quad II following partial approval by local planning board. Final approval delayed until commercial center and industrial building reached certain stage of development.

July 1970	Twin Rivers Holding Corporation became a wholly-owned subsidiary of American Standard. American Standard bought 50% of Twin Rivers for cash and then merged.
July 1970	Veterans Administration approval of Quad II.
Dec. 1970	East Windsor Planning Board issued final approval of Quad II.
1971	Developer exercised options to purchase 48 acres for a Town park and 80 industrial acres.
March 1971	State Department of Community Affairs approval of Quad II.
Aug. 1971	East Windsor Planning Board approval of Quad III and construction permits issued.
Nov. 1971	Veterans Administration approval of Quad III.
March 1972	State Department of Community Affairs approval of Quad III.
Sept. 1972	Community Trust acceptance of Quads I and II delayed until performance bond of $300,000 posted by developer.
Dec. 1972	Community Trust acceptance of Quad III.
March 1973	East Windsor Planning Board partial approval of Quad IV, permits issued for one half of construction only.
March 1973	State Department of Community Affairs approval of Quad IV.
1975	Completion of Quad IV.

Land Use at Twin Rivers

Acreage	I	II	III	IV	Total
Residential	44.7	77.0	63.0	67.1	251.8
Commercial	26.6	5.4	11.8	1.3	45.1
Industrial	-- 208* --				208
Private Institutional	1*		1**		2
Open Space	32.9	35.8	34.8	16.9	168.7
Dedicated Right of Way	8.2	4.5	12**		24.7
TOTAL	444.1*		207.9**		700.3

*Quads I and II combined

**Quads III and IV combined

<u>Residential Distribution</u>	Quad I	II	III	IV	Total Dwelling Units	Dwellings per acre
Low Density						
Single Family Houses	-	83	30	26	139	
Average Dwelling Units Per Acre		4.1	4.1			4.1
Medium Density						
Townhouses	264	401*	450	511	1626	
Garden Apartments	323	144	240	192	899	
Total	587	545	690	703	2525	
Average Dwelling Units per Acre	13.2	12.4	12.4	11.5		12.4
High Density						
Apartment Buildings**	-	234	-		234	
Average Dwelling Units Per Acre		18.0	-			18.0
Town Center Apartments	-	43	-		43	
Total Residential	587	905	720	729	2941	

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*248 two-floor and 153 split-level townhouses.

**Postponed indefinitely.

APPENDIX E: INSTRUMENTATION*

The instrumentation used in the Twin Rivers housing energy research is outlined briefly in the following paragraphs. In addition to the field instrumentation systems that are described, considerable laboratory instrumentation and field checkout instrumentation has been employed.

Such instruments as the flat wire anemometer probes and heat flux probes added directly to our knowledge of the houses and the systems under investigation. Special oscilloscopes, counters, and checkout circuits insured that the field equipment was operating properly. They also were used to diagnose difficulties when they occurred.

1. Weather and highly instrumented townhouse measurement

The instrumentation systems for the highly-instrumented townhouses and the weather station are based upon using individual data acquisition systems (Esterline-Angus D-2020TTY) one of which has been expanded to 200 channels for the group of three townhouses, and the other remains at the basic 20 channel level for the banktop weather station. Each of the 20 channels provides sensitive adjustments of .1, 1 or 10 millivolts, with a range equal to about 2000 times the sensitivity. Thus in choosing the individual sensors, considerable latitude was possible with regard to sensor output. The data recording itself is accomplished within the Energy Utilization Laboratory at the University using a Digi-Data Model 1579/800W magnetic tape recorder and a 33ASR Teletypewriter after telephone line transmission of the data from Twin

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*This Appendix was prepared by David T. Harrje.

Rivers. In this approach both the benefits of taped data that can be readily interfaced with the 360/91 IBM computer, as well as the ability to scan the data following transmission have been achieved. When both the townhouses and the weather station are transmitting, the townhouse data is logged every 20 minuts, the weather data once each hour. When weather data alone is transmitted the 20 minute interval is used. The channels monitored in the weather station are listed in Table 1, those monitored in the highly-instrumented townhouses are listed in Table 2.

Both the sensors themselves and the basic requirements involved in the HIT and weather station parameter measurements have a number of similarities. For example, weather and townhouse temperatures are measured with linearly compensated thermistors (YSI #44201, #44203, and #44204), which are suitably small, accurate, provide the desired voltage output, and are relatively inexpensive (see mounted model in Fig. E-1). In a similar way, humidity is measured via YSI #9102 dual bobbin moisture sensor. Both types of sensors require a well-regulated voltage source (whose level is also recorded) so that changes of sensor resistance with temperature will result in properly interpreted voltage variations. Another requirement is to record events. In the case of appliances such as refrigerators or clothes dryers, switches are provided at the power supply which are activated at a desired current demand level (e.g., the current with the compressor on). The switch in turn energizes a small synchronous motor within the instrument package which turns a potentiometer and linearly increases the voltage level. The potential difference from one data recording interval to the next provides an accurate on-time measure of the appliance energy

Table E.1

Channels Monitored in our Weather Station
(data are recorded hourly)

Outside humidity - dewpoint (°F)

Outside temperature (°F)

Wind speed averaged (mph)

Wind speed instantaneous (mph)

Wind direction (degrees)

Solar flux - total (Btu/sq. ft/hr)

Solar flux - shaded (Btu/sq. ft/hr)

* Solar flux - west (Btu/sq. ft/hr)

* Solar flux - east (Btu/sq. ft/hr)

Rainfall (per .01 inch)

* Ground temperature (°F)

Barometric pressure (in Hg.)

System voltages (volts)

*Obtained for limited time periods.

Table E.2

63 Channels Monitored in our Three Highly-Instrumented Townhouses*
(scan every 20 minutes onto magnetic tape
in Energy Laboratory at Princeton)

1	Thermostat setting (°F)
2	Basement temperature (°F)
3	First floor temperatures - 6 total (°F)
4a	Second floor temperatures - 3 total (°F)
4b	Attic temperature (°F)
5a	Furnace operation (cu ft) or air conditioner operation (kwhr)
5b	Furnace fan operation (min)
5c	Duct flow rates - 9 total (cfm)
5d	Supply and return flow rates - 4 total (cu ft)
5e	Register temperatures - 9 total (°F)
5f	Supply and return temperatures - 4 total (°F)
5g	Supply and return humidity - 2 total (°F dewpoint)
6a	Electric hot water heater (kwhr)
6b	Electric range (kwhr)
6c	Electric dryer (min)
6d	Electric refrigerator (min)
7a	Front door opening (min)
7b	Front living room window opening (min)
7c	Front bedroom window opening (min)
8a	Back door opening (min)
8b	Back bedroom #1 window opening (min)
8c	Back bedroom #2 window opening (min)
8d	Basement door opening (min)
8e	Vents, bathrooms - 3 total (min)
9a	Total lighting and 110-volt appliances (kwhr)
9b	Voltage level, townhouse and system - 4 total (volts)
10	Hot and cold water temperature (°F)

* Numbering system conforms to Table 3, and indicates roughly how we have "collapsed" channels in the Omnibus houses.

