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The Twin Rivers Program on Energy Conservation in Housing: Highlights and Conclusions*

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Key results and conclusions of a five-year field study of residential energy use are reviewed. Our multidisciplinary research is being undertaken in a set of nominally identical townhouses in Twin Rivers, New Jersey, a recently built community of standard construction with gas space heating, electric central air conditioning, and a full set of appliances.

Average levels of energy consumption and their dependence on weather and building type have been established, thereby permitting detailed quantitative studies of the sources of remaining variability. Starting from this baseline, we have established the level of change in energy consumption that followed the "energy crisis" in the autumn of 1973 and we have performed two kinds of controlled experiments: (1) experiments where a set of modifications (retrofits) are made to the building structure, and (2) experiments where "feedback" is provided to residents, on a regular basis, reporting their level of consumption of energy. Conclusions drawn from our modeling and experimentation are presented here, with emphasis given to those results bearing directly on the character of programs to retrofit the national housing stock.

Photographs of the site, of building defects, and of our retrofits are included, as well as a selection of graphical displays of data, each a snapshot of a kind of analysis we have found useful and are prepared to recommend to others who wish to help develop an understanding of how houses work.

Lists are included both of the program's reports and publications and of the people who have contributed to the Twin Rivers program since its inception.

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INTRODUCTION

Since July 1, 1972, our research group in 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 water heating and air conditioning. 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 (19 km) from our campus, where about 12,000 people are living in approximately 3000 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, and placed instruments in thirty-one townhouses (all identical in floor plan). One of these townhouses we have rented and occupied ourselves, turning it into a field laboratory. Our sponsors have been the National Science Foundation since 1972 and the Energy Research and Development Administration since 1975.

Section I of this report, "Principal Goals and Conclusions", presents our major messages for the policymaker. They address four subjects: (1) the effective retrofit; (2) the effective pilot program; (3) the role of the resident; (4) the larger context of space heating. In addressing the effective retrofit, we emphasize that real houses depart in important ways from the textbook idealization of the house as a warm box sitting in cold air. There are usually numerous ways of reducing energy consumption in real houses that are at least as cost effective as those that textbook models prescribe, and that can best be detected *on site.* We envisage the evolution of cadres of workers with various levels of on-the-job training — workers having various employers, including themselves.

Diagnostic tools for these workers must include both simple methods of measurement and simple methods of data reduction. For the most part these do not exist. Our research program has addressed the question: given an hour or a day in a house, and the objective of advising on the most effective strategies to reduce energy consumption, how should those giving advice spend their time?

Answers to this question will come, in part, from carefully structured pilot programs, on the scale of our program or larger. Ours might be considered a pilot study of pilot programs, and it provides insights into the opportunities and limitations inherent in disciplined, subsidized projects where a set of houses are modified and the resulting changes are monitored and interpreted.

Our data confirm the significance of resident behavior in determining energy consumption. We have been testing ways of helping the resident to conserve by providing feedback, and we have obtained some clues about attitudes and beliefs that differentiate residents according to level of energy use.

Although most of our conclusions bear particularly on energy conservation in space heating, several conclusions emphasize that space heating must be considered in the context of all uses of energy in the house — especially in the U.S.A., where energy used by appliances has been increasing much faster than energy used by heating systems. This report does not explore the still larger context of energy in buildings — the economic and social forces that have led to a housing stock so far from optimal. Nonetheless, the reader will appreciate that successful implementation of programs responsive to our conclusions requires a sophisticated understanding of a housing market that has long been skewed to respond to first costs rather than operating costs. The historic reluctance of government to invest resesearch and development funds in end-use technologies, relative to production technologies, will also thwart implementation unless confronted and overcome.

Sections II and III are cinematic. Section II contains 10 pages of photographs that give an orientation to our program and a brief history. Section III contains 10 pages of figures with annotations. Each figure is a snapshot of a kind of analysis we have found useful and are prepared to recommend to others who wish to help develop an understanding of how houses work.

Of the many reports generated in our research program, this is the one most directly aimed at the policymaker who needs a distillation of results and a general impression of how they were obtained. Those interested in experimental design, in the methodologies of data reduction, and in instrumentation are advised to turn to our other reports, many of them listed in Appendix A.

Appendix B, the *dramatis personae,* has been included in this summary as perhaps the most straightforward way of conveying the magnitude of the effort already expended. The concluding Acknowledgements begin to assign the credit due to my colleagues for leadership, imagination, and sheer hard work. There can have been few programs as interactive across disciplines and as freewheeling in choices of problems pursued.

Buildings and energy is an established field, but one acknowledged, first of all by its practioners, to be in need of new blood. The fluidity of our own program these past five years was fostered deliberately by both ourselves and our sponsors, in order to enhance the likelihood that interesting new *questions* would be found, not only answers to old questions. Assessments of our experiment in research style must begin with assessments of what we now have to say.

There are other important new questions, that have hardly been addressed. Foremost among them, perhaps, are those which concern a fuel shift at the furnace. In 20 years, it is quite possible that Twin Rivers will not be heated by natural gas. How to shift space heating away from oil and natural gas in much of the world, over a period of probably not more than 50 years, is a problem whose detailed formulation and clarification will require many times the level of effort currently engaged in research on energy conservation in housing. We expect that many of the research techniques developed over the past five years at Princeton will be helpful in this next effort.

Section I. Principal Goals and Conclusions

GOAL No. 1. The effective retrofit: To clarify the technical requirements for an effective national program to retrofit the existing housing stock to reduce the energy consumption for space heating.

Real houses

An effective retrofit program must emphasize measurements in actual houses. The textbook idealization of houses as simple shells with well defined levels of insulation, which underlies nearly all legislation and regulatory activity, has serious shortcomings. This idealization directs attention nearly exclusively to levels of insulation in the walls and roof and to window glazing, but once there is some insulation in place in all surfaces, attention must be directed more widely. Real houses reflect a haphazard accommodation to efficient energy utilization; both good and bad design, as far as energy is concerned, are largely accidental. As a result, attention to a range of issues more difficult to model but no less difficult to appraise in the field frequently should become the first order of business.

For example, one target for the field assessment of the thermal performance of a building will be the semi-exterior volumes, those volumes which, because of patterns of use, can be kept considerably colder in winter and warmer in summer than the living space. The Twin Rivers basement, whose volume is 50% of the volume of the living area, is frequently warmer than the living area in winter and colder in summer, because it contains the furnace and uninsulated ducts. The Twin Rivers attic, in spite of substantial floor insulation, provides unintended heat loss mechanisms through air exchange with the basement and through conductive links across the upstairs walls that short circuit the attic floor. Both basement and attic have proved worthy targets for design-specific retrofits. In other dwellings, semi-exterior spaces might include hallways, crawl spaces, and attached garages.

Other targets for a field assessment of thermal performance include: the levels and paths of air infiltration; the heat distribution system and its controls; the performance of the windows as solar collectors; the fraction of appliance-generated heat recovered within the living area. Our experience at Twin Rivers suggests that some of the shortest payback periods for specific retrofits are associated with a house "tune up" that addresses these issues.

Diagnostic methods

Cheap and simple diagnostic field tests can be devised to determine those parameters of a house which help discriminate among retrofit strategies. We have shown, for example, that the efficiency of delivery of heat from a furnace can be clearly separated from the quality of heat retention by the shell of the house, when an electric heater is run intermittently in the house for a test period, modulating the heating ordinarily provided by the furnace. Such a test can help decide whether to emphasize the furnace or the shell in a retrofit program. Other tests being pioneered in our research include (1) on-the-spot measurements of air infiltration rates, either by bag sampling or by continuous injection to maintain a constant concentration of tracer gas, (2) rapid assessments of the effectiveness of attic insulation by simultaneous reading of interior, attic, and outside temperature, (3) measurements of heat capacities by regular readings of interior temperature as it "floats" with the furnace shut off, and (4) assessments of furnace and distribution system by frequent (once-a-minute) temperature readings during a furnace cycle. Although all of these tests need further development, they appear at this point to lend themselves to routine implementation in the field, with hard-wired minicomputer programs more than adequate to reduce output to useful form.

Performance indices

Energy consumption in housing can be usefully discussed in terms of a simple performance index analogous to the miles per gallon (or, more precisely, gallons per mile) performance index for vehicles. The index has units of energy per degree-day. (The degree-day is a measure of the coldness of a time interval.) The Twin Rivers townhouse, for example, functions at about 30 MJ/°C-day in SI units, or at about 15 ft^3/°F-day in the energy units registered by conventional U.S. gas meters.

This performance index has shortcomings, but to the extent that we have been able to examine this index at Twin Rivers, in several extensive investigations, these appear less serious than we had expected, and no more serious than those which make miles per gallon an imperfect measure of vehicle performance. Analogous to the specification of a standard driving cycle for automobiles, one might want to specify the average outside temperature (say, 32 °F = 0 °C) and the duration of the measurement (say, one month). The index is less precise when the outside temperature is warmer or the duration of the measurement is shorter, but straightforward modeling procedures can be used with considerable confidence to extract the performance index from data obtained in milder weather or over shorter periods of time. For example, we have found average monthly gas consumption at Twin Rivers to be more nearly proportional to a modified measure of degree days, where a "best" value of 62 °F (16.7 °C), estimated from our data, is used as the reference temperature for the calculation of degree days, rather than the conventional reference temperature of 65 °F (18.3 °C) used by the U.S. National Weather Service.

Energy consumption for space heating is likely to be proportional to degree days (with a suitable reference temperature that must be independently determined) for most houses and furnaces in most climates. Straightforward data analysis can be used to include effects such as sun and wind if they have large seasonal fluctuations or directional biases.

Lower inside temperature

Relative to most other quantitative statements about energy conservation in residential heating, estimates of the savings obtainable from lowering the inside temperature are less uncertain. This is because all of the dominant heat loss mechanisms for a house are nearly proportional to the temperature difference between indoors and outdoors. Consider Fig. 1, which is a schematic rendition of several important issues. Vertical distances represent temperature differences, and the area bounded by the thick broken line (constant interior temperature) and the curve (a year's average daily outside temperature) is proportional to the annual heat loss. This heat loss is seen to be replaced in part by heat from the furnace (area below the heavy solid line) and in part by heat from the sun, appliances, and people (area above the heavy solid line). Fixing the interior temperature at a lower value (while making no other changes) results in a smaller annual heat loss, proportional to the area bounded by the thin dashed line and the curve. The resulting reduction in the heat required from the furnace is proportional to the area of the horizontal strip between the thick and the thin solid lines.

The fraction of annual energy consumption at the furnace that is saved by lowering the interior temperature one degree is given (in this simple model) by the length of the heating season, in days, divided by its severity, in degree days, both referred to the outside temperature below which the furnace is required. Figure 1 shows an initial interior temperature of 72 °F (22.2 °C) and a contribution from heating by sun, appliances, and people that lowers the temperature at which the furnace is first required by 10 °F (5.6 °C) to 62 °F (16.7 °C). The curve of outside temperature in Fig. 1 is the National Weather Service's average daily temperature profile for Trenton (15 miles from Twin Rivers). The savings at the furnace are found to be about 220 days/4200 °F-days, or about 5% per °F reduction (9% per °C reduction) in interior temperature, for locations near Trenton.

Lowering the interior temperature for part of the day gives proportionately smaller savings that nonetheless are significant. For example, lowering the interior temperature at night by 10 °F (5.6 °C) for eight hours (in a house of light enough construction to fall rapidly to the lower temperature setting) results in a savings of roughly $1/3 \times 10 \times 5 = 17\%$ in annual energy consumption at the furnace. This makes "night set-back" (and day set-back, as well, when houses are unoccupied for a period of the day) one of the most attractive strategies for retrofit programs — one, moreover, largely complementary to those which address the furnace and shell.

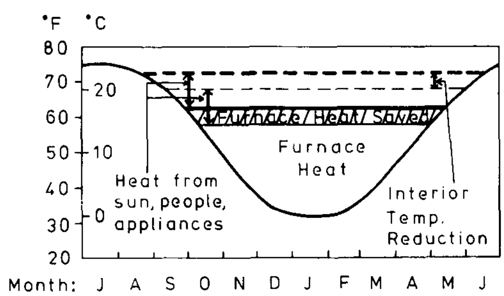


Fig. 1. Reduction in furnace heating when interior temperature is lowered.

Solar energy

Houses are already heated by solar energy, which substitutes for energy at the furnace when it enters through windows (and, to a lesser extent, through walls). At Twin Rivers, gas consumption at the furnace provides 60% of the annual space heating (compare Fig. 1), appliances 20%, body heat from occupants 5%, and solar energy 15%. All attempts to increase the efficiency with which incident sunlight displaces energy consumed at the furnace are directly comparable, from a public policy standpoint; those which improve the retention of incident sunlight (like better insulation) are equivalent to those which increase the amount captured. At Twin Rivers, enlarging the south window and giving it shutters, a strategy we are currently studying, is a cheaper approach to partial solar space heating than installing a collector on the roof; as long as one is not trying to cut loose entirely from the existing energy supply systems, the same conclusions will apply widely. A serious problem with very large windows — overheating of the living space in mild weather — needs solutions based on architectural design, thermal storage and internal air movement that remain to be developed.

Side effects

The national retrofit program is imperiled by universal ignorance about the side effects of prominent retrofit strategies, in areas of health, safety, and comfort. As a case in point, our measurements of the range of air infiltration rates in a single house obtained under varying conditions of outside weather draw attention to the possibility of creating an overtight house in low wind and mild weather in the process of reducing average air infiltration rates; but "overtight" is imprecisely understood at present. Other effects in need of research would appear to include health effects of insulation fibers, effects of humidity on the durability of materials, and possible conflicts with both noise control and fire prevention.

Learning by doing

Because quantitative indices (like energy per degree day) are easily employed to obtain rough indications of the savings obtained in retrofit programs, the monitoring of programs as they occur should be relatively inexpensive and instructive. Such monitoring can have high pay-off. In the U.S.A., alone, there are more than sixty million homes, and in nearly all of them retrofitting is warranted. Only a small proportion of these homes will be retrofitted each year, and many initially unfamiliar situations will be encountered again and again. The first retrofits will not be as cleverly designed or as cost-effective as those a decade from now. But improvement will come much more quickly if provision is made in the early retrofit programs for detailed evaluation of the level of success achieved.

