Arnold Schwarzenegger
Governor

ENERGY EFFICIENT LOW INCOME HOUSING PROGRAM

PIER FINAL PROJECT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
ADM Associates, Inc.
Texas A&M University
Florida Solar Energy Center
University of Nebraska
Lawrence Berkeley National Laboratory

March 2007
CEC-500-2007-017

Prepared By:
ADM Associates, Inc.
Taghi Alereza, D.Sc., P.E.
Donald Dohrmann, Ph.D.
Mugimin Lukito
Sacramento, CA 95827
Texas A&M University
Florida Solar Energy Center
University of Nebraska
Lawrence Berkeley National Laboratory
Contract No. 400-00-036

Prepared For:
California Energy Commission
Public Interest Energy Research (PIER) Program

Chris Scruton
Contract Manager

Ann Peterson
Building End-Use Energy Efficiency Program Team Leader

Daryl Mills
Office Manager
ENERGY EFFICIENCY RESEARCH OFFICE

Martha Krebs, Ph.D.
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

B. B. Blevins
Executive Director

DISCLAIMER
This report was prepared as the result of work sponsored by the California Energy Commission. It does not necessarily represent the views of the Energy Commission, its employees or the State of California. The Energy Commission, the State of California, its employees, contractors and subcontractors make no warrant, express or implied, and assume no legal liability for the information in this report; nor does any party represent that the uses of this information will not infringe upon privately owned rights. This report has not been approved or disapproved by the California Energy Commission nor has the California Energy Commission passed upon the accuracy or adequacy of the information in this report.

Acknowledgments

ADM Associates, Inc., wishes to extend sincere thanks to the following organizations and individuals who have provided valuable contributions to this project:

- Nancy Jenkins, Phil Spartz, Eric Stubee, Chris Scruton and all others at the California Energy Commission who provided guidance and project management
- Jeff Haberl, Ph.D., P.E., and his graduate students at Texas A&M University
- Charles Culp, Ph.D., at Texas A&M Energy System Laboratory
- Hashem Akbari, Ph.D.
- Mario Medina, Ph.D., P.E. at the University of Kansas
- Dale Tiller, Ph.D., at the University of Nebraska
- Janet McIlvaine at Florida Solar Energy Center
- Greg Krekelberg, Greg Brown and Marc Moore at Occam Development
- Habitat for Humanity Sacramento
- Habitat for Humanity Fresno
- Habitat for Humanity Visalia
- Mercy Housing California
- Skyline Homes
- Louisiana Pacific Corp

ADM would also like to recognize the following individuals who have played a significant role in accomplishing this research project:

- Taghi Alereza, D.Sc., P.E., Principal, Project Manager, Author
- Donald Dohrmann, Ph.D., Principal, Author
- Mugimin Lukito, Project Coordinator, Author
- Dan Mort, Senior Monitoring Specialist
- Safdar Chaudhry, Ph.D., Senior Engineer
- Lonnie Smith, Senior Engineer
- Lillie Mozaffari, Senior Engineer
- Richard Ely, Ph. D., Senior Economist
- Sabratnam Thamilseran, Ph.D., P.E., Senior Engineer
- Doug Thomas, Monitoring Specialist
- Seung-Uk Lee, Research Specialist
- Holly Farahbakhsh, Architect
- Richard Burkhart, Administrative Specialist

Please cite this report as follows:

Alereza, Taghi, Donald Dohrmann, and Mugimin Lukito. 2007. *Energy Efficient Low Income Housing Program*. ADM Associates, Inc. for the California Energy Commission, PIER Building End-Use Energy Efficiency Program. CEC-500-2007-017.

Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), conducts public interest research, development, and demonstration (RD&D) projects to benefit the electricity and natural gas ratepayers in California.

The PIER program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Energy Efficient Low-Income Housing Program is the final report for the Energy Efficient Low Income Housing project (contract number 499-00-036), conducted by ADM Associates, Inc. The information from this project contributes to PIER's Building End-Use Energy Efficiency program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier/ or contact the Energy Commission at 916-654-5164.

Table of Contents

Preface iii
Abstract ix
Executive Summary 1
1.0 Introduction and Background 7
1.1. Background for Program 7
1.2. The Interrelated Research Projects 7
1.3. Transferring Research Findings to the Real World 10
2.0 Project 2.1: Attic Ventilation 11
2.1. Background for Project 2.1 11
2.2. Selection of Research Houses 12
2.3. Outcomes for Project 2.1 13
2.4. Conclusions and Recommendations for Project 2.1 17
3.0 Project 2.2: Attic Heat for Water Heating 19
3.1. Background for Project 2.2 19
3.2. Attic Water Heating System Designs 19
3.3. Houses Tested and System Installation 24
3.4. Outcomes for Project 2.2 25
3.5. Conclusions and Recommendations for Project 2.2 29
4.0 Project 2.3: Ducts in Conditioned Space 31
4.1. Background for Project 2.3 31
4.2. Interior Duct System Designs for Project 2.3 32
4.3. Field Testing for Test and Control Houses 35
4.4. Outcomes for Project 2.3 38
4.5. Costs of Installing Ducts in Conditioned Space 41
4.6. Conclusions and Recommendations for Project 2.3 42
5.0 Project 2.4: Envelope and Interior Air Quality Interaction 45
5.1. Background for Project 2.4 45
5.2. Selection of Test Houses 47
5.3. Monitoring Equipment and Procedures 48
5.4. Outcomes for Project 2.4 48
5.5. Conclusions and Recommendations for Project 2.4 51
6.0 Summary for Project 2.5: Simplified HVAC Controls 53
6.1. Background for Project 2.5 53
6.2. Baseline Data on Household Control of HVAC Thermostat 55

6.3. Household Survey Responses ... 57
6.4. Designing and Testing a Simple Thermostat ... 59
6.5. Outcomes for Project 2.5 ... 62
6.6. Conclusions and Recommendations for Project 2.5 ... 62
7.0 Summary for Project 2.6: Evaporative Cooling/Whole House Fan Integration ... 65
7.1. Background for Project 2.6 ... 65
7.2. Description of Test Houses ... 66
7.3. Monitoring Equipment and Procedures ... 68
7.4. Outcomes for Project 2.6 ... 68
7.5. Conclusions and Recommendations for Project 2.6 ... 72
8.0 Summary for Project 2.7: Energy Efficiency Through Community Design ... 73
8.1. Background for Project 2.7 ... 73
8.2. Issues Researched in Project 2.7 ... 74
8.3. Community Design for Habitat for Humanity Community ... 75
8.4. Collection of Ambient Temperature Data ... 75
8.5. Outcomes for Project 2.7 ... 79
8.6. Conclusions and Recommendations for Project 2.7 ... 81
9.0 References ... 83
10.0 Glossary ... 87

List of Figures

Figure 1. Relationships among projects ... 9
Figure 2. Schematic of the single-pipe water pre-heating system ... 21
Figure 3. Schematic of the double-pipe water pre-heating system ... 21
Figure 4. Drawings of the first and second designs of the heat recovery systems ... 22
Figure 5. Diagram of valve arrangement at the water heater ... 23
Figure 6. Schematic of the third attic heat collection system design ... 24
Figure 7. Average daily hot water consumption by month ... 26
Figure 8. Average energy consumption (Btu) for domestic hot water by month ... 26
Figure 9. Monthly energy savings (Btu) of the water pre-heating systems by design ... 27
Figure 10. Monthly percentage of energy savings by design ... 28
Figure 11. Hot water energy consumption by domestic hot water heater and pre-heating system for different designs (June–September) ... 29

Figure 12. Schematics of designs for ducts in conditioned space 32
Figure 13. Floor plan for houses at Mercy Housing Esparto 33
Figure 14. Floor plan for houses built by HfH Visalia 35
Figure 15. Floor plan for houses built by Mercy Housing Esparto 48
Figure 16. Installed Simple Thermostat 60
Figure 17. Temperature profiles for a test house in Winters, California 63
Figure 18. Sample evaporative cooling control system 67
Figure 19. Evaporative cooler operation on a typical day for test house 5 (Atwater, CA) 71
Figure 20. Layout of the HfH Shasta community prior to redesign 76
Figure 21. Layout of the HfH Shasta community after the redesign (characterized by narrower streets and addition of street trees and a community park) 77

List of Tables

Table 1. Project 2.1 test house types and locations and types of ventilation systems 13
Table 2. Energy savings from installing radiant barrier 15
Table 3. Energy savings from radiant barrier retrofit in existing low-income houses 15
Table 4. Results of radiant barrier monitoring in manufactured homes 15
Table 5. Energy savings from radiant barrier installation in manufactured homes 16
Table 6. Energy savings from roof spray installation 17
Table 7. Estimated material cost for each design 24
Table 8. Potential energy savings (March–September) 29
Table 9. Results of air leakage testing at test and control houses 38
Table 10. Energy savings from placing ducts in conditioned space 39
Table 11. Comparison of costs of installing an interior duct system versus a standard duct system 42
Table 12. Comparison of safety standards for carbon monoxide 46
Table 13. Average CO_2 concentration levels inside Visalia houses 49
Table 14. Average CO_2 concentration levels inside Esparto houses 50
Table 15. Breakdown of monitored houses by housing and thermostat types 55
Table 16. Summary statistics for 24-hour temperature profiles: heating season 55

Table 17. Summary statistics for 24-hour temperature profiles: cooling season.....56

Table 18. Numbers of monitored households using temperature setbacks during heating and cooling seasons.....57

Table 19. Summary statistics on summer and winter indoor temperature when heating or cooling system is operating (°F).....58

Table 20. Summary of energy savings observed in Fresno test houses.....69

Table 21. Canopy coverage for monitored communities 78

Abstract

ADM Associates, Inc., and a team of subcontractors have undertaken a program that addresses energy efficiency for housing for low-income households. The program was designed to work with agents who are already active in the housing market for low-income households. In particular, the team collaborated with Habitat for Humanity affiliates in several areas and Mercy Housing in Sacramento in building houses for testing the technology concepts for the different projects described here. Several manufactured home builders also participated in the program.

Through seven research projects, the program focused on research that affects and benefits housing for low-income households directly—and not simply as a by-product of research directed at the more general population. In particular, the research projects addressed low-cost options that reduce monthly energy costs and improve the quality of life by enhancing comfort levels in homes. One set of research projects concentrated on either dispersing or making use of the heat that builds up in residential attics during the summer. A second set of projects focused on improving the energy efficiency of housing for low-income households under constraints imposed by comfort requirements and indoor air quality considerations. Another research project examined how the design of a low-income housing development affects ambient temperature.

Keywords: energy efficient technologies for housing for low-income households, energy efficiency for low-income housing, attic radiant barrier , attic water heating system, whole house fan, ducts in conditioned space, tree planting, energy efficient landscaping, cool communities, urban heat islands, solar space heating system, programmable thermostat, Simple Thermostat, Habitat for Humanity, Mercy Housing

Executive Summary

Introduction

Energy efficiency in housing for low-income households is hindered by several constraints, as defined in a study by the RAND Corporation *The Public Benefit of California's Investments in Energy Efficiency* (Bernstein 2000). Specifically, this study noted that ". . . low-income households derive the greatest benefit from reduced energy expenditures. While low-income households spend less on energy than higher income households, the burden as a percent of income is much higher for lower income populations." Moreover, this study observed that ". . . energy efficiency programs at the household level provide two services: they directly reduce monthly energy costs, thereby increasing the disposable income of the low-income population, and they improve quality of life by improving the comfort level in homes."

Purpose

The Energy Efficient Low-Income Housing program has developed information, strategies, and technologies to help reduce energy use and its related expense in housing for low-income households. This research has focused on low-cost options that reduce monthly energy costs and improve the quality of life by enhancing comfort levels in homes. To help move program results into the housing market, the project collaborated with organizations already involved in housing for low-income households.

Project Objectives

- To quantify the effects of technologies and processes for either dispersing or making use of the heat that builds up in home attics during the summer
- To improve the energy efficiency of housing for low-income households within comfort requirements and indoor air quality requirements by examining duct placement, different cooling strategies, and a simplified programmable thermostat
- To explore use of community-level factors, such as street width and tree canopy, to reduce ambient temperatures, thereby decreasing cooling loads throughout a neighborhood of low-income households
- To bring study findings to the building industry, energy professionals, and consumers

Project Outcomes

Dispersing or Using Attic Heat

Studies to examine reducing attic heat yielded these findings:

- As a retrofit item, a radiant barrier can achieve cooling energy savings of 2–8% depending on the level of attic insulation. The benefits of the radiant barrier on the attic temperature were found to be greater in manufactured homes than in conventional homes.
- The residential roof spray system was as effective as the radiant barrier in reducing the attic temperature. In a test house, the attic temperature was reduced by an average of 12.5°F during the peak hours in the summer. The roof spray system's relatively low

parts cost, low water use, and ease of installation should make this a viable alternative to the radiant barrier retrofit.

Another project demonstrated the feasibility of tapping into attic heat in the hot summer months to supplement domestic water heating using systems constructed from widely available materials. The three designs showed energy savings of between 15–24 percent in the peak summer months; a design using 4-inch chlorinated poly vinyl chloride (CPVC) pipe was the most effective. Considering the reasonable cost of materials and low labor cost, installing the proposed pre-heating system in low-income houses could make financial sense in areas with hot summer days and reasonably warm nights.

Considering Energy Efficiency within Comfort and Indoor Air Quality Requirements

One project examined placing ducts in conditioned space and found that homes with conventional flex-ducts had average leakage of 23.6 percent, while homes with ducts in conditioned space had only 1.1 percent leakage. The average annual energy savings from reduced air leakage and heat conduction are estimated to be 35 therms of natural gas (or 19.7 percent of heating energy) and 266 kilowatt-hours (kWh) of electricity (or 16.8 percent of cooling energy).

Four houses with ducts in conditioned space were tested for indoor air quality problems. The carbon dioxide (CO_2) and interior humidity levels in houses with ducts in conditioned space were consistently lower than the levels observed in houses with flex-ducts. However, two of the houses with interior ducts had consistently high levels of carbon monoxide (CO). The source of the CO was traced to pilot lights inside the oven that had not been adjusted properly. The interior ducts did not appear to aggravate the problem. Nonetheless, all houses should have Combustion Appliance Safety (CAS) test performed on all appliances annually.

Another study examined programmable thermostats as an energy efficiency measure. Activities included conducting a survey to examine use of current programmable thermostats and developing Simple Thermostat, a one-of-a-kind thermostat that removes the complexity of programming often cited by users as a nuisance. A working model installed in 12 low-income houses had only three buttons and yet was capable of retaining a week's worth of memory. Monitoring data suggested that Simple Thermostats set to an active setting (as opposed to those habitually turned off when not needed) reached a regular schedule after extended use. However, the Simple Thermostat might be ill-suited for low-income households due to residents' strong preference for lower cost over comfort, which leads to minimal use of heating and cooling equipment.

A final study of comfort evaluated three different systems that integrate evaporative cooling, whole house fans, and standard air conditioning. This study found that an evaporative cooler integrated with a standard air conditioner saved an average of 532 kWh throughout the summer in four test houses. Considering the low cost of adding an evaporative cooler, especially as a new construction item, this measure may be economically viable for houses built for low-income households.

The study also found that it is possible to install an economizer in manufactured homes. However, such installations are not common due to a number of constraints imposed by the structural conditions and placement of mechanical equipment.

Community Design

This project examined the effects of community design on energy efficiency on communities of housing for low-income households. One issue examined was how self-help housing organizations, such as Habitat for Humanity (HfH), can apply energy efficiency community design principles to housing that they build. For example, ADM Associates provided HfH Shasta with a new design of a subdivision that included narrow streets, shade trees, and a small park.

To understand the impact of planting shade trees in mobile home communities, several mobile home parks with varying levels of canopy coverage were monitored extensively. Using the resulting data, the team developed a mathematical model based on Fourier Series Approximation that demonstrates that on a moderately hot summer day, the presence of tree canopy could cause the ambient temperature to decline 4–5°F from the reference temperature. On a very hot summer day, this reduction could be as high as 6–8°F. This model could be used to aid the development of future regulations related to tree planting.

Transferring Results

Several technology transfer mechanisms were included in the program to bring the findings of the research projects to the building industry, energy professionals, and consumers. Foremost, the program worked with agents active in the housing market for low-income households, such as Habitat for Humanity affiliates, Mercy Housing, and several manufactured home builders. Through these collaborations, the project team became involved in a network of individuals and firms active in building housing for low-income households. As another benefit, the local contractors who work with HfH to build houses for low-income households gained first-hand exposure to the different energy efficiency technologies and their applicability to the houses built for the general market.

Conclusions

When compared to higher income groups, low-income households incur a disproportionate energy cost burden as a percent of income. Because of cost barriers commonly associated with energy efficiency measures, the research in this program has focused on low-cost options that reduce monthly energy costs and improve the quality of life by enhancing comfort levels in homes. The participation of HfH and manufactured housing builders in the program will help move program results into this housing market.

Conducting research on housing for low-income households under a single program has offered the added value of ensuring that the research has maintained its focus. Housing for low-income households is not the same as that for higher-income households. The houses are generally smaller, and economic constraints usually preclude installation of materials and equipment that carry high first costs. By looking specifically at housing for low-income households, the resources for the research could be used to maximum effect. Further, because the projects were interrelated, data, research methods, and results could be shared easily across projects within a given set and across sets.

Findings showed that it is possible to develop energy efficient measures geared toward this market that provide the desired benefits and that are relatively low cost and easy to install. By

creating connections within the community concerned with housing for low-income households, this project laid the groundwork for wider awareness and penetration of these technologies. Further efforts, particularly those outlined below, can help advance the development and adoption of these measures.

Recommendations

The promising methods developed in this project would benefit from additional efforts, including the following:

- Radiant barrier in manufactured housing merits industry support. The manufactured housing industry is regulated by the Department of Housing and Urban Development (HUD); California's Title 24 that calls for installation of radiant barrier in all newly constructed homes does not apply to manufactured homes sold in California. Individual home manufacturers will be key to ensuring that the radiant barrier is more widely installed in new manufactured homes.
- Installing the proposed domestic water pre-heating system in low-income houses could make financial sense in the California's Central Valley or other areas with hot summer days and reasonably warm nights. Further studies are recommended to determine ways to lower the installation and material costs, and a market study is needed to assess the demand and pricing of such products for the low-income housing and other markets.
- Organizations that build housing for low-income households view technical guidance, especially in the design of the air ducts, as critical to installing ducts in conditioned space. It is recommended that a program be created by utilities or by state or local governments to provide assistance in the designing and planning of installing ducts in conditioned space.
- Building ducts in conditioned space could be attractive to commercial homebuilders. Constructing a dropped ceiling used as a plenum without sheet metal costs less than installing flexducts throughout the house. Building the plenum along hallways also has little effect on the interior appearance. Aggressive efforts are needed to inform California homebuilders of this option.
- Simple Thermostats should be tested in markets other than low-income housing to determine their ability to save energy and increase comfort. The Simple Thermostat could be further refined through collaborations with thermostat manufacturers and data sharing to better meet household needs in many markets.
- Houses in areas with milder summer climates than that of the test houses might see strong cooling benefits from the adding an evaporative cooler. Testing this technology in other California climates will determine potential energy savings in each climate zone. The test data could be used to construct and calibrate an energy simulation that can predict the energy savings resulting from such an integrated system.
- While possible, economizer installations in manufactured homes are constrained by structural conditions and placement of mechanical equipment. An informative marketing campaign to increase homebuyer awareness of an economizer might create enough demand to drive design changes aimed at easier economizer installation.

- The model to predict the energy savings from planting trees could be used to help develop future tree planting regulations. The model could also be integrated into DOE-2 to assess the impact of tree canopies on the cooling loads of buildings within a community. Further, developing a stand-alone tool or software based on this mathematical model would allow community planners in California to determine the community-wide temperature impact of varying canopy coverage based on parameters such as community size, type and quantity of trees, and the climate zone.

Benefits to California

By allowing for reduced energy use without compromising comfort, many of the methods examined in this project would benefit low-income households by cutting their energy bills while improving comfort. As an added benefit, these households would be able to devote the income formerly spent on energy to other goods or services that enhance quality of life.

In addition, some methods appear to be suitable in markets beyond that for housing for low-income households. As these methods are developed and adopted in households of all types throughout the state, they could substantially reduce California's energy use overall.

Further, considering energy efficiency in the design of California communities by narrowing streets, planting more trees, and devoting land for parks will beautify our state while enhancing the lives of thousands.

1.0 Introduction and Background

Under Contract No. 400-00-036 with the Public Interest Energy Research (PIER) Program of the California Energy Commission, ADM Associates, Inc. (ADM) and a team of subcontractors have undertaken a program that addresses energy efficiency for housing for low-income households. The following subcontractors participated with ADM in the program:

- Florida Solar Energy Center (FSEC) at the University of Central Florida
- Energy Systems Laboratory at Texas A&M University
- University of Nebraska
- Dr. Hashem Akbari
- Robert Penny Enterprises

Besides involving knowledgeable researchers, the program worked with agents who are already active in the housing market for low-income households. For example, Habitat for Humanity (HfH) affiliates in several areas and Mercy Housing in Sacramento worked with the program team in building houses for testing the technology concepts that were addressed with different projects. In addition, several manufactured home builders participated in the program.

The overall goal of the Energy Efficient Low-Income Housing program has been to develop information, strategies, and technologies to help reduce energy use and its related expense in housing for low-income households. When compared to higher income groups, low-income households incur a disproportionate energy cost burden as a percent of income. Because of cost barriers commonly associated with energy efficiency measures, the research in this program has focused on low-cost options that reduce monthly energy costs and improve the quality of life by enhancing comfort levels in homes. The participation of Habitat for Humanity and manufactured housing builders in the program will help move program results into this housing market.

1.1. Background for Program

This PIER program comprised seven research projects directed at improving the energy efficiency of housing for low-income households. Recent studies have demonstrated the importance of improving energy efficiency for low-income households. In their study *The Public Benefit of California's Investments in Energy Efficiency*, (Bernstein 2000) the RAND Corporation noted that "low-income households derive the greatest benefit from reduced energy expenditures. While low-income households spend less on energy than higher income households, the burden as a percent of income is much higher for lower income populations." Moreover, the RAND study observed that ". . . energy efficiency programs at the household level provide two services: they directly reduce monthly energy costs, thereby increasing the disposable income of the low-income population, and they improve quality of life by improving the comfort level in homes."

1.2. The Interrelated Research Projects

The seven separate, yet interrelated, energy efficiency projects within the program follow:

- Project 2.1 Attic Ventilation
- Project 2.2 Attic Heat for Water Heating

- Project 2.3 Ducts in Conditioned Space
- Project 2.4 Envelope and Interior Air Quality (IAQ) Interaction
- Project 2.5 Simplified Heating, Ventilation, and Air Conditioning (HVAC) Controls
- Project 2.6 Evaporative Cooling and Whole House Fan Integration
- Project 2.7 Energy Efficiency through Community Design

Figure 1 shows the relationships among the various projects in the program under the central theme of improving energy efficiency in low-income housing. Specifically, the program has focused on research that affects and benefits housing for low-income households directly—and not simply as a by-product of research directed at the more general population. Thus, the research has been intended to produce results and products specifically intended for new and existing housing for low-income households.

The projects within the overall program fell into several sets that further link projects:

- One set includes research projects pertaining to either dispersing or making use of the heat that builds up in attics in houses during the summer. These projects examined different non-mechanical methods of attic ventilation, studied the effects of installing ducts in conditioned space for small stick-built and manufactured houses, and designed and implemented a heat recovery system that uses attic heat to pre-heat the water for electric (or gas) water heaters.