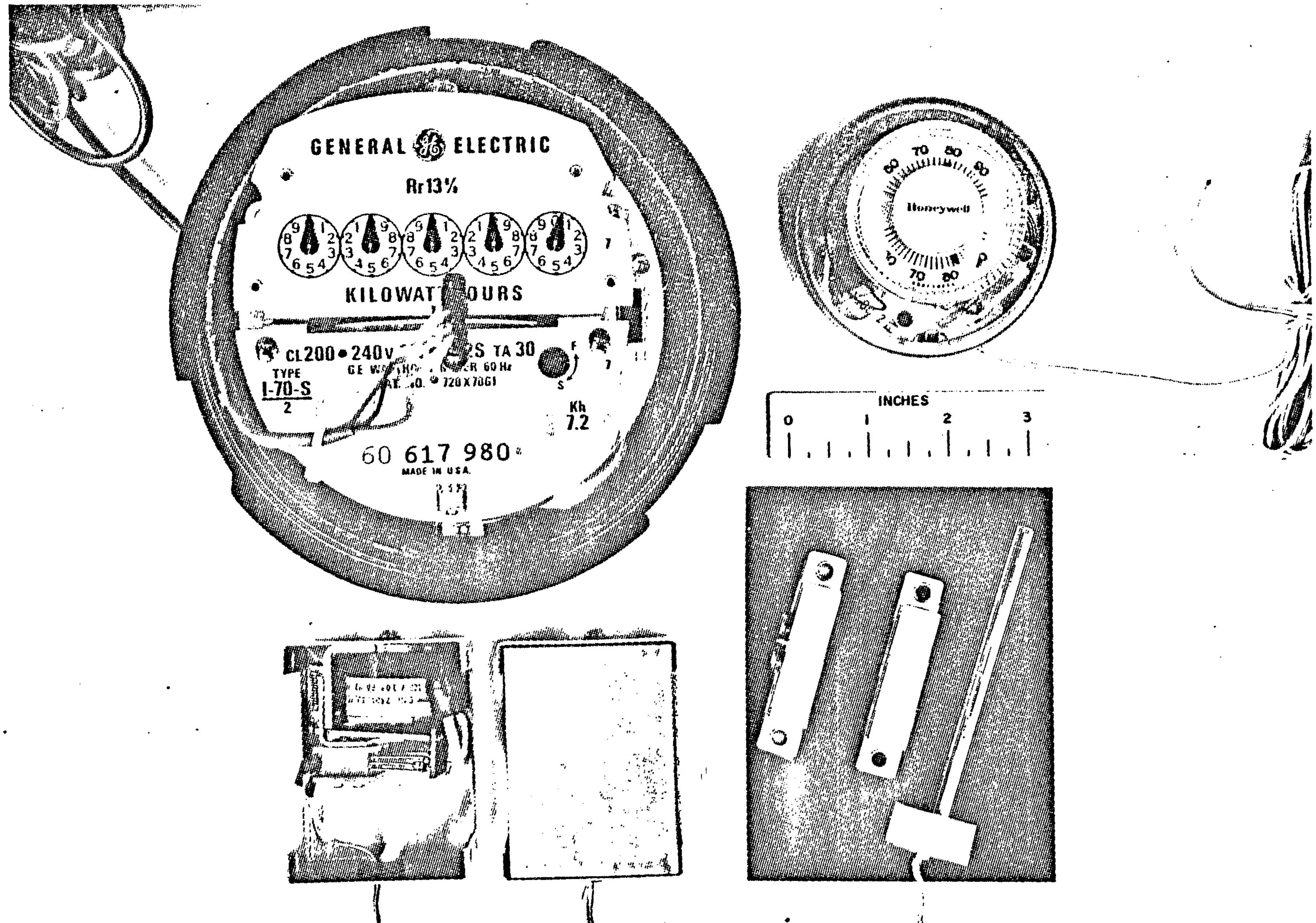


Fig. E-1 Sensors. Clockwise from upper left: adapted watt-hour meter, adapted thermostat, thermistor, magnetic switches, dual water-heater relays.

consumption. Another sensing approach uses standard burglar alarm switches on the windows and doors to run similar motors, and "open-time" is thus measured (see Fig. E-1). In the case of appliances such as the range, where energy consumption levels are uncertain (because there are a number of energy functions), individual electric meters are employed with switches that are tripped as the Airy discs spin in the meters (Fig. E-1). Still another measurement that is performed in both weather station and townhouses is the counting of rotation rate. In the average wind measurement the rotations of the spinning Gill 3-cup anemometer (R.M. Young Model 12101 D) are added over the recording interval. This results in a proportional voltage buildup on a counter card, with recycling each time the level reaches 10 volts. Also in the case of the spinning duct air flow anemometers in the townhouses, disk rotations chop the light beam in an optical switch and recording again involved the digital counters, using D to A converters on the counter cards. In the cases where instantaneous readings are sufficient, the same anemometer outputs are read as a pulse rate on three-to-a-card tachometers. To measure a second wind velocity, a Gill 3-cup anemometer (RM Young Model 12101) drives a direct current generator to record wind gusting.

There are several other sensors worth mentioning. One is the Honeywell thermostat to which has been added an internal linear potentiometer. Each temperature setting has a proportional voltage (see Fig. E-1). The same principle is used in measuring wind direction where a Gill Microvane weathervane movement alters a potentiometer setting with wind direction. Also there is the rain gauge (Science Associates, Remote Reading Rain Gauge), tipping bucket type, which sends a record of each tip to the counter card (this measurement approach has also been modified to measure air conditioner condensate). For the recording of solar flux we read millivolt output readings over time stored on a Lintronics Mark V digital volt-time integrator. Both direct and shaded solar readings have been recorded using either a Lintronic dome solarimeter (temperature compensated) or an Eppley black and white pyronometer. Finally barometric pressure is measured on an H.E. Sostaman and Co. Model 363A transducer. The reader is referred to CES report Numbers 6 and 21 for more details on this instrumentation.

2. Omnibus townhouse measurements

The Omnibus instrumentation packages as shown in Figure E-2 are used in the lightly-instrumented homes and can provide up to 12 channels of quarter-hour data. As shown in Fig. E-3 and Table 3, a careful selection was made to include what we considered to be the most important energy-related parameters. This instrumentation approach depends upon recording pulses on a slowly moving magnetic tape - the recorder involved is the Westinghouse WR-4C widely used by the utilities. The four channels of the basic recorder include the (1/4 hour) time pulse channel and 3 data channels, which have been subdivided into quarter-hour segments using a multiplexing arrangement developed in our laboratory. The sensors, which are shown in Fig. E-1, provide the pulses through the use of resistance controlled oscillators contained in integrated circuit chips. Temperatures from basement to attic are measured using YSI 44007 uncompensated thermistors. These probes provide the pulses through the change in resistance with temperature. When windows or doors open, the