GOAL No. 2. The effective pilot program: To clarify the role of controlled field experiments and demonstration programs in the evaluation of specific retrofits and retrofit packages

Uncertain outer limits of savings

The outer limit of financially sensible conservation cannot be probed without an aggressive field program, based on a succesion of retrofits. First-round retrofits may be expected both (1) to include some which, upon subsequent evaluation, turn out to have a low return on investment and (2) to omit retrofits that have high returns. In our program, unanticipated and significant channels for heat loss revealed themselves only as known channels were closed off. Even our second round of retrofits, which appears to have reduced annual gas consumption to one-third of the pre-retrofit value, has not exhausted the list of cost effective retrofits at Twin Rivers.

Uncertain estimates of savings

Without the underpinning of field experiments under controlled conditions, quantitative claims for percentage reductions in energy consumption associated with specific retrofits will be and should be viewed skeptically. Our first-round retrofit experiments with 8- and 16-house samples showed a wide spread in the size of the effects obtained, not easily attributable to prior differences among houses. Our standard retrofit package reduced energy consumption for space heating by 15 - 30%, with interior temperatures unchanged. Apportioning the savings among the components of the package (addressing attic, windows, and basement ducts) has proved difficult, and effects are probably not additive. Pilot programs to estimate savings should not use samples any smaller than ours.

Uncertain estimates of costs

The dollar costs of retrofits are difficult to assess, because most retrofits are labor-intensive yet not very difficult to perform. Costs, therefore, are sensitive to the treatment of the residents' own labor in the accounting. Several retrofits that have been slow to spread at Twin Rivers have very low costs if performed on a do-it-yourself basis. This suggests that one objective of demonstration programs should be the investigation of how confidence and skill can be generated in a community such that specific labor-intensive retrofits, once ignited, will be adopted widely.

Early warnings

The side effects of retrofits (see above) are likely to be visible even in small experiments. *Positive* side effects in terms of increased comfort were found in the Twin Rivers retrofit program, when increased attic insulation and decreased basement duct losses reduced an inequality (perceived to be annoying) between temperature upstairs (cold) and downstairs (warm). Gaining familiarity with positive and negative side effects appears a significant reason to conduct controlled experiments.

GOAL No. 3. The role of the resident: To clarify the role of behavior in energy consumption for space heating

The resident matters

The observed variation in energy consumption for space heating (in townhouses with identical floor plans, furnaces and appliances) is primarily assignable to the resident rather than to structural features that persist independent of the resident. Strongest evidence comes from studies of houses where there has been a change of owner; new occupants of the same structure have consumption levels nearly unrelated to their predecessors. Additional evidence comes from studies of houses receiving common retrofits: the rank ordering of consumption (highest, second highest, etc.) remains largely intact in spite of major physical modifications.

Variations among residents

Profiles of the high and low users of energy have proved to be very difficult to establish. Relative use of energy in summer correlates with only a few answers to questions designed to probe attitudes, preferences, and general knowledge, posed in questionnaires administered to Twin Rivers residents. Attitudes toward expending *effort* to conserve energy are particularly salient, as captured, for example, in the degree of agreement with the statement: "It is *just not worth* the trouble to turn off the air conditioner and open the windows every time it gets a little cooler outside". Also significant are beliefs about comfort and health.

Our questionnaires have been even less definitive in illuminating the reasons for variation in winter, other than beliefs about comfort. Moreover, it is still unclear what specific behavior brings about high or low energy consumption for space heating, other than choice of interior temperature. There is very little window opening at Twin Rivers in winter. Opening of outside doors, positioning of interior doors, and management of drapes are probably all associated with variations in gas consumption, but this remains to be proved.

Feedback

Residents of Twin Rivers reduce their summer electricity consumption by 10 - 15% and their winter gas consumption by up to 10%, when information about their level of consumption is supplied on a daily basis in controlled "feedback" experiments. Such savings were anticipated by our psychologists, who look on energy conservation as a problem in learning new skills. Our results lead away from the meter in the basement and the bill in the mail that record consumption in inscrutable units. The analog of the future meter is the sportscar's dashboard, giving consumption (in money units?) separately for the major appliances, with buttons to reset some meters to zero. The future bill makes comparisons with one's own past performance and with the current performance of one's peers.

The response to the "crisis"

At Twin Rivers, the alteration in the pattern of energy consumption that followed the "energy crisis" during the autumn of 1973 can be approximated by a one-shot, 10% response, occurring during the 1973 - 74 winter, with no subsequent relaxation but (through the 1975 - 76 winter) only minimal further conservation. The response occurred across all levels of consumption (high users and low users) and was greater (in amount of energy saved) in colder weather. The response must have taken the form, primarily, of lower interior temperatures, because it occurred too quickly to reflect retrofitting. The response may be described as price anticipation, since the price of gas rose steadily, not abruptly. (During the period 1971 - 76, the price approximately doubled, in current dollars, and rose 50% in constant dollars.) Alternatively, it may be described as a prompt response to a pulse of exhortation and information.

GOAL No. 4. The larger context of space heating: To clarify the relationship of energy conservation in space heating to energy conservation elsewhere in the residential sector of the economy

Appliances

Energy conservation in domestic appliances is receiving inadequate attention, given its relative magnitude and the potential for retrofit and replacement. Over a year, the Twin Rivers resident spends more money on water heating than on space heating. (The 8000 kWh of electricity used annually for water heating corresponds to 100 GJ of coal or oil consumption at the central station power plant, compared to 80 GJ of gas consumption at the home furnace, so water heating is also more costly in energy terms.) Nearly as much dollar expense and energy consumption is associated with the combined tasks of air conditioning and refrigeration as with space heating. A simple retrofit to the water heater at Twin Rivers, in the form of a jacket of insulation to reduce losses from the tank, reduces the electricity used by the water heater more than 10% and has a payback period of less than a year.

Systems within a house

Energy conservation in domestic appliances should not be considered in isolation from space heating. At Twin Rivers, about 20% of annual space heating is already provided by appliance heat, and the potential is present to reach 40% through improved retention of appliance heat (especially, waste hot water) in winter. Appliances, moreover, may be usefully coupled together (for example, the refrigerator rejecting its heat into the water heater) so as to reduce energy consumption simultaneously for two or more services. We have been struck by the particular potential for encouraging such innovation at the time of construction of communities, like Twin Rivers, where the builder supplies the basic appliance package and purchases hundreds of identical models at one time. With appropriate subsidies, such communities become laboratories for field research on appliance systems.

Scale

Consideration of Twin Rivers as a community reveals that the residents spent about 2.5 million dollars for gas and electricity in 1975, \$800 per dwelling unit in 3000 dwelling units. The community consumed gas at a rate of 200 million ft^3 (6 million m^3) per year and electricity at an average rate of 6 MW. There is an obvious need to investigate economies of scale in energy systems at the 10-house level (the townhouse building), at the 50-house level (the street of buildings), at the 300-house level (the "quad") and at the level of the community as a whole (which also contains shops, offices, and light industry). Energy end-use systems at all of these scales are totally absent at Twin Rivers, with the exception of some water heating on a 10-unit scale where there are rented apartments. Several promising technologies, among them thermal energy storage (including annual storage) and on-site cogeneration of electricity and heat, might play a central role in advanced retrofits in communities like Twin Rivers and might be usefully assessed in communities where good data at the single-house level already exist.

Summers

Energy consumption for air conditioning shows even more variability at Twin Rivers than energy consumption for space heating. Moreover, the levels of consumption for air conditioning and for space heating are uncorrelated across houses. In response to the energy crisis, there appears to have been no conservation in summer electricity consumption, half of which is for air conditioning, even though opportunities for conservation (at the thermostat, front door, etc.) are as readily available as in winter space heating.

The modeling of the summer energy balance of a house is complicated by the absence of any single term as dominant as the losses due to conductive heat flow in the winter energy balance. Yet careful models that include solar effects, variable air conditioner efficiency, humidity, appliance heating, and thermal storage are a necessary precondition to the refinement of cost-effective retrofits to reduce summer electricity consumption.

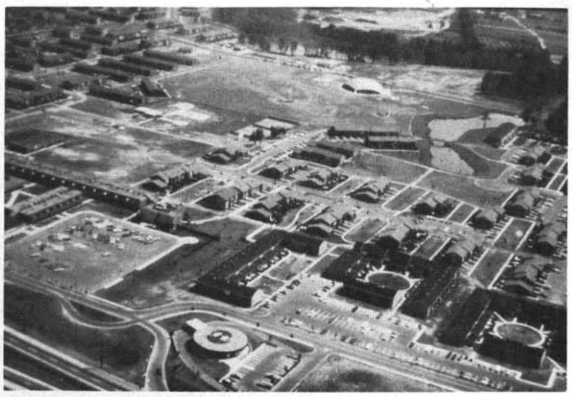
Section II. A Photographic Tour of the Program

The ten pages of photographs in this Section were taken by various members of the research group over the past five years. They should offer a quick grasp of the program.

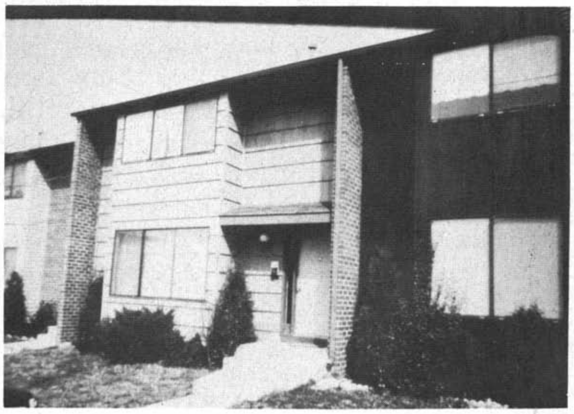
Photo Page 1: The Site

Roughly one-fourth of the houses in Twin Rivers, New Jersey, may be seen in the aerial view shown (top). Twin Rivers was New Jersey's first Planned Unit Development, and its beginnings are associated with new state and local zoning legislation to permit a mix of industrial, commercial, and residential structures, the latter including detached houses, townhouses, and apartments [1 - 3]. Twin Rivers is governed as a portion of East Windsor township. In an average year, the heating degree-days total 4900 °F-days (2700 °C-days), based on a reference temperature of 65 °F (18.3 °C).

Also shown (bottom) is the townhouse rented by our program. It is located in the townhouse complex (Quad II) at the top left of the aerial photo, where most of the other nominally identical townhouses studied in our program are also found. These townhouses are of conventional construction, with masonry bearing walls and wood framing for floors and roof. They provide approximately 720 ft^2 (67 m^2) of space on each of two floors, above a full, unfinished basement. They sold for approximately \$30,000 when they were built in 1972, and they sell for about \$40,000 now (1977).



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.



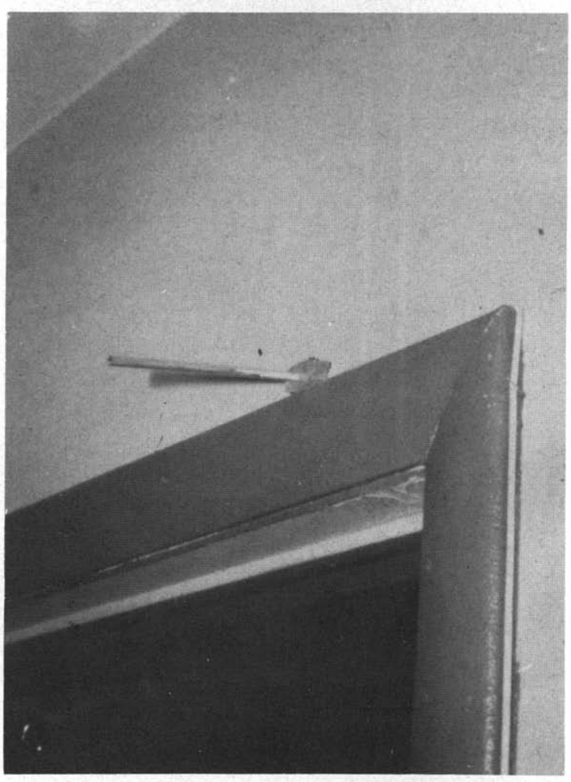
Front view of Quad II townhouse rented by Princeton. Masonry firewalls project beyond the structure in brick. Central projection (with windows of living room and master bedroom) terminates one foot above ground level (behind bushes).

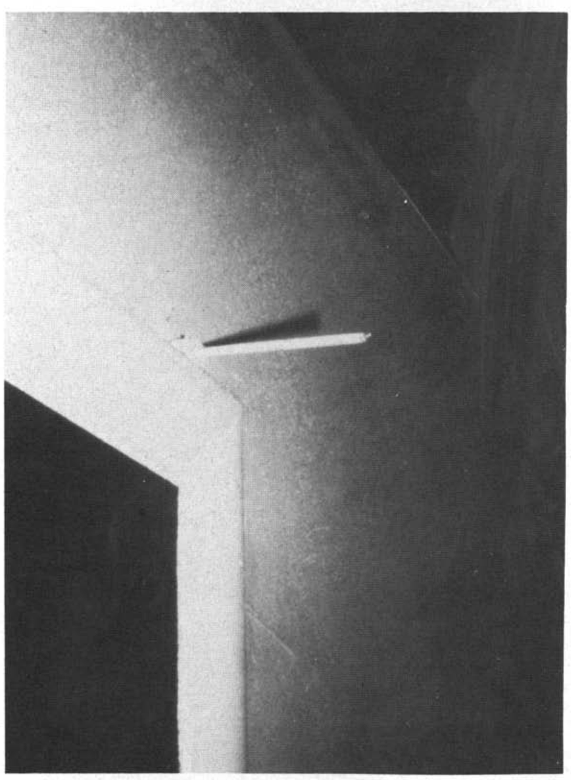
Photo Page 2: Identical Houses

This Page shows two thermistors measuring "hall temperature" above the door to the basement in two of the more than thirty three-bedroom townhouses where we have made that same measurement. The pair of photographs symbolize our attempt to standardize not only houses but also measurements. Thereby, experimental artifacts are highly unlikely to be the source of observed house-to-house variations in interior temperature, or in appliance use, or in furnace gas consumption [4].

Several further sources of variation are largely absent in our sample. Nearly all of the families have small children, typically one when they moved in and another since. Their townhouse is the first home most families have owned. Many of the adults grew up in apartment houses in New York City. About half are Jewish; 96% are white. Nearly all of the wage earners are mobile professionals, and many of them commute to New York City on buses that leave Twin Rivers every five minutes in the morning. [The town is one-half mile (1 km) from Exit 8 of the New Jersey Turnpike, and the 50-mile (80 km) trip takes 55 minutes.] The annual family income of townhouse owners at the time of purchase averaged $20,000, and it did not vary greatly.