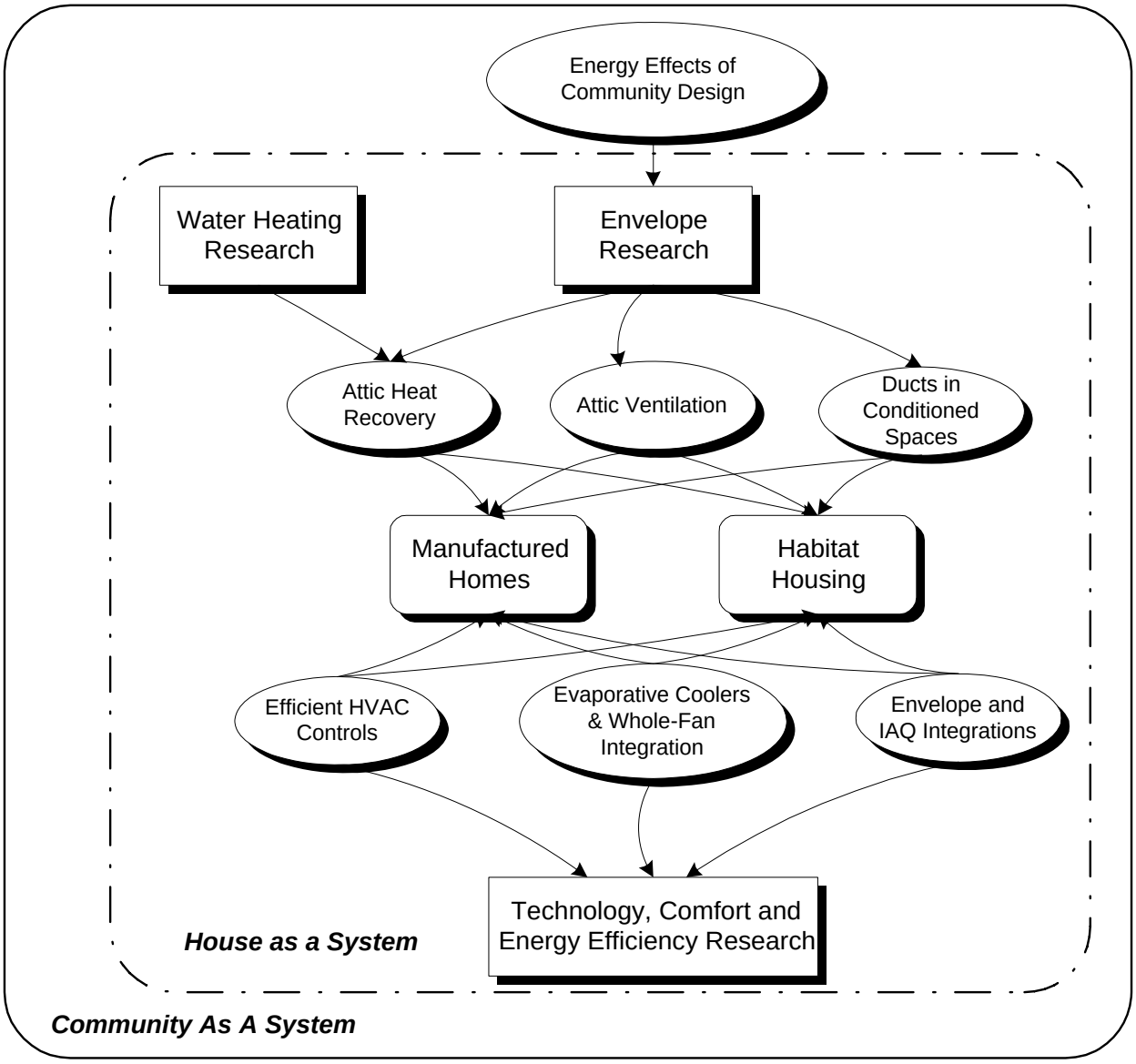

Figure 1. Relationships among projects

- A second set of projects pertained to improving the energy efficiency of housing for low-income households under constraints imposed by comfort requirements and indoor air quality considerations. Construction practices for Habitat for Humanity houses and manufacturing processes for manufactured homes have resulted in a stock of "tight" houses in the market for low-income households. However, accumulating evidence suggests that such tightness may be contributing to worsening indoor air quality. This set of projects examined the effect of different envelope construction and system control methods on indoor air quality, the effectiveness of integrating whole-house fans with standard or evaporative cooling systems, and how controls installed to improve energy efficiency (e.g., programmable thermostats) can be made easier to use for low-income households.

- Common to all of the projects is the cooling load impact of ambient climate conditions on houses. A research project was therefore initiated to examine how the design of a low-income housing development affects ambient temperature. Specifically, the project explored use of such community-level factors as street width and tree canopy to reduce ambient temperatures and thereby decrease cooling loads throughout a neighborhood of low-income households.

Conducting research on housing for low-income households under a single program has offered the added value of ensuring that the research has maintained its focus. Housing for low-income households is not the same as for higher-income households. The houses are generally smaller, and economic constraints usually preclude installation of materials and equipment that carry high first costs. By looking specifically at housing for low-income households, the resources for the research could be used to maximum effect. Further, because the projects were interrelated, data, research methods, and results could be shared easily across projects within a given set and across sets.

1.3. Transferring Research Findings to the Real World

A key objective of the PIER Program has been to conduct research, development, and deployment (RD&D) activities that produce results that will be applied in the real world and thus produce benefits for California's electricity ratepayers. Several technology transfer mechanisms were included in the program to bring the findings of the research projects to the building industry, energy professionals, and consumers.

Foremost, the program worked with agents active in the housing market for low-income households. In particular, the project team worked with several self-help organizations (such as Habitat for Humanity affiliates and Mercy Housing) to build houses for testing the technology concepts being addressed with the different projects. The team also worked with several manufactured home builders to conduct research on technologies that could be applied in manufactured homes.

By working with these organizations and firms, the project team was involved in a network of individuals and firms active in building housing for low-income households. Because local contractors volunteer to work with Habitat for Humanity to build houses for low-income households, these contractors gained first-hand exposure to the different energy efficiency technologies and their applicability to the houses built for the general market. Further, contractors working on the program's test houses gained first-hand exposure to and knowledge of the energy efficiency technologies that were the subjects of the research.

2.0 Project 2.1: Attic Ventilation

The objective of Project 2.1 was to compare the performance of different passive non-mechanical methods for ventilating attics in HfH and manufactured housing and to evaluate the relative effectiveness and costs of the methods in reducing space conditioning loads and energy use.

The work in Project 2.1 included the following:

- Review prior research
- Prepare a monitoring plan
- Select sites and construct eight homes
- Implement ventilation methods
- Instrument eight home
- Collect data and use those data to model and evaluate the ventilation effectiveness of the techniques

This work is summarized in the following sections.

2.1. Background for Project 2.1

Attics in houses in the Central Valley and desert regions of California can be extremely hot during a summer day. Attic temperatures of up to 150°F are not unusual for houses in these regions. These high attic temperatures can affect air conditioning loads through transfer of heat from the attic to interior space and to ducts in the attic space.

The increased air conditioning load in the summer presents an additional burden, especially on low-income households that have limited means to pay for the increased utility bills. The objective of this project was to compare the performance of different passive non-mechanical methods for ventilating attics in houses built for low-income households by Habitat for Humanity or other self-help housing organizations and in manufactured housing to evaluate the relative effectiveness and costs of the methods in reducing space conditioning loads and energy use.

The project team initially considered several non-passive attic ventilation methods, including methods practiced to varying degrees in new residential construction:

- Ridge vents with soffit vents
- Sealed attic construction with no venting
- Radiant barrier systems
- White reflective roofs
- Enhanced attic ventilation and roof tiles

A literature review of prior research on the methods above identified two different types of attic ventilation systems as meriting research effort, particularly based on their applicability in self-help and manufactured houses, as described below.

2.1.1. Installing a radiant barrier system in the attic

The first ventilation method researched involves installing a radiant barrier system in the attic of retrofit (or rehab) single-family homes built by self-help organizations such as HfH or Mercy Housing. Modifying existing homes donated to HfH is not an unusual practice for HfH affiliates across California. Since radiant barrier installation is not required in these homes, some affiliates prefer to opt out of using the measure to avoid the extra cost. Installing the radiant barrier, however, has been shown to be effective in reducing the overall home cooling cost. The research in this study attempted to verify its cost-effectiveness for the retrofit homes.

This study also compared the effectiveness of alternate placement options of the radiant barrier. In one case, the radiant barrier is laid on top of the insulation, and in the other, the radiant barrier is installed along the roof (or rafter) line.

The second type of homes of interest for this research, manufactured homes, is regulated by the federal building code instead of the California code. Therefore, these homes are not required by law to have radiant barrier installed. This study evaluated the effectiveness of installing radiant barrier in new manufactured homes.

2.1.2. Roof spray systems

The second ventilation method investigated is a roof spray system. Roof wetting that has been used to cool commercial and industrial facilities, but rarely been used for residential homes. This study tested and evaluated the viability and effectiveness of using this ventilation method for single-family homes. The system was designed to enable a minimal amount of water to remove the heat build-up on the roof surface. With this method, the roof surface is wetted just enough to form a very thin layer of water that evaporates in minutes. This process reduces the heat being transferred to the attic space, and subsequently reduces the overall temperature inside the house.

2.2. Selection of Research Houses

The team researched the two ventilation systems by installing them on selected houses and measuring their effects. Four houses were selected as test houses for the radiant barrier research, and two houses were selected for the research on the roof spray system. Table 1 identifies the types of house, the locations of the houses, and the type of ventilation system installed. Control houses enabled comparison of results.

Table 1. Project 2.1 test house types and locations and types of ventilation systems

Test House	*Type of House*	*Location*	*Type of Ventilation System*
1	Habitat For Humanity	Sacramento, CA	Radiant barrier on top of insulation level
2	Habitat For Humanity	Fresno, CA	Radiant barrier stapled to the rafters
3	Manufactured Home	Arbuckle, CA	Radiant barrier in a manufactured house
4	Manufactured Home	Delhi, CA	Radiant barrier in a manufactured home
5	Habitat For Humanity	Sacramento, CA	Roof spray system
6	Habitat For Humanity	Visalia, Ca	Roof spray system

2.3. Outcomes for Project 2.1

The results of testing the two selected attic ventilation technologies at the six test houses are summarized in this section. Section 2.3.1 addresses the results for radiant barriers in stick-built houses, Section 2.3.2 addresses the results for manufactured homes, and Section 2.3.3 addresses the results for the roof spray system.

2.3.1. Performance of radiant barrier in single-family houses in Sacramento and Fresno

For Test House 1 in Sacramento, where the radiant barrier was installed horizontally on top of the attic insulation, temperature data inside the attic and immediately underneath the radiant barrier layer were collected between the summer of 2002 and winter of 2003. This interval captured periods of occupancy (after January 2003), and non-occupancy (before December 2002).

The monitored data collected during summer of 2002—when test conditions in the test and control houses were identical because both were not yet occupied—showed that the installation of radiant barrier had a minimal effect on the space temperature inside the attic.

However, the monitored data during the same period on the variation in maximum temperature at the attic insulation level relative to the outdoor temperature showed a pronounced difference between the test and control case. Thus, the attic-level insulation temperature is clearly a better measure of the impact of the radiant barrier on ceiling heat flux than is attic space temperature.

Therefore for Test House 1, the insulation-level temperature will be referred to as the attic temperature. The mean difference between the attic temperature in the test and control house is 6.8°F, with the maximum difference being 10.8°F.

The temperature data for Test House 2 in Fresno, where the radiant barrier was stapled to the rafters, were collected within a similar timeframe. Data collection began in summer of 2002 and concluded in winter of 2003. In the first six months of data collection, test conditions in the

control and test houses were identical: the construction of the houses was identical, the two houses are separated by less than 100 feet, and both were unoccupied. The monitored data showed that the reduction in attic temperature attributable to the addition of radiant barrier along the roof rafters is very similar to the reductions observed in Test House 1. The mean attic temperature difference between the test and control houses is 6.7°F, while the maximum difference is 11.7°F.

Medina (Medina 1992a) developed a transient and mass transfer model for a residential attic to predict the ceiling heat flux reduction and energy savings resulting from the installation of radiant barrier. Using this model, a simulation of a standard house with R-19 thermal insulation inside the attic was performed for several cities in California, including Sacramento and Fresno. For the house in Sacramento, the model predicts a maximum reduction of 10.8°F at peak times, which is the same as the maximum reduction measured here. For Fresno, the model predicts a maximum reduction of 10.6°F, which is slightly below the measured maximum of 11.7°F.

Both test houses 1 and 2 were occupied by early 2003. Monitoring continued during this period and into the summer of 2003. The results from monitoring during this period provide a stark contrast from the previous year, when the attic conditions were nearly identical. The monitored data for Sacramento showed a somewhat more narrow difference in the maximum attic temperature between the test and control house. The mean temperature difference was 3.7°F, and the maximum difference was 7.2°F. The Fresno data revealed a highly inconsistent difference in maximum attic temperature between the test and control house after occupancy. The temperature difference narrowed, and when the outdoor temperature climbed, the difference declined.

Evidently, occupancy of these houses introduced a number of factors that affected the attic temperature. Since all the monitored houses have space conditioning equipment, the ceiling heat flux is clearly impacted. The data collected from Fresno suggests that during a hot day, as the likelihood of the house occupants operating the air conditioner increases, the difference in attic temperature becomes more inconsistent. The changes in ceiling heat flux, however, should only account for a small change in attic temperature.

Since all of theses houses have conventional ducts located in the attic, air leakage can be considered as the dominant factor altering attic space temperature. The problem of air leakage from conventional ducts is documented in *Project 2.3: Ducts in Conditioned Space Final Report.* For the 10 low-income houses tested in that project, the average duct leakage was 23.6%. This finding underscores the necessity of maintaining closely controlled conditions when performing any tests related to attic ventilation, especially in the presence of space conditioning equipment.

To estimate the cooling energy savings, energy simulations were performed for both the test and control houses in Sacramento and Fresno. In the simulation, the thermal resistance of the attic floor was adjusted to reflect the actual insulation level at the test houses (R-38), as well as the equivalent thermal resistance that would provide a ceiling heat flux reduction consistent with the finding above. The savings calculated are presented in Table 2.

Table 2. Energy savings from installing radiant barrier

House ID	*House Type*	*Location*	*kWh Savings/yr*	*% Savings*
Test House 1	HfH single-family	Sacramento	42	3.0%
Test House 2	HfH single-family	Fresno	75	2.2%

Existing low-income houses, however, typically have less insulation than newly constructed or rehabilitated houses. In these houses, an average ceiling insulation of R-14 can be expected, and the anticipated cooling energy savings would be higher. Savings assuming this level of insulation for the houses tested are shown in Table 3.

Table 3. Energy savings from radiant barrier retrofit in existing low-income houses

House ID	*House Type*	*Location*	*kWh Savings/yr*	*% Savings*
Test House 1	HfH single-family	Sacramento	141	7.4%
Test House 2	HfH single-family	Fresno	248	5.8%

The results above do not indicate a significant difference in the effectiveness of either method of installing the radiant barrier (horizontal vs. along rafters). In either case, the measured temperature reduction is within 10% of the predicted maximum temperature reduction using the simulation model developed by Medina that assumes placement of radiant barrier along the rafters. Given this, laying down the radiant barrier horizontally is anticipated to be the more popular method for radiant barrier retrofit, considering that the length of time and complexity of installation is not as demanding as the alternative.

2.3.2. Radiant Barrier Performance in Manufactured Homes

Data collection in the two manufactured homes (located in Arbuckle and Delhi) where radiant barriers were installed took place in 2003. The measured values for temperature difference (ΔT) between the test and control houses are summarized in Table 4.

Table 4. Results of radiant barrier monitoring in manufactured homes

House ID	*Location*	*Mean ΔT (°F)*	*Maximum ΔT (°F)*
Test House 3	Arbuckle	23.6	33.5
Test House 4	Delhi	10.1	22.9
Average		**16.9**	**28.2**

The higher temperature reduction for the manufactured homes can be traced to the attic configuration of these houses. The attics in the manufactured homes tested are shorter

(approximately 2.8 feet [ft] along the roof line) that attics in regular homes (which are approximately 6 ft at the tallest point). Unlike test houses 1 and 2 that have gables with soffit vents, test houses 3 and 4 have multiple small vent holes at the gable and no soffit vents. Lacking these attributes, the manufactured homes have much lower attic ventilation flow rates than do conventional homes.

The manufactured houses studied were occupied at the time of data collection. As observed previously from the temperature data in HfH houses with radiant barriers, the use of space conditioning equipment in these houses could have affected the attic temperature. However because the ducts in the manufactured homes were placed underneath the house, duct leakage had no impact on the attic temperature.

Energy use simulations were performed for test houses 3 and 4. The thermal resistance of the attic floor was adjusted to reflect the actual insulation used for these houses (R-30) and the increased performance of the radiant barrier observed in manufactured homes. The results of the savings calculations are shown in Table 5.

Table 5. Energy savings from radiant barrier installation in manufactured homes

House ID	*House Type*	*Location*	*kWh Savings/yr*	*% Savings*
Test House 1	Manufactured Home	Arbuckle	160	4.6%
Test House 2	Manufactured Home	Delhi	387	16.1%

2.3.3. Roof Spray System Performance in Sacramento and Visalia

The roof spray systems for test house 5 in Sacramento and test house 6 in Visalia were monitored in 2003 and 2004. Both test houses were occupied at the time of monitoring. Neither house has a radiant barrier or any other attic ventilation device that might contribute to large variations in the attic temperature. The same test houses were also used as control houses during periods when the roof spray system was completely shut off.

The data collected through the monitoring showed that, on average, the roof spray system operated for about 11 minutes daily between June and September. The water consumption averaged 29 gallons a day for the Sacramento house and 23 gallons a day for the Visalia house.

The observed differences between the attic and the outdoor temperatures were dissimilar in the two houses—perhaps due to the presence or absence of mechanical cooling. As established previously, the duct leakage and conditioned interior contribute to reducing the attic temperature. The Sacramento house, which had an air conditioner and conventional ducts in the attic, saw a smaller temperature differential between the attic and outdoor temperature. The Visalia house did not have any cooling equipment, and the effects of the roof spray are more consistent. The absence of cooling equipment that might interfere with data collection allowed the impact of the roof spray system to be isolated. The average temperature reduction seen in test house 5 was 2.8°F when the roof spray system was on, and the temperature reduction in test house 6 was 12.5°F.

Energy simulations were performed to account for the cooling energy savings for both test houses. Since the Visalia house does not have mechanical cooling, a scenario assumed use of a standard air conditioner with a seasonal energy efficiency ratio (SEER) of 10. For the simulations, the team employed an approach similar to that used for evaluating radiant barrier. The attic thermal resistance was adjusted appropriately to reflect the level of insulation used in each house, and the simulation accounts for the difference in effectiveness between the radiant barrier and roof spray system in reducing the attic temperature.

Table 6 shows the cooling energy savings in the two test houses. The effects of the roof spray system on the attic temperatures were very similar to those of radiant barrier. The temperature reduction achieved in the Visalia house indicates that a roof spray system can be as or more potent than a radiant barrier.

Table 6. Energy savings from roof spray installation

House ID	*House Type*	*Location*	*kWh Savings/yr*	*% Savings*
Test House 1	Manufactured Home	Arbuckle	24	1.8%
Test House 2	Manufactured Home	Delhi	215	8.0%

Although both roof spray systems remained relatively maintenance-free during the test period, one recurring problem should be considered for future installations of a roof spray system. In Visalia, it was observed that mineral deposits could collect inside the sprinkler heads and clog the system. In the period of more than a year when the spray system was closely monitored, the sprinkler heads broke off twice. This problem did not occur in Sacramento. A filtration system should be considered for areas where the water is known to have high mineral content.

2.4. Conclusions and Recommendations for Project 2.1

The research in Project 2.1 examined the effectiveness of potentially cost-effective methods of attic ventilation for housing built for low-income households. The major conclusions from that research can be summarized as follows.

- As a retrofit item in low-income houses, radiant barrier can achieve cooling energy savings in the range of 2 to 8% depending on the level of attic insulation. Both methods of installing the radiant barrier—laying down the radiant barrier horizontally on top of the insulation and stapling the radiant barrier along the roof rafters—produced very similar attic temperature reduction. Therefore, the less-demanding method of laying the radiant barrier horizontally is preferable in a retrofit. This method of installation, however, has been found to be prone to accumulation of dust that may render the radiant barrier less effective. Dust removal upkeep every few years may be necessary.
- The impact of radiant barrier on the attic temperature in manufactured homes was found to be more pronounced than in conventional homes. The probable causes for this increase in performance are the lower roof height and less attic ventilation. Radiant barrier has not been widely offered as a standard or even optional equipment in manufactured homes. The good performance of radiant barrier in this type of housing should merit some consideration from the industry. The manufactured housing industry

is regulated by the Department of Housing and Urban Development (HUD); California's Title 24 that calls for installation of radiant barrier in all newly constructed homes does not apply to manufactured homes sold in California. Participation from individual home manufacturers will be key to ensuring that radiant barrier is more widely installed in new manufactured homes. Among the possible next steps to engage these manufacturers is dissemination of information, gauging manufacturers' interest through focus groups, and providing incentives to manufacturers to encourage more widespread adoption of this technology.

- The residential roof spray system was found to be as effective as radiant barrier in reducing the attic temperature. In a test house located in Visalia, the attic temperature was reduced by an average of 12.5°F during the peak hours in the summer. The system's relatively low parts cost and ease of installation should make this a viable alternative to radiant barrier retrofit. The additional use of water due the system was less than 30 gallons a day, equivalent to water used in a five-minute shower with a regular showerhead.

3.0 Project 2.2: Attic Heat for Water Heating

The objective for Project 2.2 was to design and evaluate systems for recovering heat from attics in housing built for low-income households and using that heat for domestic water heating.

Achieving this objective involved the following work:

- Reviewing literature
- Developing conceptual designs for systems using attic heat to pre-heat water for domestic use
- Installing the designed systems in several test houses
- Installing monitoring equipment to collect data on system performance
- Analyzing the collected data to evaluate the energy savings provided by the systems
- Estimating the costs of installing the systems
- Preparing a final report on the project

3.1. Background for Project 2.2

Attics in houses in California's Central Valley can become very hot during a summer day. The temperature inside the attic can climb to over 150°F, providing a ready source of heat. Project 2.2 examined using this heat to provide hot water for domestic—a concept that is especially appealing for low-income houses with electric water heating. Most of the research on technologies for improving the efficiency of electric water heating has focused on heat pump water heaters. However, the first cost of such technology generally precludes its use in housing for low-income households. An opportunity exists for a lower-cost passive technology that taps into the heat already available in the summer.

The use of heat collectors in the attic is not entirely new. In one instance, a company in Minnesota (SolarAttic, Inc.) has designed and produced an attic heat water heater specifically designed to heat swimming pools (Skerrett 1993). The design makes use of a fan coil system to assist in the heat transfer process. This commercially available design takes advantage of a longer time to raise the pool water temperature. No specific design, however, has been proposed for domestic hot water use, which requires water heating at a faster rate. As another drawback, some of the energy savings for such a system would be offset by the energy consumed by the fan coil system.

3.2. Attic Water Heating System Designs

The project team developed designs for an attic water heating system intended for a primary target market of low-income houses. As such, the designs emphasized simplicity, low cost, and easy access to materials for construction. Because the construction of low-income homes is often coordinated by non-profit organizations such as Habitat for Humanity or Mercy Housing and typically involves volunteers and amateur construction workers, ease of installation is also critical, and could determine the success of these designs in the low-income housing market. To avoid production costs that could add substantially to the price tag of the system, the focus of the design effort was on a passive system with parts that could be easily assembled at the construction site.

The primary goal of the passive recovery systems developed in this project was to collect heat in the attic during hot summer afternoons, when the temperature in the attic could be up to 50°F higher than the outdoor temperature. However, such systems could also act as a heat emitter during cold nights, especially in the winter. Use of domestic hot water is typically intermittent; during the intervals when the hot water consumption is low, the heat recovery system should also be able to serve as a water storage device that loses as little heat as possible. To facilitate this option, the systems were designed to serve not only as heat collectors, but also as hot water storage tanks. In such a system, the water collected in the attic heating system is routed into the water heater and heated further if necessary.

The choice of the materials for the heat transfer surface and storage tank would determine whether a given system is more effective as a heat collector or as a storage unit. Metals that have high thermal conductivity, such as copper, make a great heat collector, and they are widely available. However, they would be a poor material for storage. Plastics are perhaps the second most common type of water transport and storage materials. PVC plastic is commonly used as a material for outdoor pipes. However, durability concerns prevent more widespread use of PVC for interior piping. CPVC, a stronger version of PVC, is becoming more popular for both exterior and interior pipes. Because CPVC has a much lower thermal conductivity (k = 0.95 British thermal unit [Btu] ·in/hr ft^2 °F) than copper tubing (k = 2700 Btu ·in/hr ·ft^2 ·°F), less insulation is needed for regions with extreme temperatures. The ease of installation (no brazing or welding required) also contributes to the increasing popularity of CPVC.

The first two pre-heating designs developed use CPVC or PVC as their primary material. Many areas in California, including the California's Central Valley, experience a rather significant temperature drop in the evenings. The temperature overnight can drop below 60°F, even in the summer. This raises a concern that the system could potentially lose energy through heat loss overnight. Using CVPC/PVC as the material could slow down the heat loss.

In the first design, the system comprises a 6-inch (in) Schedule-80 CPVC (or PVC) pipe hung at an angle in the attic. The length of the pipe is 20 ft, enough to store nearly 30 gallons of water. The pipe is hung at a maximum allowable angle with the high side closer to the water heater to take advantage of heat stratification. The upper half of the pipe is heavily insulated to reduce heat loss from the pipe. Overnight, when the temperature of the attic is potentially lower than the temperature of water inside the pipe, water with higher temperature is expected to flow upwards and remain at the insulated top portion of the pipe due to stratification, thus minimizing the heat loss. Figure 2 is a graphical rendition of the first design.

The second design has a similar concept, except that it uses double 4-in Schedule-80 CPVC pipes instead of a single 6-in pipe. This design's capacity of approximately 27 gallons is comparable to that of the first design. The use of the smaller pipes increases the overall heat transfer surface area. Figure 3 is a graphical rendition of the second design. Figure 4 contains the mechanical drawings of both designs.