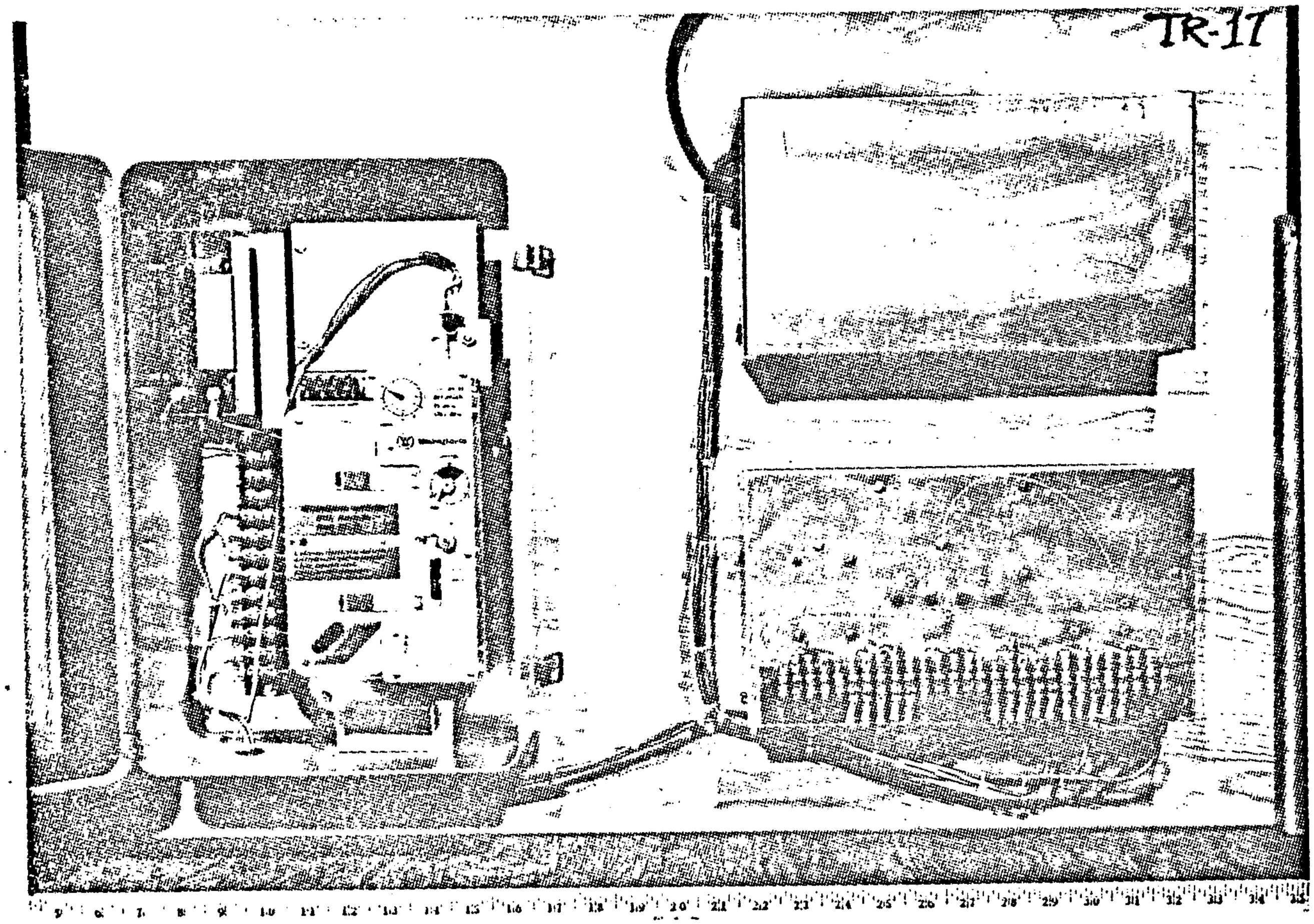


Fig. E-2 Instrumentation Package

Table E.3

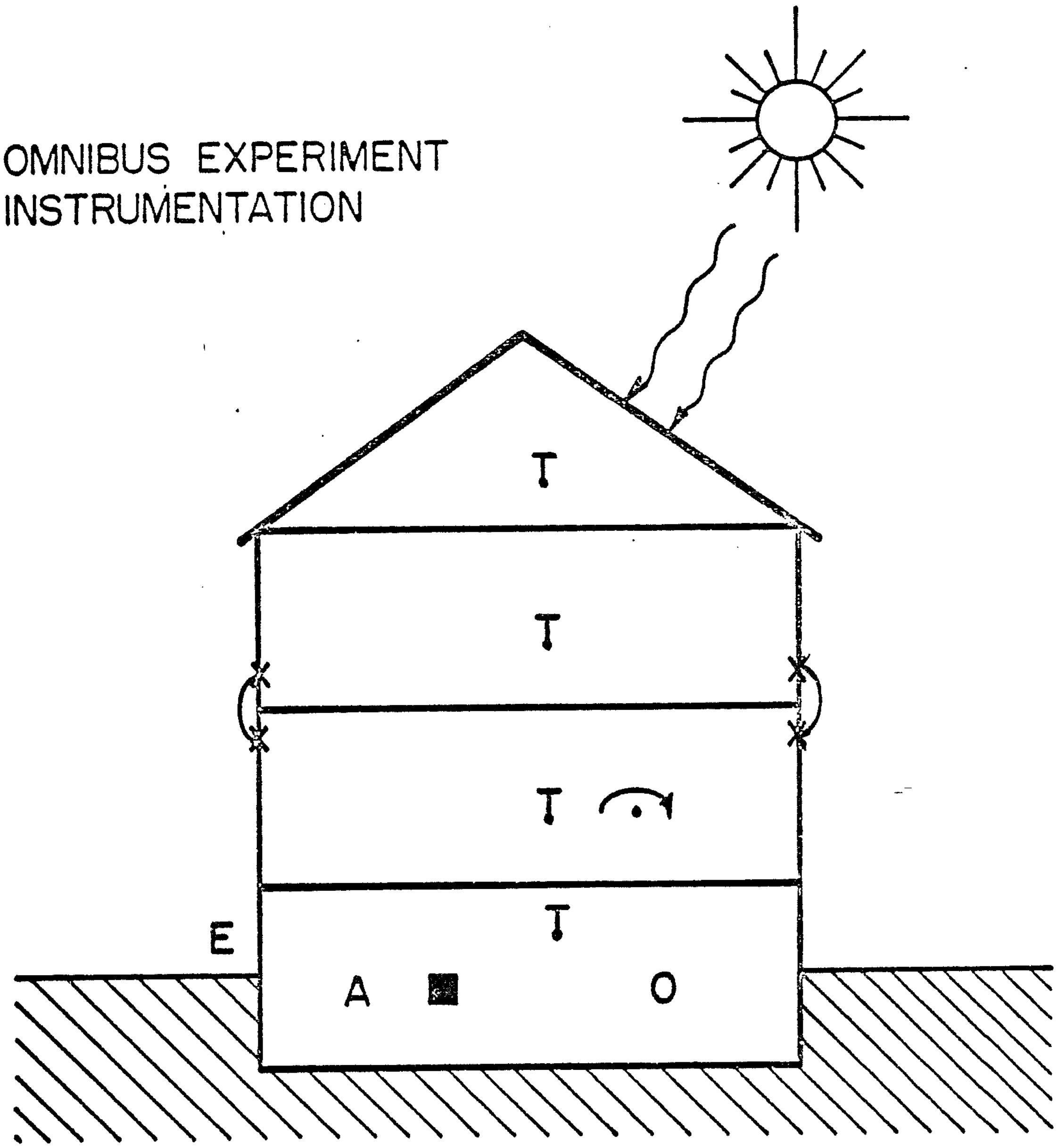
Channels Monitored in our Lightly-Instrumented ("Omnibus") Townhouses

1. Thermostat setting (°F)
2. Basement temperature (°F)
3. First-floor temperature (°F)
4. Second-floor temperature (°F)
5. Furnace operation (min/hr) or air conditioner operation (min/hr)
6. Electric hot water heater operation (min/hr)
* 7. Front door or front window opening (min/hr)
* 8. Back door or back window opening (min/hr)
9. Total electric consumption (min/hr)

Channels 1-8 are recorded hourly, and channel 9 is recorded at 15 minute intervals, onto a Westinghouse WR-4C magnetic tape cassette in the basement. The details of the instrumentation package are to be found in Ref. 4.

