THE TWIN RIVERS PROGRAM ON ENERGY CONSERVATION
IN HOUSING: A SUMMARY FOR POLICYMAKERS

by

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ABSTRACT

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 from our campus, where about 12,000 people are living in approximately 3,000 homes. Our group has monitored the house construction, interviewed many of those responsible for energy-related decisions in the planning and construction phase, formally surveyed and informally interacted with the residents, obtained a complete record of monthly gas and electric utility meter readings, built a weather station at the site, 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:
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 United States, 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 research 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.
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.

Conclusions

1.1 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 semiexterior 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 percent 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.
furnace and distribution system by frequent (once-every-ten-seconds) 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.

1.3 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 (megajoules per Centigrade degree-day)

in SI units, or at about

15 cf/°F -day (cubic feet per Fahrenheit degree-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 that 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
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 A shows an initial interior temperature of $72^\circ F$ ($22.2^\circ C$) and a contribution from heating by sun, appliances, and people that lowers the temperature at which the furnace is first required by $10^\circ F$ ($5.6^\circ C$) to $62^\circ F$ ($16.7^\circ C$).

The curve of outside temperature in Figure A is the National Weather Service's average daily temperature profile for Trenton, New Jersey (15 miles from Twin Rivers). The savings at the furnace are found to be about 220 days/4200°F-days, or about 5 percent per °F reduction (9 percent per °C reduction) in interior temperature, for locations near Trenton.
1.6 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.

1.7 Learning by doing Because quantitative indices (like energy per degree day, see Conclusion 1.3) 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 United States, alone, there are more than sixty million homes, and in nearly all of them retrofitting is warranted. Only a few percent 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.
2.3 Early warnings The side effects of retrofits (see Conclusion 1.6) 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.

Conclusions

3.1 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.
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.

3.4 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 percent 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 can 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 percent in constant dollars.) Alternatively, it may be described as a prompt response to a pulse of exhortation and information.
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.

4.3 Scale Consideration of Twin Rivers as a community reveals that
the residents spent about 2.5 million dollars for gas and electricity in 1975,
$800 per dwelling unit in 3000 dwelling units. The community consumed gas at
a rate of 200 million cubic feet (6 million m$^3$) per year and electricity at
an average rate of 6 megawatts. 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.
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.

Each facing page contains a commentary on issues raised by the photographs. References are listed in Section IV.
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).
TYPE YSI 44204 LINEARLY-COMPENSATED THERMISTORS READ TEMPERATURE ABOVE DOOR TO BASEMENT IN HALLWAY OF TWO "IDENTICAL" TOWNHOUSES.
BANK OF ELECTRIC METERS IN TOWNHOUSE BASEMENT SEPARATE THE USAGE OF AIR CONDITIONER, HOT WATER HEATER, RANGE, DRYER, AND EVERYTHING ELSE.

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

PHOTO PAGE 3
INFRARED EQUIPMENT IN MASTER BEDROOM, BEING TUNED BY RICHARD GROT, NATIONAL BUREAU OF STANDARDS, AND WATCHED BY LYNN SCHUMAN (N.B.S.) AND OWNER OF HOME.

INFRARED PHOTO REVEALS ANOMALOUS COLD PATCH IN UPSTAIRS CEILING.

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

PHOTO PAGE 4
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 5
VIEW OF OPEN SHAFT AROUND FURNACE FLUE FROM BASEMENT TO ATTIC. IN FOREGROUND DUCT TO UPSTAIRS BEDROOM PASSING THROUGH FIRST PART OF SHAFT. ATTIC END OF SHAFT (NOT VISIBLE) WILL BE SEALED, AS PART OF PRINCETON RETROFIT PACKAGE D.

INSULATION BATT BEING STAPLED ONTO ATTIC FLOOR TRAP DOOR, PART OF PRINCETON RETROFIT PACKAGE A.
FOUR VIEWS OF GAPS BETWEEN WALL FRAMING AND MASONRY FIREWALL.

SEEN AT TIME OF CONSTRUCTION, DOWNSTAIRS.

GAPS AT ATTIC FLOOR

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

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

PHOTO PAGE 7
TOP LEFT: INFRARED CAMERA SCANS A CORNER, WITH OUTSIDE WALL TO LEFT, WALL FRONTING A FIRE WALL TO RIGHT.

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

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

PHOTO PAGE 8
FOUR ASPECTS OF PRINCETON'S AIR INFILTRATION RESEARCH.

AIR INFILTRATION MEASUREMENT DEVICE, ALONGSIDE GAS FURNACE.