However, the residents of Twin Rivers townhouses are far from a homogeneous population in many other respects. They differ in their "temperature preference", interior temperatures showing a standard deviation of about 2 °F (1 °C) in winter. They differ in their commitment to modifying their homes, such that six years after purchase some of the originally unfinished basements have dropped ceilings and paneled walls, while others are unchanged. They differ in level of knowledge about the equipment in their home, in their attitudes towards sun and towards dryness, and in their (at least expressed) concern for saving money. Psychologists have played a central role in our research program since 1974, and they have helped greatly in sharpening the exploration of this wide class of behavioral and attitudinal variables [5 - 11].





Type YSI #44204 linearly-compensated thermistors read temperature above door to basement in hallway of two "identical" townhouses.

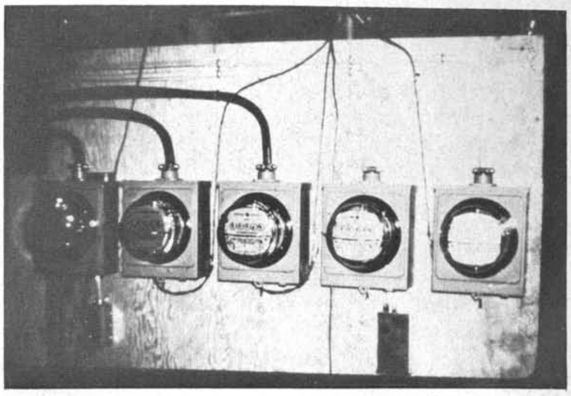
Photo Page 3: Appliances

The bank of electric meters that separates the electric load into its major components is seen in the upper photo. Our estimates of the major contributors to an average annual consumption of 16,200 kWh are:

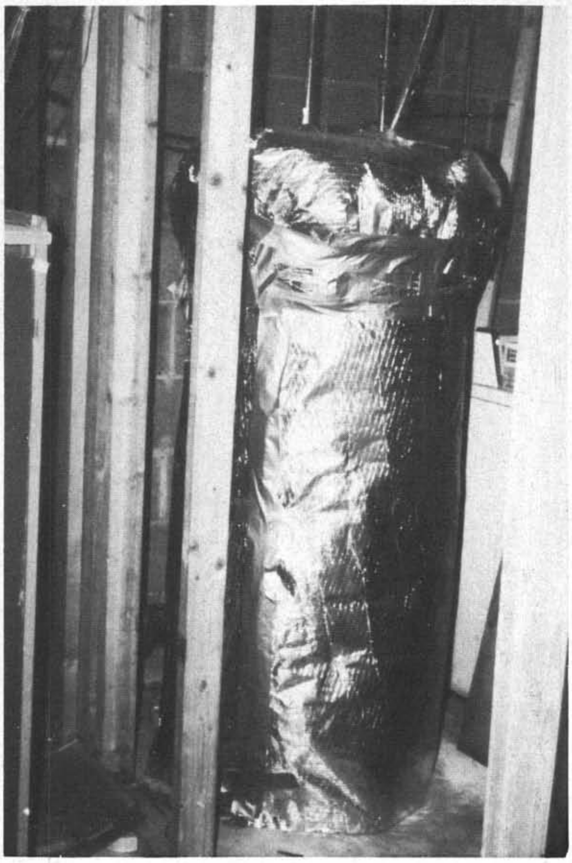
water heater	8000 kWh/year
air conditioner	2500
refrigerator	2000
range (cooker)	700
dryer	500
other	2500
total	16,200 kWh/year

Also shown (bottom) is a water heater, following a retrofit in which two inches (5 cm) of foil-backed fiberglass insulation are wrapped around the tank. The payback period for this retrofit is less than one year [12].

With a gas water heater, care must be taken to leave adequate air flow for combustion and exhaust gases.



Bank of electric meters in townhouse basement separate the usage of air conditioner, hot water heater, range, dryer, and everything else.

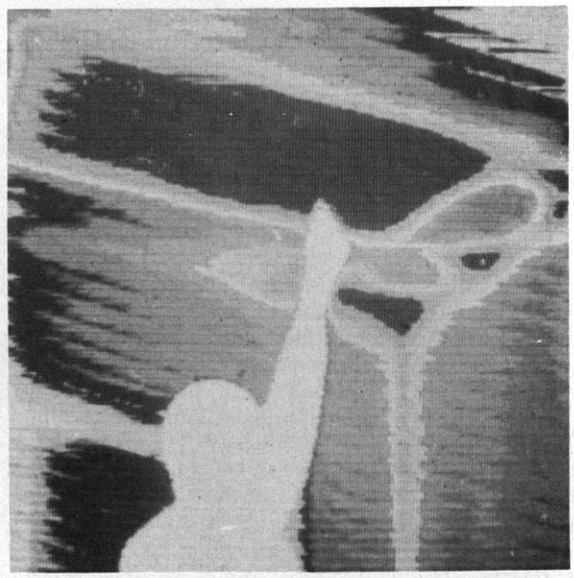


Electric water heater following retrofit. Wrapped in foil-backed R-7 insulation.

Photo Page 4: Looking for Trouble

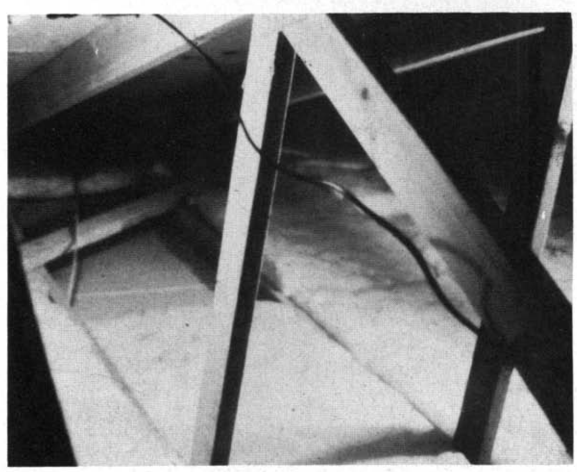
Richard Grot, now of the National Bureau of Standards and a principal investigator in the research program, 1972 - 1974, when at Princeton, is shown adjusting the controls of the Bureau's infrared camera [13] (below). The equipment is in the master bedroom. In another such bedroom, when the camera scanned the ceiling, it picked up a thermal anomaly, (top right). confirmed to be a missing panel of insulation (bottom right).

Infrared devices have been made smaller and less costly than the research device shown on this page. Surface temperature probes, moreover, often can be substituted for thermography. 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 problems in the thermal characteristics of a house with minimal time, minimal cost, and minimal bother to the resident [14 - 16].



Infrared photo reveals anomalous cold patch in upstairs ceiling.

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.



Cause of patch in upper photo is traced to missing batt of attic insulation.

Photo Page 5: Heat Distribution

The heat distribution system is a neglected subject in discussions of energy conservation in housing, but it offers significant opportunities for productive retrofits. Energy as hot air at the furnace plenum is distributed by forced convection through a network of ducts branching off the plenum and leading to nine individual registers located next to the outside wall in each room. The five ducts feeding the downstairs run along the basement ceiling, while the four ducts feeding the upstairs are embedded in the interior walls and in the first floor ceiling for about two-thirds of their length. In all, 160 feet (49 m) out of the 246 feet (75 m) of ducting runs along the basement ceiling, two views of which are seen here.

The entire hot air distribution system delivers only half of its heat to the rooms via the registers, one-third of the heat flowing initially into the basement and one-sixth flowing initially into the interior structure above the basement. Much of the heat not entering the living area through the registers nonetheless heats the living area, and it is not clear whether the flow of heat into the interior of the structure above the basement (in the spaces between interior studs, for example) should be avoided. But the loss of heat to a cold overhang, seen in these photos before and after retrofit, is surely undesirable [17 - 19].

Living room overhang at time of construction.

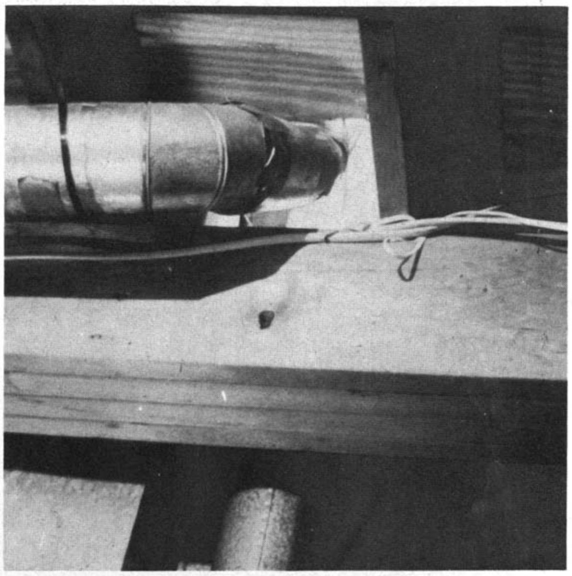
Ducts passing into living room overhang, casually insulated.

Insulation of duct and overhang, part of Princeton retrofit package C.

Photo Page 6: An Open Shaft

An adverse impact of building codes on energy conservation is revealed in these photos: an open wooden shaft, with a 1.8 ft^2 (0.16 m^2) cross-section is built around the flue. Many building codes require such a shaft to insure that the hot flue is not a fire hazard. The shaft at Twin Rivers is open top and bottom, and thus provides a path of communication for air moving between basement and attic. The view (top) of the shaft from below shows that this flow will be doubly enhanced when the furnace is firing, because a duct to upstairs runs through the lower part of the shaft. This shaft is one of several paths by which heat can reach the attic, which is unexpectedly warm, in spite of insulation. One of the less important paths is through and around the hatch to the attic, shown (bottom) being given a backing of insulation.

Our retrofit to the shaft is a tight-fitting fiberglass plug at the attic floor. The temperature at the surface of the flue at this elevation is about 130 °F (55 °C), compared to a char temperature for fiberglass of about 800 °F (430 °C). The plug, formed simply by wrapping the flue with a 4 ft (1.3 m) section of 6 in. (15 cm) unbacked fiberglass and pressing it tightly into the opening, not only improves the retention of heat but also reduces the likelihood that a fire could spread through the house [20].



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.

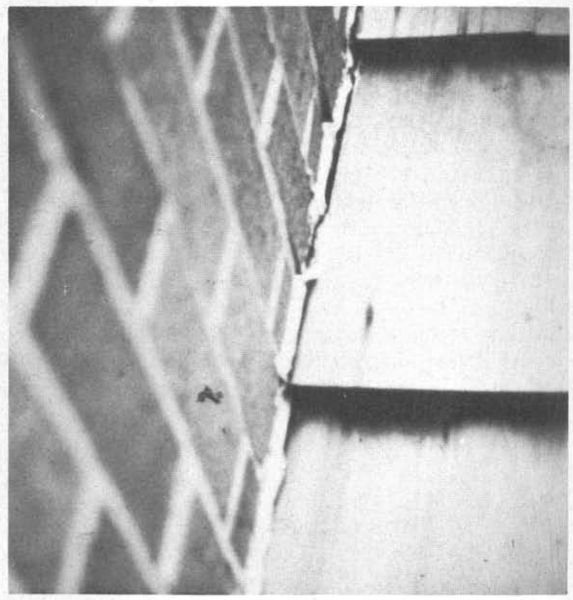
Insulation batt being stapled onto attic floor trap door, part of Princeton retrofit package A.

Photo Page 7: Other Open Passages

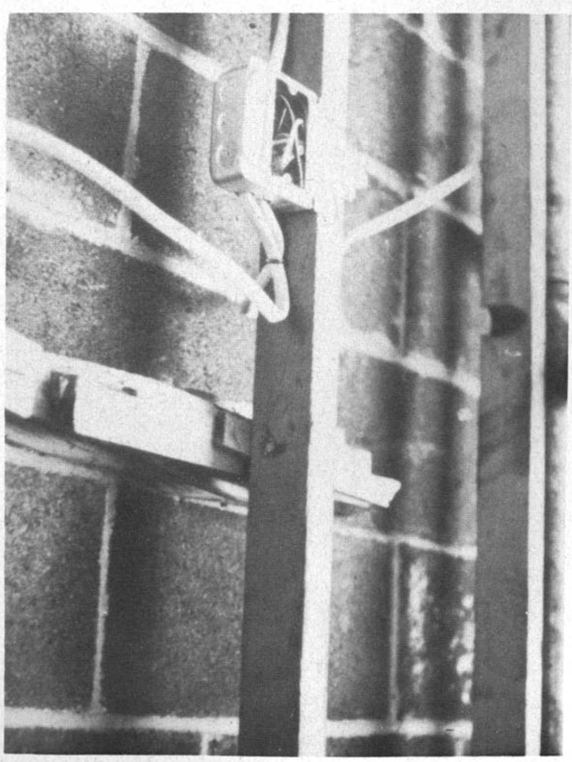
Additional unintended paths for air flow are created behind the interior side walls of the living area, as shown here. As a result of differential settling over time, a gap opens up between the floor joists and the masonry firewall that separates townhouses from one another (top right). The cross-sectional area for flow between basement and attic through these gaps ranges up to 1 ft^2 (0.1 m^2) in the Twin Rivers townhouse. Access to these passages behind the side walls (bottom left) is also provided through cracks in the caulking material that initially sealed the joints between firewall and both front and back walls (center right). The net effect is to open up paths for the movement of cold air into the firewall cavity from outside, and then into the basement and attic through the gaps [21]. In our retrofit program, we have both recaulked from outside and stuffed the gaps at attic and basement with fiberglass (bottom right) [20].

Defects such as the shaft shown in Photo Page 6 and the gaps and cracks shown here apparently degrade performance rather uniformly across townhouses. They have a measurable effect, for their repair leads to reduced consumption. On the other hand, these defects cannot be responsible for much of the observed house-to-house variation in gas used for space heating, because (1) such defects would be likely to persist when a townhouse changed owner, but (2) we have found almost no "memory" in a townhouse, when occupied by a new family, as to whether previously it was high or low on the scale of relative use of gas [22].

Gap at attic floor.



View of gap from outdoors. Caulking comes away at wood–masonry joint.



Gap at time of construction, downstairs.