*The measurements of channels 7 and 8 were combined to channel 7, and the free channel 8 was assigned to attic temperature (°F) just prior to the 1976 winter.

OMNIBUS EXPERIMENT
INSTRUMENTATION



LEGEND:

T TEMPERATURE; ① UPSTAIRS, ② DOWNSTAIRS, ③ BASEMENT

④ THERMOSTAT

WINDOWS & DOOR OPENINGS ⑤ FRONT ⑥ REAR

O ⑦ WATERHEATER

⑧ FURNACE

E ⑨ ELECTRIC TOTAL

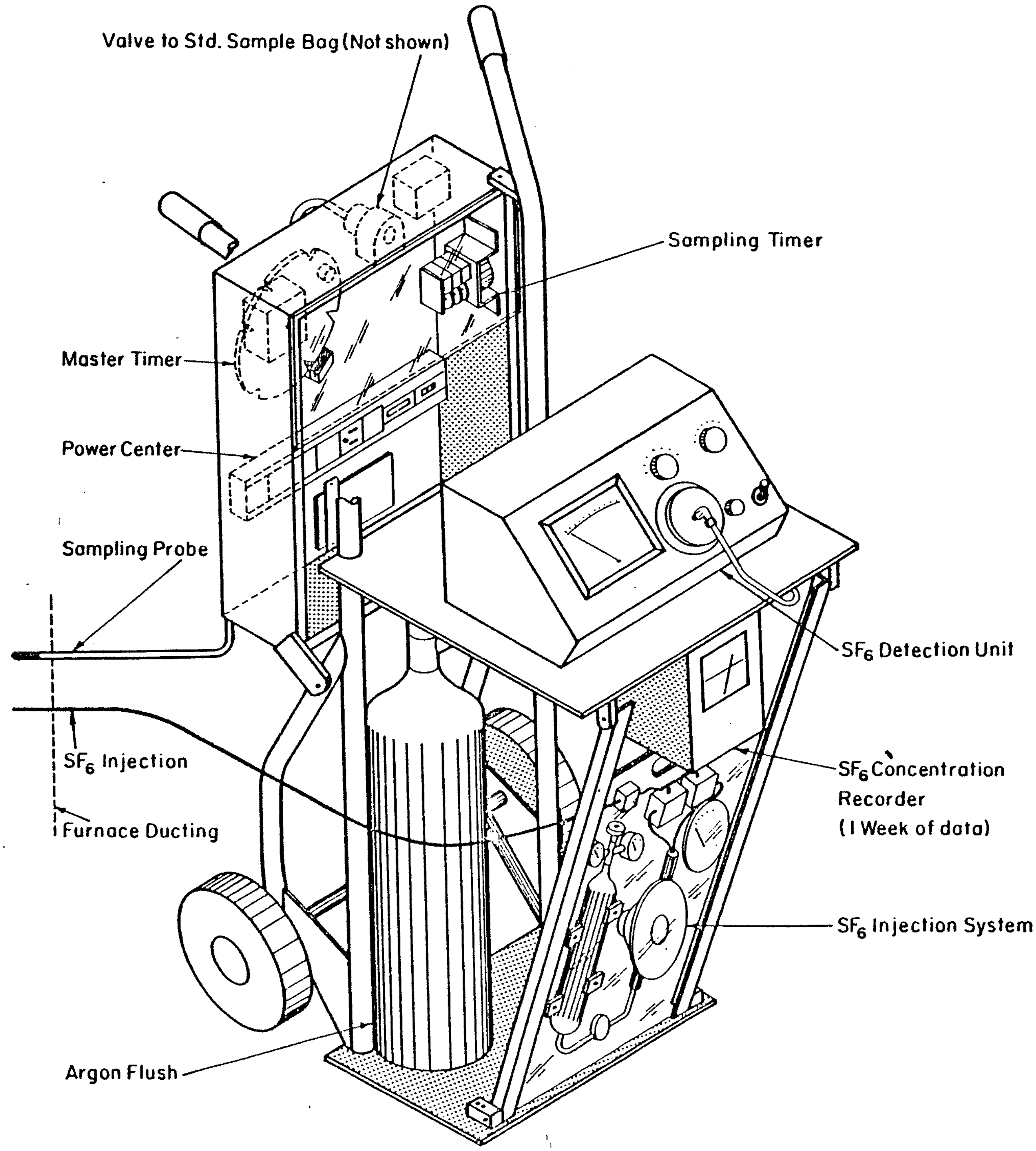
A AIR INFILTRATION MEASURED SEPARATELY

FIGURE E-3

motor-potentiometer arrangement (previously described) provides the changing resistance. When either the furnace or the air conditioner is used, the measurement of "on-time" is to monitor the signal emanating from the furnace control transformer. In the case of the electric water heater, relays (shown in Fig. E-1) click on when power is consumed; or in the gas units thermal switches located in the flue activate with heating. All of these "on-time" measurements use the motor-potentiometer approach. The temperature setting on the thermostat varies the internal potentiometer setting and provides the necessary pulse output. Details of this system including complete schematic diagrams are found in Center for Environmental Studies Report 21.

3. Air infiltration measurements

Air infiltration in an average residence constitutes one major source of energy loss. Our approach to the difficult problem of air infiltration measurement has been to develop an automated field unit in cooperation with the National Bureau of Standards (CES Report 13). Using sulfur hexaflouride as the tracer gas, concentrations are maintained between 10 and 30 parts per billion within the home under test using the furnace blower to keep the air well mixed. Small volumes of gas are involved so that complete safety is assured should the entire week's supply of SF_6 escape. The detector measures the gas concentration every 15 minutes in the mechanically activated timing system employed in the Mark II units (see Figure E-4). In the latest Mark III designs one is able to measure concentrations at intervals of 2, 5, 10 or 15 minutes using solid state timing circuits, digitalized displays and recording



AUTOMATED AIR INFILTRATION UNIT – MARK II

FIGURE E-4

directly on a magnetic tape cassette. The Mark II recording method had previously used a paper roll chart to record the individual concentration spikes characteristic of this gas chromatograph-type data.

One week in the field without attention has been routinely achieved by both Mark II and III units. The digital display of Mark III has aided on-the-spot readings which have been desirable in such research as zone interaction within the homes. One small gas bottle of high purity argon, 30 cubic centimeters of 25 psig SF_6 and a new tape cassette are now all that is necessary for one week of testing. Field replacement of supplies are routine.

4. Infrared scanning measurement

The ability to diagnose the level and coverage of insulation in a completed home presents a difficult challenge. One approach is to use infrared scanning equipment which makes use of modern technology to observe the heat profile over the surface of the building. This technique, thermography, provides one with a qualitative survey of just where insulation difficiencies are located.

The equipment used in this portion of the program is owned by the National Bureau of Standards. The equipment consists of an AGA Model No. 680 thermovision unit with both a black and white and 10 color monitor. The camera uses a 25 degree angle lens. Scanning of walls, floors, and ceilings has revealed large discrepancies in the relative surface temperatures suggesting the need for corrective action. The sources of such problems have been weather penetration behind walls, frame-masonry joining problems, missing or poorly installed insulation, the lack of proper insulation provided by wood corner treatments, openings to the outside especially in the basement area, etc. When used on internal walls the infrared scanning has revealed the degree of heat losses from the ducting enroute to the second floor, the heat losses from the furnace flue, as well as areas where weather has moved well within the house shell. External scanning has revealed hot attics and vents, losses from the firewall area, problems around overhanging closets and window treatments, etc.