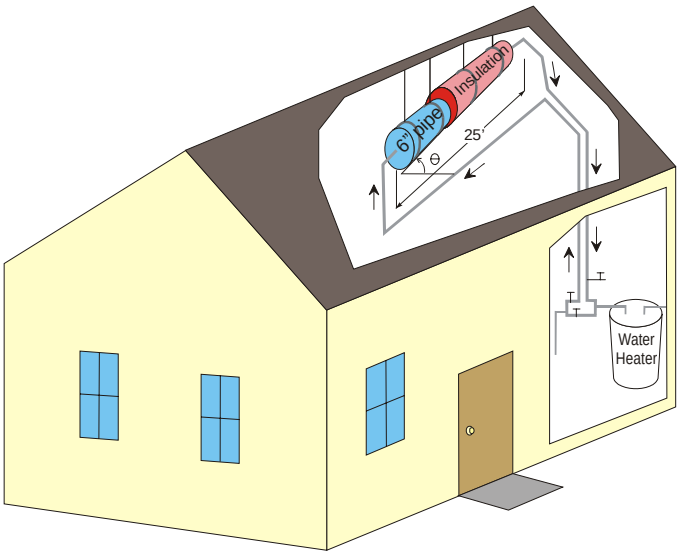

Figure 2. Schematic of the single-pipe water pre-heating system

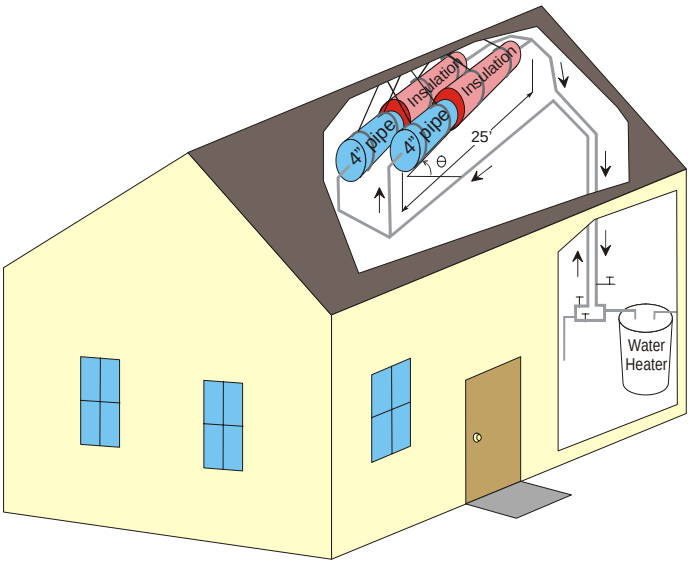

Figure 3. Schematic of the double-pipe water pre-heating system

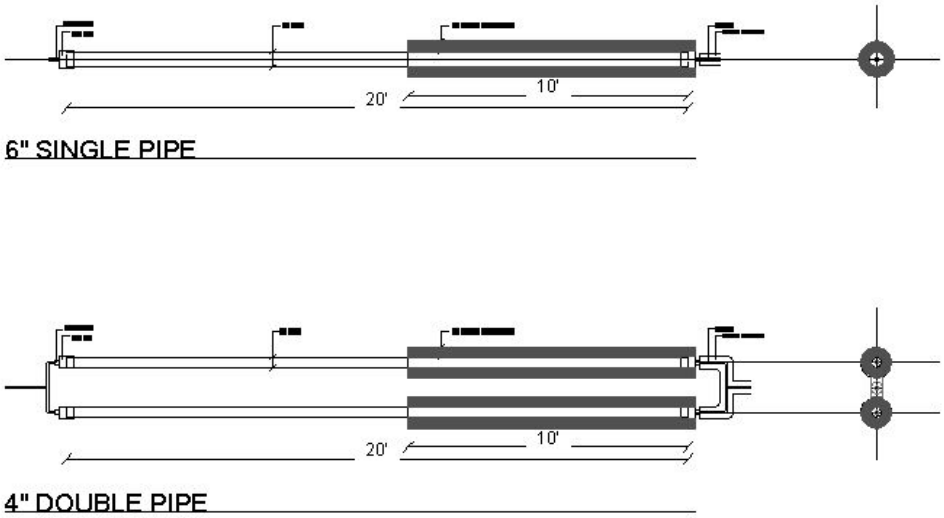

Figure 4. Drawings of the first and second designs of the heat recovery systems

The attic heat recovery system is connected to the water heater using ¾-in copper pipes. The portion of the ¾-in pipe from the heat recovery system to the water heater is insulated using fiberglass insulation with an R-value of at least 4.4. At the water heater, the valve arrangement is designed to allow the user to select to bypass the pre-heating system by changing the positions of the valves. In certain California climate zones, where freezing might occur in the winter, it is recommended that the attic pre-heater be drained in the coldest months to prevent clogging caused by ice formation inside the system. The typical valve arrangement can be seen in Figure 5.

Both designs of the pre-heating system are hung inside the attic using standard galvanized steel C-clamps that are widely available. The C-clamp is connected to a threaded steel rod that will be attached to an L-bracket screwed into the top web of the roof trusses. To minimize swinging in the lateral direction of the pipe, the rods are angled at approximately 90º from one truss member to the next. To prevent swinging in the direction along the pipe, another threaded steel rod along this direction is added to both ends of the pipe. Based on the structural calculations, the overall weight of the system with water inside (approximately 320 pounds [lb]) does not significantly affect the integrity of the roof framing. Most building departments in California require a submission of plan changes to demonstrate than the additional weight will not affect the structural integrity of the house.

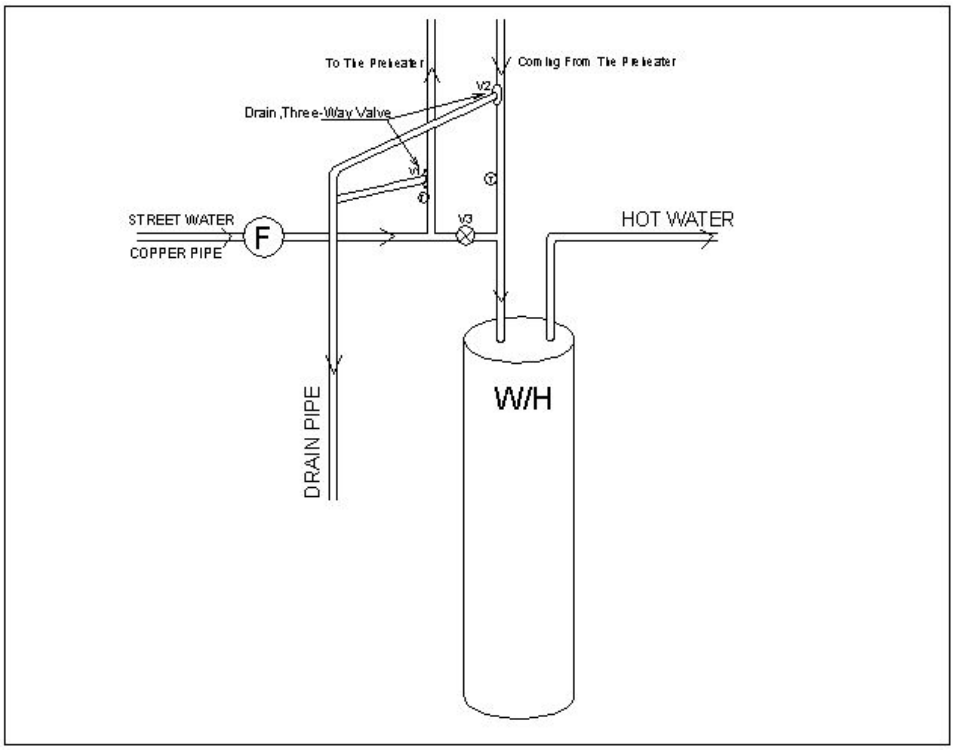

Figure 5. Diagram of valve arrangement at the water heater

In contrast to the first two designs, the third design emphasizes heat collection properties. Copper tubing is used as the primary material, and the heat collection area is increased significantly. To enhance the heat transfer rate across the pipe, the entire length of the pre-heater is designed using 2-in copper pipe. The total length of the heat collection pipe is 120 ft. Figure 6 shows a graphical rendition of the third design. A three-way valve that enables the system to be turned off during winter (see Figure 5) is also integrated into this design. This particular design is useful for families that do not use a lot of domestic hot water in the morning but use plenty in the afternoon and early evening.

The costs of materials for the three designs are presented in Table 7. CPVC pipes are stronger and more durable than PVC pipes; however, their cost can be up to three times higher. The labor required for installation is reasonably low. It is estimated that a crew of two needs four to five hours to install the first design, and eight to nine hours to install the second design. Unskilled workers, who tend to make up the labor pool for self-help housing organizations, can install the first two designs rather easily. The copper piping, however, should be left to a professional plumber, an arrangement that is customary to self-help housing projects. Another two to four hours are required to complete the routing of the copper pipes to and from the water heater. For the third design, a professional plumber can perform the installation much more efficiently than unskilled volunteers. It is estimated that installation of the third design it requires between four and six hours of labor.

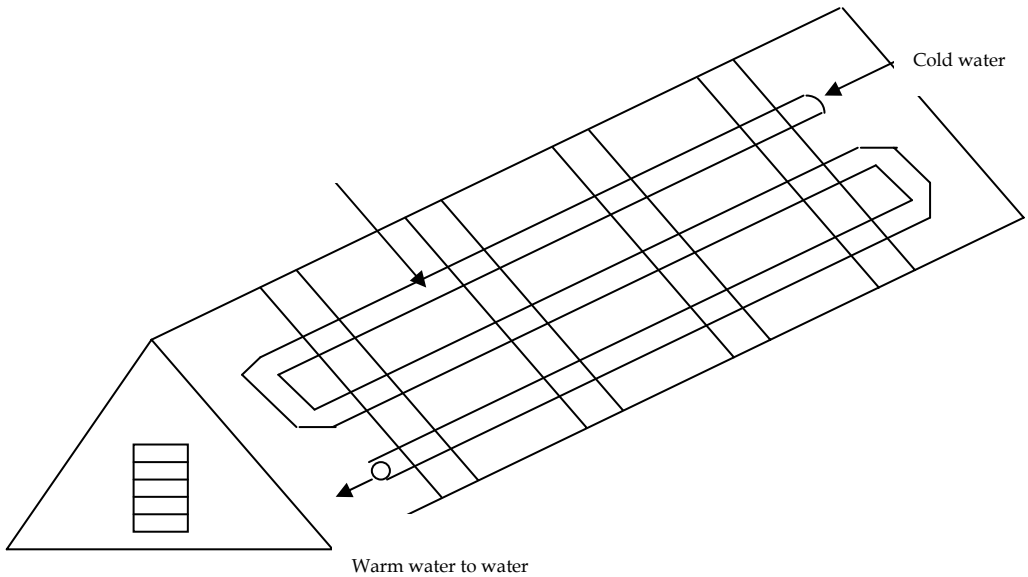

Figure 6. Schematic of the third attic heat collection system design

Table 7. Estimated material cost for each design

Design	*Type of Materials*	*Cost of Materials*	
1	PVC	$	498.22
1	CPVC	$	904.58
2	CPVC	$	1,092.80
3	Copper	$	599.70

3.3. Houses Tested and System Installation

The project team tested three designs for using attic heat to pre-heat domestic hot water in several houses built for low-income households.

- Test houses 1 and 2 are located in Visalia, California. These houses were built by Habitat for Humanity Visalia and completed in late 2003. Large families occupy these two houses, and the domestic hot water use in these houses is substantial. The hot water pre-heater was installed in the summer of 2003. Design 1 (which calls for 6-in single CPVC/PVC pipe) was installed in both houses. Since the City of Visalia allows use of PVC pipe in the attic, the attic system was constructed out of 6-in Schedule 40 PVC instead of CPVC. The installation took place at the time recommended for this type of installation, when the roof frame was completed but the roof and wallboard had not yet been put up. This allowed easy maneuvering of the large pipe in the attic area.
- Test house 3 is located in Sacramento, California. It was built by Habitat for Humanity Sacramento in mid-2002. This house was constructed as part of an exhibit at the

California State Fair held in August 2002, and transported to its final site in Sacramento upon completion. Installation of design 1 with CPVC pipe was completed at the State Fair.

- Two designs of the attic heating system were installed in six houses in a housing development built by Mercy Housing California in Esparto, California. Design 1 was installed in test houses 4, 5 and 6, and design 2 was installed in test houses 7, 8 and 9. All houses were completed and occupied by the middle of 2003. All of the attic heating systems installed in these test houses used CPVC as the primary material. In test houses 4, 5, and 6, flow meters were installed to determine the end-uses for domestic hot water with the assistance from the University of Nebraska.
- The third design of the water heating system was installed in two houses built in Fresno, California, by HfH Fresno. The installation of the entire system was left to a professional plumber. Because the homeowners lacked expertise in copper tubing, the primary tubing used in this design, they did not participate in the installation. HfH homeowners are usually trained with various skills to perform construction, but are not usually trained in plumbing.
- The team installed several temperature sensors and flow meters at each house to monitor the effects of the attic temperature on temperature of the water stored inside the attic pre-heating system. The flow meters were incorporated into the piping system. Because of concerns over potential leaks if the temperature sensors were inserted into the pipe, the sensors were instead mounted over the copper pipe sections and heavily insulated to minimize ambient heat transfer. The runtime of the gas water heaters was monitored using a *Thermapile* flame detector. The sensors were connected to a centralized data collection system that recorded the data at 15-minute intervals. The pre-heating system temperature information was only collected when there was a flow across the pre-heating system.

Comprehensive monitoring data were collected from all test houses where the water pre-heating systems had been installed. Notably, the water temperature inside the pre-heater climbed to as high as 108°F on a day when the attic temperature reached a peak of 118°F.

3.4. Outcomes for Project 2.2

For all sites monitored, the average domestic hot water use was 69 gallons a day. The variation in the average hot water use by month is shown in Figure 7. Hot water use in winter months (November to February) is evidently higher than the rest of year. The energy consumption related to the hot water use by month is presented in Figure 8. The winter months show a remarkable increase in energy consumption due to colder supply water.

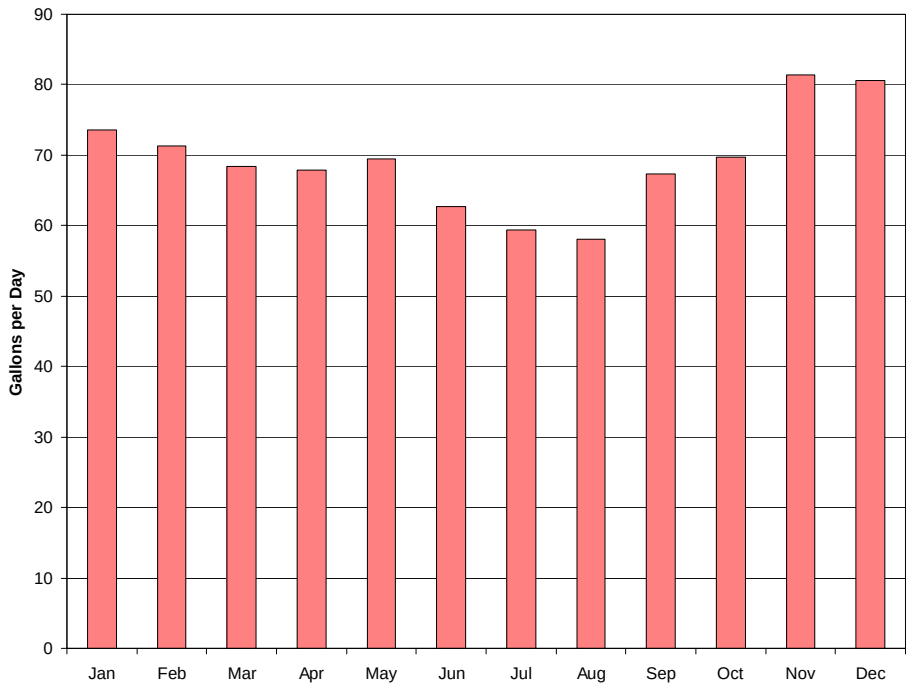

Figure 7. Average daily hot water consumption by month

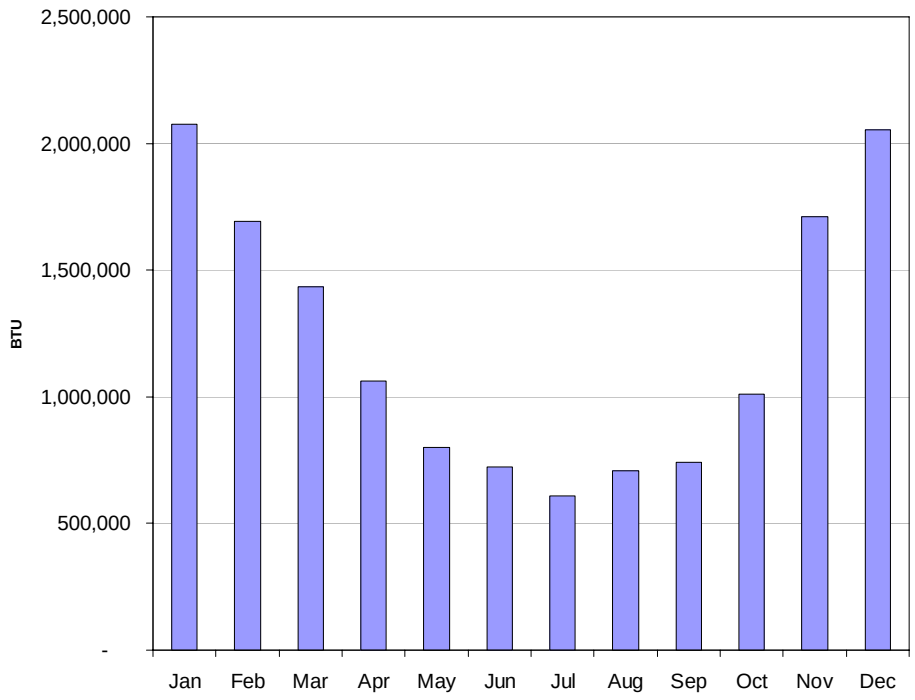

Figure 8. Average energy consumption (Btu) for domestic hot water by month

Data collected for the three houses equipped with end-use monitoring equipment allowed the breakdown of average hot water use by end use. This calculation was made using data for January, April, and October. The hot water use in July, at the height of summer, is 12% lower than in January. The heaviest end-use, in the bathroom, decreases by 9% from January to July, and there is a slight shift in the time of use as well. There seems to be more bathroom hot water use in the early afternoon in the summer than in the winter. This can perhaps be attributed to the occupants' tendency to take earlier showers to cool off when the weather is hot. On an annual basis, the average hot water consumption for bathroom use makes up 67%, kitchen use 12% and clothes washer use 21% of the total hot water consumption.

A water pre-heating system is anticipated to generate the most saving in the peak of summer. Figure 9 shows that for all three designs of the pre-heating system, energy savings could be reaped between the months of March and September in the California's Central Valley. Outside of these months, the designs are anticipated not to save energy, or even to lose energy, as the temperature in the attic begins to drop when the weather gets cooler. The percentage of monthly energy saving for the three different designs is shown in Figure 10. Among all the designs, the third design with 2-in copper tubing was observed to be the least effective, with potential heavy losses in the winter.

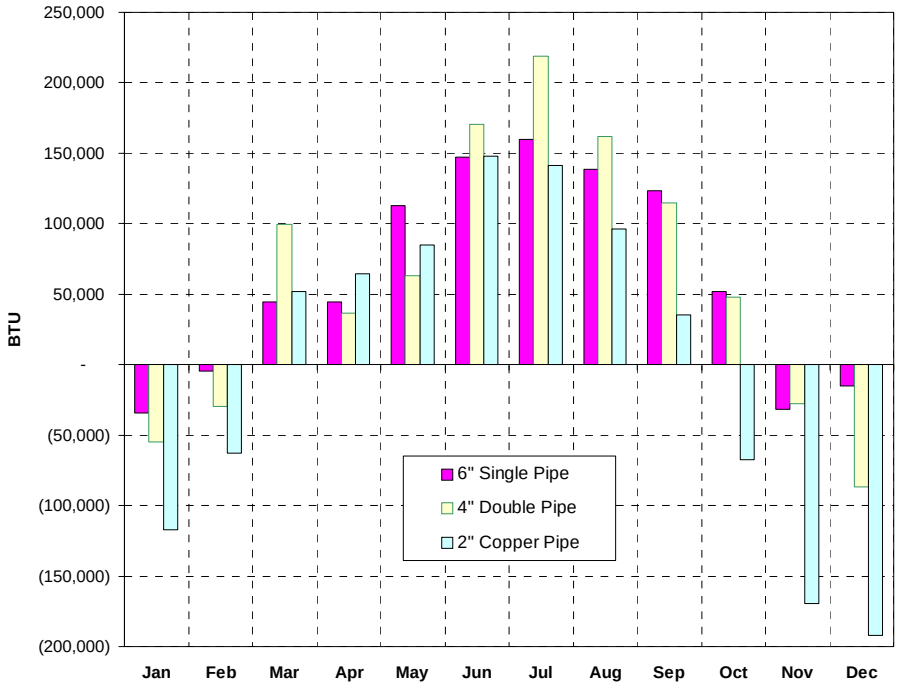

Figure 9. Monthly energy savings (Btu) of the water pre-heating systems by design

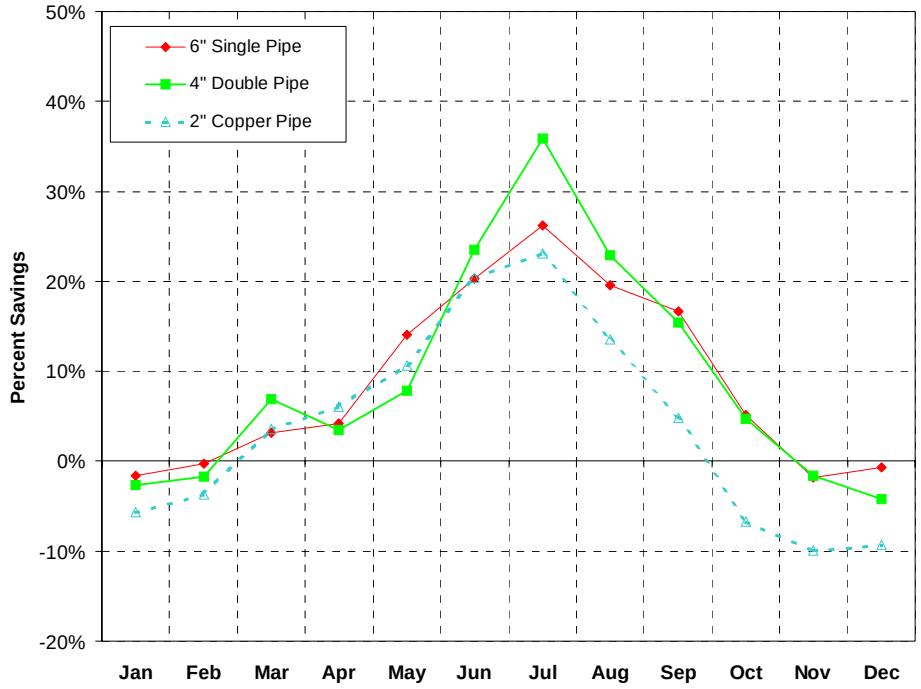

Figure 10. Monthly percentage of energy savings by design

The average hourly energy provided by the domestic water heater and the pre-heating system for the different designs was analyzed using data for July, the most effective month. This analysis showed that the pre-heating systems are most effective in the late afternoon. The single 6-in pipe and double 4-in pipe designs that have some storage properties could provide some hot water in the early morning hours. Nevertheless, the conventional water heater is still the primary provider of hot water in the morning, which suggests that the pre-heating system is not as effective as a hot water storage tank overnight.

On the other hand, the 2-in copper pipe design is not able to provide any hot water after midnight. It could even be anticipated to lose some energy in the cool Central Valley mornings. In the late afternoon, however, the 2-in copper pipe design is capable of providing much more heat than the other two designs. In the houses tested with the 2-in copper pipe system, the pre-heating system is able to produce enough hot water for most of the late afternoon use. In contrast, the other two designs only provide supplemental heating in the late afternoon. Whereas the 4-in and 6-in designs work well in houses with a balanced use of hot water between the morning and late afternoon, the 2-in copper design will work best in houses that use the bulk of the hot water in late afternoon.

After adjusting for the variation in amount of hot water consumption in all houses, the potential energy savings from the water pre-heating systems in the peak summer months (June through September are shown in Figure 11. Of the three designs tested, the double-pipe 4-in was observed to provide the largest amount of energy savings (24%), followed by the 6-in single-pipe (20%) and 2-in copper pipe (15%). The savings for the 2-in copper pipe design, however, could have been much higher in households that use hot water primarily in the late afternoon.