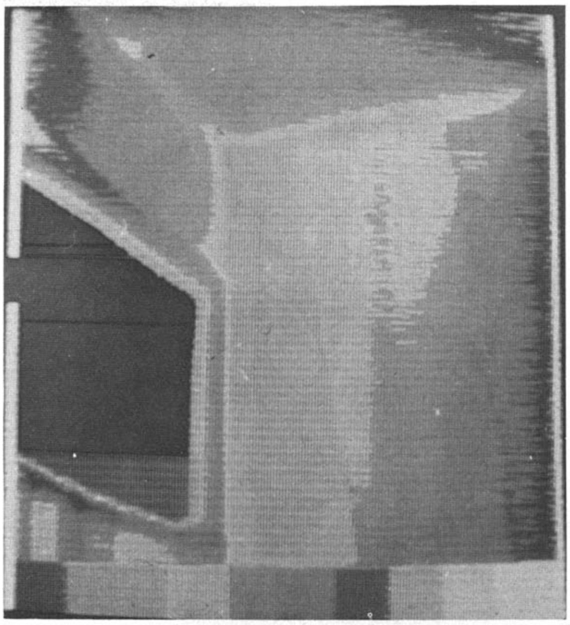
Plug of gap from basement by fiberglass, part of Princeton retrofit package B.

Photo Page 8: Cold Walls

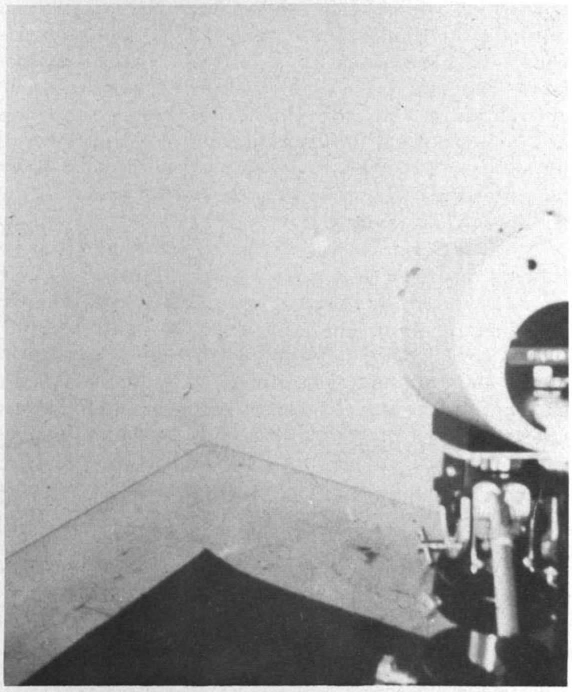
The National Bureau of Standards' infrared camera dramatizes the heat losses at the corners of the house through the *interior* walls that parallel the firewalls. The corner patterns seen on these photos (top right and bottom right) have proved to be the rule rather than the exception in inspections of more than ten townhouses [13]. These patterns shrink (for a given temperature scale) following retrofit, reflecting warmer surface temperatures. Much of the information about surface temperature is lost in these black and white prints, when compared to the colored thermographs that clearly distinguish ten temperature levels. (A temperature scale may be discerned at the bottom of the two infrared photographs.) The surface temperature of the window in the upper photograph has exceeded the temperature scale; the window is nearly always the coldest interior surface, even when double glazed.

Cold surfaces are readily perceived by the human body, as a result of radiative heat loss to these surfaces. Whereas the window may be covered by a curtain or drape when it is cold, the cold interior wall is not as easily dealt with and is widely perceived to be a source of discomfort at Twin Rivers.

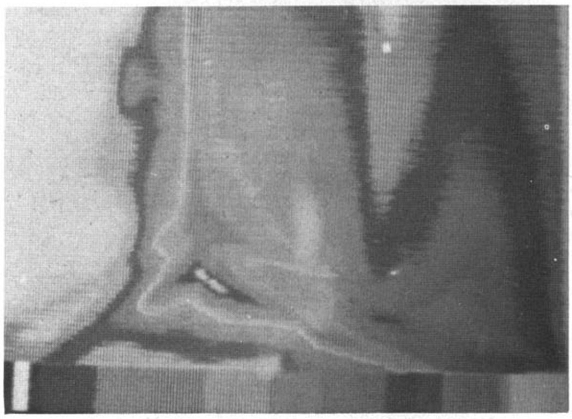
The upper right photograph was the cover (in color) of the August 1975 issue of *Physics Today*, to illustrate an article [23] giving highlights of the American Physical Society's summer study, "Efficient Use of Energy", held at Princeton in July 1974 [24].



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.



Infrared camera scans a corner, with outside wall to left, wall fronting a fire wall to 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.

Photo Page 9: Air Infiltration

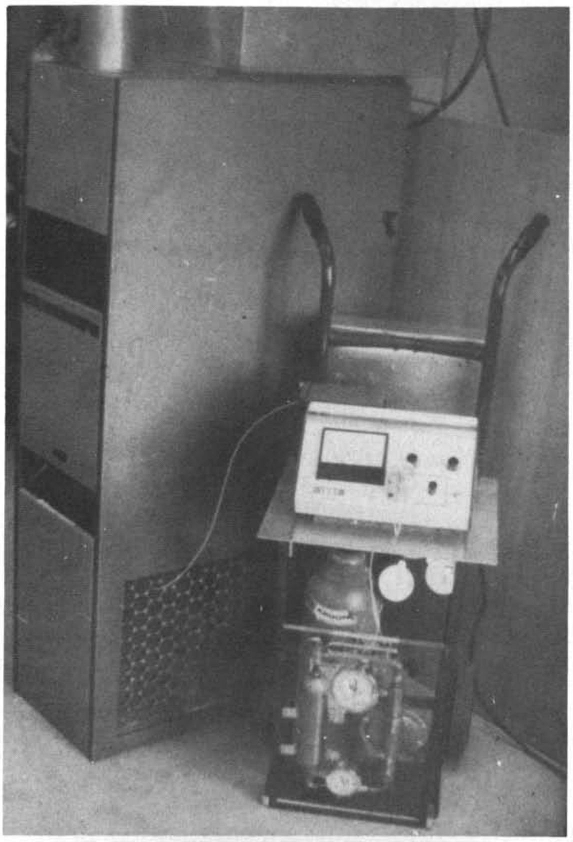
Once a house has wall insulation complying even with today's minimal standards, heat losses through air infiltration usually constitute at least one-third of heat losses through the shell. Very little is known about these heat losses, which are driven by outside weather forcing air through a multitude of cracks — in contrast to what happens in a modern commercial building, where forced ventilation is almost entirely controlled by electrically driven fans forcing air through clearly defined passages.

Instrumentation to measure air infiltration rates in houses (top left) has been developed over several years, in collaboration with the National Bureau of Standards [25, 26]. Using the hot air distribution system, about 10 cm^3 of sulfur hexafluoride (SF_6) are injected into the house (whose volume is about 3×10^8 cm^3, 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, when reinjection occurs. The rate of decay of concentration is a measure of the air infiltration rate. Measured values range from 0.25 to 2.5 exchanges per hour, and average about 0.75 exchanges per hour.

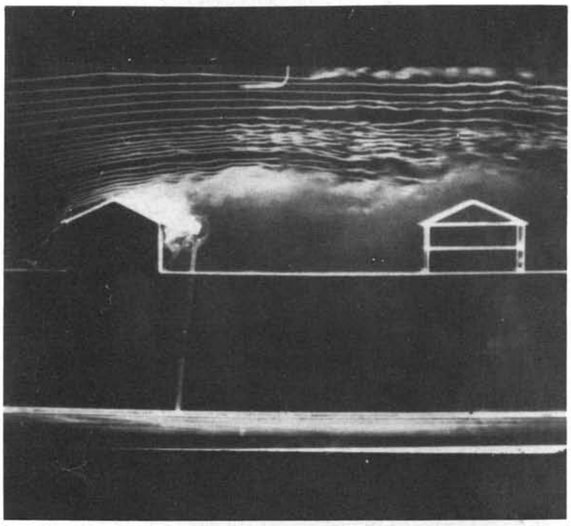
The very large exchange rates occur in high winds. (In fact, the design day for sizing of a home furnace should be a very windy day, rather than a very cold day.) To study the pressure distribution at the house under high winds, scale models were placed in a wind tunnel (top right). These tests [27] facilitated the choice of dimensions for a full-scale test of a windbreak (bottom left). The experiment, performed in collaboration with the U.S. Forest Service, appears to have reduced air infiltration rates in westerly winds by about 0.2 exchanges per hour, according to direct measurements in one townhouse before and after the windbreak was erected [28].

Air infiltration is also driven by buoyancy (hot air flowing out of the top of the house, replaced by cold air below). Air infiltration rates can approach one exchange per hour on a very cold day with *no* wind. The effects of buoyancy and of wind add in non-linear ways that have proved difficult to model [29, 30]. But both effects are reduced by attention to the larger cracks such as those along the metal window frames (bottom right).

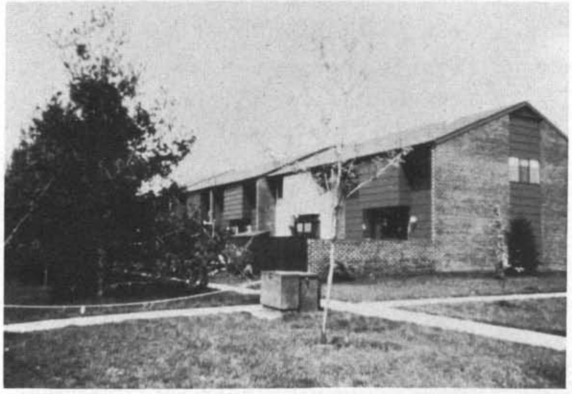
Will well built or well retrofitted houses become overtight on mild days with little wind? Our group is currently attempting to make this issue more precise, and several designs for passive devices to regulate the air exchange rate have been proposed [31 - 33].



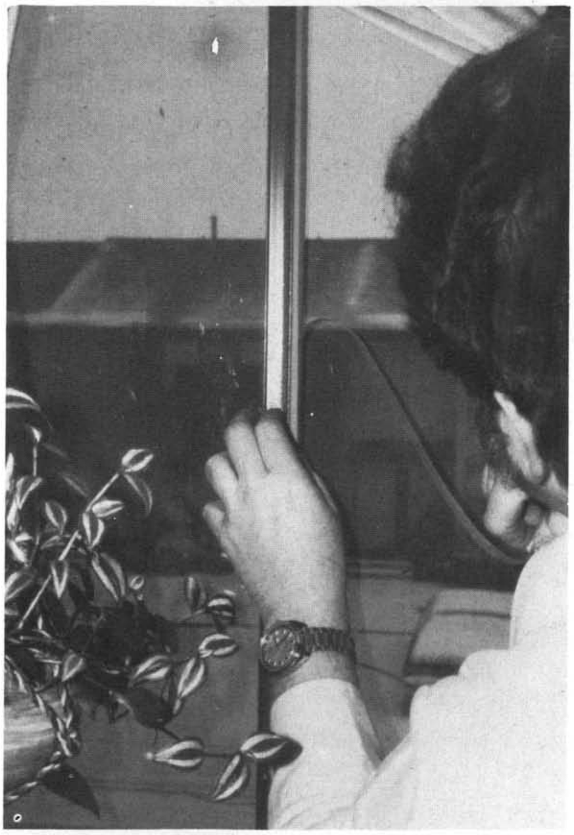
Air infiltration measurement device, alongside gas furnace.



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.

Photo Page 10: Attics

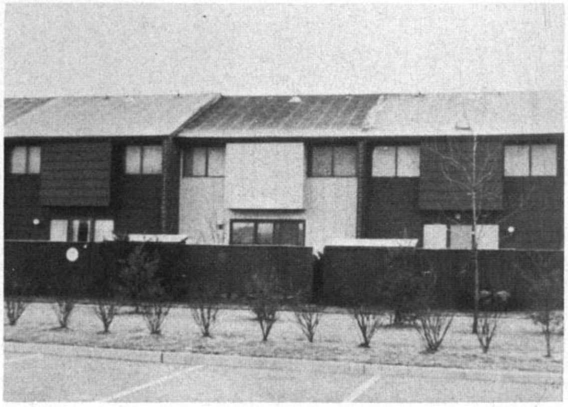
On a frosty morning, one can tell which attics have been retrofitted. The middle roof shown here (bottom) belongs to a house whose attic is untouched, at a time when extra insulation has been added (top) to the attic floor of its two neighbors. The frost is maintained longer on colder roofs, and roofs are colder when less heat flows into the attic from below.

Thus, the rare frosty morning at Twin Rivers offers the opportunity for advertizing one's citizenship. It also provides the opportunity for neighbors to monitor one another and for authorities to monitor everyone. The latter do not have to wait for frosty mornings, because infrared photography easily picks out the insulated attic, whatever the weather (as long as it is cold).

It is not hard to imagine ways in which campaigns to encourage retrofits by home owners could develop, such that the protection of civil liberties became a pressing concern. The attic has been rendered useless as a storage area by the retrofit shown here, and it is quite possible that for some residents the choice between more storage and more fuel conservation would be decided in favor of more storage. A sensitive campaign would at least offer a more elaborate attic retrofit that left the attic more usable, for those who wanted it. It would, hopefully, also offer the choice of doing nothing [34].

The retrofits shown on Photo Pages 3, 5, 6, 7, 9 and 10 were the principal components of Princeton's first retrofit experiment. They were undertaken in varying combinations and sequences in 31 townhouses [20].

Blown fiberglass insulation lies on top of original 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.

Section III. Some Characteristic Results in Graphical Form

The ten pages of Figures in this Section distill some of our most important quantitative results. Several also represent innovative methods of data reduction that others may consider adopting.

Figure Page 1: Five-year history of nine houses

Four issues central to our research program are evoked by Figure Page 1: variation across houses, a performance index for gas consumption in variable outside weather, conservation in response to the energy crisis, and further conservation as a result of our retrofits. The nine houses shown, coded by an integer label, all participated in the Princeton retrofit experiment during the 1976 winter. Monthly meter readings for these houses provide a full record of winter gas use from the date of first occupancy four years earlier.

Variation across houses

All nine houses are three-bedroom interior units in Quad-II of Twin Rivers. They have identical floor plans, furnaces, and basic appliance packages. Yet the gas consumption in House 4 is seen to be a bit more than twice the gas consumption in House 7 in each of the first two winters of occupancy. The same houses are "high" gas consumers, winter after winter, with only minor changes in rank ordering. A glaring exception is the plunge of House 1 from highest to lowest between the winters of 1975 and 1976, which corresponded to a change of owner in House 1 during the 1975 summer, the only change of owner over the five years for the nine houses.