Using temperature probes or standards in conjunction with the infrared scanning, plus taking special care with respect to the emissivity characteristics of the materials being viewed, one can gather quantitative data measuring thermal variations to a fraction of a degree of measuring the degree of change after retrofitting for energy conservation. For complete before and after thermographs of retrofitted houses see Grot, R.A., Harrje, D.T., and Johnston, L.C., "A Thermographic Evaluation of Retrofitted Townhouses," now in preparation at the National Bureau of Standards.

5. Rapidscan

The Rapidscan data logging system consists of a 100 channel data acquisition unit (Doric Digitrend Model 220), a seven track magnetic tape drive (Kennedy 1600) and a specially designed signal conditioning package. The system is capable of scanning 20 data points per second. The signal conditioning package allows data collection in both an event activated mode (e.g., where a device in the dwelling such as the gas valve or furnace fan is turned on or off) and periodically (adjustable from 5 seconds to 1 hour but normally set for 1 minute). The event data is binary encoded and recorded on two data channels allowing the monitoring of the status of sixteen events. A data record of the system consists of the day, hour, minute and second followed by the voltage output of the sensor channel being monitored.

APPENDIX F: DETAILS OF THE RETROFIT PACKAGES A, B, C AND D*

1. Retrofit A (attic)

The final specification to the contractors for Retrofit A (the attic retrofit) included the following: (1) Roll unbacked fiberglass and stuff openings that exist between the outer attic floor joists (two-by-fours) and the masonry fire wall. For an interior townhouse unit, this involves two walls between the front and rear of each dwelling. (2) Cover the hatch door to the attic space with 8 inches of fiberglass insulation, stapling or glueing in place. (3) Protect against blown insulation moving into the soffit areas or through the attic hatch opening by using unbacked insulation around the hatchway and along the front and rear portions of the attic floor that are adjacent to the soffit areas. In the case of the blown cellulose, this barrier was formed by fire retardant corrugated cardboard walls stapled into place. (4) Install either cellulose or fiberglass insulation by blowing into place (to avoid the problems of the many joists supporting the roof) to achieve a total value of thermal resistance of at least R-30. This has meant that, in addition to the initial value of R-11 for the 3 1/2 inch vapor-barrier-backed fiberglass, a value of R-19 of additional insulation must be added. For cellulose, with an R-value of 3.7 per inch, we have called for 5.5 inches. With fiberglass, with an R value of 2.3 per inch, we have called for 8 3/4 inches. The area covered is 720 square feet.

---

*This Appendix was prepared by D. Harrje.

The contractors charged us $155 per house for the installation of cellulose insulation and $158 per house for fiberglass. In the latter case, the cost for materials (about $70 per house) was contributed by Certain-teed, a leading fiberglass manufacturer.

2. <u>Retrofit D (shaft to attic)</u>

The purpose of retrofit D is to eliminate the largest channel for air communication between basement and attic. In conjunction with retrofit A, it puts a thermal lid on the house, but even without retrofit A it should terminate the heat loss due to circulation between attic and basement. A plug of unbacked fiberglass is used to seal, at the attic floor, the shaft which surrounds the furnace flue. The cross section of the shaft is approximately 16 inches square. The temperature of the surface of the flue at this elevation was measured to be less than 130°F. As fiberglass has a char temperature greater than 800°F, there is no danger of fire whatsoever* in performing this retrofit. (Indeed the temperatures are greater on the ducting in the basement - see Retrofit C.) To perform this sealing operation, a four-foot section of 6-inch unbacked fiberglass insulation is wrapped around the flue and pressed into the shaft opening. The elimination of any vertical air movement up the shaft is readily detected using one's hand after the seal has been completed. The cost of this item is included in Retrofit A.

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*By sealing this vertical shaft we are performing a service to the homeowner in reducing the chance that a fire could spread through the house.

3. Retrofit B (basic living space and other gaps and cracks)

The object of this retrofit is to limit the amount of air infiltration resulting from crack openings, especially around windows and doors. The leakage around windows has been traced to three causes: (1) The lack of squareness of the window frames, leading to open spaces even with the windows shut. Either these frames were installed as a parallelogram (see Figure F-1) or the house has settled after the window installation. (2) The poor condition of the seal between the glass and aluminum frame. (3) Air channels past the moulding surrounding the window. Leakage around the patio door was found to have similar origins. Leakage around the front door was found to be the result of a poor alignment at the threshold and the poor condition of the magnetic seal strips on the sides and top of the door.

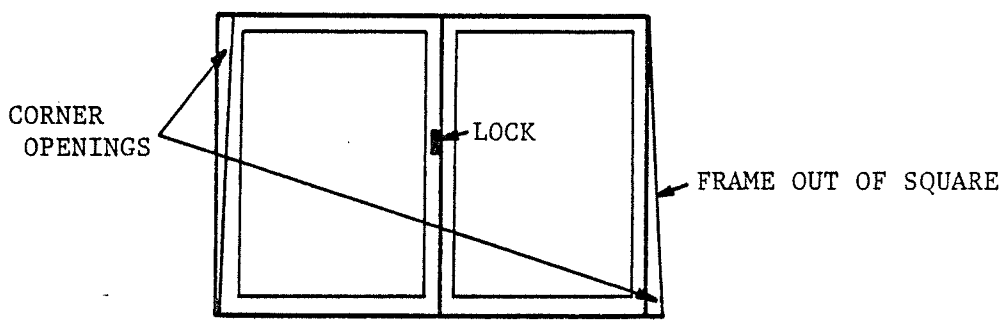

Figure F-1

The windows were improved in the following manner: The normal seal on the sliding window, which relies on a stiff fuzz strip, was augmented by the use of closed cell vinyl foam strips (3/16" x 3/8") cross section) attached to the sliding windows (see Figure F-2). The lock mechanism was also adjusted to force the windows into the frame. Where the metal frames are attached to the wood frame, where the glass is attached to the metal frame, and where the wood moulding is attached to the wallboard, a fillet of silicone caulking was placed on any suspicious areas. This

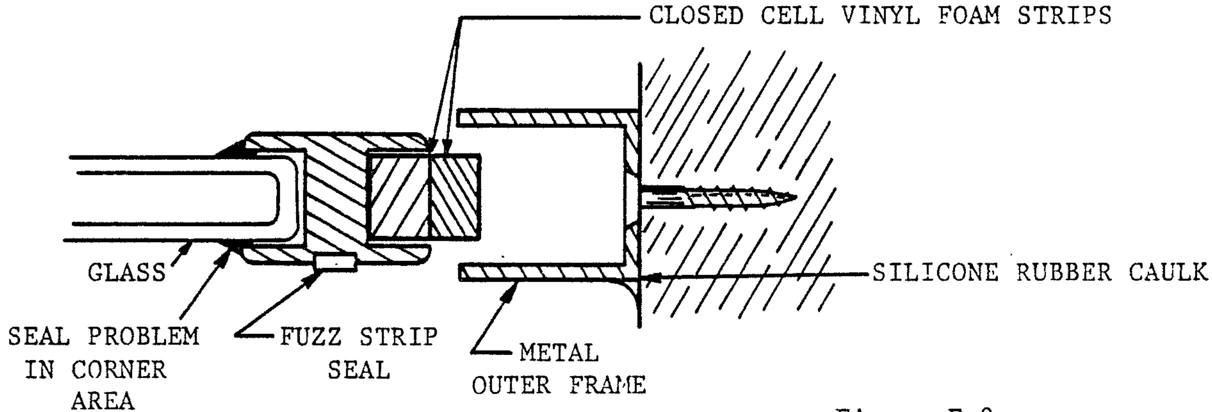

Figure F-2

material is clear, long-lasting (10 year guarantee), and almost invisible, thus matching any decor. This same material was used on the panels of the patio door and in the overhanging closets of the back upstairs bedrooms wherever air leakage was present. The patio door received a more substantial foam strip (1/2" x 3/4") to aid in sealing.