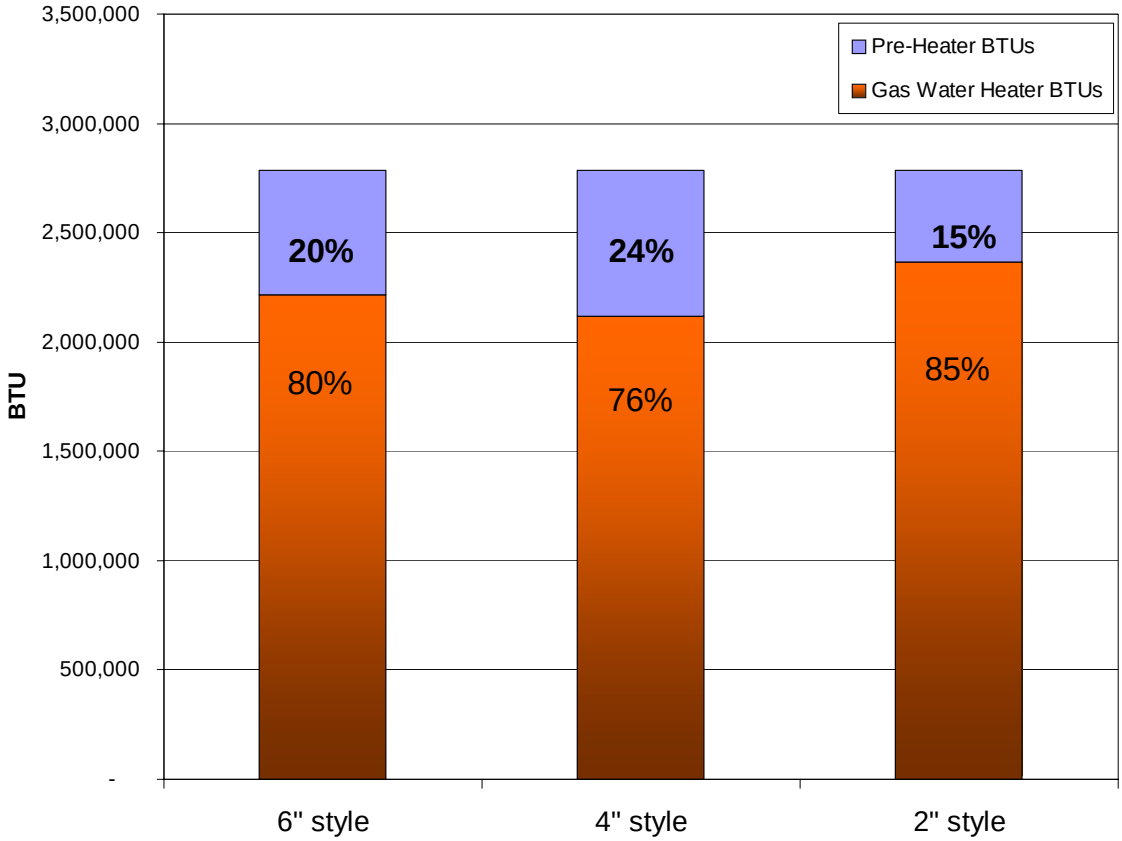

Figure 11. Hot water energy consumption by domestic hot water heater and pre-heating system for different designs (June–September)

The calculated energy savings for each design between the effective months of March and September are shown in Table 8. Considering the easy access to and reasonable cost of materials, the installation of a pre-heating system could be worthwhile. Moreover, the labor cost of installation is low, since volunteers could provide much of the labor for installation (especially for the 6-in and 4-in designs). The cost could potentially be scaled back further by optimizing the installation process. For instance, instead of hanging the pipes, the trusses could be reconfigured to allow the pre-heating pipe to rest on the trusses. This would simplify the installation process and eliminate the material cost of hangers. Further studies will be needed to look into simplifying the installation process.

Table 8. Potential energy savings (March–September)

Design	*6-in Single Pipe*	*4-in Double Pipe*	*2-in Copper Pipe*
Annual Savings (therms)	8.23	9.13	5.54

3.5. Conclusions and Recommendations for Project 2.2

The research undertaken in Project 2.2 demonstrated the feasibility of tapping into attic heat in the hot summer months to supplement domestic water heating by using a system constructed from widely available materials. Three designs for an attic pre-heating system were installed in

a number of single-family homes occupied by low-income households. Two of the designs used large plastic (CPVC or PVC) pipes and the third used medium-size copper pipes as heat collectors. The three systems were closely monitored to evaluate their performance. The three designs showed energy savings of between 15% and 24% in the peak summer months, with the design of two 4-in CPVC pipe being the most effective.

The water pre-heating system has been observed to be the most effective for providing hot water in late afternoon. Due to fluctuations of daily temperature in the California's Central Valley, the supplemental water heating provided by the pre-heating system in the morning is minimal, even in the summer. The design with 2-in copper pipes does not provide any hot water storage capability overnight, and it is the most effective if used in houses where domestic hot water is consumed primarily in the late afternoon. The water pre-heating system could also potentially lose energy in the winter, although the losses are relatively modest compared to the summer savings, with the exception of the design with copper pipes. The test systems were equipped with "bypass" valves that allowed the incoming water to be rerouted directly into the domestic water heater in the winter months, thereby avoiding the heat losses.

Considering the reasonable cost of materials and low labor cost, since much of the work could be done by volunteers, installing the proposed pre-heating system in low-income houses could make financial sense in the California's Central Valley or other areas with hot summer days and reasonably warm nights. The low-income builders who participated in this study liked the idea of being able to install the technology using volunteer labor. However, most would like to assess the cost/benefit of such products if they become available commercially. The installation process could be optimized further to lower the cost of labor and materials.

It is recommended that further studies be conducted to determine the ways to lower the installation and material costs. A market study also needs to be conducted to assess the demand and pricing of such products within and beyond the low-income housing market.

4.0 Project 2.3: Ducts in Conditioned Space

The objective of Project 2.3 was to examine and develop designs for interior duct systems that could reduce or eliminate energy losses from ducts usually placed in unconditioned spaces in housing for low-income households. Achieving this objective involved the following work:

- Recruiting organizations that build housing for low-income households and preparing design plans for incorporating ducts into conditioned space for the houses that they build
- Per the designs developed, incorporating ducts into conditioned space for the houses the participating organizations were building and conducting field tests at these test houses
- Monitoring control houses to assess duct losses for new houses with standard duct systems
- Analyzing results of testing
- Refining details of interior duct system designs, if needed
- Preparing report on the results of the project

This work for Project 2.3 is summarized in this chapter.

4.1. Background for Project 2.3

With typical housing designs and construction practices in California, duct systems are installed in unconditioned spaces (e.g., attics, crawlspaces) that are not part of the heated or cooled areas of the house. For example, a study of residential new construction conducted for Pacific Gas and Electric Company (Regional Economic Research 2002) showed that only 1.1% of newly-constructed single-family detached houses studied had ducts located in conditioned space. Ducts in most of the houses (94.1%) were located in the attic. Ducts were located in the wall for 8.5% of the houses, in a crawlspace for 5.8%, in a basement for 0.4%, and in other locations for 0.4%.

When ducts are located in unconditioned space, energy intended to heat or cool the house may be lost because of air leaks from the ducts and heat conduction through the duct walls. The effects of duct leakage in increasing energy use have been shown in duct leakage studies. For example, one study showed that average measured energy savings from duct sealing in 150 homes were 20.4% for heating and 17.2% for cooling.

Duct leakage in an unconditioned space is also known to have undesirable effects on indoor air quality. Duct leakage affects indoor air quality by introducing tiny particles from building materials (e.g., fiberglass insulation), allergens (e.g., pollen), toxic fumes (e.g., carbon monoxide from garages, out-gassing from building materials, chemical gases from areas where cleaning fluids and pesticides are stored), and other particulates from unconditioned and ambient air (Cummings et al. 1991.) Duct leakage involving unconditioned air creates zonal pressure imbalances that often lead to greater infiltration during operation of the air handler.

To determine appropriate design plans for interior duct systems for Project 2.3, the project team and staff of the Florida Solar Energy Center FSEC met to review studies FESC had prepared on interior duct system design. In a recent report, FSEC pointed out that locating ducts in conditioned space is one approach to mitigating the adverse effects of duct leakage. (Other approaches include sealing the ducts or locating the ducts in unvented attics or crawlspaces).

However, although the rationale of locating ducts in a conditioned space is apparent, many of the details are not well understood. As described in FSEC's report (McIlvaine, Beale, and Fairey 2002), locating ducts in conditioned space:

> ". . . involves putting the entire forced air system, including the air handler, inside the conditioned space. Technically, this means inside the air boundary as well as the thermal boundary, and within the space that is served by the conditioning system. Field data evaluating the success of this strategy is scant. The primary challenges in this approach involve establishing an air barrier around the ducts, overcoming code challenges, and integrating the new detail into the design and construction process. Theoretically, interior ducts will yield the savings of eliminating duct leakage plus the savings of reduced thermal gain/loss of the duct system."

Following FSEC's taxonomy, there are basically three alternative methods for locating ducts in conditioned space. These methods are shown schematically in Figure 12.

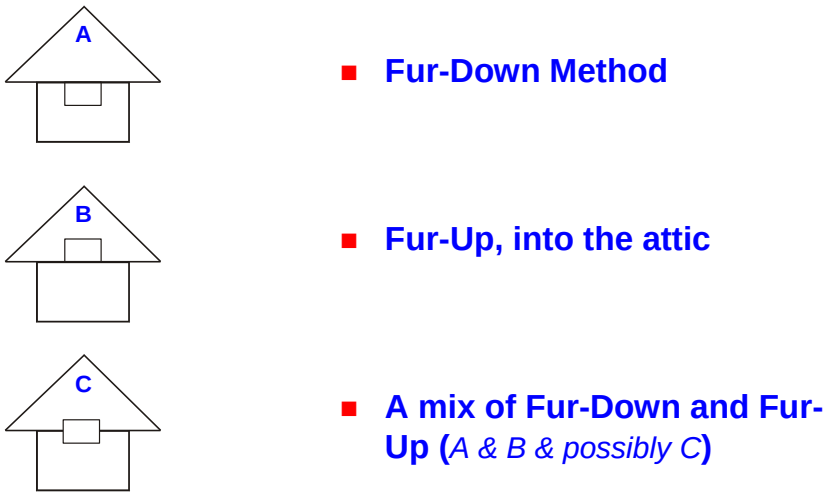

Figure 12. Schematics of designs for ducts in conditioned space

With the fur-down method, a chase is built down into the conditioned space. Fur-down chases generally occupy the upper portion of hallways, run along walls, and/or cut across open living areas as architectural elements. With the fur-up method, a chase is built in the attic and insulated with the ceiling. Viewing from the living area, a fur-up chase is indistinguishable from the finished ceiling. Viewing from the attic, the chase appears as a boxed-out area covered with insulation. As indicated in Figure 12, the fur-down and fur-up methods can also be combined into a single design.

4.2. Interior Duct System Designs for Project 2.3

In practice, any of the methods for placing ducts in conditioned space requires a change in usual construction design and practice. Accordingly, participant builders or organizations for Project 2.3 had to be recruited early enough to ensure that the designs could be prepared that met their needs. Several self-help housing organizations that work with low-income households to build new homes were contacted to identify and recruit those with sufficient interest and construction lead time to both prepare designs for and construct ducts in conditioned space in the houses they were building.

Designs for interior duct systems were prepared during this project in cooperation with two self-help housing organizations: Mercy Housing Esparto and HfH Visalia. The designs developed were specific to the requirements of these participating organizations.

4.2.1. Interior duct system designs for Mercy Housing

A design for installing ducts in conditioned space was prepared for two houses in a development that Mercy Housing was building in Esparto. These two houses shared an identical floor plan, as shown in Figure 13. Each house was 1,485 ft². The layout for this particular floor plan had a straight hallway that made the installation of ducts in conditioned space easy. With hallways that are not straight and bend sideways (for example "L" or "T" shape), turning vanes would be needed to help the flow of the air across the bends. With the straight hallway design of the Mercy houses, such vanes were unnecessary.

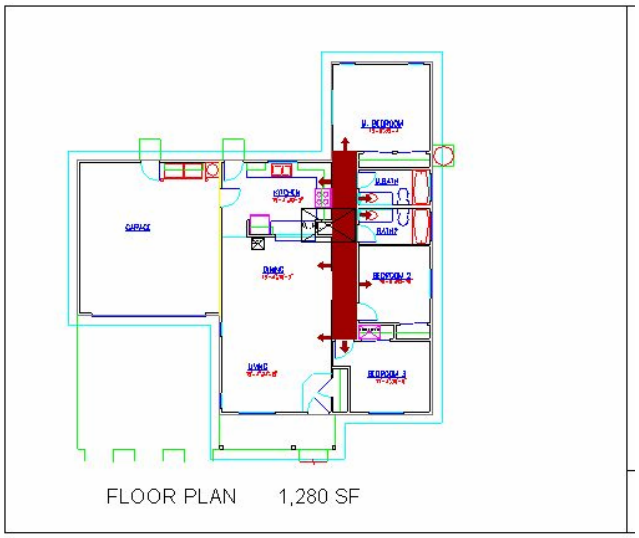

Figure 13. Floor plan for houses at Mercy Housing Esparto

The team preparing the plans for the interior duct systems for these houses considered the design concerns expressed by Mercy Housing staff. For example, the staff had strong concerns about whether it was appropriate to build interior ducts extending past the hallway, fearing that ducts in the living room and kitchen area would be an aesthetic nightmare. They were also concerned that homeowners would not have the skills to build adequate soffits—a component that entails some technical complexity. Because of these concerns, houses were selected that had floor plans that would allow coverage of all areas with ducts only in the hallways.

Another design difficulty was determining where to place the HVAC unit. The weight of the HVAC unit—which would require a platform below it—was a consideration in developing a configuration that would allow the trusses to support the unit. In the final designs, the HVAC unit was located in one-half of a two-door hallway closet.

Local building codes generally require that attic access be located a certain distance away from the platform for easy access to the HVAC unit; Yolo County requires a distance of 10 ft. This requirement poses a difficulty, since it can result in awkward attic access locations. For example, in one house, attic access would need to be placed in the kitchen. The homeowner for

this unit objected to that placement and abandoned the idea of having the ducts placed in conditioned space for his house.

Because Yolo County requires a sprinkler system in residences, it was necessary to work with the sprinkler company to readjust the length of the sprinkler pipes entering the living space. An extension of about 6 to 7 inches was required.

During a meeting of the Program Advisory Committee that reviewed the designs for installing ducts in conditioned space, concerns arose about the possibility of sound transmission across the hallway through the plenum. The concern was heightened by the fact that the bedrooms in the test houses were located across from each other, with the doors facing one another across the hallway. A suggested solution to this possible sound transmission problem was to stagger the location of the air registers so that they would not be directly across from each other. This suggestion was implemented during construction.

A pictorial documentation of how the ducts were installed in conditioned space for Mercy Housing Esparto is provided in the project report for Project 2.3. Actual construction for placing the ducts in conditioned space required several changes to the usual construction practices that Mercy Housing followed, as described below:

- Additional framing had to be attached to the wall board that made up the lower portion of the plenum. In the design of the interior duct system, the plenum height was set at 6 ft to allow as much height room as possible for the occupants. However, this height was below the height of the header, which was 8 ft. As a result, Mercy Housing builders had to cut through the wall header, making the process of framing the plenum more difficult. Because of this, future designs should match the height of the plenum to the height of the header.
- The bottom portion of the plenum can be framed only after the drywall has been installed on the wall and ceiling that make up the plenum. There are two ways to do this. The first is to install the drywall for all of the house first, then frame and drywall a second time. The second option is to drywall around the plenum first, and drywall the house along with the bottom portion of the plenum the second time around. Mercy Housing builders (along with other participating builders) preferred the second option.
- Installing the HVAC unit in the closet was new to Mercy Housing staff. However, this set-up is actually easier than putting the HVAC unit on the roof. When the HVAC unit is installed in a closet, a custom transition is required from the unit to the plenum. However, the transition is short, and any need for mixing boxes required for flex-ducts is eliminated. This lowered the material and fabrication cost.

The interior duct system design developed for Mercy Housing Esparto differed from the general method developed by FSEC in that no sheet metal work was required. Researchers studying interior duct system designs for other regions of the country have indicated concerns about moisture content that might erode and dampen the wall board. However, the relatively low levels of humidity in California reduce this concern.

For this design, the plenum sealing process was deemed critical and was closely supervised by ADM staff. After erecting the interior ducts, a VEC moisture barrier was stapled to the roof truss chords. This barrier is necessary to reduce the amount of moisture transfer between the

attic and the interior ducts. After the sheetrock was in place, the corners and sheetrock joints were sealed with mastic tape. Any other penetrations, such as areas where the electrical cables or sprinkler heads extended into the hallways, were covered up and sealed with mastic tape. After the bottom portion of the plenum was added, all the corners and penetrations were again sealed with mastic tape. The finished duct was then tested for leakage and any found leaks were carefully resealed.

4.2.2. Interior duct system designs for HfH Visalia

Preparing the designs for the interior duct systems for the houses being built by HfH Visalia was more complicated than preparing the designs for the houses at Mercy Housing Esparto because the floors plans for the HfH Visalia houses did not have straight hallways. Figure 14 shows the floor plan for the houses being built by HfH Visalia. Each house had 1,320 ft². As can be seen, the interior ducts extended past the hallways and wrapped around the kitchen area.

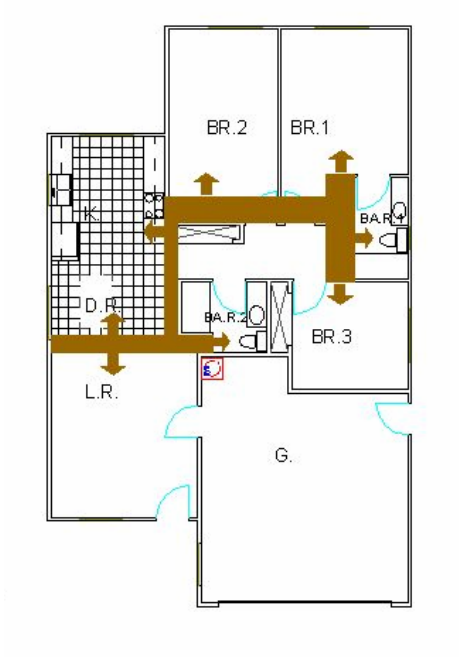

Figure 14. Floor plan for houses built by HfH Visalia

Because of the configuration of the interior duct system, soffits had to be installed. The HfH construction supervisor built these soffits. HfH workers also installed the drywall themselves, so the logistical problem of scheduling the drywall contractor the second time was eliminated. As with the houses at Mercy Housing Esparto, the HVAC unit was located in a closet and a transition was built from the unit to the interior ducts.

A pictorial documentation of the duct installation in conditioned space for HfH Visalia is provided in the project report for Project 2.3. The HfH houses in Visalia were completed and occupied in late summer 2003.

4.3. Field Testing for Test and Control Houses

Field testing was conducted in 14 houses (4 with ducts in the conditioned space and 10 control houses with conventional duct construction) to collect data for determining how effectively

ducts placed in conditioned space reduced energy losses. Of the 4 test houses with ducts installed in conditioned space, 2 were selected from Mercy Housing's Esparto development and 2 from HfH Visalia's development. The control homes were selected based on their similarity in design, dimensions, and construction procedures to the test houses. Of the 10 houses selected as controls, 8 were from Mercy Housing's Esparto development and 2 from HfH Visalia's development. The selected control houses in Esparto had been built during the same time frame as the test houses, and the control houses in Visalia had been built within five years prior to the test houses.

At each test and control house, the duct system was checked for leakage through a pressurization test using a Minneapolis Duct Blaster. Standard testing procedures were used:

- Each house was prepared for the blower door measurements by closing any dampers to the outside, taping any exhaust vents, and sealing all supply and return duct registers with duct mask. With all other registers closed and sealed, a calibrated fan was connected to the return register of the ventilation system. The system was pressurized to 25 Pascals (Pa), and two blower door measurements were taken. The first measurement was taken when both the duct system and the house envelope were pressurized. The second measurement, which occurred 30 minutes after the first, was taken when only the house envelope was pressurized.
- Duct leakage to the unconditioned space could then be calculated by taking the difference between these two measurements. That is, any airflow through the calibrated duct blaster fan is the air leakage loss within the duct system.
- For the test houses, a set of measurements at other standard house pressures was also made for comparison to the control homes. These measurements were taken at standard pressures of 16, 25, 32, 40 and 50 Pa.
- During the testing, the duct system was visually inspected for leaks. Any leaks were repaired, and the blower door test was repeated to update the measurements.
- After testing, the duct system was air balanced to make sure that all areas in the house receive the designated air volume. To allow this, all dampers installed were adjustable dampers. The air balancing was performed using a Balometer.

The reduction in energy losses that result from placing ducts in conditioned space are attributable to two factors:

- Reduction in conditioned air losses through cracks and openings in the duct system
- Reduction in heat conduction losses to the attic space (for duct systems located in attics)

Reductions of energy losses due to reduction in conditioned air losses were computed for heating and cooling separately using the following equations:

- Cooling Energy Savings

$$Savings(kWh) = \frac{TF_C * (CFM_B - CFM_T) * 1.08 * CDH}{3413 * COP}$$

Where:

TF_C = Fraction of time that the cooling system is expected to run during the cooling season. This is determined as the ratio of equivalent full load hours to the number of hours during which the system would be turned on.

CFM_B = Air leakage rate for the control houses; in cubic feet per minute (CFM).

CFM_T = Air leakage rate for the test houses; in CFM.

CDH = Cooling degree hours.

COP = Coefficient of performance.

- Heating Energy Savings

$$Savings(Therms) = \frac{TF_H * (CFM_B - CFM_T) * 1.08 * HDH}{100{,}000 * EFF}$$

Where:

TF_H = Fraction of time that the heating system is expected to run during the heating season. This is determined as the ratio of equivalent full load hours to the number of hours during which the system would be turned on.

CFM_B = Air leakage rate for the control houses; in CFM.

CFM_T = Air leakage rate for the test houses; in CFM.

HDH = Heating degree hours.

EFF = Efficiency of the heating system.

Equivalent full load hours were calculated using results from simulations performed on the test houses that had ducts in the conditioned space. The simulations provided estimates of energy use for both cooling and heating. The estimated energy use and the size of equipment used for heating and cooling were applied to estimate equivalent full load hours.

Heating and cooling degree hours were calculated for heating and cooling season. The base temperatures for these calculations were 65°F for heating and 78°F for cooling. The base temperature indicates the point at which the heating or cooling system will start to provide conditioned air. The cooling and heating degree hours only factor in the period when the cooling or heating system is in use. This method for calculating degree-hours is according to the ASHRAE variable base degree-day method. California Building Standards weather data for climate zones 12 and 13 were used to calculate the degree-hours.

The numbers of hours during which either heating or cooling was required were also calculated, based on 65°F and 78°F, using the same weather information.

Heating in the test houses is provided by central gas heating systems whose efficiency was rated at 83%. Cooling in the test houses was provided by central air conditioning systems, with the COP of the cooling units rated at 2.6. The duct leakage measurements made on the test and control houses provided air flow loss data in cubic feet per minute.

Reductions of duct conduction losses were calculated using the following procedure. CALRES was used to calculate the energy use associated with the test houses. Simulations were made for two scenarios. For the first scenario, it was assumed that the houses had standard ducts with R-4.2. For the second scenario, the calculations were repeated using the option of ducts in conditioned space in CALRES. Weather data for CEC climate zones 12 and 13 were used to make these calculations. Baseline estimates of total cooling and heating energy consumption used to obtain percentage cooling and heating energy savings were also calculated using CALRES simulations, with the assumption that the average duct leakage is 23.6%.

4.4. Outcomes for Project 2.3

The outcomes for Project 2.3 pertained to air leakage testing and energy loss calculations, testing for sound transmission, and the costs of installing ducts in conditioned space. These outcomes are addressed in this section.

4.4.1. Results of air leakage testing and energy loss calculations

The results of the air leakage testing for the test and control houses are reported in Table 9.

Table 9. Results of air leakage testing at test and control houses

House ID	*Location*	*Duct Leakage (CFM)*	*% System Flow Loss*
Test #1	Mercy Housing Esparto	13.6	2.0%
Test #2	Mercy Housing Esparto	6.8	1.0%
Test #3	HfH Visalia	3.0	0.5%
Test #4	HfH Visalia	5.0	0.8%
Average		**7.1**	**1.1%**
Control #1	Mercy Housing Esparto	160	23.5%
Control #2	Mercy Housing Esparto	126	18.5%
Control #3	Mercy Housing Esparto	60	8.8%
Control #4	Mercy Housing Esparto	176	25.9%
Control #5	Mercy Housing Esparto	153	22.5%
Control #6	Mercy Housing Esparto	174	25.6%
Control #7	Mercy Housing Esparto	217	31.9%
Control #8	Mercy Housing Esparto	72	10.6%
Control #9	HfH Visalia	205	32.5%
Control #10	HfH Visalia	214	36.3%
Average		**155.7**	**23.6%**

For the four test houses, the average duct leakage rate was 7.1 CFM, with the average system flow loss being 1.1%. Duct leakage and system flow loss were somewhat higher for the two test houses at Mercy Housing Esparto than at HfH Visalia. By comparison, the average duct leakage rate for the ten control houses was 155.7 CFM, with an average system flow loss of 23.6%. As this comparison shows, placing the ducts in conditioned space considerably reduced duct leakage and system flow loss.

Placing the ducts in conditioned space also reduced energy losses due to duct leakage and heat conduction. Table 10 provides estimates of the savings in heating and cooling energy use for the four test houses. Separate estimates of savings are shown for reducing duct leakage and for reducing heat conduction, along with an overall estimate of the savings.