Performance index

The vertical scale has units of energy per degree day; a central finding of our research program is that such an index is adequate for most discussions. The calculation of degree days in the U.S.A. is usually done relative to a reference temperature of 65 °F (18.3 °C), and such a reference temperature is also adequate. It is always safer, however, to do comparisons for the same average outside temperature, as is essentially the case when entire winters are compared. Comparisons of gas consumption for two periods with differing outside temperature may be made more accurate by fitting simple curves to previous data for such houses. At Twin Rivers, winter gas consumption for the average townhouse is found to be nearly directly proportional to $(R - T)$, where T is the average outside temperature and R = 62 °F = 16.7 °C. A simple adjustment to the index that reduces its sensitivity to outside temperature can therefore be devised; it is applied here for the data of the two fragments of the 1976 winter before and after retrofit.

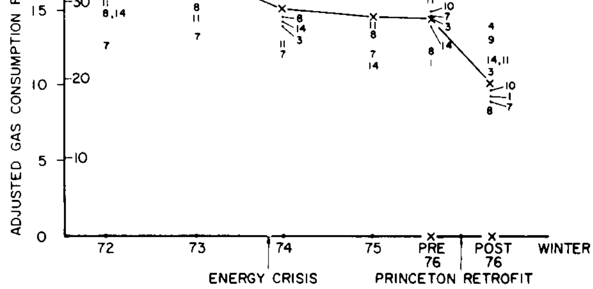
Energy crisis

All of the houses shown here reduced their gas consumption between the 1973 and 1974 winter, in response to the "energy crisis" of the autumn of 1973. A new plateau was established in the average consumption, one that persisted until the Princeton retrofit.

Princeton first-round retrofit

The performance index of the average of seven houses coded 3, 4, 7, 8, 10, 11 and 14, having dropped from 17 ft^3/°F-day to 15 ft^3/°F-day following the energy crisis, was brought down to 10 ft^3/°F-day by Princeton's first-round retrofit package [20]. (In SI units, it fell from 33 to 28 to 20 MJ/°C-day.) The retrofit package had only a small effect on the rank ordering of the nine gas consumers, however, suggesting that faults in house design addressed in the retrofit package probably do not play a significant role in creating variability in gas consumption, but rather have a relatively uniform effect in degrading building performance.

A second round of retrofits has been performed on one townhouse, featuring thermal shutters on the windows. Combined with the first-round retrofits, it appears to have reduced annual gas consumption to about one-third of the pre-retrofit level [35].



5 year history of nine Omnibus houses fully retrofitted by Princeton in winter 76.

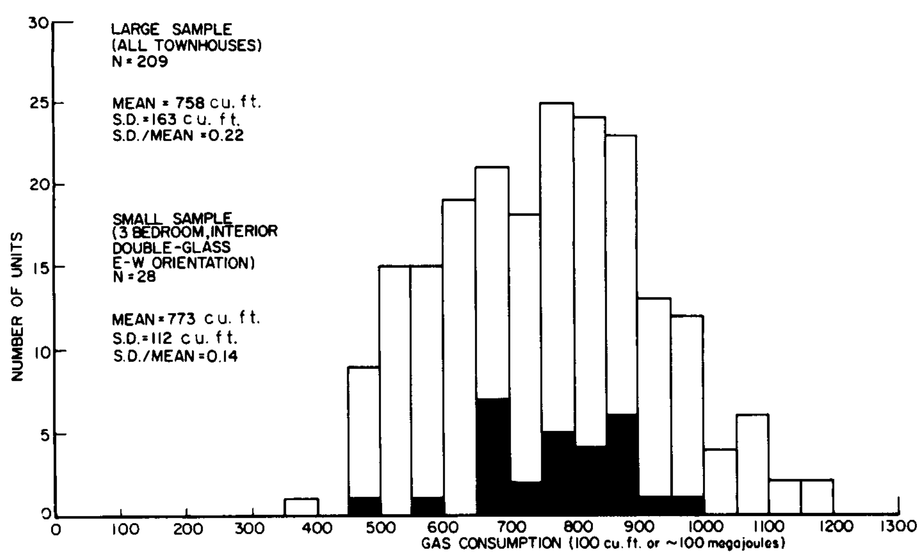
Figure Page 2: Variation in gas consumption

This page presents two histograms (a sample and one of its subsamples) that are characteristic of our data. The gas consumption plotted here is the average of two six-month winters (November 1971 to April 1972 and November 1972 to April 1973).

The large sample differs from the small sample in that: (1) the large sample contains units with two, three, and four bedrooms; all units in the subsample are three-bedroom units, with common floor plan; (2) all compass orientations are found in the large sample; all units in the subsample face either east or west; (3) units in the large sample occupy both interior and end positions in the townhouse row; all units in the subsample are interior units; (4) units in the large sample differ in amount of double glazing, an option at the time of purchase; all units in the subsample have double glazing throughout. As expected, variability is reduced when these four variables are held constant. Winter gas consumption for space heating varies by more than three-to-one for the large sample (209 townhouses), by two-to-one for the subsample (28 houses), and the ratio of the standard deviation to the mean drops from 0.22 to 0.14.

The variability in both samples is one of the startling results of our program. Natural gas is used exclusively for space heating, so that the entire variability must reflect variations in the structures or in the way people use those structures. The reduction in variation in passing from the large sample to the subsample can be apportioned among the four physical variables just described, using the methods of linear regression analysis. Double glazing, averaged over the winter, is found to reduce the rate of gas consumption by 14 ± 4 W/m^2 of double glass installed, or 4 ± 2% for a three-bedroom unit (194 ft^2, or 18.0 m^2 of glass), about half of the 9% savings predicted by heat load calculations. The 13% penalty for the end wall, the 9% penalty for the interior four-bedroom unit, and the 26% benefit for the interior two-bedroom unit, relative to an interior three-bedroom unit, are close to the values expected from heat load calculations. Orientation effects are buried in the statistical noise, an indirect consequence of nearly equal glass area front and back [36 - 38].

The remaining variation confounds a conventional approach: the usual computer programs make no allowance for variable patterns of use and would predict a single value for the gas consumption of the 28-unit subsample. Evidence that factors specific to the residents, rather than to the dwellings, are responsible for most of the variation in such subsamples has been obtained by comparing gas consumption in two different winters for houses having the same owner and houses having two different owners [22, 38].



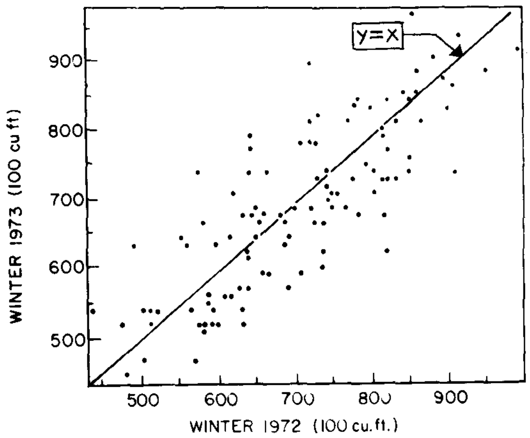
Average gas consumption over two six-month winters (1971 - 72, 1972 - 73)

Figure Page 3: The pattern of response to the energy crisis

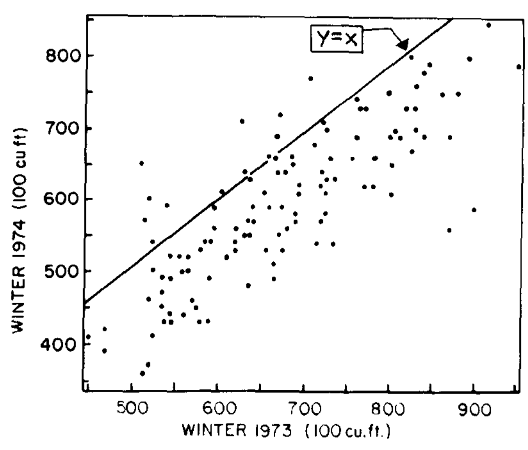
The short-term response to the energy crisis is rendered in a striking fashion by the two cross plots in these Figures. Here gas consumption for the four-month winters of 1972, 1973 and 1974 are compared, using the gas meter readings for the split-level townhouses in Twin Rivers (a set of townhouses adjacent to those from which all other Figures in this Section are drawn). At the nearby station of the National Weather Service at Trenton there were, respectively, 3291, 3151 and 3251 °F-days during each four-month period, and so one might have expected a drop in consumption of 4% from the first winter to the second and a climb of 3% from the second winter to the third, if outdoor temperature were the only determinant of consumption.

The cross plots tell a different story. The winters of 1972 and 1973, plotted against one another in the upper cross plot, both preceded the energy crisis; the houses (each a dot on the graph) scatter nearly symmetrically about the straight line, on which gas consumption is the same in both winters. The two winters plotted in the lower cross plot, 1973 and 1974, straddle the "energy crisis" in the autumn of 1973; the pattern of the upper cross plot is displaced downward, corresponding to conservation of roughly 10% of expected gas consumption in 1974 [39, 40].

Conservation in 1974 is seen to take place among high users and low users to roughly the same extent, with individual users varying greatly in the degree of response. The ratio of variance to mean, in fact, remained unchanged by the crisis. The extent of variation in any single winter is comparable to that displayed in the histograms on Fig. Page 2.



Winter 1972 *vs.* winter 1973 gas consumption.



Winter 1973 *vs.* winter 1974 gas consumption

Figure Page 4: Conservation and price

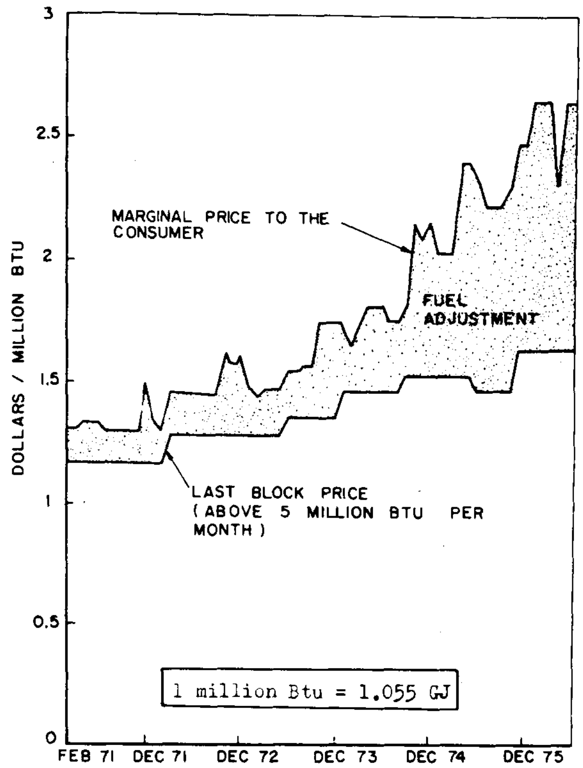
The upper graph shows the price of natural gas paid by the Twin Rivers resident, which approximately doubled, in current dollars, from 1971 to 1976. The lower graph shows the reduction in average rate of gas consumption (normalized by degree days) that has accompanied the rising price.

The price shown is the price for the last block of the rate structure, and applies to all gas consumption above 5 million Btu (50 therm, or 5.1 GJ) per month. This is the marginal rate faced by all Twin Rivers residents, in December through March, and by all except a few very low consumers in the months of November and April; this is, therefore, the traditional price for economic analysis. It is seen to be the sum of two components, a regulated price, revised once or twice a year by the New Jersey Public Utility Commission, plus a fuel adjustment, computed monthly, by means of which short-term changes in the price paid by the utility for gas are passed through to the customer. The price shown is not adjusted for inflation. One regional price index (Consumer Price Index — City Average, as reported in the Monthly Labor Review, a monthly index covering New York City and Northern New Jersey) climbed from 128 to 170 from November 1971 to November 1975 (relative to 1967 = 100). The marginal price rise by a factor of 2.0 in current dollars in the four-year interval is, thus, a rise by a factor of 1.5 in constant dollars.

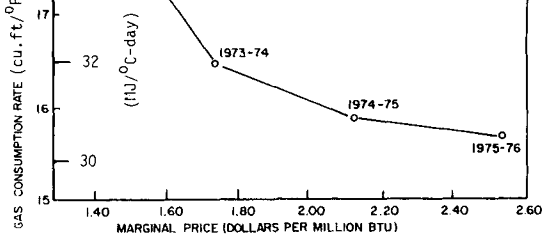
Plotted against the marginal price (in current dollars) in the lower graph is the gas consumption rate, averaged over 151 Quad-II townhouses (a sample that excludes houses that have had a change of owner). The rate is normalized by dividing by degree days (with 65 °F = 18.3 °C reference temperature); the resulting performance index drops from 17.8 ft^3/°F-day (34.5 MJ/°C-day) to 15.7 ft^3/°F-day (30.5 MJ/°C-day) in five years, a drop of 12%, much like the drop observed for the seven-house average in Figure Page 1.

Based on the data for the winters of 1972 and 1975, a four-winter elasticity of demand of −0.5 may be computed, the ratio of an increase in marginal price (in constant dollars) of 23% and a reduction in the performance index of 11%. The pattern of consumption *versus* price, however, is inconsistent with a constant elasticity of demand operating for the whole interval, because most of the reduction in demand occurred in the winter immediately following the crisis, whereas most of the increase in price occurred later. One may describe the pattern of the lower graph equally well as price anticipation or as a fast response to the pulse of exhortation that characterized the 1974 winter. It is significant that no deterioration of the performance index is observed since the energy crisis, in contradiction to a frequent prediction that over time the residential consumer would "relax" [40, 41].

Following the energy crisis Twin Rivers residents appear to have reduced their electricity consumption marginally, if at all. This result confounded our expectations, as the price history for electricity has been similar to that for natural gas and strategies to reduce electricity consumption appear to be no more difficult to execute. Median winter electricity consumption was down 6% in 1974, relative to 1972 and 1973, an effect that vanished when mean values were compared. Summer electricity consumption was at the same level in 1974 and 1975 as in 1972 and 1973, when periods of equivalent *cooling* degree-days were compared. These results strongly suggest that levels of air conditioning were not curtailed following the energy crisis [40, 42].



Marginal price of residential natural gas, 1971 - 76.