The front door sill was adjusted in height to meet the original seal surface on the lower portion of the door. When this alone was inadequate, an additional strip of vinyl with aluminum backing was screwed to the door (see Figure F-3).

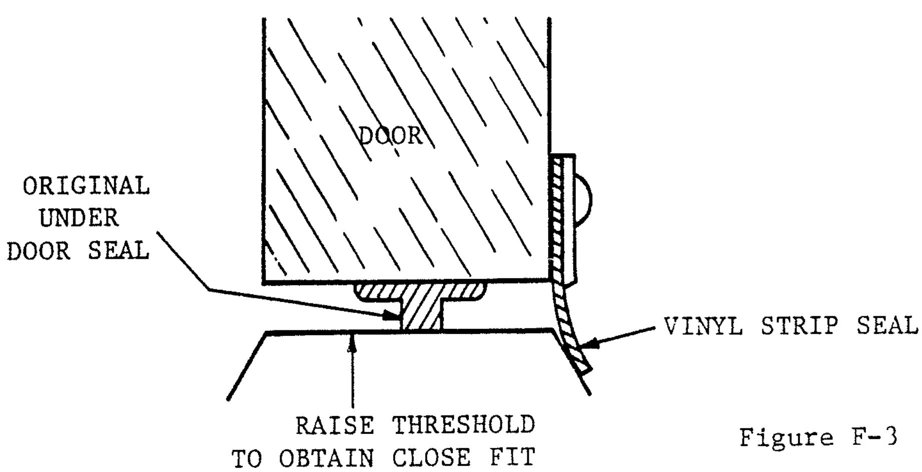

Figure F-3

The magnetic seals on the sides and top of the door opening were repaired where problems, particularly corner gaps, were found. In a few cases an additional lip seal was added (see Figure F-4).

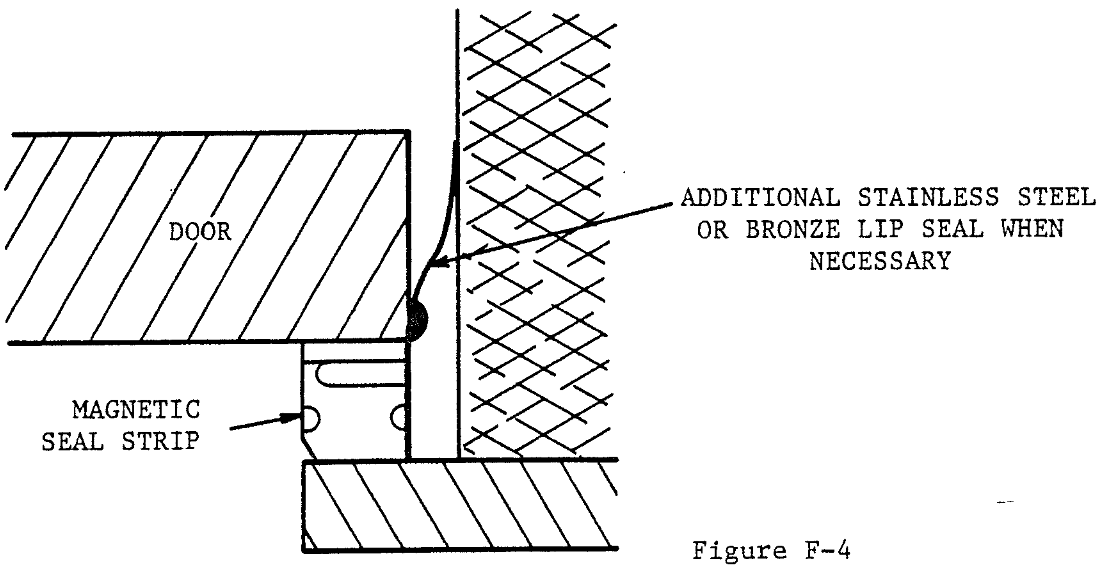

Figure F-4

The attic hatch cover also received a rim made from the foam vinyl strips to seal against vertical air flows.

Exterior caulking was used around the patio door frame and the closet overhang. When the vertical joint between masonry and frame was inspected, it was found that the principal cause for infiltration (as first suggested by the infrared photographs) was warping of the batten in the batten-board homes (see Figure F-5).

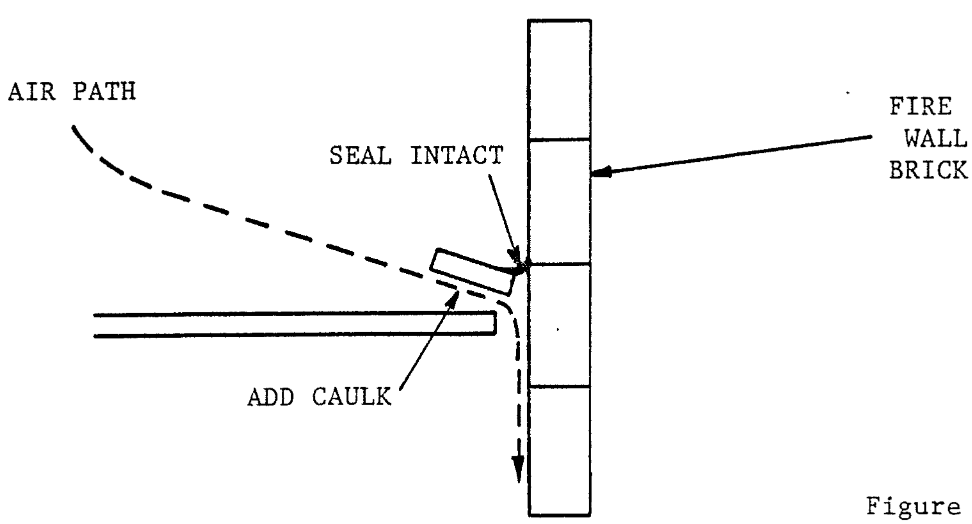

Figure F-5

In these homes a caulking joint was made, using the appropriate color poly-sulfide synthetic rubber sealant or clear silicon rubber sealant.

The last item under Retrofit B was the sealing of openings in the basement. The openings between the basement ceiling joists (2" x 8") and the fire wall were addressed. Table F-1 gives the timing of implementation of the winter retrofits, as in item (1) of Retrofit A: fiberglass was forced into the openings. Among other basement openings that required sealing were gaps at the corners and spaces around the piping to the kitchen, the dryer exhaust, and the service wiring. Caulking was used along the sill joint and for smaller wall openings. Costs for materials for retrofit B was approximately $28.