- With respect to savings from reducing duct leakage, heating savings averaged 8.4% across the four test houses, and cooling savings averaged 6.6%. Heating and cooling savings were somewhat lower for the Mercy Housing sites than for the HfH sites.
- With respect to savings from reducing heat conduction, heating savings averaged 11.3% across the four test houses, and cooling savings averaged 10.3%. There was no difference between the Mercy Housing and HfH sites in percentage savings for heating and cooling.
- With respect to total savings from placing ducts in conditioned space, heating savings averaged 19.7% across the four test houses, and cooling savings averaged 16.8%. Heating and cooling savings were somewhat lower for the Mercy Housing sites than for the HfH sites.

Table 10. Energy savings from placing ducts in conditioned space

House	***Location***	***Heating Savings (therms)***	***Cooling Savings (kWh)***	***% Heating Savings***	***% Cooling Savings***
		Savings from Reducing Duct Leakage			
Test #1	Mercy Housing Esparto	14	83	6.6%	5.4%
Test #2	Mercy Housing Esparto	15	87	6.9%	5.7%
Test #3	HfH Visalia	14	124	10.1%	7.6%
Test #4	HfH Visalia	14	123	10.0%	7.6%
Average		*14*	*104*	*8.4%*	*6.6%*
		Savings from Reducing Heat Conduction			
Test #1	Mercy Housing Esparto	25	158	11.3%	10.3%
Test #2	Mercy Housing Esparto	25	158	11.3%	10.3%
Test #3	HfH Visalia	16	166	11.3%	10.3%
Test #4	HfH Visalia	16	166	11.3%	10.3%
Average		*20*	*162*	*11.3%*	*10.3%*
		Total Savings from Placing Ducts in Conditioned Space			

Test #1	Mercy Housing Esparto	39	240	17.9%	15.6%
Test #2	Mercy Housing Esparto	40	245	18.3%	15.9%
Test #3	HfH Visalia	30	290	21.4%	17.9%
Test #4	HfH Visalia	30	289	21.3%	17.8%
Average		*35*	*266*	*19.7%*	*16.8%*

4.4.2. Results from testing for sound transmission

Because of concerns about sound transmission expressed by Program Advisory Committee members, the duct system at a test house was also tested for sound transmission. A sound generator was set to deliver 50 decibels (dB) of sound into the living room space. This level was matched on microphone level indicators on a mixing board. The filtering section of the mixing board was used to isolate the frequencies between 390 and 410 kilohertz (kHz), so that the output of the mixing board would only be between 390 and 410 kHz. A second microphone was placed in an adjacent room that was sealed from the living area by a sound-deadening drape. The resulting input and output levels would be recorded in decibels on the meters of the mixing board. (The meters used measure decibel levels between −60 dB and +100 dB.)

A level reading taken of the 400 Hz sound from the second microphone was measured at −55 dB, which is considered inaudible. Even when the microphone was placed in front of the register outlet, the sound was inaudible. This sound testing was done from room to room in the home with no discernable change in the decibel level from room to room of the 400 Hz tone.

A second test was done at the 70-dB level. It was performed the way the first test was performed. For this test, the transmitted level was measured at −50 dB, which again is considered inaudible.

4.5. Costs of Installing Ducts in Conditioned Space

The test results presented above show that installing ducts in conditioned space reduces energy losses and provides savings in heating and cooling costs. Inspection of the costs for installing ducts in conditioned space for the Mercy Housing Esparto test houses shows that construction costs are lower than installing a standard duct system.

This comparison of costs is provided in Table 11. The total cost for installing a standard duct system in a house similar to the Mercy Housing Esparto test house would be $1,482.26, while the cost of installing an interior duct system per the design developed during this project was $560.55. Thus, the cost of installing a duct system in conditioned space was $921.71 less than the cost of installing a standard duct system.

4.5.1. Consideration of hybrid systems

Some house designs do not lend themselves well to the installation of ducts in conditioned space; these include designs with hallways that are long and not straight. On the other hand, designs that have more open spaces with limited hallways are not suitable for the dropped ceiling approach either. In these cases, a combination of methods may be more appropriate. A combination of the fur-up and fur-down methods, for instance, is a possible strategy to cover as much area outside of the hallways as possible. The execution of such design however, could be rather difficult, in part due to the complex transition between the interior and attic plenums.

Table 11. Comparison of costs of installing an interior duct system versus a standard duct system

Equipment	Cost	Count	# Needed	Cost Eqpt	Labor Hours/Unit	Labor Cost/hr*	Labor	Project Item Total
16" flex duct	$ 1.57	foot	8	$ 12.56	0.25	$ 25.00	$ 50.00	$ 62.56
10" Flex duct	$ 0.91	foot	33	$ 30.03	0.25	$ 25.00	$ 206.25	$ 236.28
8" flex duct	$ 0.72	foot	45	$ 32.40	0.25	$ 25.00	$ 281.25	$ 313.65
Mixing box	$ 150.00	each	1	$ 150.00	4	$ 25.00	$ 100.00	$ 250.00
Transitions	$ 3.55	each	12	$ 42.60	1	$ 25.00	$ 300.00	$ 342.60
							Cost	$ 1,205.09
							Contractor mark-up	$ 180.76
							Misc fittings screws	$ 96.41
							Total cost	**$ 1,482.26**
Wall board ducts								
AH transition	$ 12.00	each	1	$ 12.00	1	$ 25.00	$ 15.00	$ 27.00
5/8 sheetrock	$ 7.48	4X8 sheet	4	$ 29.92	4	$ 25.00	$ 100.00	$ 129.92
Gallon rock mud	$ 3.45	each	1	$ 3.45	1.5	$ 25.00	$ 37.50	$ 40.95
2x4 stringers	$ 0.79	each	4	$ 3.16	3	$ 25.00	$ 75.00	$ 78.16
Additional drywalling		each			8	$ 25.00	$ 200.00	$ 200.00
Transition fabrication		each			1.7	$ 25.00	$ 43.00	$ 43.00
								$ 519.03
							No mark-up	0
							Misc nails, screws	$ 41.52
							Total cost	**$ 560.55**

*The estimated labor cost reflects the lower rate that contractors usually charge low-income housing organizations. It is not uncommon for contractors to donate their time to low-income housing projects.

A more feasible strategy is to combine the use of fur-down method in the hallways and flex-ducts for areas far from the hallways. The potential savings from implementing such strategy is anticipated to be less than incorporating duct ceiling for the entire house. The cost of building such a hybrid system, however, is still anticipated to be comparable to running flex-ducts to all areas of the house. A further study is needed to assess the effectiveness and cost/benefit of this hybrid system.

4.6. Conclusions and Recommendations for Project 2.3

Under this project, four houses were built in Esparto and Visalia with ducts in conditioned space. These houses were designed to have dropped ceilings along the hallways and other areas

of the house. The cavity between the dropped and actual ceilings is used as a plenum for conditioned air.

Duct leakage tests performed on similar houses revealed that the duct leakage with conventional flex-ducts had an average of 23.6% leakage compared to 1.1% leakage for houses constructed with ducts in conditioned space. The average energy savings from reduced air leakage and heat conduction are estimated to be 35 therms in natural gas annually (or 19.7% of heating energy) and 266 kilowatt-hours (kWh) in electricity (or 16.8% of cooling energy).

The majority of installation work was performed by self-help housing organizations and their volunteers. Both HfH and Mercy Housing are interested in building more houses with ducts in conditioned space, since the dropped ceiling technique has been demonstrated to be technically feasible and more economical to install than regular flex ducts.

One concern that they have is the need to reschedule some of the contractor activities. However, if all houses within a same development are constructed in this manner, this potential problems raised by this need would diminish. They also view technical guidance, especially in the design of the air ducts, as a critical factor that could shape their decision on whether to install ducts in conditioned space. Not having the expertise themselves, the low-income housing organizations involved in this project require that some assistance, especially during the design and planning stages. It is recommended that a program be created either by the utilities, state, or local governments to provide assistance in the designing and planning of installing ducts in conditioned space.

Building ducts in conditioned space could potentially be a measure that is attractive to commercial homebuilders as well. Some apprehensions that exist with these homebuilders are generally related to cost and appearance of such duct system. This study, however, has demonstrated that both concerns are unfounded. The cost of installing a dropped ceiling used as a plenum without sheet metal has been shown to be less than the cost of installing flexducts throughout the house. Building the plenum along hallways will also leave very little impact on the general appearance of the house interior, aside from a marginally lower ceiling along the hallways. More efforts, however, need to be dedicated toward informing California homebuilders of this option. The program above could be extended to commercial homebuilders in the efforts to educate and promote this technology for new houses built in California.

5.0 Project 2.4: Envelope and Interior Air Quality Interaction

The objective of Project 2.4 was to evaluate energy efficiency measures that can be implemented in housing for low-income households without exceeding indoor air quality (IAQ) standards. Toward this end, carbon dioxide (CO_2) and carbon monoxide (CO) concentrations were measured in test homes equipped with whole house fans, evaporative coolers, ducts within conditioned space and/or attic hot water pre-heaters. These measurements were compared to similar measurements made for several control houses.

The work in Project 2.4 was as follows:

- Prepare a literature review
- Evaluate strategies to reduce adverse indoor air quality impacts
- Prepare a plan for monitoring IAQ at test and control houses
- Apply IAQ strategies to test houses
- Monitor IAQ at test and control houses
- Analyze data to assess impacts on IAQ

This work for Project 2.4 is summarized in this chapter.

5.1. Background for Project 2.4

Indoor air quality can be affected by indoor pollution sources that release gases or particles into the air or by outdoor gases or pollutants brought into the house through infiltration, natural ventilation, or mechanical ventilation. Inadequate ventilation can increase indoor pollutant levels by not bringing in enough outdoor air to dilute emissions from indoor sources and by not carrying indoor air pollutants out of the home. If too little outdoor air enters a home, pollutants can accumulate to levels that can pose health and comfort problems. Indoor pollution sources are the primary cause of indoor air quality problems in homes.

A wide range of indoor pollutants from can affect indoor air quality. Pollutants such as CO_2, methane and water vapor can result from human metabolism, and combustion appliances can produce CO, CO_2 and nitrogen dioxide. Biological contaminants can include bacteria, molds, mildew, viruses, animal dander, dust mites, cockroaches, and pollen; other common pollutants include tobacco smoke, household products, formaldehyde, and radon.

Not all of these pollutants were directly addressed in the project. Rather, project 2.4 primarily focused on evaluating the impacts on indoor air quality for houses equipped with ducts in conditioned space. These houses were monitored for pollutants such as carbon dioxide and carbon monoxide and the levels of these pollutants were compared to those in the control houses. The study of carbon dioxide and carbon monoxide increase understanding of ventilation within the houses and indicate if any serious back drafting or combustion problem is occurring for combustion appliances within the conditioned space.

Outdoor CO_2 concentrations typically range from 300 to 450 parts per million [ppm]). Carbon dioxide is always present in occupied buildings in concentrations above outdoor levels since it is a byproduct of human respiration. Carbon dioxide is a simple asphyxiant at concentrations above 1.5% (15,000 ppm). The health effects associated with elevated CO_2 concentrations can include loss of mental acuity, headaches, dizziness, and increased breathing rates. Some have

suggested that in tight houses the "deep sleep" experienced by some people is due to elevated CO_2 concentrations.

There are various recommendations and guidelines by industry organizations for ventilation rates and CO_2 concentrations in houses. The EPA recommends a maximum CO_2 level of 1000 ppm in buildings that subject occupants to continuous exposure, specifically schools and residences. ASHRAE Standard 62-1989 recommends an indoor CO_2 guideline of 1000 ppm based not based on health effects, but on the building occupancy/ventilation ratio and for comfort (odor) reasons. The primary health-based standard used for control of indoor air pollution is the 8-hour personnel exposure level (PEL) of 5000 ppm in Occupational Safety and Health Administration (OSHA) standards. However, this standard does not apply to residences.

Carbon monoxide, another byproduct of combustion, is chemical aphyxiant that can be dangerous at high levels. High interior levels of CO can cause immediate deleterious effects on health of the occupants, ranging from a throbbing headache to death. CO has a much higher affinity toward combining with hemoglobin than does oxygen, depleting the human body of much needed oxygen in the process. Common indoor sources of CO are fossil-fuel burning appliances, including stoves, kerosene lanterns and heaters, space heaters, and water heaters. Tobacco smoke is also cited as one of the common contributors to a high interior CO level. Attached garages could potentially raise the CO level when the air mixed with automobile exhaust could be pulled into the living space.

Different organizations have set different standards for a safe CO level. These standards are compiled in Table 12.

Table 12. Comparison of safety standards for carbon monoxide

	Canadian	WHO/Europe	NAAQS/EPA	NIOSH Rel	OSHA	ACGIH	MAK
Level Exceeding Safety	11 ppm (8 hr) 25 ppm (1 hr)	8.6 ppm (8 hr) 25 ppm (1 hr) 51 ppm (30 min) 86 ppm (15 min)	9 ppm (8 hr) 35 ppm (1 hr)	35 ppm (8 hr) 200 ppm (1 hr)	35 ppm (8 hr) 200 ppm (15 min)	25 ppm (8 hr)	30 ppm

Moisture problems that lead to mold and mildew growth have also been known to have adverse effects on occupants' health. Improper design and careless use of new materials are often the causes of moisture problems in buildings (Kelly 1982). Mold and mildew have been found to grow where the relative humidity of a surface is greater than 70%. This level usually corresponds to 50% relative humidity in the building (ASHRHAE 1997). Having the ducts in conditioned space results in a tighter house as duct leakage is reduced from 24% for houses with flex-ducts to less than 2% for houses with interior ducts (See report for Project 2.3: *Ducts in Conditioned Space*). Naturally, concerns over increased interior moisture content due to the reduced air change rates from tighter ducts are valid. One aspect of this study was to look into the moisture levels in the test houses with interior ducts and compare them to similar houses with the traditional flex-ducts.

A study by the California Air Resources Board that surveyed a representative sample of California's population indicated that many households used little natural ventilation during winter and night time, and that households in parts of state with extreme weather conditions also used little natural ventilation (Phillips et al. 1990) Furthermore, low-income households, mobile home residents, persons with a high school education level or less, and persons 17–19

years old have greater-than-average use of gas stoves for space heating. These data on activities pattern suggest that such population groups may be more likely to experience high exposures to some indoor air pollutants. It should be noted, however, that none of such activities were observed in the houses studied in this project.

For ventilation, the ASHRAE Standard 62 recommends 15 cfm of outside air per person or 0.35 air changes per hour (ACH) for residences. This standard has been controversial and is under revision. A proposed revision uses 5 cfm per 100 square feet of house area. The Home Ventilating Institute, a ventilation equipment trade organization, recommends 0.5 ACH.

The best method to control indoor concentrations of CO_2 is to ventilate using outside air. Mechanical ventilation is best used for pollutants resulting from human and for occupant activities generating moisture, such as bathing, laundering clothes, and dish washing. Most houses need two types of ventilation. Local ventilation should be used intermittently to reduce humidity levels in kitchens and bathrooms quickly, while general ventilation should be ongoing in order to change the air in the entire house.

Another approach to lowering the concentrations of indoor air pollutants in a house is to increase the amount of outdoor air coming indoors. Most home heating and cooling systems, including forced air heating systems, do not mechanically bring fresh air into the house. Opening windows and doors, operating window or attic fans, when the weather permits, or running a window air conditioner with the vent control open increases the outdoor ventilation rate. Local bathroom or kitchen fans that exhaust outdoors remove contaminants directly from the room where the fan is located and also increase the outdoor air ventilation rates.

5.2. Selection of Test Houses

For the research in Project 2.4, four test houses were selected from participants of Project 2.3: Ducts in Conditioned Space. Two of the selected test houses are located in Visalia, California, and two in Esparto, California. Similar houses in each city were selected as the control houses. The houses in Visalia were built by Habitat for Humanity Visalia; the houses in Esparto were built by Mercy Housing California.

Test houses 1 and 2 are identical houses completed by the HfH Visalia in December 2003. The layout (showing the interior ducts) of these houses is shown in Figure 14. Test house 1 is occupied by a family of six, and test house 2 is occupied by a family of five. Both families prepare meals at least twice daily inside the house, an activity that could contribute to the indoor air pollution. None of the occupants, however, smoke inside the house. The control houses used for comparison purposes were built within the last 10 years and are similar in size to the test houses. Control house 1 is occupied by a family of six, and control house 2 is occupied by a family of five. Both families also cook twice daily, and one person in control house 1 smokes inside the house.

Test houses 3 and 4 are also identical houses located in Esparto and finished by Mercy Housing California in mid-2003. Figure 15 shows the layout of the houses, with the interior ducts highlighted. Test house 3 has five family members, test house 4 has six family members. Both families regularly cook at least twice a day. There are no smokers in either house. Control house 3 in Esparto is occupied by a family of five, and the house was built at the same time as the test houses.

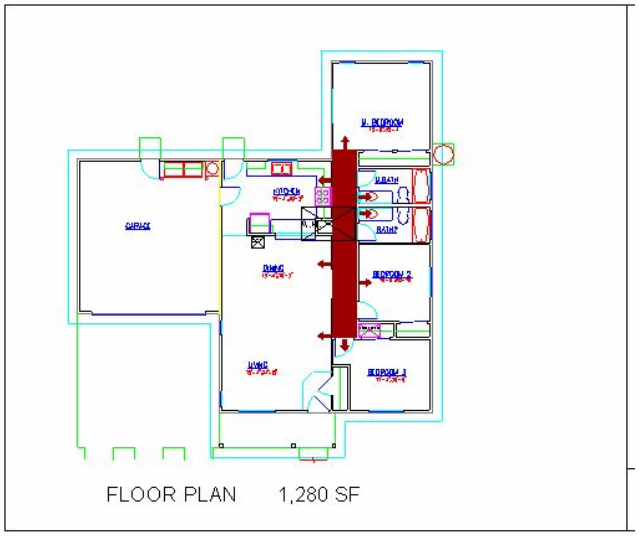

Figure 15. Floor plan for houses built by Mercy Housing Esparto

Several manufactured, migrant, and self-help houses were also tested for signs of IAQ problems resulting from the implementation of energy efficient measures designed for this program. Two migrant houses in Atwater, California (test houses 5 and 6) and a manufactured house in Sacramento (test house 7) had an evaporative cooler that was equipped with a water shut-off control. One manufactured house in Arbuckle (test house 8) had an economizer. Four HfH houses in Fresno were equipped with an evaporative cooler integrated with the packaged HVAC system (test houses 9-12). All of these test houses also served as control houses during the period the energy efficient technology was shut off. The technologies were designed in conjunction with Project 2.6: Evaporative Cooler and Whole-House Fan Integration.

5.3. Monitoring Equipment and Procedures

The CO_2 and CO concentrations inside the test and control houses were monitored at regular intervals for several weeks after the houses were completed. A monitoring device was designed and produced for testing purposes. This device, called a canary box, resembles a shoebox in size and appearance. Each canary box holds a number of data loggers that collect CO_2, CO, temperature and relative humidity information. Each is also equipped with a small fan that blows air across the sensors continuously. The canary box was placed in the area of the house where the house occupants spent most of their time, usually the living room. In addition to the canary box, a handheld CO meter was used to detect and measure CO around combustion appliances, such as stoves, ovens, water heaters, and furnaces

5.4. Outcomes for Project 2.4

The concentration of indoor pollutants is usually highest during the winter months, when windows and doors stay shut the majority of the time due to the cold weather. For areas with very hot summers, IAQ is also a concern at the height of summer, when the lack of outside air infiltration causes the indoor pollutants to accumulate inside the house. Monitoring was performed for the test and control houses in the coldest months of the California's Central Valley, between December and February. The average CO_2 concentration levels during different

time periods of the day inside the monitored houses in Visalia are shown in Table 13. Table 14 shows the CO_2 concentration levels observed in the Esparto houses.

Table 13. Average CO_2 concentration levels inside Visalia houses

	CO_2 CONCENTRATION (ppm)			
	Test House 1	***Test House 2***	***Control House 1***	***Control House 2***
0:00-8:00				
AVERAGE	1,207	1,469	1,724	2,197
MAXIMUM	1,898	1,853	2,272	2,485
MINIMUM	880	1,091	1,337	1,642
8:00-16:00				
AVERAGE	897	1,058	1,540	1,707
MAXIMUM	1,136	1,513	2,090	2,126
MINIMUM	538	623	851	1,222
16:00-24:00				
AVERAGE	963	1,240	1,912	1,673
MAXIMUM	1,343	1,942	2,239	2,431
MINIMUM	717	912	1,531	898

Table 14. Average CO_2 concentration levels inside Esparto houses

	CO_2 CONCENTRATION (ppm)		
	Test House 3	***Test House 4***	***Control House 3***
0:00-8:00			
AVERAGE	1,489	951	1,630
MAXIMUM	1,763	1,289	2,485
MINIMUM	1,150	624	1,115
8:00-16:00			
AVERAGE	1,321	919	1,037
MAXIMUM	1,785	1,466	2,220
MINIMUM	1,028	596	586
16:00-24:00			
AVERAGE	1,706	965	1,403
MAXIMUM	2,136	1,591	2,009
MINIMUM	972	681	813

These data show that the average CO_2 concentrations in test houses with interior ducts were consistently lower than in the houses with flex-ducts. Although the addition of interior ducts resulted in increased house tightness due to reduced air leakage into the unconditioned space of the house, it did not appear to cause alarmingly high levels of CO_2. Aside from human respiration, there are a number of other factors—primarily cooking and smoking—that may influence the CO_2 concentration inside the house. The lowest levels of CO_2 were observed during the day, when the houses had the least number of occupants. In the evening, when most of the cooking took place, the CO_2 levels were found to rise significantly. In Control House 2, the high levels of CO_2 were sustained throughout the day due to smoking inside the house.

Interior humidity levels were also found to be comparable between the test and control houses.

- In Visalia's test houses, the interior humidity levels consistently range from 35%–50% during the winter months, while in the control houses, the humidity levels were observed at between 48%–58%. The consistency of humidity levels inside the control houses suggests that the occupants of the control houses did not regularly open their doors or windows during the test period, an observation that was confirmed through an interview with the homeowners. This was also one of the contributing factors to consistently high CO_2 levels inside these houses.
- The interior humidity inside the Esparto houses was observed at 45%–65% during the winter, with scarcely any difference between the interior humidity observed in the test and control houses. Note that the months of December to February are the wettest

months of the year in the Central Valley. Outside humidity hovers between 80% and 100% on a regular basis. The high indoor humidity level was in part due to the outdoor weather conditions.

Data collected from test houses 5-12 revealed no IAQ problems related to the implementation of the corresponding energy efficient technology. In some cases, the energy efficient technology (evaporative cooler water shut-off control and economizer for manufactured house) did not operate enough to impact the IAQ in a considerable manner. In houses with integrated AC and evaporative cooler, no IAQ problems were observed aside from occasional increases in CO and CO2 due to cooking that cleared out afterwards. The addition of the evaporative cooler was observed to have very little impact on the IAQ of these houses.

5.5. Conclusions and Recommendations for Project 2.4

Replacing flex-ducts with interior ducts located in the conditioned space of the house substantially reduces air leakage (from 24% to 2%). Although the addition of the interior ducts reduces the energy losses significantly, this change also results in a tighter house that may cause undesirable effects on the indoor air quality. Four houses with ducts in conditioned space were tested for indoor air quality problems. Continuous measurements of CO and CO_2 gases and of the relative humidity were made and the results compared to similar houses with conventional flex-ducts.

The testing results showed no evidence that the interior ducts impacted the indoor air quality negatively. The CO_2 and interior humidity levels in houses with ducts in conditioned space were found to be consistently lower than the levels observed in similar houses with flex-ducts. Similarly, the CO levels in the houses with interior ducts in Esparto were comparable to the levels observed in the houses without interior ducts.

However, the test data did reveal that two of the houses with interior ducts in Visalia had consistently high levels of CO. The CO concentration levels were observed to build up overnight. The source of the CO was traced to pilot lights inside the oven that had not been adjusted properly. The interior ducts did not appear to aggravate the problem, since unlike the CO levels, the CO_2 levels did not exhibit unusually high levels during the testing period. For safety reasons, it is recommended that houses with interior ducts should have Combustion Appliance Safety (CAS) test performed on all appliances prior to move-in. Annual CAS test is also recommended for houses with interior ducts. In fact, this practice should be extended to all houses, with or without interior ducts.

6.0 Summary for Project 2.5: Simplified HVAC Controls

The objectives for Project 2.5 were as two-fold:

- Evaluate options for easier-to-use controls (e.g., thermostats) for space conditioning systems to understand how these measures may affect energy use by low-income households
- Determine how occupant use of air conditioning or heating equipment compares to their reported use provided in interviews

Achieving these objectives involved the following work:

- Selecting homes, thermostats, and instrumentation for study of the behavior of low-income households in adjusting thermostats
- Conducting interviews with 100 low-income households and installing temperature loggers in their houses
- Revisiting the 100 houses to collect the loggers and collected data
- Preparing specifications and design for a Simple Thermostat
- Installing prototype Simple Thermostats in 12 test houses
- Collecting and analyzing temperature data for test houses
- Preparing final report on project

This work for Project 2.5 is summarized in this chapter.