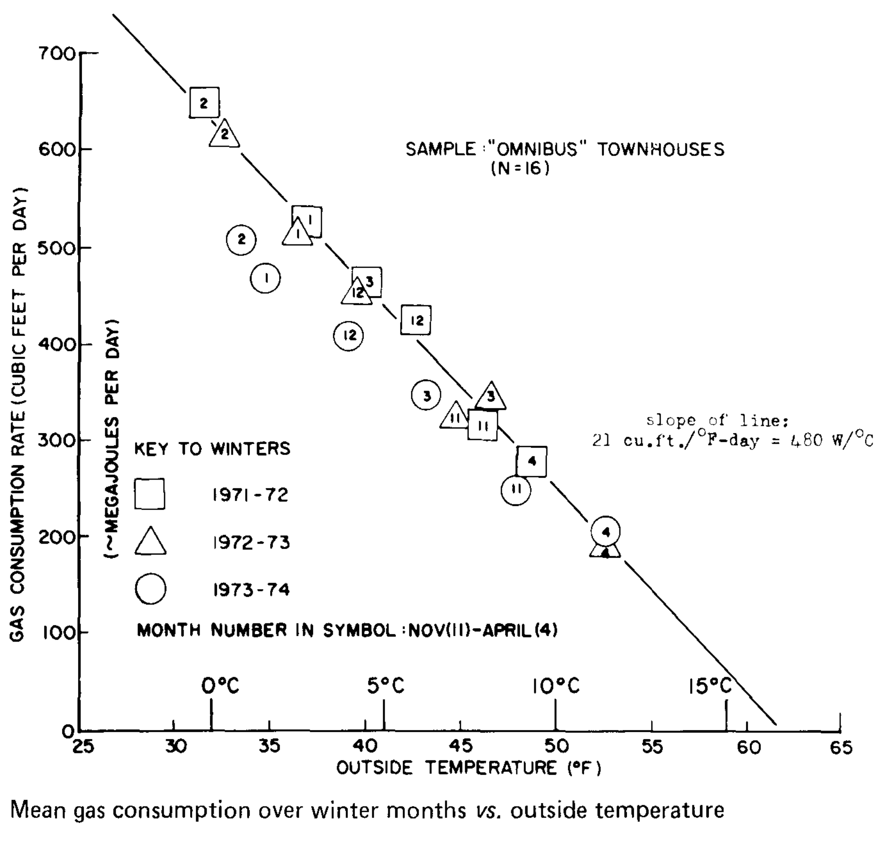
Price *vs.* rate of consumption of gas

Figure Page 5: Outside temperature: the critical variable

The average rate of gas consumption of 16 townhouses later to be retrofitted by Princeton is plotted against the average outside temperature in the Figure. The monthly data shown covers three winters of six months each. The first two winters precede the "energy crisis", and the twelve data points fit a single straight line extraordinarily well. The last six data points correspond to months of the 1974 winter, and the conservation of gas at Twin Rivers during these months reappears here. The amount of gas conserved is seen to be largest in the coldest months, a pattern confirmed in studies of a larger sample of houses and one inconsistent with a constant reduction of interior temperature throughout the winter. The reduction of interior temperature, relative to the previous two years, appears to have been 4 °F (2 °C) in the colder months, but only 1 °F (0.5 °C) in the milder months [18, 41].

A linear relationship between gas consumption and outside temperature is not unexpected. It follows, for example, if the auxiliary heating from the sun and the electrical appliances, the average air infiltration rate, the furnace efficiency, and the interior temperature are all constant over months, and in fact none of these varies substantially at Twin Rivers. A prolonged investigation of solar, appliance, furnace, and wind effects has led us to the following energy balance in the Twin Rivers townhouse: (1) appliances, people, and sun lower by 10 °F (5.6 °C) the temperature at which the furnace is required for space heating, from 72 °F (22.2 °C) (the interior temperature, now constant) to 62 °F (16.7 °C); of the total, 6 °F (3.3 °C) represents auxiliary heating from appliances and people and 4 °F (2.2 °C) represents solar heating; (2) the efficiency of the furnace, as a converter taking chemical energy from gas and delivering heat to a volume defined by basement plus living area is about 70%; (3) the heat losses, by which the heat from furnace and auxiliary sources is dissipated, are distributed: 40% by air infiltration, 30% by conduction through windows, and 10% *each* by conduction through attic, walls, and basement. The heat loss rate is roughly 640 Btu/h °F (340 W/°C), when long-term (monthly) data are considered [21, 35, 37, 43].

For most house-furnace systems in most locations, a linear relationship between the energy consumption for space heating and the outside temperature, similar to the plot below, should represent the data quite well. Then the determination of two parameters (slope and intercept) from an analysis of data for various outside temperatures will suffice to make useful quantitative statements about conservation strategies [44]. In a few special situations, such as houses with heat pumps (whose efficiency drops with colder weather), three-parameter fits to the data may be warranted. Field determinations of the parameters in simple models of energy consumption can form the core of an effective retrofit program, helping initially in choosing among retrofits and later in verifying the degree of success of those implemented [45 - 47].



Mean gas consumption over winter months *vs.* outside temperature

Figure Page 6: Savings due to first-round retrofits

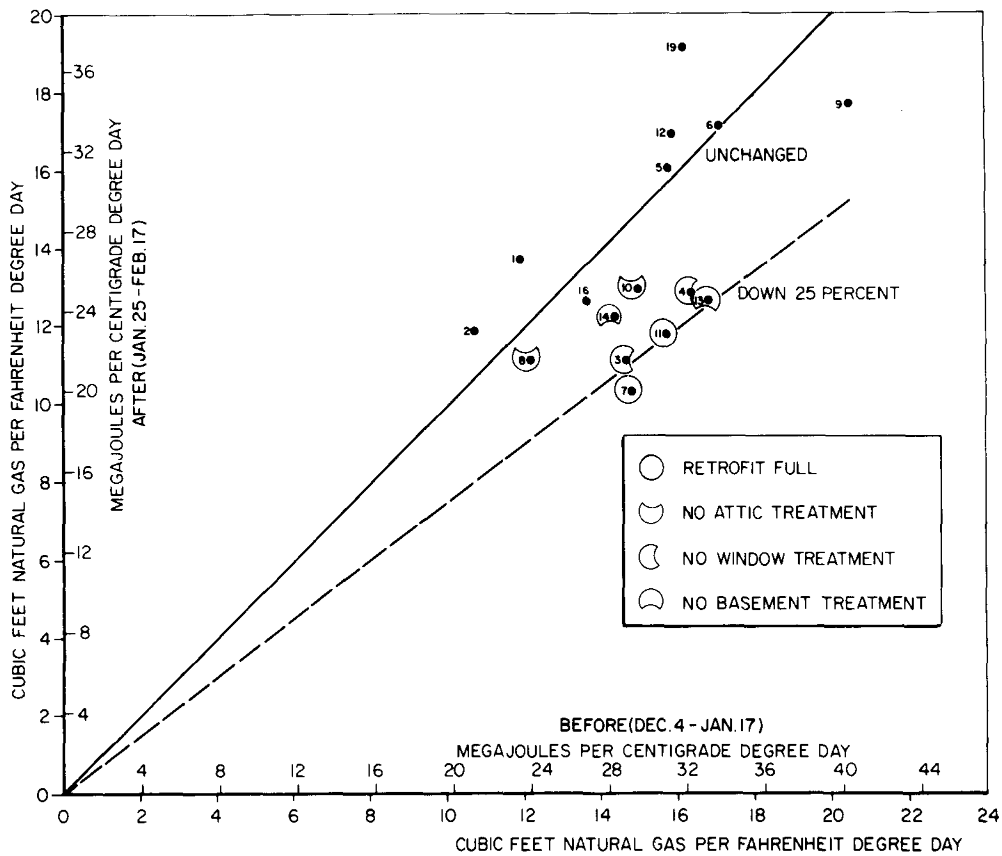
The display of house-by-house gas consumption in the Figure opposite provides an accurate view of the effectiveness of the retrofits installed in the Twin Rivers townhouses, as confirmed by subsequent more detailed analysis. A performance index, gas consumption per degree day, is calculated for each house for time intervals on both sides of a period of retrofit, and a cross plot is constructed with the "before" and "after" indices as coordinates. It is desirable for the weather to be as nearly the same in the two time intervals as possible; here the outside temperature averaged 34.5 °F (1.4 °C) in the six-week period before and 36.7 °F (2.6 °C) in the three-week period after the one-week period of retrofit.

Our experimental design simplified the interpretation of the cross plot. Eight of the sixteen houses were left untouched (the control group), while the other eight received differing combinations of the components of the full retrofit package. The cross plot strongly suggests that all of the retrofits had some effect, that the relative effectiveness, in terms of amount of gas conserved, is window treatment (smallest), then basement treatment, then attic treatment (largest). The combined winter savings appear to be up to 30%, relative to a control group manifesting a slightly larger rate of consumption "after" than "before" [12, 18]. Summer conservation appears to be very small, for reasons not fully understood [48].

More detailed analysis has revealed two pitfalls in this method of winter data reduction. First, spurious effects of house orientation are easily enhanced in such cross plots, making it necessary to take care when the sample of houses contains a mix of orientation. In the Figure here, Houses 7, 9, 10, 11, 13 and 16 are oriented east and west, and the sun systematically shifts them downward on this plot, relative to the other houses [nine oriented north and south, one (House 5) oriented northeast and southwest]. This shift is a special case of the following solar effect: in periods of comparable sunniness, the sun improves (lowers) the performance indices of houses with east and west windows by an amount that becomes increasingly significant the further from December 21 the time interval under assessment; no comparable enhancement occurs for south windows, the effect of longer days being almost exactly cancelled by the effect of a higher sun. In the assessment of the Princeton retrofits, the inclusion of this solar shift turns out to reduce estimates of the savings by about ten percentage points [49].

The second pitfall of calculating the percentage fuel saved for a short period in midwinter is not recognizing that the percentage fuel saved over the *whole* winter will generally be larger. There are two consequences of improving either the tightness of a house or the thermal resistance of its shell: not only does less heat flow out of the house at each outside temperature, but also the auxiliary heat generated by sun, appliances, and people is more effectively retained. The second effect leads to a shortening of the heating season, *i.e.*, to a 100% reduction in amount of gas consumption required on certain mild days. The percentage reduction in gas consumption resulting from most retrofits will be smallest in coldest weather, and the annual average reduction will be that of a stretch of average winter days rather than that of a stretch of cold ones. Given data for a limited period, the accomplishments of a retrofit over a winter can, however, be estimated quite accurately with a simple model of daily winter temperature (and, possibly, sunlight and wind).

Of course, one is not likely to have to contend with either of these two pitfalls if one has a full year of data "before" and "after" a retrofit, but this requires a long wait for results.



Average rate of gas consumption before *vs.* after first retrofits.

Figure Page 7: Details of interior temperature

Four interior temperature traces are shown in each of the figures below. Three cycles of furnace operation last approximately two hours, during two cold winter nights, one before and one after Princeton's full retrofit package was installed in this townhouse.

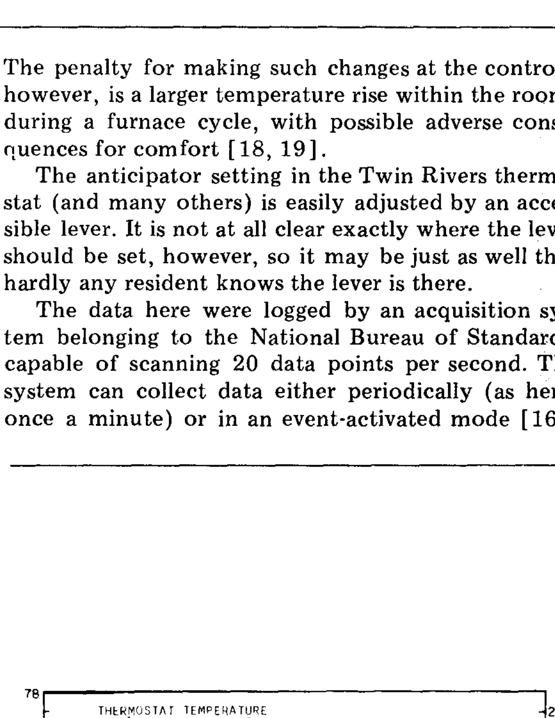
The following results of the retrofits may be discerned: (1) the basement has become 5 °F (3 °C) colder; (2) the basement temperature rises less sharply and less far and it falls more slowly; (3) conversely, the downstairs temperature rises more sharply and further, and it falls more rapidly; (4) the upstairs and the downstairs temperature have become much more nearly equal, the downstairs having previously been 2 °F (1 °C) warmer. The basement retrofit is responsible for the first three effects: insulation of basement ducts means less heat lost to the basement and more heat delivered immediately to the living area through the registers rather than delivered slowly through the basement ceiling. The fourth effect, a warmer upstairs, is brought about principally by the attic retrofit, which reduces the heat flow through the attic and upper side walls [50].

A detailed look at a single furnace cycle reveals significant information about the furnace controls. The temperature inside the thermostat (located downstairs) rises far more steeply (1 °F, or 0.6 °C, per minute) than the temperature in the rooms. The difference in rates of climb is reflective of a resistive heating element within the thermostat, the "anticipator", that is active when the furnace is on and shuts off when the furnace shuts off. The length of time the furnace will fire during any cycle (for a given "dead band" on the thermostat) is seen to be more sensitive to changes in the size of the resistance in the anticipator than to changes in the size of the furnace.

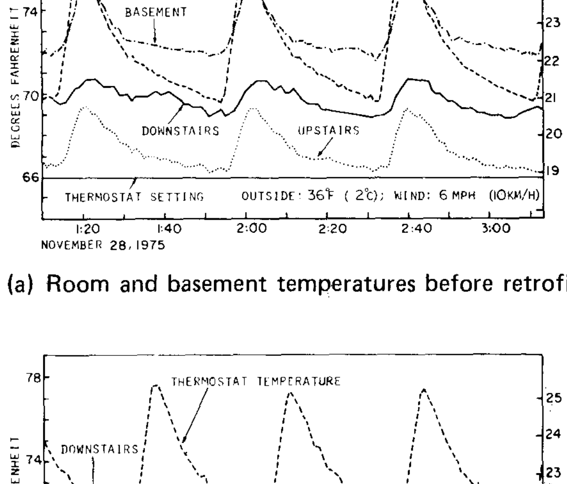
It is often argued that furnaces are oversized. The upper Figure shows that, when the outside temperature is 36 °F (2 °C), this Twin Rivers furnace runs for 7 minutes (while the temperature within the thermostat rises 7 °F, or 4 °C), then stays off for 33 minutes, thereby firing only 18% of the time. Such a furnace is oversized by any usual criteria. The case against "oversizing" is a very loose one, however, grounded in a vaguely formulated case against "transients" in furnace combustion and in duct heat transfer. Moreover, such transients can be reduced, *without* changing the fraction of time that the furnace is on, either (1) by increasing the deadband at the thermostat, or (2) by reducing the rate of heating by the anticipator. Both are more modest changes than resizing the furnace. The penalty for making such changes at the controls, however, is a larger temperature rise within the rooms during a furnace cycle, with possible adverse consequences for comfort [18, 19].