4. Retrofit C (cellar)

This retrofit concentrated exclusively on the cellar and included: (1) insulating the furnace and its warm air distribution system, (2) wrapping the hot water heater, and (3) packing the overhang area under the living room window, which includes two ducts.

The furnace plenum, the main left and right supply ducts, and the nine individual 5-inch diameter room ducts were wrapped with 2-inch thick fiberglass backed by aluminum foil with reinforcing thread. Where the 5-inch ducts ran between the 2 x 8 ceiling joists, 3 1/2" thick aluminum foil-backed fiberglass was stapled across the beams. At first ordinary duct tape was used, but a superior product was discovered by one of the contractors, a tape with the same reinforcing thread plus a superior bonding surface that eliminated problems of peeling with repeated heating of the ducts. Insulation was extended to completely cover the registers as well; the insulation was stapled to the underside of the floor.

The same 2-inch thick fiberglass* was used on the water heaters, again using the new tape. On gas water heaters, care must be taken to use the insulation only on the sides of the tank, staying away from the air inlet on the bottom and the exhaust at the top.

The last item is the overhang under the front living room window. Here two ducts extend between the beams to the registers and the insulation is either marginal or missing. The retrofit included blowing cellulose or fiberglass into the openings, or (where blowing equipment wasn't available) hand packing of fiberglass insulation into these cavities. Gaps to the outside are a particular problem in this location which was difficult for the builder to complete properly (since it is only one foot above ground level).

The cost for Retrofit C ranged from $125 to $145 depending on the contractor performing these tasks.

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*Where 3 1/2 inch thick fiberglas can fit, the additional heat resistance (R-11 vs R-7) is worthwhile.

Table F.1
Schedule Followed in Retrofitting

Omnibus	Jan 19-23,	26-30	Feb 16-20,	23-27	Mar 15-19
1			ABCD		
2			AD		
3	ACD		B		+B outside
4	ACD		B		
5			C		
6				BD	A
7	ABCD				
8	C	BD	A		
9			ABCD		B outside
10	C	BD	A		
11	ACD	B			
12				BD	A
13	ABD				
14	ABD		C		
16			C	BD	
* 17			BD	A	
* 18			C	BD	
19			AD		
* 21			CAD	B	

HIT	Dec 15-19,	22-26	Jan 12-16,	19-23	Mar 15-19
1	B	C	D	AB	B outside
2	AD	C		B	
3	ABD				C partial

* Quad III townhouse - gas appliances.

\+ Outside caulking on batton-board siding homes.

APPENDIX G: PRINCETON REPORTS TO DATE

Reports

"Energy Conservation in Housing: Work in Progress and Plans for 1975-76," R.H. Socolow, D.T. Harrje, L.S. Mayer, and C. Seligman. Center for Environmental Studies Report No. 19, April 1975.

"Wind and Trees - Air Infiltration Effects on Energy in Housing," G. Mattingly and E. Peters. Center for Environmental Studies Report No. 20, May 1975.

"Instrumentation for the Omnibus Experiment," S. Hall and D.T. Harrje. Center for Environmental Studies Report No. 21, May 1975.

"Summer Air Conditioning and Appliance Use Patterns: A Graphical Analysis," J. Robinson and J. Yeung. Center for Environmental Studies Report No. 22, May 1975.

"Energy Utilization in Townhouses in a Planned Community in the United States," R.H. Socolow. Center for Environmental Studies Report No. 26, February 1976.

"Modelling Attic Temperature in Three Highly Instrumented Townhouses in Twin Rivers, New Jersey," A. Pollack. Center for Environmental Studies Report No. 28, June 1976.

"Retrofitting: Plan, Action, and Early Results Using the Townhouses at Twin Rivers," D.T. Harrje. Center for Environmental Studies Report No. 29, June 1976.

Working Papers

"Comparison of Opinion Research Corporation and Twin Rivers Respondents to Identical Energy Questions," E. Schorske and C. Seligman. Center for Environmental Studies Working Paper No. 17, April 1975.

"Strategies to Encourage Energy Conservation: Research in Progress," C. Seligman. Center for Environmental Studies Working Paper No. 18, April 1975.

"Time-Series Models for the Energy Balance in a House," R. Socolow. Center for Environmental Studies Working Paper No. 19, April 1975.

"A Model of Heat Flow in an Attic," R. Socolow. Center for Environmental Studies Working Paper No. 20, May 1975.

"Space Heating by the Sun," R. Sonderegger. Center for Environmental Studies Working Paper No. 23, December 1975.

"Construction Variables in Twenty Twin Rivers Townhouses: Results of an Inspection," J. Elliott. Center for Environmental Studies Working Paper No. 24, February 1976.

"Humidifying a House: Where the Water Goes and How Much it Costs," R. Sonderegger. Center for Environmental Studies Working Paper No. 25, May 1976.

"Thermal Storage in Houses," R. Sonderegger. Center for Environmental Studies Working Paper No. 26, June 1976.

"Some Statistical Analyses of the Residential Furnace: A Summary," T. Woteki. Center for Environmental Studies Working Paper No. 27, July 1976.

"Omnibus Project Retrofit Log," J. Elliott and K. Gadsby. Center for Environmental Studies Working Paper No. 28, July 1976.

"Energy Conservation in Existing Residences: Your Home Deserves a House Call," R.H. Socolow. Presented at the Conference: Energy Efficiency as a National Priority, Washington, D.C., May 20, 1976.

Notes

"Air Flows in the Flue and its Shaft," F. Sinden, Twin Rivers Note #1, January 6, 1976.

"Heat Transfer from the Flue," F. Sinden, Twin Rivers Note #2, January 6, 1976.

"Note for Dick Grot's Handbook," F. Sinden, Twin Rivers Note #3, January 27, 1976.

"Conductive Losses from Basements," F. Sinden, Twin Rivers Note #4, February 18, 1976.

" Results from the First Attic Retrofits at Twin Rivers," R. Socolow, Twin Rivers Note #1, January 1976.

"Combustion Air Effect on Air Infiltration," R. Socolow, Twin Rivers Note #2, January 1976.

"The Definition of Furnace Efficiency: A Slippery Slope," R. Socolow, Twin Rivers Note #3, March 22, 1976.

"Night Setback and Energy Savings," D. Harrje, Twin Rivers Note #1, March 22, 1976.

"Materials and Techniques for Retrofit," D. Harrje, Twin Rivers Note #2, March 23, 1976.

"Theoretical Basis for Tracer Gas Measurements of Air Infiltration," F. Sinden, Twin Rivers Note #5, March 1976.

"The Effects of Weather on Home Heating: A Micro Level Analysis of Three Residential Furnaces, Part I," T. Woteki, Twin Rivers Note #1, March 25, 1976.

"The Electric Connection: Influence of Electricity Use on Furnace Gas Consumption," G. Dutt and R. Socolow, Twin Rivers Note #1, April 5, 1976.

"Wind, Temperature and Natural Ventilation," F. Sinden, Twin Rivers Note #6, June 1, 1976.

"Preliminary Winter Retrofit Data," D. Harrje, Twin Rivers Note #3, March 1976.

Publications

"Energy Utilization in a Residential Community," Energy: Demand, Conservation and Institutional Problems, R. Socolow and R. Grot, ed. by M.S. Mackrakis, M.I.T. Press, 1974.

"Energy Conservation in Housing: Concepts and Options," R. Socolow. To be published in the Proceedings of the Conference on Energy, the Environment, and Land Use, Rutgers University, ed. by G. Stenlieb, Rutgers University Press, 1975.