6.1. Background for Project 2.5

Two types of thermostats are commonly used to control HVAC systems: electromechanical and electronic.

- Electromechanical thermostats, usually the easiest devices to operate, typically have manual controls, such as movable tabs, for temperature settings. These thermostats work with most conventional heating and cooling systems. Electromechanical thermostats generally are manually set and need no battery backup.
- Electronic or "programmable" thermostats are the most commonly installed type, even though they may be more expensive that the electromechanical thermostats. Many U.S. states, including California, require the installation of programmable thermostats in newly built houses. Programmable thermostats are identified by their digital readout and data entry pads or buttons. They offer the widest range of features and flexibility, and digital thermostats can be used with most heating and cooling systems. They provide precise temperature control, and they permit custom scheduling. Programming some models can be fairly complicated.

Programmable thermostats can operate in two modes, automatic or manual. The programming options or complexity vary depending on the thermostat. Most programmable thermostats have a minimum capability of five- and two-day settings and two to four periods within the day type. The periods for each day or day type allow temperature set backs for a desired length of time, allowing the user to save energy. Depending on climate zone, nighttime setbacks can save

1–2% of the heating or cooling energy use per degree Fahrenheit of setback. However, people may be intimidated by programmable thermostats and hesitate to use them to their advantage. Energy savings won't be realized if the controls are not set or are set incorrectly.

Manual thermostat operation can provide the most energy savings, but at a cost of diligent operation. For that reason, they are not generally recommended when conserving energy is desired. Manually controlling the temperature with a thermostat also introduces a certain amount of inconvenience. This includes waking up in a cooler than normal house in the winter and possibly forgetting to adjust the thermostat (during any season) when leaving the house or going to bed.

Occupant behavior and understanding of controls for their thermal comfort greatly affects energy use. The best thermostat will depend on the life style and comfort level needed by the household. While automatic and programmable thermostats can save energy, a manual unit can be equally effective if it is diligently regulated and a chilly house on winter mornings is acceptable. If an automatic thermostat is used, it can be set to raise the temperature before the occupants wake up and spare some discomfort. It will also perform consistently and dependably to keep the house at comfortable temperatures.

Other types of controls include operation of window coverings, open and closing of windows, closing unoccupied rooms of the house, closing vents in unoccupied rooms, and using fans to accelerate the exchange of air to the outside.

Ventilation can be used to anticipate conditioning needs. For example, occupants can precool a house by opening windows all night and allowing the house to fall below the cooling setpoint. This not only lowers the air temperature, but also cools the contents (thermal mass) of the house delaying the need for air conditioning later in the day.

The installation of programmable thermostats is often espoused as an energy efficiency measure. Indeed, many houses now being built for low-income households in California are equipped with programmable thermostats, as required by California's Title 24. However, both monitored data and survey responses raise questions about the effectiveness of programmable thermostats when installed in housing for low-income households. Monitored data, albeit somewhat limited, suggest that low-income households are not using the programmable thermostats to control their space conditioning systems. Moreover, residential surveys in which households are asked "At what temperature do you keep the house in the winter and what temperature do you keep the house in the summer" show that many respondents cannot give an answer that follows a systematic logic that can be used in computer simulation of the household energy use. Thus, the actual effectiveness of programmable thermostats as an energy efficiency measure is an open research question.

The motivation for Project 2.5 was that a compromise between a manual or a programmable thermostat for energy savings and comfort might be reached by designing and testing a "Simple Thermostat." The Simple Thermostat would be designed to have the functionality of a programmable thermostat, but with the ease of use of a manual thermostat. It would enable the user to set a program for the desired space temperature without having to manually enter the program into the thermostat. It has been well documented that the process of programming can often be difficult and intimidating. A Simple Thermostat would be designed to remove this

obstacle by registering the room temperature as set by the user and updating the inherent program appropriately based on the changes.

6.2. Baseline Data on Household Control of HVAC Thermostat

Baseline data on how low-income households control their HVAC systems were collected by instrumenting 100 houses occupied by low-income households in California with a monitoring device that recorded the interior temperature for a period of four months or longer. Table 15 shows the distribution by housing type and by thermostat type of the 100 houses that were instrumented. These houses are located in California's Central Valley (California Climate Zones 11, 12 and 13). All of the houses instrumented had central air conditioning.

Table 15. Breakdown of monitored houses by housing and thermostat types

Type of Housing	*Type of Thermostat*		***Total***
	Non-programmable	*Programmable*	
Manufactured House	26	10	36
Single-Family Detached	4	60	64
Total	30	70	100

The instrumentation equipment installed at the houses of the low-income households was used to collect data on temperature readings in the houses during periods of heating or cooling. The data allowed calculation of 24-hour temperature profiles for both heating and cooling for the houses. These profiles are reported in the project report for Project 2.5. The data for the temperature profiles are summarized in Table 16 for the heating season and Table 17 for the cooling season.

Table 16. Summary statistics for 24-hour temperature profiles: heating season

	HOUR OF THE DAY																								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**AVG**
Mean	70	69	68	68	68	68	68	68	69	69	69	69	70	70	70	71	71	71	71	71	71	71	71	70	70
Std. Deviation	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3	3	3	4
Minimum	63	62	62	62	61	61	61	61	61	61	61	61	61	62	62	63	63	63	63	64	64	64	64	63	62
10th Percentile	66	65	65	64	64	63	63	63	63	64	65	65	65	65	65	66	66	66	66	66	66	66	67	66	65
25th Percentile	68	67	66	66	65	65	65	65	66	66	66	66	67	67	68	68	68	68	69	69	69	69	69	68	67
50th Percentile	69	69	68	68	68	67	67	69	69	69	69	69	70	70	71	71	71	71	71	71	71	71	71	70	70
75th Percentile	72	71	71	71	71	71	71	71	71	72	72	72	72	73	73	73	73	74	74	73	73	73	73	72	72
90th Percentile	73	73	73	72	72	72	73	73	73	74	73	73	74	74	75	75	75	75	75	75	75	74	74	74	74
Maximum	79	78	78	78	78	79	79	79	79	80	81	81	82	82	82	83	83	82	82	82	82	82	81	81	81

Table 17. Summary statistics for 24-hour temperature profiles: cooling season

	HOUR OF THE DAY																								
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	AVG
Mean	79	79	78	78	77	77	76	76	76	77	77	78	79	80	80	81	81	81	81	81	80	80	80	79	79
Std. Deviation	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	2
Minimum	74	73	73	73	72	72	71	71	71	71	72	73	74	75	75	75	75	75	76	75	75	74	74	74	73
10th Percentile	76	76	75	75	75	74	73	73	73	74	74	76	76	77	77	77	77	77	77	77	77	77	76	76	76
25th Percentile	77	77	77	76	75	75	75	74	74	75	76	77	78	78	78	79	79	79	79	79	78	78	78	77	77
50th Percentile	79	78	78	78	77	77	76	76	76	76	77	78	79	80	80	81	81	81	81	80	80	80	80	79	79
75th Percentile	81	80	80	79	79	78	78	78	78	78	79	80	81	82	83	83	84	83	83	83	82	82	82	81	81
90th Percentile	82	82	81	81	81	80	79	79	79	80	80	81	82	83	84	84	85	85	85	85	84	84	83	82	82
Maximum	84	83	83	82	82	81	81	80	80	81	82	83	84	84	85	87	88	88	88	88	87	86	85	85	84

The temperature data for each household were also analyzed to assess the consistency with which the temperature inside the house was controlled. This analysis showed that most of the households were either very consistent or somewhat consistent in how they controlled the inside temperature during both heating and cooling seasons.

The temperature data were also used to characterize households as to whether they used temperature setback during either daytime hours or nighttime hours. The results of this characterization are presented in Table 18. During the heating season, just over a third of the households use temperature setback during the day, while only one household could be identified as using setback at night. During the cooling season, none of the households could be identified as using temperature setback during the day, while about half used setback at night.[1]

1 Identifying daytime setback during the heating season is difficult because if the heater is used in the morning, the house can coast through the afternoon without much heating. Similarly, identifying nighttime setback during the cooling season is difficult because of the outdoor temperature dip overnight in the Central Valley region where the monitored houses were located.

Table 18. Numbers of monitored households using temperature setbacks during heating and cooling seasons

Used Setback	*Cooling Season*		*Heating Season*	
	Daytime Setback	*Nighttime Setback*	*Daytime Setback*	*Nighttime Setback*
Yes	37	1	0	49
No	48	84	96	47
No data	15	15	4	4
Totals	100	100	100	100

6.3. Household Survey Responses

As part of the data collection effort, a questionnaire was administered to the households where temperatures were being monitored. Interviewees were asked questions that pertained to their behavior in determining temperature levels in their houses and their operation of thermostats to control the indoor temperature. The following general topics are covered:

- How do households generally operate their heating and cooling systems?
- What factors are involved in how households try to control the temperature in the house?
- What methods other than thermostat control do households use to control the indoor temperature?
- How do households operate their thermostats to control indoor temperatures?

Statistical tabulations of the responses to this survey are provided in the project report for Project 2.5. A summary of those responses is provided here.

6.3.1. Summer and winter temperatures maintained while operating heating/cooling systems

Households were asked about the temperatures that they usually maintain inside their houses in summer and winter when the heating or cooling system is on. Summary statistics on their responses are provided in Table 19.

Table 19. Summary statistics on summer and winter indoor temperature when heating or cooling system is operating (°F)

Summary Statistics for Reported Temperatures	*Households with Non-Programmable Thermostats*		*Households with Programmable Thermostats*		*All Households*	
	Summer	*Winter*	*Summer*	*Winter*	*Summer*	*Winter*
Number of responses	25	26	67	59	92	85
Mean temperature	76	71	75	72	75	72
Standard deviation	4	5	5	6	5	6
Minimum temperature	68	55	60	60	60	55
10th percentile	70	69	68	65	68	65
25th percentile	73	70	70	68	71	68
Median	76	70	75	70	75	70
75th percentile	80	73	78	78	78	76
90th percentile	80	76	80	80	80	80
Maximum	81	80	85	85	85	85

6.3.2. Use of heating and cooling systems by type of thermostat

- Of the households with non-programmable thermostats, 66.7% (20 of 30 households) indicated that they used their cooling system during the summer either rarely or moderately. Of households using programmable thermostats, 42% (29 of 70) reported using their cooling system rarely or moderately during the summer.
- Of the household with non-programmable thermostats, 63.3% (19 of 30) indicated that they used their heating system during the winter either rarely or moderately. For households with programmable thermostats, 62.8% (44 out of 70) using their heating system rarely or moderately during the winter.

6.3.3. Energy use patterns

- About three-fourths of the respondents indicated that the cost of energy influenced the temperature that they kept inside the house.

- About one-fourth of respondents reported there a household member (such as a young baby or an elderly person) who required that house be kept at a certain temperature.
- Most households indicated that they used fans and opened windows for cooling in addition to using their air conditioning units.
- About a third of the households never turn off heating or cooling systems when nobody is in the house.

6.3.4. Thermostat use

- A higher percentage of households with programmable thermostats reported not being able to use their thermostats than did households with non-programmable thermostats.
- Nearly 43% of the households with programmable thermostats reported not knowing how to program the device.
- Over half (56%) of the households with programmable thermostats reported not having their thermostats programmed for night/day setback (allowing the thermostat to automatically adjust to a lower temperature).
- Of households with a digital programmable thermostat, 63% operated their thermostat in an auto mode (or program) mode, and 37% operated their thermostat manually.
- Nearly 60% of the respondents did not think that setting thermostat to lowest temperature during a hot day would allow house to cool faster. This percentage was nearly the same for houses with or without programmable thermostats.
- In two-thirds of the households with non-programmable thermostats, only one person can adjust the thermostat setting. By contrast, two or more persons can adjust thermostat settings for about three-fourths of the houses with programmable thermostats. However, many of those adjusting the programmable thermostats do not know how to use the programming functions, but rather adjust the buttons until they achieve the desired result.
- All of the respondents in households with non-programmable thermostats reported that the household members who used the thermostat knew how to operate it. However, about 44% of the respondents from households with programmable thermostats reported that those using the thermostat did not know how to use it.

6.4. Designing and Testing a Simple Thermostat

The survey data summarized in the sections above are consistent with the hypothesis that there is a possible market among low-income households for a thermostat with a simpler programming procedure than in currently available thermostats currently. In particular, nearly 43% of the low-income households with programmable thermostats that were surveyed indicated that they did not know how to program their programmable thermostat.

In designing the Simple Thermostat, the objective was to remove the difficulty of programming a thermostat that low-income homeowners often face, while maintaining the ability to schedule the thermostat based on the daily activities of the house occupants. Many programmable thermostats in the market today come with numerous buttons (as many as 10) and complicated instructions. For many members of low-income households who did not grow up with English as their first language, reading the thermostat instructions can be a challenge.

Many self-help housing organizations (e.g., Habitat for Humanity, Mercy Housing) are fully aware of this difficulty. To alleviate this problem, they hold classes specifically to train homeowners on how to program their thermostats prior to moving in. Survey results indicate that the success rate for such classes is modest at best.

Figure 16 shows a Simple Thermostat as installed. The design of the Simple Thermostat is focused on the simplicity of the interface and a more intuitive operation for the homeowner. It has three buttons, two for temperature control, and one to allow the user to save energy across the entire schedule. It has the look and feel of a manual thermostat, but it maintains a schedule based on the user's temperature control habits. When the user changes the setting of the thermostat, this change is treated as an input that updates the memory of the program. The altered memory is then saved and reused at the same hour the following week. The thermostat allows hourly memory in both heating and cooling modes for the entire week (168 hours). The thermostat time is acquired using a wireless time reference, which spares the user the hassle of having to program the time into the thermostat.

Figure 16. Installed Simple Thermostat

When the user presses the temperature up or down button, this user temperature offset, γ_i, is registered and added to the cumulative temperature offset, γ, observed so far in the week. The effective change at every hour is limited to ±6°F.

This updating process is represented by the following equation:

$$\gamma = \gamma + \gamma_i$$

with γ updated in real-time. The absolute temperature setting of the thermostat, T, is affected by this offset in the following manner:

$$T = T_m + \gamma + \delta,$$

where,

T_m = temperature in the memory for that particular hour

δ = saving offset.

At the hour rollover (i.e., end of the hour), the memory is updated accordingly. Some limits, however, are imposed on the memory updating, to prevent sudden and extreme change in temperature resulting from unique situations. The memory update is as follows:

$$T_m = T_m + \gamma_r$$

where

γ_r = the temperature offset, γ, at the end of the hour. It is limited to a maximum change of 4°F. If γ at the end of the hour is greater than the allowable change, then γ_r will be set at either 4°F or -4°F.

The temperature offset is reset to zero at the beginning of each week (or called the week rollover). The week rollover time could be factory set at any hour, but for the prototypes, it was set at 4:00 Pacific Standard Time or 5:00 Pacific Daylight Time Sunday.

The third button is the saving offset button. Whenever the button is activated, it will cycle over to the next mode. There are four different modes that the thermostat could operate in, and for each mode, δ, the value of is assigned as follows:

- Comfort Mode: $\delta = 0$ for heating and cooling
- Save Mode: δ = -2°F and 2°F for heating and cooling respectively
- Save More Mode: δ = -5°F and 4°F for heating and cooling respectively
- Save Max Mode: δ = -10°F and 8°F for heating and cooling respectively

Since the saving offset is not registered into the memory, it allows the user to alter the temperature setting on a whim. For instance, when the house is left empty for several hours only for that week but not the following week, the user can select the "Save Max" mode without registering this change in the memory. This button is designed to encourage the homeowners to conserve energy whenever possible without having to register this change in their weekly thermostat schedule.

The full specifications of the Simple Thermostat are provided in the project report for Project 2.5.

6.5. Outcomes for Project 2.5

After testing the first prototype Simple Thermostat in-house for two week to ensure that all the specifications were met, Simple Thermostats were replaced the programmable thermostats in 12 of the 100 houses monitored for the baseline study. Four of the test houses are located in Fresno, and eight in Winters.

The test houses were monitored for complaints for one year after installation. The complaints received were mostly unrelated to functionality. Instead, they were minor issues with faulty parts that were addressed promptly.

The Simple Thermostats were also equipped with data recording capability for the first three months after installation. From the data collected through the monitoring, it was frequently observed that some households were inclined to turn the thermostats off when they did not need space conditioning. According to the majority of homeowners, turning off unneeded equipment was a habit that seemed intuitive. Since the Simple Thermostat was rendered inactive when in "Off" position, few sustained scheduling changes were observed in these houses for the first three months of operation. However, when the Simple Thermostat was left operating all the time, there seemed to be a convergence toward a regular schedule after extended use, as observed in some test houses in Winters (installed in January 2004). A schedule sample is shown in Figure 17. The homeowner in this case used the "Save More Mode" to lower the temperature in the house instead of using the temperature offset buttons.

6.6. Conclusions and Recommendations for Project 2.5

An energy efficiency measure often espoused is the installation of programmable thermostats. Indeed, many Habitat for Humanity houses now being built are equipped with programmable thermostats. However, earlier research raised questions about the effectiveness of programmable thermostats when installed in housing for low-income households. Monitored data, albeit somewhat limited, suggest that low-income households are not using the programmable thermostats to control their space conditioning systems. Moreover, many households asked the survey question "At what temperature do you keep the house in the winter and what temperature do you keep the house in the summer" cannot give an answer that follows a systematic logic suitable for use in computer simulation of the household energy use. Thus, the actual effectiveness of programmable thermostats as an energy efficiency measure was an open research question.

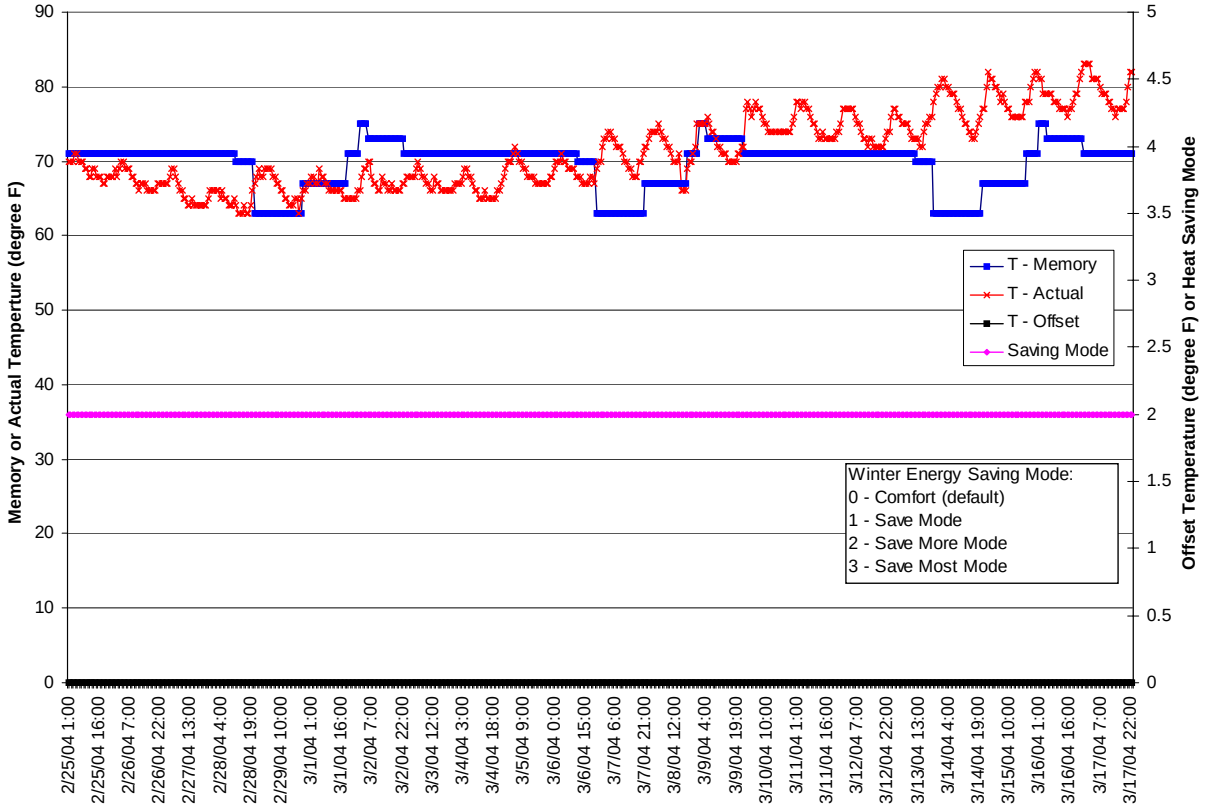

Figure 17. Temperature profiles for a test house in Winters, California

The survey data collected during Project 2.5 are consistent with the hypothesis that there is a possible market among low-income households for a programmable thermostat with simpler programming than that of today's units. A major finding from the survey was that nearly 43% of the low-income households with programmable thermostats surveyed did not know how to program their thermostat.

To address this problem, Project 2.5 developed a Simple Thermostat, a one-of-a-kind thermostat with minimal user interface programming requirements. Development of the Simple Thermostat demonstrated that is possible to create a programmable thermostat that removes the complexity of programming often cited by users as a nuisance. A working model of the thermostat with only three buttons and yet capable of retaining a week's worth of memory was produced and installed in twelve low-income houses. Monitoring data suggested that thermostats set to an active setting (as opposed to those habitually turned off when not needed) reached a regular schedule after extended use.

The energy savings potential from operating the Simple Thermostat instead of a conventional programmable thermostat remains to be determined. Most of the test houses used the HVAC equipment very sparingly. Variations in household characteristics before and after the installation, such as occupants moving in and out, precluded making an accurate estimation of the thermostat's impact on cooling or heating energy consumption for the household. These

findings suggest that the Simple Thermostat might be ill-suited for low-income households due to their strong preference for lower cost over comfort.

To further test the applicability of Simple Thermostat in promoting both comfort and energy conservation, it is recommended that more Simple Thermostats be tested in markets other than low-income housing. The involvement of thermostat manufacturers in such testing would be highly desirable. It is anticipated that the Simple Thermostat could be further refined through collaborations with thermostat manufacturers and data sharing to better meet household needs outside of the low-income market.

7.0 Summary for Project 2.6: Evaporative Cooling/Whole House Fan Integration

The objective of Project 2.6 was to evaluate whether integrating different cooling technologies—such as a whole house fan, standard or an evaporative cooling system, and an economizer—provides an economically viable and efficient alternative for comfort cooling needs in new houses for low-income households.

The following work was performed in Project 2.6:

- Investigate factors affecting combined technologies
- Evaluate and develop alternative designs
- Prepare monitoring plan
- Install technologies in eight homes
- Monitor test and control homes
- Analyze data
- Prepare project report

This work is summarized in this chapter.

7.1. Background for Project 2.6

With lower operating and maintenance costs, up to 80% less energy intensity, and greater ventilation effect compared to a mechanical conditioning system, evaporative cooling could provide affordable comfort to a wider range of homes in an environment of increasing power costs. The objective of Project 2.6 was to evaluate the viability of creating an economically efficient alternative for meeting comfort cooling needs in new houses for low-income households by combining different cooling options, such as a whole-house fan and standard or evaporative cooling systems. The impact of such integration on the air indoor quality of the homes was evaluated in Project 2.4: Envelope and Indoor Air Quality Interactions.

Project 2.6 evaluated three different integrated systems in different housing types:

- System 1, created by integrating an evaporative cooling system with a standard packaged air conditioner. A controller cycles the evaporative and standard air conditioning systems based on outdoor temperature. Specifically, the evaporative cooler is operated whenever the outdoor temperature is below a selected set point. Because evaporative cooling is much less energy intensive than a standard air conditioner, this arrangement reduces cooling energy requirements during the summer hours when the air is below the set point temperature, usually the case during non-peak hours. This system was installed in four low-income houses built by the Habitat for Humanity Fresno.
- System 2, created by converting an evaporative cooling system into a whole-house fan. A controller cuts off water supply to the wetting media of the evaporative cooler based on the outdoor temperature. In this setting—which can be used in the morning and late afternoon when the weather is cooler to reduce indoor humidity and energy consumption—the evaporative cooler is effectively converted into a whole-house fan

that pressurizes the house. This system was installed in three homes occupied by low-income households.

- System 3, created by integrating an economizer with a standard air conditioning system and a temperature control for a manufactured home. Economizers are very rarely installed in manufactured homes, due to several constraints. This system was installed in a new manufactured home.

7.2. Description of Test Houses

The three different integrated systems were installed in different test houses.

Four identical single-family detached houses built by Habitat for Humanity Fresno were designated test houses 1–4. Construction of the houses was completed in 2002. Each house had a roof-mount packaged air conditioning system. In September 2003, an evaporative cooler was added to the packaged air conditioning system of each house (system 1). To prevent air infiltration from outside when the cooling system is not in operation, a barometric damper was added to the ductwork connecting the evaporative cooler and inlet duct. A control system designed by ADM was wired to both pieces of equipment. This control system automatically selects either the standard air conditioning equipment or the evaporative cooler to operate based on the outdoor temperature. The addition of the controller does not affect the use of the thermostat. It is compatible with all makes and models of thermostat.