The anticipator setting in the Twin Rivers thermostat (and many others) is easily adjusted by an accessible lever. It is not at all clear exactly where the lever should be set, however, so it may be just as well that hardly any resident knows the lever is there.

The data here were logged by an acquisition system belonging to the National Bureau of Standards, capable of scanning 20 data points per second. The system can collect data either periodically (as here, once a minute) or in an event-activated mode [16].



(a) Room and basement temperatures before retrofit



(b) Room and basement temperatures after retrofit

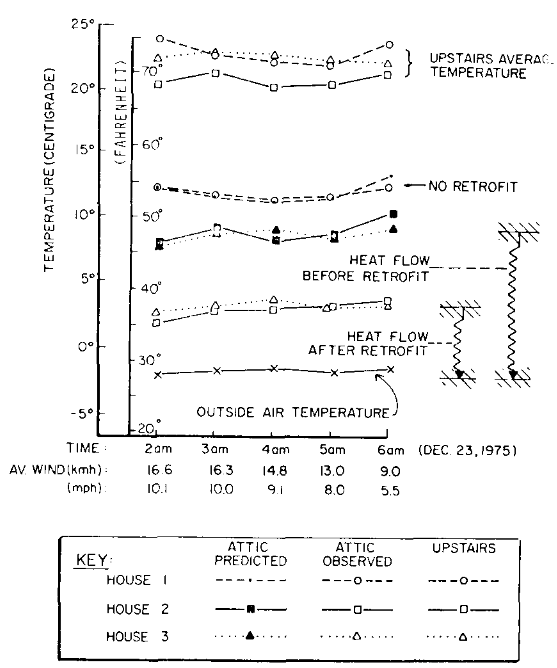
Figure Page 8: The attic temperature index

The attic temperature is particularly easy to measure, and we are convinced that it is also particularly informative, if one is seeking to characterize the thermal properties of a house. In many cases this temperature is an immediate index of the quality of the thermal system which isolates attic from living area. The homeowner can monitor attic temperature before and after an attic retrofit to obtain a nearly immediate assessment of its efficacy.

An attic temperature at night predicted from a simple linear model is compared with the temperature actually observed, for three attics, in the Figure below. Two of the three attics had been retrofitted (floor insulation added and air passages from basement blocked) between the period of time during which the parameters of the model were established and the night shown here. The third attic (House 1) was untouched. The retrofitted attics are seen to be 10 °F to 14 °F (6 °C to 8 °C) colder than predicted, the expected result of better isolation of the attic from the living area; the attic of House 1 is seen to have the expected temperature, within 1 °F (0.6 °C) [45, 51].

The linear model used in these predictions involved only upstairs temperature, outside air temperature, and wind velocity. Parameters are established using standard linear regression techniques. The model has been found to be broadly useful, in extensive tests. The parameters in the model, however, have turned out not to be easily interpretable in terms of the thermal properties of the building materials in the townhouse, an unexpected result. The attic is much warmer, both before and after retrofit, than was anticipated. Detailed investigation of air flow and thermal storage in the attic is under way to establish the detailed correspondence between the parameters of the model and the physical properties of the attic. Large, unexpected channels for heat flow into the attic that bypass the attic insulation have been found. It is becoming clear that retrofits which block these channels are even more cost-effective than conventional attic insulation [21, 52 - 54].

Linear regression models have been developed for other variables, notably the air infiltration rate and the rate of gas consumption, with the same expectation that the parameters in these models may be useful numerical surrogates for complex physical effects [55, 56]. This approach has enabled us, for example, to model buoyancy-driven and wind-driven air infiltration [30] and to produce simple measures of the effectiveness of solar heating through windows and walls. We expect that, very generally, field assessments of the quality of a building and the priorities for its retrofit will rely heavily, in the near future, on the determination of the parameters in such relatively simple models, and on the comparison of such parameters against norms determined by experience to be desirable [43, 57 - 59].



Effect of attic retrofit on attic temperature

Figure Page 9: Gas and electricity

Gas consumption and electricity consumption are superposed in two different ways in these Figures. The upper Figure presents the thermal energy content, *at the house*, of the chemical energy in the gas and the electrical energy in the wires. The lower Figure presents 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 approximates the conversion inefficiency of the electric power plant, while the gas energy is left unchanged. (A complete consideration of conversion losses would include various 10% effects, like the energy to pump the gas from the wellhead and the energy lost in electric power lines and transformers. Slightly larger multiplicative weights would result.)

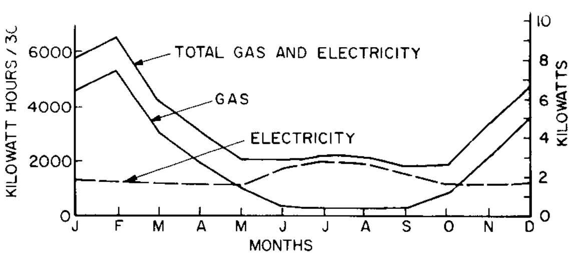
The rates of energy consumption across months shown here are averages over the 248 two-floor townhouses in Quad II at Twin Rivers. In these townhouses, gas is used exclusively for space heating (and, rarely, for outdoor barbecues). Electricity is used for all other purposes. We use data on gas and electric consumption from 1973, and we normalize the variable (and noncoincident) periods between meter readings to 30-day periods.

The upper Figure is appropriate for judging the significance of the electrical energy consumed by appliances as an auxiliary source of space heating, relative to the gas consumed by the furnace. In the mild months of April and November, the energy content of the electricity is roughly 35% of the total energy consumed at the house, and even in the coldest month, February, it is 20%. The second role for electric appliances as auxiliary sources of residential heating needs to be addressed in an overall program of residential energy conservation. Considerations of appliance location and heat recovery are relatively unfamiliar, for the relative role of appliances in residential space heating has only recently grown to the levels shown here. Our detailed studies suggest that the potential for increasing the fraction of the heat recovered from appliances is a task comparable in significance to the task of increasing the effectiveness of the heat source represented by the sunlight striking the building.

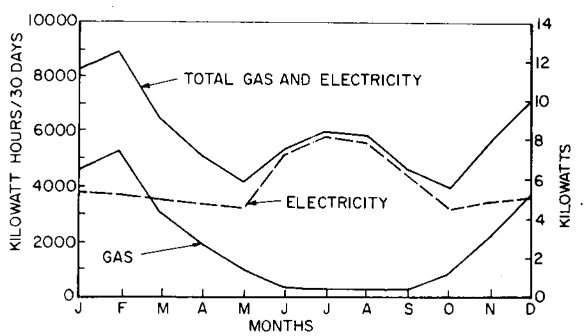
The bulge in the summer months in an otherwise flat electricity profile represents consumption by the air conditioner; the air conditioner accounts for nearly half of total electricity consumption in July and August. The summer gas consumption (7 hundred cubic feet, or 0.8 GJ, per month) is attributable to a single pilot light on the furnace, shut off in very few houses, a heat source equivalent to a 300 W bulb burning continuously. As the upper Figure shows, this is about 20% of the energy consumption rate from electrical appliances other than the air conditioner. Minimizing the "second role" of gas and electric appliances in summer, as sources of unwanted heat, requires strategies complementary to those designed to retain winter appliance heat.

Summing over the twelve months yields annual totals: 780 hundred cubic feet (800 therms, or 84 GJ) of gas and 16,200 kWh (58 GJ) of electricity consumed in the average townhouse.

The lower Figure is appropriate for judging the drain imposed on natural resources by space heating relative to that imposed by the electric appliances. Roughly one-third of the fossil fuel combustion required to "power" the Twin Rivers townhouse for a year occurs at the furnace and two-thirds at the electric power plant. Moreover, as the relative dollar costs paid by the resident closely parallel the lower Figure, it also is appropriate for judging the drain on the pocketbook. A cost profile over months that has two nearly equal winter and summer peaks is characteristic of most gas heated, electrically air conditioned houses in a climate like New Jersey's [18, 38].



Rate of thermal energy release at the house by gas and electricity use



Rate of fossil fuel energy consumption for gas and electricity use

Figure Page 10: The water heater

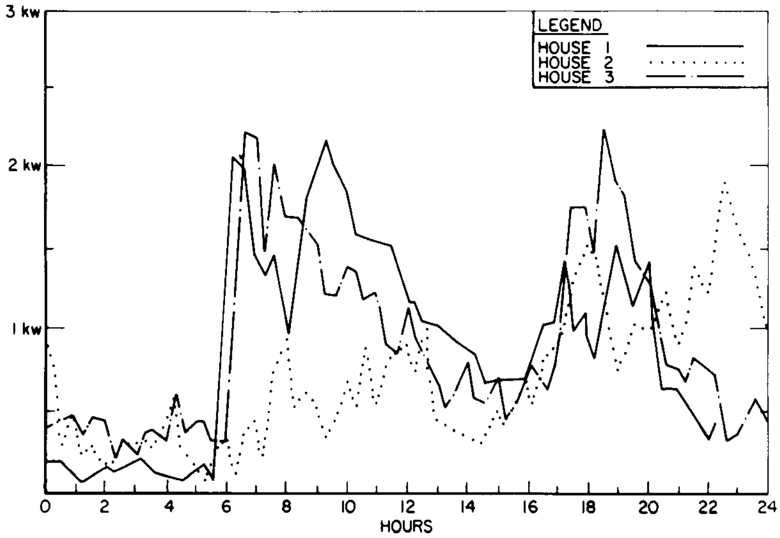
The electric water heater uses 8000 kWh of electricity over the year in an average Twin Rivers townhouse, roughly half of the total electricity. The annual cost of electricity for hot water (about \$300 in 1975) exceeds the annual cost of gas for space heating (about \$220 in 1975). The provision of hot water, clearly, merits attention!

The Figure below shows the distribution of electricity consumption over the hours of the day, for three water heaters. The data for each hour, in these "load profiles", are obtained by averaging the consumption during that hour for 97 winter days in 1975. Electricity consumption is seen to be very uneven, with peak to trough ratios exceeding 10 to 1. Moreover, the peaks occur at nearly the worst possible times, from the point of view of the electric utility system — not during the nighttime hours when the system is operating its least costly baseload plants, but rather during the morning and evening, when the system is operating its more expensive (and less efficient) peaking capacity [60].

The electric consumption of the water heater can be approximated by the sum of two terms: (1) continuous consumption at a rate of about 200 W, compensating for the steady loss of heat into the basement through the poorly insulated sides of the tank (visible) as the minimum level of consumption between midnight and six a.m.) and (2) intermittent consumption, averaging 700 W, occurring nearly simultaneously with the use of hot water in the house. Assuming that the water is heated from 60 °F (15.6 °C) to 145 °F (62.8 °C) before use, 700 W corresponds to 80 gallons (0.30 m^3) of hot (145 °F, or 62.8 °C) water consumption per day.

The Twin Rivers water heater contains two 4.5 kW heating elements, only one of which is on at a time. These enable near instantaneous response to demand for hot water, but evidently with the result that the water heater operates only 0.9 kW/4.5 kW = 20% of the time. The capacity of the water heater, 80 gallons, is approximately equivalent to one day's use, so shifting the time of heating to off-peak hours, with such large heating elements and a well-insulated tank, should not be difficult. Time-of-day pricing, to be sure, would provide an incentive to do so.

Approaches to energy conservation in water heating include (1) improving the insulation on the tank (see Photo Page 3), (2) lowering the thermostat setting at the tank to reduce tank heat losses, (3) providing heat exchange between incoming cold water and waste hot water, (4) capturing heat rejected by appliances, like the refrigerator, (5) capturing heat vented up the furnace flue, and (6) capturing solar energy. A combination of the six strategies (in conjunction with strategies, like faucet design, that reduce water consumption directly) should permit energy consumption at the water heater to be eliminated entirely [61].



Load profiles of water heaters in three adjacent townhouses.

ACKNOWLEDGEMENTS

A few of the ideas presented in this summary have single authors, but most have emerged after many stages of discussion, experimentation, data analysis, and more discussion, with my associates at Princeton. Not a single idea presented here feels like mine alone.

My own debts and the program's are the same. David Harrje has directed all of the experimentation in the field, for a crucial period assisted by George Mattingly. Harrje has also directed the program of retrofits, and he has been the principal link with the buildings professionals and with the researchers in the energy companies.

It was Richard Grot's conviction in 1971 that he could measure what was going on in houses in new and better ways which led to our first funding from the National Science Foundation in 1972, when conservation of energy was not yet on any political agenda. Grot has proven his contention year after year, continuing to spend long days at Twin Rivers even after moving to the National Bureau of Standards in 1974.

Frank Sinden has given lustre to the program's physical modeling since his arrival in 1976. With the help of Gautam Dutt and Jan Beyea, Sinden has pointed the program in several new directions.

Lawrence Mayer, from 1974, and Thomas Woteki, from 1975, both statisticians, have rescued the program from the well-known disaster where data displace ideas, supplying professional data management and greatly expanding the range of hypotheses that can be evaluated and reported in ways that are respectable. Mayer, too, has been the one in our group most insistent on having us address the needs of policymakers, not just our own professional colleagues. The orientation of this particular summary reflects his persuasiveness.

The social science experimentation initially addressed issues of design and decision-making and was led by Harrison Fraker, Jr., an architect, assisted by Elizabeth Schorske. It has changed emphasis and escalated in intensity under the direction of Clive Seligman, Lawrence Becker, and John Darley, all psychologists, who, while they educate the rest of us, are carving out new territory in their discipline.

From the length of the list of students involved (see Appendix B), one correctly gathers that there has been a continuous effort to make a program of research simultaneously a valid activity in educational terms. Robert Sonderegger has now gained the program's first doctorate, after a stretch of research that included two years at Twin Rivers conducting clever experiments in his home. Sonderegger is my co-author in a larger but more informal review of the program, prepared a year ago, for which we collected all of the Figures and Photos presented in this summary. The present product could not have emerged without that first exercise.

The program has had the help of three master's students and more than forty undergraduates. John Fox, who followed his MSE with study at the Wharton School, did the first analyses of the variations in consumption across nominally identical houses. Thomas Schrader, now with the Federal Environmental Protection Administration, extended that analysis to reveal the hidden difficulties that complicate the analysis of gas consumption in terms of degree days. Nicholas Malik, now with the consulting firm of Gamze, Korobkin and Caloger in Chicago, played a principal role in the development of equipment and the analysis of data bearing on air infiltration. Of the undergraduates involved, I accept the charge of favoritism in identifying the particularly critical roles played by Malcolm Cheung, Jon Elliott, Shawn Hall, Peter Maruhnic, Mark Nowotarski, and Alison Pollack. The dedication of our students has reflected a commitment to the subject matter as well as amazing personal standards of excellence. Student work underlies nearly all of our most cherished conclusions.