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

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

KENNETH GADSBY INSTALLS WEATHERSTRIPPING IN SLIDING PANEL OF PATIO DOOR, PART OF PRINCETON RETROFIT PACKAGE B.
BLOWN FIBERGLASS R-30 INSULATION LIES ON TOP OF EXISTING BATT INSULATION ON ATTIC FLOOR, PART OF PRINCETON RETROFIT PACKAGE A.

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

PHOTO PAGE 10
Section III. Some Characteristic Quantitative 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.

Each facing page contains a commentary on issues raised by the Figures. References are listed in Section IV.
NUMBER LABELS HOUSE.
X: AVERAGE EXCLUDING HOUSE 1
(CHANGE OF OWNER IN 1975
SUMMER) AND HOUSE 9
(INCOMPLETE DATA)

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

FIGURE PAGE 1
LARGE SAMPLE
(ALL TOWNHOUSES)
N = 209

MEAN = 758 cu. ft.
S.D. = 163 cu. ft.
S.D./MEAN = 0.22

SMALL SAMPLE
(3 BEDROOM, INTERIOR
DOUBLE-GLASS
E-W ORIENTATION)
N = 28

MEAN = 773 cu. ft.
S.D. = 112 cu. ft.
S.D./MEAN = 0.14

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

FIGURE PAGE 2
WINTER 1972 VS WINTER 1973 GAS CONSUMPTION

WINTER 1973 VS WINTER 1974 CONSUMPTION

FIGURE PAGE 3
Marginal price to the consumer

Last block price (above 5 million BTU per month)

1 million BTu = 1.055 GJ

Marginal price of residential natural gas, 1971-76

Price vs. rate of consumption of gas

Figure page 4
SAMPLE: "OMNIBUS" TOWNHOUSES (N=16)

GAS CONSUMPTION RATE (CUBIC FEET PER DAY)

GAS CONSUMPTION (MEGAJOULES PER DAY)

KEY TO WINTERS
- □ 1971-72
- △ 1972-73
- ○ 1973-74

MONTH NUMBER IN SYMBOL: NOV(11)-APRIL(4)

OUTSIDE TEMPERATURE (°F)

MEAN GAS CONSUMPTION OVER WINTER MONTHS

FIGURE PAGE 5

slope of line: 21 cu.ft./°F-day = 4.80 W/°C
(a) ROOM AND BASEMENT TEMPERATURES BEFORE RETROFIT

(b) ROOM AND BASEMENT TEMPERATURES AFTER RETROFIT
EFFECT OF ATTIC RETROFIT ON ATTIC TEMPERATURE

FIGURE PAGE 8
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 9
LOAD PROFILE - WATER HEATER AT TWIN RIVERS, N.J.

FIGURE PAGE 10
Section IV. Selected Reports and Publications

Note: Unpublished works were produced for Princeton University. They have been disseminated from the Center for Environmental Studies (CES), Princeton University, Princeton, New Jersey, 08540.

A. Program Review


B. Construction of Twin Rivers


C. Psychology and the Resident


F. Air Infiltration


J. Related Publications


Section V. 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

John Fox
Jeff Jacobs
Nicholas Malik
Thomas Schrader
Robert Sonderegger

C. Undergraduate Students (through June 1976)

Rosalind Alpert
Bradley Bellows
Heidi Bode
Anthony Caine, Jr.
John Cella
Malcolm Cheung
Karl Danz
David Donoho
Bruce Duncan
Jonathan Eckstein
Jon Elliott
Rick Ferris
Steven Fisher
Miles Gessow
Michael Guerin
Lucy Hackney
Shawn Hall
William Holstein
Cindy Horowitz
John Kadyszewski
Jeff Kang
Raymond Kang
Sylvia Kuzmak
David LaPlante
Andrew Lazarus
Robert Levin
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
Raymond Radloff
Alex Schwarzkopf
David Seidman
Thomas Sparrow
Charles Thiel
Seth Tuttle
William Wetmore

B. Energy Research and Development Administration — Conservation

Lynn Collins
Gerald Leighton
David Pellish
Howard Ross
Maxine Savitz
V. Subjects of Interviews (1972-74)*

Original Developer

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

The Developer's Staff: Twin Rivers Holding Corporation**

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

Architects

Robert Hillier, assisted by Edward Wilson, Princeton, N.J.
William Conklin, Conklin and Rossant, NYC, original architect

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

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

** Developer: Herbert Kendall, President.
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
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 indispensable 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 and Deborah Doolittle at home base. Our advisory committee, whose membership is found in Section V, gives the group indispensable 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 results 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, and at the National Science Foundation, Division of Research Applied to National Needs, have always included assistance in the substantive aspects of the program.