Test houses 5 and 6 are in Atwater, California. The houses tested belong to the Housing Authority of the County of Merced. From early April to late September, the houses are occupied by low-income migrant workers who work for various plantations in the area. The houses are attached single-story homes cooled using an evaporative cooler. A water shut-off control for the evaporative cooler of each house was installed in July 2002 (system 2). This water shut-off control was designed to activate below a certain pre-set temperature. The controller was intended to convert the evaporative cooler into a whole-house fan in the morning and late afternoon.

Test house 7 is an existing manufactured home in Sacramento, California. The house is cooled using only an evaporative cooler. The same controller as shown in Figure 18 was installed on the evaporative cooler unit (system 2). The occupant of the house activated the evaporative cooler as needed throughout the year.

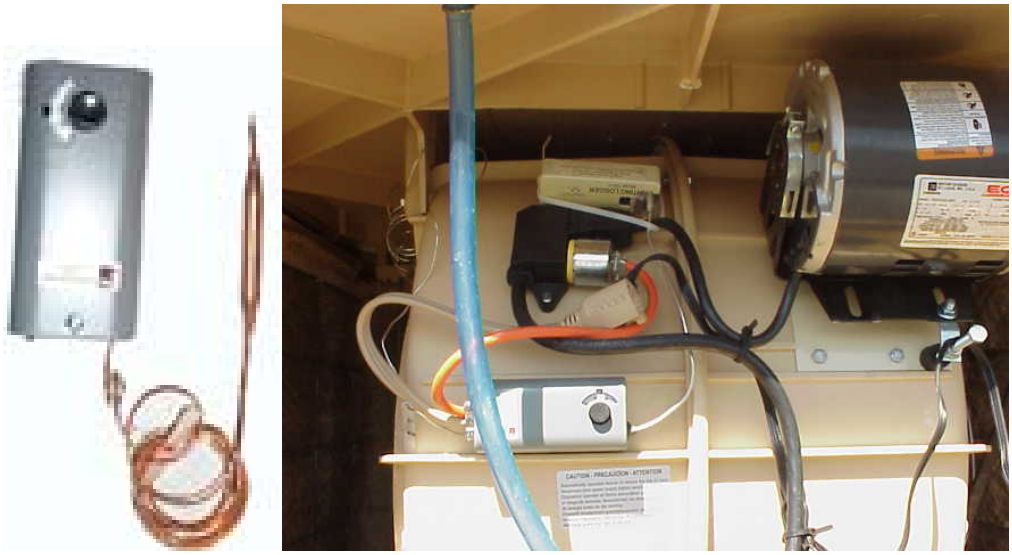

Figure 18. Sample evaporative cooling control system

Test house 8 is a new manufactured home located in Arbuckle, California. In September 2003, this house was equipped with a duct-damper combination economizer commonly used for single-family houses. The installation process required some modification to the original HVAC system of the house (system 3). That is, the heating and cooling units in manufactured homes are typically downdraft units that feed main supply ducts built into the subfloor with floor registers throughout the home. The air handlers are typically factory installed, and the options offered with the heating/air conditioning system are usually limited to increase the efficiency of installation. There is usually no return air system in manufactured homes. Instead, the return air flows to the hallways and directly into the air handler.

Economizer placement is the key factor determining the feasibility of adding an economizer to a manufactured house. With downdraft units, the only feasible location for the economizer is in the attic. Airflow direction precludes placing an economizer below the house—even though space is usually available. Furthermore, the air handling unit is typically placed in a closet that is close to an outer wall, limiting the attic space above the air handling unit. Economizer dampers designed for residential systems available today typically require a certain height clearance. The diameter of such dampers will most likely also require a larger roof penetration, a process that would possibly trigger a lengthy review from the design department of the home manufacturer.

To circumvent this problem, the HVAC unit for Test House 8 was custom ordered. The unit installed was a stand-alone packaged unit—rather than a closed unit—that could be located outside of the house. A return duct system was installed in the original location of the HVAC system inside the closet. Both the return and supply duct systems were located underneath the house, and the damper system was connected to the return ducting. With this arrangement, the homeowner would be able to control the damper system and use the economizer as a whole-house fan when desired.

Installation of the damper system was fairly difficult. Unlike the ducts, which were installed in the factory, the damper system was installed onsite after the HVAC unit had been installed. The

limited crawlspace underneath the house added to installation difficulties. Had the manufacturer offered, the damper system could be done in the factory. Another option would be to purchase a unit that has an economizer built into it. However, this option removes the ability to control the damper, making its operation similar to that of economizers in commercial facilities with individual packaged units.

7.3. Monitoring Equipment and Procedures

Monitoring equipment was installed at the various test houses to collect data for assessing the performances of the different integrated systems.

- For test houses 1-4, the auto-switch controller was equipped with a monitoring device that characterized which equipment was being turned on at any given time. A Hobo logger was used to monitor the outdoor ambient temperature. The Hobo logger was inserted into a naturally aspirated radiant shield and hung from the north eave of the house. Another Hobo logger was used to monitor the indoor temperature inside each test house. The indoor temperature sensor was placed next to thermostat where applicable to capture the room temperature as sensed by the thermostat.
- For test houses 5, 6, and 7, the cooler's water pump was reconfigured to allow a small incandescent lamp to turn on when the pump was in operation. A lighting logger was then used to monitor the exact times the water pump came on and off. The use of a motor logger to monitor the water pump was not feasible due to the size of the pump. The air supply fan, however, was monitored using a motor logger to determine the on/off periods. The indoor and outdoor temperatures were monitored using Hobo temperature loggers.
- Test house 8 was not monitored. The main purpose of Test House 8 was to demonstrate the feasibility of adding an economizer to a manufactured house and to learn about the obstacles facing such addition. Energy savings from a residential economizer have been well documented by many previous studies, and the benefit of monitoring this test house for the purpose of quantifying the energy savings would have been minimal.

7.4. Outcomes for Project 2.6

This section presents and discusses the outcomes of evaluating the performances of the integrated systems.

7.4.1. System 1: Evaporative cooler and standard air conditioner

In a system where an evaporative cooler is integrated with a standard air conditioner, the evaporative cooler is intended to replace the air conditioner when the outdoor air is below a set temperature. For the test houses in Fresno, this temperature was set at 90°F throughout the duration of the test.

The data collected in test houses 1, 3, and 4 showed that the use of the evaporative cooler alternated with the use of the standard air conditioner. During the hottest summer days in Fresno, the transition from standard air conditioner to evaporative cooler typically takes place after 5:00 pm, when the outdoor temperature is over the peak. The evaporative cooler was also observed to come on during early morning hours. One of the houses equipped with the integrated system (test house 2) used very little cooling during this period. According to the homeowner, he did not have an adequate income during the period of study to support

prolonged use of the cooling system. Any results obtained from this house should be interpreted with caution.

Assuming that the thermal cooling supplied by the evaporative cooler would have been supplied by the air conditioner in the absence of the evaporative cooler, the energy savings provided by the evaporative cooler could be estimated as follows:

$$Savings(kWh) = EU_{EC} * \left(\frac{COP_{EC}}{COP_{AC}} - 1 \right).$$

where:

EU_{EC} = annual energy consumption of the evaporative cooler in kWh

COP_{EC} = coefficient of performance of the evaporative cooler

COP_{EC} = coefficient of performance of the air conditioner

The annual energy savings observed in the four test houses are summarized in Table 20. Based on the values observed in these test houses, integrating an evaporative cooler can be an economically viable strategy to reduce monthly utility bills in the summer, especially if the evaporative cooler is installed in new homes, where the cost of installing such system will be substantially lower than retrofitting it at a later time.

Table 20. Summary of energy savings observed in Fresno test houses

	Test House 1	Test House 2	Test House 3	Test House 4	Average
Average Cooling Season % Run Time	12.6%	2.2%	22.1%	19.6%	14.1%
Annual Evaporative Cooler Full-Load Operating Hours	691.2	122.6	1,217.2	1,078.0	777.3
Evaporative Cooler One-Time Measurement, kW	0.46	0.53	0.47	0.52	0.50
Evaporative Cooler COP	6.50	6.50	6.50	6.50	6.50
Air Conditioning System COP	2.70	2.70	2.70	2.70	2.70
Annual Evaporative Cooler Energy Use, kWh	318	65	566	564	378
Estimated Annual Air Conditioner Energy Use when Evaporative Cooler was Used, kWh	765	157	1,363	1,357	911
Annual Energy Savings, kWh	**448**	**92**	**797**	**794**	**532**

There were no complaints from any of the homeowners related to a reduction in comfort level due to increased humidity or any other factors caused by the evaporative cooler. In fact, all the homeowners were very pleased with the system, and the majority commented on a remarkable reduction in their utility bills in the summer when this system was in operation. It was noticed

that in all the houses tested, the indoor temperature climbed as high as 85°F. The average indoor temperature maintained during the testing period was 79°F.

The impact of the evaporative cooler operation on the indoor air quality of these houses was also studied. The design and results of the study of indoor air quality are presented in the Final Report for Project 2.4: Envelope and IAQ Interactions.

7.4.2. System 2: Whole-house fan and evaporative cooler integration

The performance of a system that integrated a whole house fan with an evaporative cooler was evaluated using data collected from Test Houses 5, 6, and 7. These data revealed that in California's Central Valley, there are very few opportunities to convert an evaporative cooler into a whole-house fan based on the outdoor ambient temperature. In many areas in the Central Valley during the cooling season (May to September), the outdoor temperature stays well above 70°F during daylight hours.

Figure 19 shows operation of the system on typical summer day for Atwater, California. As shown, the operation of the evaporative cooler (both the fan and pump) started in the late morning, when the temperature climbed above 85°F. The temperature, however, did not drop below 70°F until midnight. The cut-off temperature, when water flow to the wetting media would be stopped, was set at 70°F. Based on the temperature profile, the only time of day in the summer suitable for such conversion would be in the morning. From the data collected in the test houses, however, it was evident that use of the equipment in the morning was minimal. Since the weather in the morning is cool and comfortable, the idea of turning on the cooling equipment did not seem to be intuitive to the house occupants. It is inconclusive whether the use of such control in the morning would be effective in reducing energy use in the California's Central Valley.

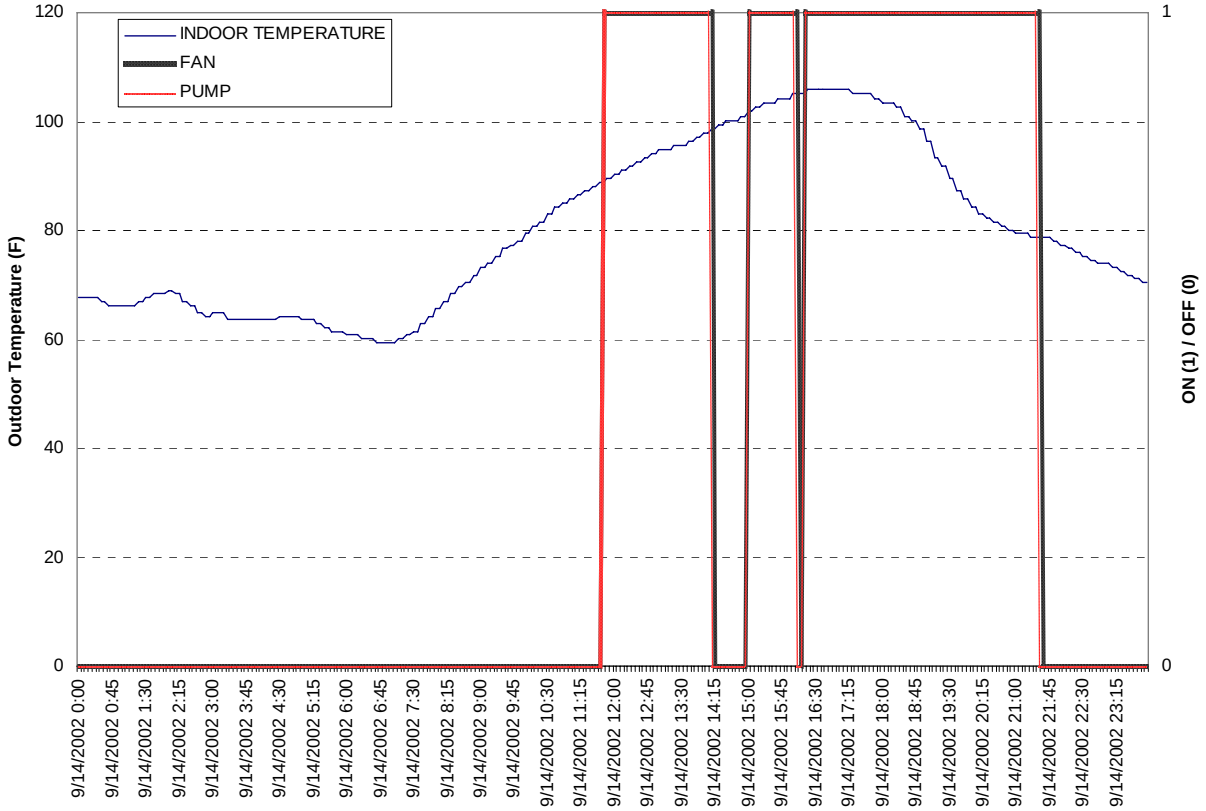

Figure 19. Evaporative cooler operation on a typical day for test house 5 (Atwater, CA)

The benefits of using this type of control system in areas where the climate is milder are unknown. Further investigation is needed to learn about the impact of converting the evaporative cooler into a whole-house fan especially in the morning. The impact of "pre-cooling" the house in the morning also needs to be carefully evaluated and contrasted against the effectiveness of simply running the evaporative cooler all through the afternoon. Performing such a study, however, needs a tightly controlled environment that requires the same temperature control habits in both the test and control houses.

7.4.3. System 3: Economizer installation in manufactured homes

Installing an economizer in the manufactured home that was the test house for this system required custom work. However, according to several manufacturers, custom HVAC systems are not very popular with households buying manufactured homes. They estimated that less than 1% of homebuyers would opt for installing the air handler outside of the house. When they do, they are usually faced with a higher cost, since the equipment has to be custom ordered and installed separately from the house. Most prefer the convenience of selecting the default equipment, either because they are not well informed of the alternative or they are not comfortable with the idea of needing the extra step and cost to install the HVAC system.

The manufacturers tend not to push for the alternative either, so this option is often left unexplored. Given the current market, installation of economizer is seen as lacking in

practicality. Although the work in this project demonstrated that such installation is within the realm of possibility, the market forces tend to discourage it from happening.

There are two factors that perhaps could hasten a more widespread use of economizers in manufactured homes:

- Persuade manufacturers to redesign the existing placement and configuration of the standard HVAC system to purposely allow for an economizer to be installed
- Promote the benefits and inform buyers of the option of installing economizer to alter the market dynamics, possibly through additional rebates or incentives

As it stands currently, the use of economizer in manufactured homes is limited to homeowners who have a good understanding of the technology and knowingly choose to have it installed.

7.5. Conclusions and Recommendations for Project 2.6

For Project 2.6, three different types of systems that integrate evaporative cooling, whole house fans, and standard air conditioning were evaluated.

System 1, an evaporative cooler integrated with a standard air conditioner, in four test houses in Fresno demonstrated substantial energy savings through the summer. For the four houses tested, the savings averaged 532 kWh annually. This integrated system was also very well received in all of the houses tested. Considering the low cost of adding an evaporative cooler, especially as a new construction item, this measure may be economically viable for houses built for low-income households. Another option to lower the cost of this technology is to consider bundling the air conditioner and evaporative cooler into a single equipment. A first-generation fully integrated air conditioner and evaporative cooler sold as a single piece of equipment has just been introduced to the market.

Houses in other areas in the Central Valley that have a milder summer climate than that of the test houses might benefit even more from the addition of the evaporative cooler. Performing a similar test in houses in different climate zones in California might be a logical next step to determine the potential energy savings in each climate zone. The test data could be used to construct and calibrate an energy simulation that can predict the energy savings resulting from such an integrated system. It is also recommended that a market assessment be conducted for this product to determine the potential demand for and the prospect of such product in the residential market.

Project 2.6 showed that the installation of an economizer in manufactured homes is possible. However, such installations are not common due to a number of constraints imposed by the structural conditions and placement of mechanical equipment. The addition of economizer requires extra steps outside of the standard house manufacturing and installation process that may be seen as a nuisance for most homeowners or even homebuilders to a certain degree. Because of the lack of demand for economizers, the manufactured home industry does not seem compelled to make changes that would allow a less complicated installation process. An informative marketing campaign to increase homebuyer awareness of an economizer, however, might create enough demand to drive some design changes that would allow for easy addition of this energy efficient product.

8.0 Summary for Project 2.7: Energy Efficiency Through Community Design

The objective of Project 2.7 was to determine how best to incorporate narrow streets and shade trees into the designs of low-income single-family housing developments to reduce ambient temperature.

The work in Project 2.7 was as follows:

- Select housing developments where temperature monitoring equipment would be installed
- Prepare monitoring plan
- Install monitoring equipment
- Collect data
- Develop database
- Analyze data and develop algorithms

This work is summarized in this chapter.

8.1. Background for Project 2.7

According to the U.S. Department of Energy report, *Landscaping for Energy Efficiency* (U.S. Department of Energy 1995), careful landscaping can save up to 25% of a household's energy consumption for heating and cooling. Action 9, Cool Communities, of the Clinton-Gore Climate Change Action Plan called for mobilizing community and corporate resources to strategically plant trees and lighten the surfaces of buildings and roads to reduce cooling energy use of the buildings.

While trees around houses can reduce cooling energy consumption by direct shading of houses, street trees reduce cooling energy consumption by reducing the surrounding ambient air temperature. The unshaded dark surface of a street acts as heat storage, absorbing heat during the day and releasing it in the afternoon and evening. A substantial tree canopy can directly shade paved surfaces. Such shading in combination with evapo-transpiration, can significantly reduce ambient temperatures, thus reducing overall cooling energy requirements for a neighborhood. Studies (Akbari 1995; Sailor et al. 1992) have produced estimates that as much as 10% of urban peak electric demand is the result of the heat island effect. Studies have reported a temperature difference of up to 8°F between areas with high tree canopy and areas with no trees.

According to a study by researchers at Lawrence Berkeley National Laboratory, it costs about $0.01 to reduce peak-load energy demand 1 kWh by planting trees. The cost of saving that same kWh by improving the efficiency of electrical appliances is about $0.025. One kWh generated by a new peaking power plant costs $0.10.

However, such estimates of the effectiveness of planting trees in reducing energy use are often based on computer simulations. Relatively little empirical evidence is available quantify the effects of different levels of tree planting on ambient temperature and energy use. Thus, there is no empirical basis for determining what level of tree planting is the most cost effective, especially at the neighborhood level. Lawrence Berkeley National Laboratory researchers have

themselves suggested that such data are needed to provide a quantitative assessment of tree planting strategies so as to determine and select the most promising for implementing and incorporating in urban design and planning decisions.

8.2. Issues Researched in Project 2.7

Because this PIER Program is targeted at housing for low-income households, the aspects of community design researched for this project examined how the general research findings described in Section 8.1 could be applied for communities where housing for low-income households is built.

One issue examined was how self-help housing organizations, such as Habitat for Humanity, can apply energy efficiency community design principles to housing that they build. Self-help housing organizations often do not have the luxury of developing large neighborhoods for their homeowners. For many HfH affiliates, especially those in urban areas, small plots of land usually become available through in-kind donations or some other arrangements that allow the land to be purchased at a price lower than market value.

When HfH affiliates are able to secure large plots of land to build a sizeable neighborhood, the process of construction can be slowed down by a number of factors, chief of which is the availability of funds to build. It is not unusual for a large development overseen by HfH to last 10 years or longer from the time of planning to the time the last house is built. As a component to this project, ADM worked with several affiliates to design upcoming communities with narrow streets and dense tree canopies to reduce cooling energy load.

The second major issue examined was the effects of street tree canopy coverage on the ambient temperature of a neighborhood. This research focused on communities comprised primarily of manufactured homes.

Manufactured homes, which make up another segment of low-income housing in the United States, have become increasingly popular in the last 20 years. Manufactured homes account for approximately 25% of all U.S. houses sold. New manufactured home communities are sprouting across California. Often called mobile home parks, these communities vary in size, encompassing anywhere from tens to thousands of houses.

Unlike single-housing developments, where the homeowners usually also own the plot of land the houses sit on, a manufactured home community is typically owned by individuals or corporations who lease out housing space to the homeowners. Therefore, the decision to add more vegetation or adjust street width is often controlled solely by the park owner. In many instances, the number of trees and amount of vegetation in these parks are kept at a minimum to allow easy movement of the houses in and out of the park. Streets in these communities are often designed to be fairly wide also for the convenience of moving the houses in and out. The minimum width of streets in mobile home parks is regulated by city ordinances.

To learn about the impact of tree canopies on the ambient temperature inside a park, five mobile home communities in Sacramento with varying amount of tree shade were extensively monitored. An empirically validated model for showing the tree canopy effect relevant to manufactured home communities was developed from the data collected at these communities.

8.3. Community Design for Habitat for Humanity Community

As previous studies have shown, the strategic placement of street trees and narrow streets can reduce the impact of solar radiation on the cooling load of a community.

To show how the principles of street design and tree planting can be implemented for communities of low-income households, ADM Associates worked with the Habitat for Humanity affiliate in Shasta, California, to redesign the plan of an upcoming large community.

The starting plan for the community's design is shown in Figure 20. With the starting plan, there was a sprawling community of 69 houses with minimal street trees and regular street width.

The redesigned plan for the community is shown in Figure 21. Under the redesigned plan, the community is transformed into a more compact community with narrower streets and a row of trees lining both sides of the street. Another feature of the redesigned plan for the community is that a small park just slightly larger than 1.5 acres has been added at the center of the community. The main street into the community is also redesigned with a center partition where additional trees could be planted.

The new community design allows for 5 sites fewer than the original design. However, the addition of a park and more room for street trees should greatly enhance the ambience of the community and lessen the need for mechanical cooling during the hottest period of the year.

8.4. Collection of Ambient Temperature Data

The second major aspect of the research in Project 2.7 was to collect and analyze data on ambient temperatures in neighborhoods where housing for low-income households was located and to use these data to develop a mathematical model for predicting how different levels of tree canopy coverage will affect ambient temperatures. The collection of the ambient temperature data for that research is described in this section, while the analysis of the data and the development of the model are described in Section 8.5.