Anyone who knows experimental research in a university knows how indispensible is the role of the supporting staff. The program has enjoyed unusual dedication from its technicians, Kenneth Gadsby, Roy Crosby, Jack Cooper, Victor Warshaw and Richard Whitley, from Stephen Kidd in the office of grants and contracts, and from Jean Wiggs, Selma Lapédes, Deborah Doolittle and Terry Brown at home base. Our advisory committee, whose membership is found in Appendix B, gives the group indispensible insights into its strengths and weaknesses in regular, spirited day-long sessions. The guidance from above, from Professors George Reynolds and Irvin Glassman, successive directors of the Center for Environmental Studies, has been a model of intelligence and tact.

The management of the program has been subject to an unusual amount of interaction with our sponsors, the result of its topicality, its accessibility, and the large number of disciplines into which it has intruded. The relationships with our monitors at the Conservation Division of the Energy Research and Development Administration (now, Department of Energy), and at the National Science Foundation, Division of Research Applied to National Needs, have always included assistance in the substantive aspects of the program.

Throughout this program, and to an increasing degree every year, we have profitted from the numerous probing questions of visitors from industry and government "passing through" and by visits of members of our group to their offices and laboratories. Three of these relationships deserve to be singled out: The public utilities who service Twin Rivers, Public Service Electric and Gas and Jersey Central Power and Light, have cooperated with our program since its inception, and the collaboration has steadily widened. Norman Kurtz and his consulting firm, Flack and Kurtz, were especially helpful in bringing real world experience to the early stages of this program. The National Bureau of Standards (the guardians of a lean program of conservation research through the years of energy affluence), with parallel grants from N.S.F. and E.R.D.A., has assisted in numerous ways, providing the prototype devices for the measurement of air infiltration, carrying out infrared photography, collaborating in the reduction of data, and sharing in our decisions about overall strategy.

This report has benefitted from critical readings by Aart Beijdorff, John Eyre, Joseph Stanislaw, and Philip Steadman and from the wondrous typing of Jan Jenkins.

I wish to thank Dr. Richard Eden for providing the hospitality of the Energy Research Group at the Cavendish Laboratory, Cambridge, England, where this report was prepared. The sojourn at the Cavendish was made possible by Fellowships from the German Marshall Fund of the United States and from the John Simon Guggenheim Memorial Foundation.

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APPENDIX A. SELECTED REPORTS AND PUBLICATIONS (regrouping of previous references)

A. Program Review

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A2 R. H. Socolow, Energy utilization in a planned community in the United States, in R. G. Courtney (ed.), *Energy Conservation in the Built Environment*, Proc. CIB Symp. BRE, Garston, Watford, April 1976, Construction Press, Lancaster, 1976, pp. 447 - 457.

A3 R. H. Socolow and R. C. Sonderegger, The Twin Rivers Program on Energy Conservation in Housing: Four-Year Summary Report, CES Report No. 32 (1976).

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B. Construction of Twin Rivers

B1 H. Fraker, Jr. and E. Schorske, Energy Husbandry in Housing: An Analysis of the Development Process in a Residential Community, Twin Rivers, N.J., CES Report No. 5 (1973).

B2 L. D. Hackney, A Political Analysis of the Development Process in East Windsor Township, *Senior Thesis*, Dept. of Politics (1975).

C. Psychology and the Resident

C1 C. Seligman and J. Darley, Feedback as a means of decreasing residential energy consumption, *J. Appl. Psychol.*, 67 (1977) 363 - 368.

C2 C. Seligman, J. Darley and L. J. Becker, Psychological Strategies to Reduce Energy Consumption, CES Report No. 41 (1976).

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D. Aggregate Energy Consumption

D1 J. Fox, Energy Consumption for Residential Space Heating — A Case study, *MSE Thesis*, Dept. of Aerospace and Mechanical Sciences (1973) (also CES Report No. 4).

D2 M. Cheung, The Effect of the Energy Crisis on the Winter Gas Consumption of Quad II Split-Level Townhouses at Twin Rivers, New Jersey, Junior Independent Work, Dept. of Statistics (1974).

D3 L. Mayer and J. Robinson, A Statistical Analysis of the Monthly Consumption of Gas and Electricity in the Home, CES Report No. 18 (1975).

D4 T. Schrader, A Modified Degree-Day Method for Predicting Energy Consumption for Residential Space Heating: Evaluation at Twin Rivers, Term Paper, Woodrow Wilson School of Public and International Affairs (1975).

D5 R. A. Alpert, Electricity: Residential Consumption and Conservation, *Senior Thesis*, Dept. of Statistics (1976).

D6 C. E. Horowitz and L. S. Mayer, The relationship between the price and demand for natural gas, *Energy Res.*, 1 (1977) 193 - 222.

D7 L. S. Mayer, Estimating the effects of the onset of the energy crisis on residential energy demand, *Energy and Resources*, (1978) in press.

D8 L. S. Mayer and Y. Benjamini, Modeling residential remand for natural gas as a function of the coldness of the month, *Energy and Buildings*, 1 (1977/78) 301.

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E. Equivalent Thermal Parameters to Characterize a House

E1 R. H. Socolow, Time-Series Models for the Energy Balance in a House, CES Working Paper No. 19 (1975).

E2 R. H. Socolow, A Model of Heat Flow in an Attic, CES Working Paper No. 20 (1975).

E3 F. Sinden, Conductive Losses from Basements, Twin Rivers Note No. 4 (1976).

E4 A. Pollack, Modeling Attic Temperature in Three Highly Instrumented Townhouses in Twin Rivers, New Jersey. Junior Independent Work, Dept. of Statistics (1976) (also CES Report No. 28).

E5 G. S. Dutt and D. T. Harrje, Influence of Attics on Residential Energy Conservation, CES Working Paper No. 33 (1977).

E6 T. Woteki and G. Dutt, The Two-Resistance Model for Attic Heat Flow: Theory and Results from a Retrofit Experiment, CES Report No. 52 (1977).

E7 G. Dutt and J. Beyea, Attic Thermal Performance: A Study of Townhouses at Twin Rivers, CES Report No. 53 (1977).

E8 J. Beyea, G. Dutt and T. Woteki, Critical significance of attics and basements in the energy balance of Twin Rivers townhouses, *Energy and Buildings*, 1 (1977/78) 261.

E9 R. C. Sonderegger, Modeling residential heat load from experimental data: the equivalent thermal parameters of a house. In R. A. Fazzolare and C. B. Smith (eds.), *Proc. Conf. Energy Use Management, Tucson*, Oct. 1977, Pergamon Press, New York, Vol. II, pp. 183 - 194.

E10 R. C. Sonderegger, Diagnostic Tests Determining the Thermal Response of a House, to be presented at the ASHRAE meeting in Atlanta, Feb. 1978.

E11 R. C. Sonderegger, Dynamic Models of House Heating based on Equivalent Thermal Parameters, *Ph. D. Thesis*, Dept. of Aerospace and Mechanical Sciences, 1977.

F. Air Infiltration

F1 D. Harrje, C. Hunt, S. Treado and N. Malik, Automated Instrumentation for Building Air Infiltration Measurements, CES Report No. 13 (1975).

F2 G. E. Mattingly and E. F. Peters, Wind and trees — air infiltration effects on energy in housing, *J. Ind. Aerodynamics*, 2 (1977) 1 - 19.

F3 F. Sinden, Theoretical basis for tracer gas measurements of air infiltration, *Build. Environ.*, (1978), in press.

F4 F. Sinden, Wind, temperature and natural ventilation — theoretical considerations, *Energy and Buildings*, 1 (1977/78) 275.

F5 F. Sinden, Passive Device for Controlling Ventilation. Patent disclosure dated Jan. 31, 1977, CES, Princeton, 1977.

F6 F. Sinden, Decentralized Heat Recovery Devices. Patent disclosure dated March 8, 1977, CES, Princeton, 1977.

F7 D. Harrje and R. Grot, Automated air infiltration measurements and implications for energy conservation. In R. A. Fazzolare and C. B. Smith (eds.), *Proc. Conf. Energy Use Management, Tucson*, Oct. 1977, Pergamon Press, New York, Vol. I, pp. 457 - 464.

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F9 N. Malik, Field studies of dependence of air infiltration on outside temperature and wind, *Energy and Buildings*, 1 (1977/78) 281.

G. Electrical Appliances

G1 J. Meyer, D. Niemiec and D. Harrje, Energy Efficient Design of Household Appliances, CES Report No. 11 (1974).

G2 J. Robinson and J. Yeung, Summer Air Conditioning and Appliance Use Patterns: A Graphical Analysis, CES Report No. 22 (1975).

H. Analysis of Retrofits

H1 D. T. Harrje, Retrofitting: Plan, Action, and Early Results Using the Townhouses at Twin Rivers, CES Report No. 29 (1976).

H2 T. Woteki, The Princeton Omnibus Experiment: Some Effects of Retrofits on Space Heating Requirements, CES Report No. 43 (1976).

H3 T. Woteki, Some Effects of Retrofits on Interior Temperatures in a Sample of Houses, CES Working Paper No. 31 (1977).

H4 A. Pollack, Residential Energy Conservation: The Effects of Retrofits on Summer Electricity Demand, *Senior Thesis*, Dept. of Statistics (1977).

H5 F. Sinden, A two-thirds reduction in the space heat requirement of a Twin Rivers townhouse, *Energy and Buildings*, 1 (1977/78) 243.

H6 D. T. Harrje, Details of the first-round retrofits at Twin Rivers, *Energy and Buildings*, 1 (1977/78) 271.

I. Instrumentation

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I2 S. Hall and D. Harrje, Instrumentation for the Omnibus Experiment, CES Report No. 21 (1975).

I3 R. Grot, D. Harrje and L. Johnston, Application of thermography for evaluating effectiveness of retrofit measures, in *Third Biennial Infrared Information Exchange*, AGA Corporation, St. Louis, 1976.

I4 D. T. Harrje and R. A. Grot, Instrumentation for monitoring energy usage in buildings at Twin Rivers, *Energy and Buildings*, 1 (1977/78) 293.

J. Related publications

J1 R. H. Socolow, New tasks for the energy industries, *Public Utilities Fortnightly*, 91 (12) (1973) 40 - 43.

J2 R. H. Socolow, Energy conservation in housing: concepts and options, in R. W. Burchell and D. Listokin (eds.), *Future Land Use: Energy, Environmental and Legal Constraints*, Rutgers University Press, New Brunswick, 1975, pp. 311 - 323.

J3 K. W. Ford, G. J. Rochlin, M. Ross and R. H. Socolow (eds.), *Efficient Use of Energy: A Physics Perspective*. AIP Conf. Proc. No. 25, 1975, American Institute of Physics, New York.

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J5 R. H. Socolow, Energy conservation in existing residences: Your home deserves a house call, *Conf. Energy Efficiency as a National Priority, Washington, D.C.*, May 20, 1976.

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J7 R. H. Socolow, Four anxieties about a vigorous energy conservation program in the United States, *Annals N.Y. Acad. Sci.*, (1978), in press.

APPENDIX B

DRAMATIS PERSONAE

I. *Princeton University*

A. *Senior Researchers*

Lawrence Becker
Jan Beyea
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*

Yoav Benjamini
Ellen Fagenson
Russ Fazio
John Fox
Miriam Goldberg
Jeff Jacobs
Mitchell Kriss
Nicholas Malik
Andrew Persily
John Pryor
Vita Rabinowitz (Northwestern U.)
Thomas Schrader
Robert Sonderegger
Robert Stein

C. *Undergraduate Students*

Rosalind Alpert
Bradley Bellows
Heidi Bode
Martin Booker
Charles Buckley
Anthony Caine, Jr.
John Cella
Malcolm Cheung
Karl Danz
José Davila
David Donoho
Bruce Duncan
Jonathan Eckstein
Jon Elliott
Rick Ferris
Steven Fisher
Miles Gessow
Michael Guerin
Lucy Hackney
Shawn Hall
Walter Hallagan
William Holstein
Cindy Horowitz
John Kadyszewski
Jeff Kang (Harvard U.)
Raymond Kang (Cornell U.)
Larry Krakauer
Sylvia Kuzmak
David La Plante
Adrienne Lavine (Brown U.)
Andrew Lazarus
Robert Levin
Peter Maruhnic
David Matchar
Herbert Mertz
Thomas Mills
Walter Moberg
Donald Niemiec
Mark Nowotarski
Gene Peters
Alison Pollack
Mark Ramsey
Robert Rowse (Hampshire College)
Lauren Sarno
Stewart Sender
Molly Sherrick
Linda Shookster
Steve Silverman
John Spriegel
Francis Sweeney
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
Peter Bloomfield
Robert Geddes
Robert Gutman
Suzanne Keller
Norman Kurtz

E. *Technical Staff*

Jack Cooper
Roy Crosby
Kenneth Gadsby
Victor Warshaw
Richard Whitley
Tom Williams

F. *Research Associates*

Corinne Black
Cal Feinberg
Joan Hall
Judith Hunt
Toby Kriss
James Meyer
Pam Pinkham
Jeffrey Robinson
Elizabeth Schorske

G. *Administrative Staff*

Terry Brown
Deborah Doolittle
Selma Lapedes
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
John Meyers, Oak Ridge National Laboratory
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
Roland Radloff
Alex Schwarzkopf
David Seidman
Thomas Sparrow
Charles Thiel
Seth Tuttle
William Wetmore

B. *Department of Energy — Conservation*

John Cable
Lynn Collins
Bruce Hutton
Gerald Leighton
David Pellish
Howard Ross
Maxine Savitz

COLLABORATORS

National Bureau of Standards

Jacquie Elder
Lawrence Galowin
Richard Grot
Max Hunt
Tamani Kusuda
Frank Powell
Dan Quigley
Lynn Schuman
Chock Siu
Jack Snell
Heinz Trechsel

Public Service Electric and Gas

Walter Browning	Edward Nelson
John Casazza	J. Papsycki
Gene Fornarotto	Paul Platt
Arthur Fowler	Robert Reinauer
James Griffith	Louis Rizzi
Edward Monteverdi	Richard Skank

Jersey Central Power and Light
Shephard Bartnoff
Richard Green
Charles Gurner

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–
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

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

Installer (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

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

**Developer: Herbert Kendall, President.