Efficient Energy Utilization: A Physics Perspective, report of the summer study of the American Physical Society on Technical Aspects of Efficient Energy Utilization, held at Princeton University, July 1974. (multiple authorship).

"Energy Conservation in Housing: The Twin Rivers Project," D. Harrje and R. Socolow. Proceedings of the NSF/RANN Conference on Energy Conservation Research, Airlie House, Va., February 18-20, 1974 (published by the National Science Foundation, 1975).

"Energy Conservation/Commercial Sector," R. Socolow-Chairman's Session Summary. Proceedings of the NSF/RANN Conference on Energy Conservation Research, Airlie House, Va., February 18-20, 1974 (published by the National Science Foundation, 1975).

"Energy Utilization in Townhouses in a Planned Community in the United States," R. Socolow. Prepared for delivery at the CIB W67 Symposium "Energy Conservation in the Built Environment," Garston, England, April 6-8, 1976.

APPENDIX H: DRAMATIS PERSONAE

I. Princeton University

A. Senior Researchers

John Darley
Gautam Dutt
Harrison Fraker, Jr.
Richard Grot
David Harrje
George Mattingly
Lawrence Mayer
Clive Seligman
Frank Sinden
Robert Socolow
Thomas Woteki

B. Graduate Students

John Fox
Jeff Jacobs
Nicholas Malik
Thomas Schrader
Robert Sonderegger

C. Undergraduate Students

Rosalind Alpert
Bradley Bellows
Heidi Bode
Anthony Caine, Jr.
John Cella
Malcolm Cheung
Karl Danz
David Donoho
Bruce Duncan
Jonathan Eckstein
Jon Elliott
Rick Ferris
Steven Fisher
Miles Gessow
Michael Guerin
Shawn Hall
William Holstein
Cindy Horowitz
John Kadyszewski
Jeff Kang
Raymond Kang
Sylvia Kuzmak
David LaPlante
Andrew Lazarus
Robert Levin

Peter Maruhnic
David Matchar
Herbert Mertz
Walter Moberg
Donald Niemiec
Mark Nowotarski
Gene Peters
Alison Pollack
Mark Ramsey
Lauren Sarno
Stewart Sender
Molly Sherrick
Linda Shookster
Francis Sweeny
Johnny Yeung
Douglas Zaeh
David Zuckerman

D. Faculty Advisors

Irvin Glassman, Director, Center for Environmental Studies, 1973-
George Reynolds, Director, Center for Environmental Studies, 1971-73

Farrell Bloch
Peter Bloomfield
Robert Geddes
Robert Gutman
Suzanne Keller
Norman Kurtz

E. Technical Staff

Jack Cooper
Roy Crosby
Kenneth Gadsby
Victor Warshaw
Richard Whitley

F. Research Associates

Corinne Black
Cal Feinberg
Judith Hunt
Jeffrey Robinson
Elizabeth Schorske

G. Administrative Staff

Deborah Doolittle
Jean Wiggs

II. Advisory Committee

James B. Comly, General Electric Corporate Research and Development, Schenectady, N.Y.

Maurice Gamze, Consulting Engineer, Gamze, Korobkin, and Caloger, Chicago, Illinois

William Schluter, former Senator, State of New Jersey

John Senders, Department of Industrial Engineering, University of Toronto, Ontario, Canada

Charles F. Sepsi, Professor, Dept. of Mechanical Engineering, Ohio State University

Bernard Spring, Dean, School of Architecture, City College of New York

N. Richard Werthamer, Director, New York State Energy Research and Development Administration

John Tukey, Professor, Dept. of Statistics, Princeton University

III. Program Supervision

A. National Science Foundation -- RANN

Paul Craig
Harold Horowitz
Raymond Radloff
Alex Schwarzkopf
David Seidman
Thomas Sparrow
Charles Thiel
Seth Tuttle
William Wetmore

B. Energy Research and Development Administration -- Conservation

Lynn Collins
Gerald Leighton
David Pellish
Maxine Savitz

IV. Collaborators at the National Bureau of Standards

Jacquie Elder
Lawrence Galowin
Richard Grot
Frank Powell
Dan Quigley
Lynn Schuman
Jack Snell
Heinz Trechsel

V. Subjects of Interviews (1972-74)*

Original Developer

Gerald Finn, President, The Nilsen Group, New Hope, Penn. 1964-1968

The Developer's Staff: Twin Rivers Holding Corporation

Aaron Kenton, Vice President
Arthur Rothschild, Vice President, Finance
William Lynch, Vice President, Sales and Marketing

Architects

Robert Hillier, assisted by Edward Wilson, Princeton, N.J.
William Conklin, Conklin and Rossant, NYC, original architect 1964-1968 (Whittlesey and Conklin 1964-1966)

Town Officials of East Windsor

Dana Miller, Town Manager 1970-1972
Richard Lee, Selectman 1964-1969

Planning Board, East Windsor

John Orr, Chairman, Member, 1968, Chairman 1969-1971, 1972 to present
Douglas Miller 1971-1972
Wm. B. Harvey, Secretary, 1963-1971 and Town Engineer to 1971
Wm. E. Harvey, Chairman 1968-1969
Eugene O'Connor, Vice-Chairman 1968-1969

Inspectors

George Hill, East Windsor Township, Chief Building Inspector
Robert Aasen, East Windsor Township Building Inspector
Thomas Tang, Inspection Division, State Department of Community Affairs
Abe Marland, Veterans Administration, Site Inspector

---

*Interviews were conducted by Harrison Fraker, Assistant Professor of Architecture and Elizabeth Schorske, Research Associate of the School of Engineering.

Utilities

Ted Bowman, Public Service Electric and Gas Co. Sales Representative, Princeton, N.J.
Donald Philipps, Public Service Electric and Gas Co. Industrial-Commercial Representative, Princeton, N.J.
Thomas Brennan, Public Service Electric and Gas Co. Sales Manager, Trenton, N.J. (Formerly Princeton office)
Norman Foy, Jersey Central Power and Light Sales Manager, Morristown, N.J.
Arthur Chasey, Jersey Central Power and Light, Builder Representative, Lakewood, N.J.
Wm. Farrer-Baynes, Oil Heat Council of New Jersey, Director, Technical Division, Springfield, N.J.
Fred Bauer, East Windsor Municipal Authority (sewer and water), Superintendent, East Windsor, N.J.

Board of Public Utilities Commissioners, Newark

Charles Sheppa, Principal Engineer, Engineering Division
Michael Mehr, Hearing Examiner

Installers (HVAC systems)

Sterling Apgar, Apgar Heating and Cooling, Quad I.
I.Harris, Harris Heating, Quad II and III

Construction Supervisor

Barry Fiske, Kendall Development Corporation

Civil Engineers

James Kovacs, Kovacs, Inc. Civil Engineers for Twin Rivers, 1971 to present
Peter Tobia, Engineer formerly with Kovacs, Inc. Twin Rivers Holding Corporation (1971), currently Department of Community Affairs

Veterans Administration

Thomas McCarthy, Chief, Construction and Valuation Section

Residents

Charles Matteson, President Home Owners Association 1971-1972
Myra Epstein, Twin Rivers Ecology Committee 1971-1972
Six residents: highest and lowest energy users.

Consultants

Corinne Black, Graduate student in anthropology
Suzanne Keller, Professor of Sociology and staff
Robert Gutman, Professor of Sociology, Rutgers University and
Princeton University School of Architecture