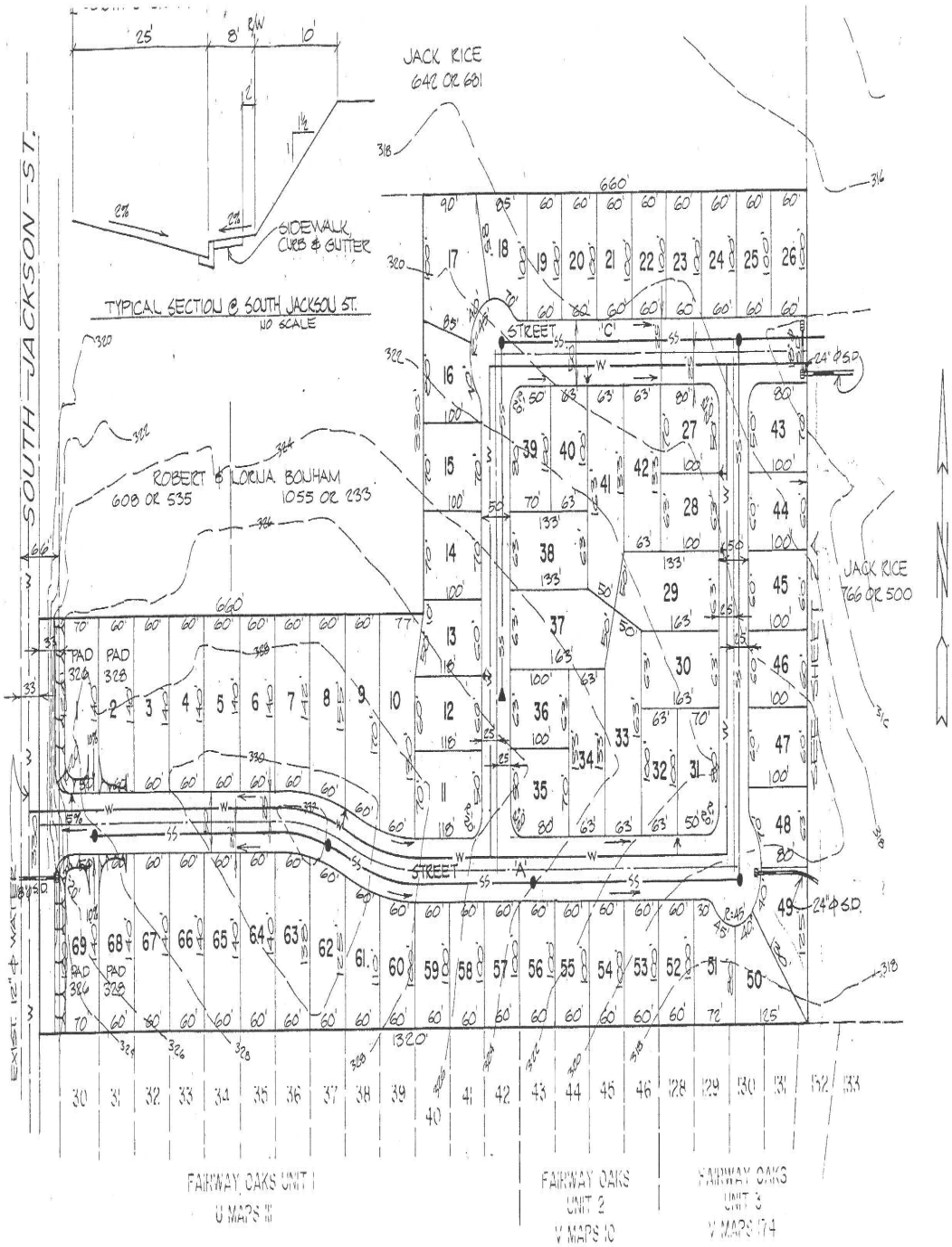

Figure 20. Layout of the HfH Shasta community prior to redesign

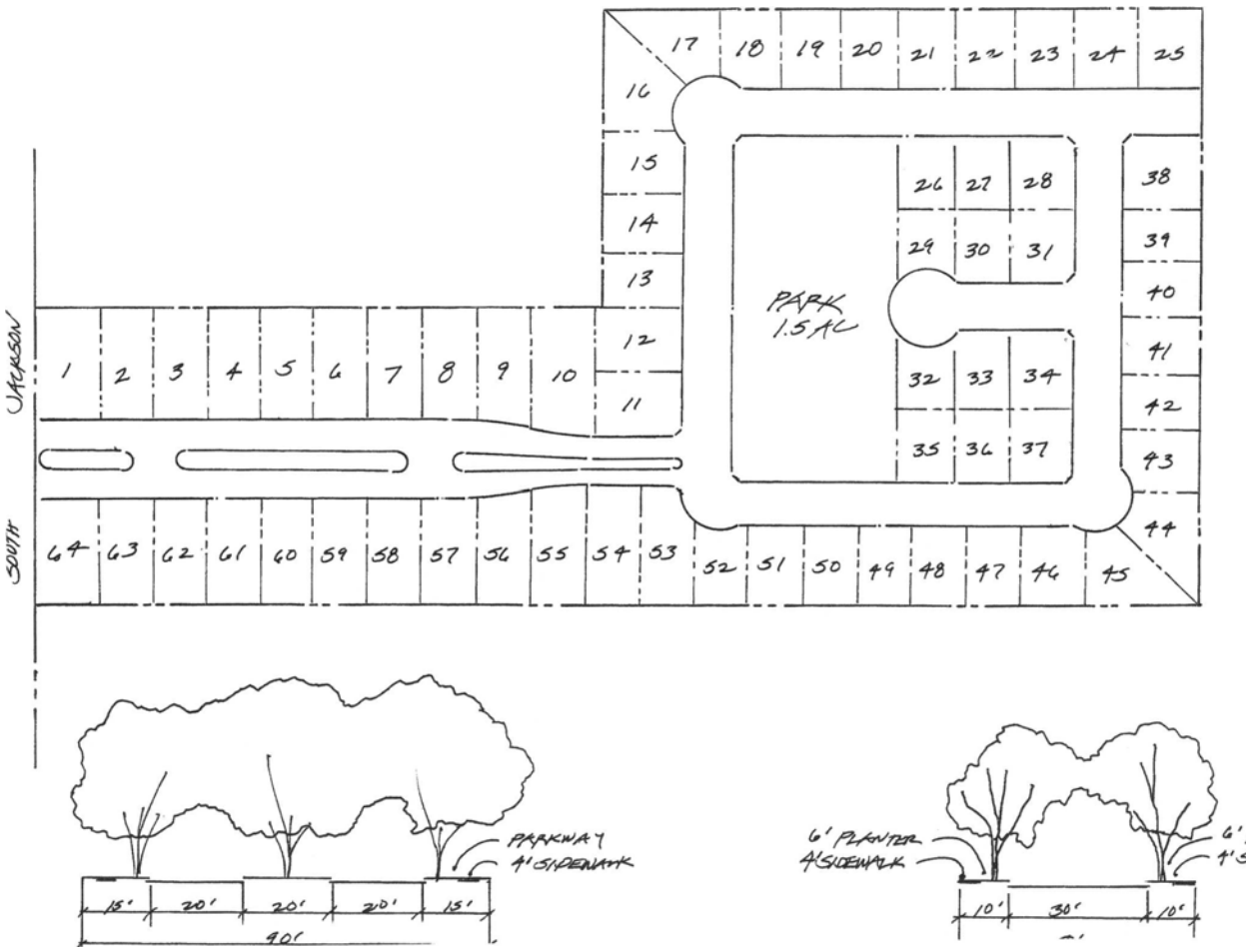

Figure 21. Layout of the HfH Shasta community after the redesign (characterized by narrower streets and addition of street trees and a community park)

8.4.1. Selection of monitoring locations

The overall purpose of the research described here was to learn about the impact of tree canopies on the ambient temperature within neighborhoods of housing for low-income households. To focus the research, five mobile home communities in Sacramento with varying amount of tree shade were selected for extensive monitoring. The participating communities were selected based on the different degrees of canopy coverage existing in each community. The communities were also selected to be away from bodies of water and large parks to minimize the influence of other sources on ambient temperatures. The level of canopy coverage was estimated based on the ratio of the areas covered with tree canopy to the total areas of the community. Wherever the aerial picture was deemed outdated based on differences observed onsite or from interview with park manager, the level of canopy coverage was adjusted appropriately to reflect these changes. Table 21 provides a summary of canopy coverage level for the five communities.

Table 21. Canopy coverage for monitored communities

Community	Location	Canopy Coverage (%)
1	Sacramento	60–70
2	Sacramento	80v90
3	North Sacramento	0–10
4	Sacramento	40–50
5	Sacramento	20–30

The street width varied little (18–22 ft) in these communities, a common finding among communities that prohibited parking on both sides of the street. A large majority of the communities visited for this purpose study did not allow parking on either side of the street. Many of the park owners and managers consulted for this study viewed any changes in street width unfavorably due to the space requirements to transport the home in and out of the park. In most instances, the street width was already kept at the minimum required by the city ordinance. Based on this finding, the effects of the street width on the ambient temperature of the park were not pursued.

8.4.2. Monitoring equipment

Temperature data loggers were placed at fifteen or more locations in each of the five mobile home parks located in Sacramento, California. Each data logger was placed inside a housing that prevented the temperature sensor from contacting any object and allowed ambient air to flow in and out naturally without the need for forced ventilation. The temperature sensor was fully shielded from direct sun radiation, and the outer surface the housing was painted white to make it more reflective. The temperature recorder was set to collect data every hour, and it was capable of holding data for a three-month period.

Two different types of housing were designed, one to be placed on top of roofs and the other to be placed on the ground. The placement of sensors at different levels was intended to minimize the influence of different type's ground surface and house overhangs on the ambient temperature as observed by the sensors. In each community, at least five of the sensors were placed at the roof level and ten sensors at the ground level.

Although efforts were made to reduce the impact of radiation on the housing by painting it white, a housing in direct path of sunlight could still potentially heat up from sun radiation over time and influence the sensor reading. To compensate for this potential small aberration, a controlled experiment was conducted to investigate into the influence of radiation on the sensor readings. An aspirated and a non-aspirated housing were tested in a temperature-controlled chamber with heat lamps shining directly on them. The temperature profiles for both scenarios were contrasted and used to calibrate the temperature data for the temperature loggers placed in locations without any shading.

In each community, a weather station was established at a public area close to the center of the community. This weather station recorded various weather data, including ambient

temperature, relative humidity, wind speed, wind direction and solar intensity. To avoid all obstructions, the weather stations were installed at least 15 ft off the ground.

8.5. Outcomes for Project 2.7

The data on ambient temperatures collected during the monitoring at the selected communities were analyzed and used to develop a mathematical model for relating ambient temperature to tree canopy. The outcomes from this analysis of the data and the development of the model are described in this section.

8.5.1. Data processing methods

The data collected with the monitoring equipment installed at the five mobile home communities were inspected to assess suitability. Researchers then removed spurious signals, applied the calibration to negate the direct radiation impact, and formed a final data set for developing the necessary correlation.

It is well understood that data of this proportion cannot be easily studied or filtered to remove any abnormal data or spurious data without employing some form of graphical representation. It is also known that only a handful of data plots can yield the necessary trends to identify and eliminate the unwanted data. Two of the usable plots are known as diurnal profile of sensor temperatures and diurnal profile of sensor differences.

For the diurnal profile of sensor temperatures, the data are grouped into ground-level sensors and roof-level sensors and plotted in groups with the reference temperature of the community. This would result in two sets of profiles for each community covering the entire data period (i.e., for community 1 this would result in 60 diurnal profiles on a side-by-side manner, with one set each for the roof-level and ground-level sensors).

For the second diurnal profile, the diurnal profile of temperature differences, the average temperature of the specific sensor for the day is subtracted from the individual data to create a temperature difference. This difference is then plotted for both sensor groups and the reference sensor for each community (i.e., again on the ground-level and roof-level data groups). While the first diurnal profile provides the trend of the sensor, the second provides the level of deviation from the normal pattern. This information, when combined with information about the sensor's location and its surroundings, forms a clear picture of how each sensor is expected to behave during the data period. Any behavior outside the expectations is then inspected to assess the suitability of the sensor data within the experimental design.

To determine the magnitude of the microclimate variation at each sensor location (roof and ground) within each community, each sensor group was compared to the reference temperature of the community. This reference temperature serves as the unbiased indicator of the community air temperature. Because of the sensor location, this reference sensor is expected to be devoid of any small-scale microclimate variation at each community.

The data were then further processed to create two representative spatial average temperatures from all the remaining sensor data. The roof-level average temperature was formed from 4 or 5 sensor temperatures in each community, while average temperatures for the ground-level sensor was formed from 7 to 10 sensors, depending on the community. This was consistent with the expected microclimate variation at these sensor locations. The period for the data ranged

from 28 days in community 3 (i.e., 1342 data points at 30-minute intervals) to 60 days for community 1 (i.e., 2976 data points). The selection of communities where the data were gathered ensured the representation of communities with low level canopies (10% in community 3 to 30% in community 5) to high-level canopies (90% in community 2). The roof-level and ground-level sensor average along with the canopy of each community is then combined to form the full data set for developing correlation.

8.5.2. Specification and estimation of mathematical model

A mathematical model based on the monitored data was developed using a Fourier series expression, with reference temperature (T_{ref}), time of the day (H) and canopy coverage (C_f) as the input. The time of the day variable was used as the frequency variable in this model and subsequently forms the necessary frequencies using the time of day as fraction multiplied by 2 π radians (i.e., 2 π × H / 24). A general Fourier series representation of a single variable linear model was extended by adding the combined variables of time of day frequency variables with T_{ref} and C_f .

This equation predicts the change in local air temperature as a result of the local canopy impact (i.e., increase in canopy coverage or canopy factor) with reference temperature, time of the day, and canopy coverage as independent variables. The canopy factor is determined by calculating the percent of tree-covered areas out of the entire community using the aerial photographs obtained in the web (Terra-server and MapQuest Internet servers) just before the start of data collection. A general Fourier series representation of a single variable linear model is as follows:

$$(1) \qquad E_h = \beta_0 + \sum_{j=1}^{j_{\max}} \left[\alpha_j \sin \frac{2\pi}{P_j} h + \beta_j \cos \frac{2\pi}{P_j} h \right] + \varepsilon_h, -\infty < h < +\infty$$

where E_h is the dependent variable at hour h, α_j and β_j are the coefficients of the jth sine and cosine frequencies and P_j is the period of jth frequency. In the extended model the T_{ref} and C_f were combined to the frequency variable (sine and cosine representation as shown above of the hour for j = - ∝ to ∝) to form additional independent variables that capture interactive effects of reference temperature with the time of day and canopy factor with the time of day.

$$(2) \qquad \begin{aligned} T_h = \quad & \beta_{10} + \sum_{j=1}^{j_{\max}} \left[\alpha_{1j} \sin \frac{2\pi}{P_j} h + \beta_{1j} \cos \frac{2\pi}{P_j} h \right] + T_{ref} \left(\beta_{20} + \sum_{j=1}^{j_{\max}} \left[\alpha_{2j} \sin \frac{2\pi}{P_j} h + \beta_{2j} \cos \frac{2\pi}{P_j} h \right] \right) \\ & + C_f \left(\beta_{30} + \beta_{300} \times C_f + \sum_{j=1}^{j_{\max}} \left[\alpha_{4j} \sin \frac{2\pi}{P_j} h + \beta_{4j} \cos \frac{2\pi}{P_j} h \right] \right) + + \varepsilon_h \ , \quad -\infty < h < +\infty \end{aligned}$$

The resulting correlation for the dependent variable (i.e., roof-level temperature and ground-level temperature) are then used to predict the local microclimate impact (i.e., local modified temperature using the reference temperature and canopy levels). The predicted ground-level temperature (T_{cpg}) can be calculated as follows:

$$
\begin{aligned}
T_{cpg} = \quad & 2.251 + \left[0.952 \sin\left(\frac{4\pi}{24} h\right) + 0.43 \cos\left(\frac{6\pi}{24} h\right) \right] \\
& + T_{ref} \begin{bmatrix} 0.921 - 0.0177 \sin\left(\frac{2\pi}{24} h\right) + 0.00364 \sin\left(\frac{6\pi}{24} h\right) \\ - 0.0194 \cos\left(\frac{4\pi}{24} h\right) + 0.00379 \cos\left(\frac{8\pi}{24} h\right) \\ - 0.00582 \sin\left(\frac{10\pi}{24} h\right) \end{bmatrix} . \\
& + C_f \begin{bmatrix} 4.094 - 2.928 C_f + 2.037 \sin\left(\frac{2\pi}{24} h\right) \\ - 1.847 \sin\left(\frac{4\pi}{24} h\right) + 3.442 \cos\left(\frac{2\pi}{24} h\right) \end{bmatrix}
\end{aligned}
\tag{3a}
$$

Similarly, the predicted roof-level temperature (T_{cpr}) is calculated as follows:

$$
\begin{aligned}
T_{cpr} = \quad & -1.019 + \left[-3.206 \cos\left(\frac{2\pi}{24} h\right) + 0.475 \cos\left(\frac{6\pi}{24} h\right) - 1.878 \cos\left(\frac{8\pi}{24} h\right) \right] \\
& + T_{ref} \begin{bmatrix} 0.9927 + 0.03053 \cos\left(\frac{2\pi}{24} h\right) + 0.03084 \cos\left(\frac{8\pi}{24} h\right) \\ - 0.0038 \cos\left(\frac{10\pi}{24} h\right) + 0.00246 \cos\left(\frac{14\pi}{24} h\right) \end{bmatrix} . \\
& + C_f \left[-0.5756 + 4.207 \cos\left(\frac{2\pi}{24} h\right) - 1.719 \cos\left(\frac{4\pi}{24} h\right) \right]
\end{aligned}
\tag{3b}
$$

The predicted temperatures can then be used to assess the derived impacts of the canopy coverage in the following procedure:

- Utilizing the regression equations, modified ambient air temperatures are calculated for every hour of the year.
- The hourly temperature data are then used to generate a modified weather data file usable under DOE-2 simulations for representing various planned communities.
- Using DOE-2 simulations, the baseline and alternate energy consumption for any community can be established by calculating the energy consumption under the existing conditions (original development plans and use of reference temperature data) and canopy modified conditions (alternate plans and canopy modified temperature data).
- The energy savings is the improvement of the alternate plan recommendations over the original plan impact. The difference between the baseline and the improved case would determine the savings.

8.6. Conclusions and Recommendations for Project 2.7

This project examined the application of general research findings on the effects of community design on energy efficiency to communities of housing for low-income households.

One issue examined was how self-help housing organizations, such as Habitat for Humanity, can apply energy efficiency community design principles to housing that they build. Many energy efficiency programs have long championed planting shade trees to reduce the cooling

load for a community. As part of the Local Energy Assistance Program, ADM Associates provided assistance in planning new residential subdivisions to cities throughout California. This planning included showing how narrower streets and walkways with tree canopies would reduce cooling energy use in a community. The same service was extended to California's low-income homebuilders, including Habitat for Humanity local affiliates in California. ADM provided HfH Shasta with a new design of a subdivision that includes planting some trees and setting aside a portion of land for a small park. Many low-income self-help homebuilders, however, often struggle with the availability of land, and often have to build on smaller parcels of land.

To learn about the impact of planting shade trees in mobile home communities (a segment of low-income housing that is growing rapidly in California), several mobile home parks with varying level of canopy coverage were monitored extensively. Multiple temperature measurement points (up to 15) were placed inside each park at both the roof- and ground-level. A weather station was also established at each location to provide the reference temperature.

Using these data, a mathematical model based on Fourier Series Approximation was developed to predict the ambient temperature with reference temperature (T_{ref}), time of the day (H) and canopy coverage (C_f) as the input. The resulting model demonstrates that on a moderately hot summer day, the presence of tree canopy could cause the ambient temperature to deviate 4–5°F from the reference temperature. On a very hot summer day, this deviation could be as high as 6–8°F. The amount of reduction in ambient temperature is also shown to depend on the level of canopy coverage and the time of day.

This model could be used to aid the development of future regulations related to tree planting. For example, Title-24 credits could be accorded to communities that meet or exceed a prescribed canopy coverage. The model could also be integrated into existing energy simulation software packages such as DOE-2 to assess the impact of tree canopies on the cooling loads of individual buildings within a community. A possible continuation of this project is development of a stand-alone tool or software based on this mathematical model to allow community planners in California to determine community-wide temperature impact of varying canopy coverage based on parameters such as community size, type and quantity of trees, and the climate zone.

9.0 References

Akbari, H. and Fisman, B. 1994. *Proceedings of the Workshop on Cool Building Materials, Action 9 Cool Communities, Clinton-Gore Climate Change Action Plan.* National Institute of Standards and Technology.

Akbari, H., Rosenfeld, A., Taha, H., Brentz S., Fishman, B., Kurn, D., and Sailor, D.,. 1995. Mitigation of Urban Heat Islands: Material, Utility Programs, Updates. *Energy and Buildings*, Vol. 22.

Akbari, H., Kurn, D., Taha, H., Bretz, S. and Hanford, J. 1997. Peak Power and Cooling Energy Savings of Shade Trees. *Energy and Buildings - Special Issue on Urban Heat Islands and Cool Communities*, 25(2), pp. 139-148. Excerpts from Lawrence Berkeley National Laboratory Report LBL-34411, Berkeley, CA.

ASHRAE. 1997. Chapter 1 - Residences, Chapter 9 – Indoor Environmental Health, and Chapters 22 and 23 – Thermal and Moisture Control in Insulated Assemblies. *Fundamentals Handbook.* American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA.

Bancroft, B. 1992. Efficiency and Solar Water Heating: Untapped Potential. *Home Energy*.

Bernstein, M., Lempert, R., and Ortiz, D. 2000. *The Public Benefits of California's Investment in Energy Efficiency,* Rand Corporation Report MR-1212.

Bryne, J. 1999. Finding the Whole-House Fan that Fits. *Home Energy Journal*. May-June.

Chaurasia, P. B. L. 2000. Solar Water Heater Based on Concrete Collectors. *Energy*, Vol. 25.

Cohen, R. M. 1985. Description of the Design, Construction, and Operation of Four Residential Solar Space Heating Systems. *ASHRAE Transactions,* Vol. 91, Pt 2B.

Cummings, J. B., Tooley, J. Jr., and Moyer N. 1991. *Investigation of Air Distribution System Leakage and Its Impacts in Central Florida Homes*. Prepared for the Governor's Energy Office. FSEC-CR-397-91.

Dale, J. D. and Akerman M. Y. 1993. Evaluation of the Performance of Attic Turbine Ventilator. *ASHRAE Transactions,* Vol. 99, Pt.1, pp 14-22.

Felver, T. G., Scofield, M. and Dunnavant, K. 2001. Cooling California's Computer Centers. *Heating/Piping/Air Conditioning Engineering Journal,* March, Vol. 73.

Hedrick, R. et al. 2002. *Alternative Design Details for Building Houses with Ducts in Conditioned Space.* Report prepared for PIER Program on Integrated Energy Systems Productivity and Building Science.

Huang, J., Akbari, H. and Taha, H. 1990. The Wind-Shielding and Shading Effects of Trees on Residential Heating and Cooling Requirements. *Proceedings of American Society of Heating, Refrigerating,, and Air Conditioning Engineers*. February 1990. Atlanta, GA. Also Lawrence Berkeley National Laboratory Report LBL-24131. Berkeley, CA.

Huang J., Davis, S., and Akbari, H. 1991. A Synopsis of Cooling our Communities: The Guidebook on Tree Planting and Light-Colored Surfaces. Chapter 20. *Energy Efficiency and the*

Environment. E. Vine, D. Crawley, P. Centolella (Eds.). American Council for and Energy Efficient Economy. Washington, D.C.

Huang, Y. J., Wu, H. F., and Hanford J. W. 1991. The Energy and Comfort Performance of Evaporative Coolers for Residential Buildings in California Climates, *ASHAE Transactions,* Vol. 97.

Kelly, K. M. 1982. Indoor Moisture: Effects on Structure, Comfort, Energy Consumption and Health. *Proceedings of the ASHRAE/DOE Conference on Thermal Performance of the Exterior Envelopes of Buildings II*. Las Vegas, NV.

Lennel, U. R. and Mudd, P. R. 1984. A Review of Materials for Solar Heating Systems for Domestic Hot Water. *Solar Energy*, Vol. 32, No. 1.

Levins, W., Karnitz M., and Knight D. 1986. Cooling Energy Measurements of Houses with Attics Containing Radiant Barriers. *Proceedings of the Third Symposium on Improving Building Systems in Hot and Humid Climates*. Texas A&M University, Arlington, Texas, pp. 78-87.

Lstiburek, J. 1997. Conditioned Attics Save Energy in Hot Climates. *Home Energy*, p. 6 (May – June).

McIlvaine, J. E. R., Beal, D., and Fairey, P. W. III. 2001. F*ield Study of Interior Duct System: Design, Construction, and Performance-Final Report*. Report No. FSEC-CR-1256-01. Florida Solar Energy Center.

McIlvaine, J. E. R., Beal, D., and Fairey, P. W. III. 2002. *Design and Construction of Interior Duct System*. Report No. FSEC-PF-365-01. Florida Solar Energy Center. Revised version July 2002.

Medina, M. 1992a. *Development of a Transient Heat and Mass Transfer Model of Residential Attics to Predict Energy Savings Produced by the Use of Radiant Barriers.* Ph.D. Dissertation, Texas A&M University.

Medina, M., O'Neal D. L, and Turner, W. D. 1992b. Effect of Attic Ventilation on the Performance of Radiant Barriers. *Journal of Solar Energy Engineering,* Vol. 114, pp. 234-239.

Medina, M. 2000. Radiant Barriers: Performance Revealed. *Home Energy,* p. 31-33 (September – October).

Philips, T. J., Mulberg, E. J., and Jenkins, P. L. 1990. Activity Patterns of California Adults and Adolescents: Appliance Use, Ventilation Practices, and Building Occupancy. *Proceedings of the ACEEE 1990 Summer Study on Energy Efficiency in Buildings: Environment,* Vol. 4, p. 4.187. American Council for an Energy Efficient Economy, Washington, D.C.

Regional Economic Research, Inc. 2002. *Residential New Construction Study: Project Year #2.* Report prepared for Pacific Gas and Electric Company.

Sailor, D., Akbari, H., and Rainer. L. 1992. Measured Impact of Neighborhood Tree Cover on Microclimate. *Proceedings of the ACEEE 1992 Summer Study on Energy Efficiency in Buildings.* August 1992. Pacific Grove, CA. p. 149.

Skerrett, P. J. 1993. The Hot Stuff, *Popular Science*, Vol. 243, Issue 3, p. 5.

U.S. Department of Energy. 1995. *Landscaping for Energy Efficiency* (DOE/GO-10095-046).

U.S. Department of Energy and Oak Ridge National Laboratory. *Radiant Barrier Fact Sheet*. http://www.ornl.gov/sci/roofs+walls/radiant/rb_01.html

Watt, J. R. 1987. Nationwide Evaporation Cooling is Here. *ASHRAE Transactions,* Vol. 93.

Wu, H. 1989. Performance Monitoring of a Two-Stage Evaporative Cooler. *ASHRAE Transactions,* Vol. 95.

10.0 Glossary

ACH	air changes per hour
ADM	ADM Associates, Inc.
Btu	British thermal unit
CAS	Combustion Appliance Safety
CFM	cubic feet per minute
CO	carbon monoxide
CO_2	carbon dioxide
COP	coefficient of performance
dB	decibel
Energy Commission	California Energy Commission
FSEC	Florida Solar Energy Center
ft	foot
HfH	Habitat for Humanity
HUD	Department of Housing and Urban Development
HVAC	heating, ventilation, and air conditioning
IAQ	interior air quality
in	inch
kHz	kilohertz
kWh	kilowatt-hour
lb	pound
OSHA	Occupational Safety and Health Administration
Pa	Pascals
PEL	personnel exposure level
PIER	Public Interest Energy Research
ppm	parts per million
RD&D	research, development, and deployment
SEER	seasonal energy efficiency ratio