CALIFORNIA
ENERGY
COMMISSION

ENERGY INNOVATIONS SMALL GRANT PROGRAM
Residential and Commercial Buildings
End Use Efficiency

Ventilation Cooling Controller Strategies

FEASIBILITY ANALYSIS

March 2004
500-04-011

Arnold Schwarzenegger
Governor

CALIFORNIA ENERGY COMMISSION

Prepared By:
Hal Clark
Grant Program Administrator
San Diego State University Foundation

Prepared For:
California Energy Commission
Energy Innovations Small Grant Program

Researcher:
Murray Milne
Department of Architecture and urban Design, UCLA

Grant Number:
99-28

Alllec Jenkins
Grant Program Manager

Marwan Masri
Deputy Director
Technology Systems Division

Robert Therkelsen
Executive Director

LEGAL NOTICE

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

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 (Commission), annually awards up to $62 million of which $2 million/year is allocated to the Energy Innovation Small Grant (EISG) Program for grants. The EISG Program is administered by the San Diego State University Foundation under contract to the California State University, which is under contract to the Commission.

The EISG Program conducts four solicitations a year and awards grants up to $75,000 for promising proof-of-concept energy research.

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

- Residential and Commercial Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research

The EISG Program Administrator is required by contract to generate and deliver to the Commission a Feasibility Analysis Report (FAR) on all completed grant projects. The purpose of the FAR is to provide a concise summary and independent assessment of the grant project using the Stages and Gates methodology in order to provide the Commission and the general public with information that would assist in making follow-on funding decisions (as presented in the Independent Assessment section).

The FAR is organized into the following sections:

- Executive Summary
- Stages and Gates Methodology
- Independent Assessment
- Appendices
    - Appendix A: Final Report (under separate cover)
    - Appendix B: Awardee Rebuttal to Independent Assessment (Awardee option)

For more information on the EISG Program or to download a copy of the FAR, please visit the EISG program page on the Commission's Web site at:
http://www.energy.ca.gov/research/innovations

or contact the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the Commission's Web site at http://www.energy.ca.gov/research/index.html.

Executive Summary

Introduction

A large percentage of California's population resides in areas where residential cooling is needed in the daytime, but the nighttime outdoor temperatures drop considerably. For these homeowners the greatest potential source of free cooling energy is outdoor night air. An automated system would capture the cool nighttime air and use it in the hot afternoon. One way to achieve this result is to cool the thermal mass of the residence using a whole-house fan and cool nighttime air. At this time there is no widely available controller or thermostat that measures outdoor air temperature and incorporates it into an intelligent strategy to optimally control a whole-house fan.

During periods when daytime temperatures are uncomfortably hot in most inland California climate zones, nighttime temperatures fall into the comfort range. A properly controlled fan can bring in the optimum amount of nighttime air to cool the building's interior thermal mass sufficiently so the building can 'coast' comfortably through the next day's heat. In 13 of the 16 California climate zones the need for air conditioning can be greatly reduced, or even completely eliminated, if the house is properly designed and if an electronically controlled fan utilizes the nighttime air as a free cooling resource.

Managed ventilation cooling is a preexisting, known concept. This project was undertaken because there exists no such control unit that is a combined thermostat controller incorporating both indoor and outdoor temperature measurements and an optimal strategy to control a whole house fan in addition to the furnace and air conditioner. This project designed and programmed the controller logic into a laptop computer used to control the whole house fan in the test facility. The benefits achievable through using such a controller were carefully documented for the researcher's test site. This control logic was then programmed into a California climate model. The benefits gained from the controller were then extrapolated across all California climate zones, providing an estimate of the savings in compressive air-conditioning energy achievable by the controlled use of ventilation cooling.

Objectives

The goal of this project was to determine the feasibility of an intelligent ventilation controller to minimize cooling energy expenditures for California homeowners by properly controlling a whole-house fan to bring in the optimum amount of nighttime air to cool the building's interior thermal mass sufficiently so the building can 'coast' comfortably through the next day's heat. The researcher established the following project objectives:

1. Design a controller that measures the following variables: indoor and outdoor temperatures, occupant's upper and lower limits of comfort temperature, time of day, and season of year.
2. Construct a prototype controller incorporating the logic developed in Objective #1.
3. Design and build instrumented test cells that permit precise evaluation of the controller performance. Test the cells to ensure equivalent thermal performance when operated under identical conditions.
4. Test the prototype controller design in one instrumented test cell. Use the other test cell as a control cell against which to measure performance improvement. This test should prove the feasibility of the intelligent ventilation controller.

5. Program a new performance model into the existing building performance simulation model to include the new controller. Validate the new performance model using data recorded from the instrumented test cells.
6. Assess the applicability of the new controller by simulating its performance in various residential buildings in California's 16 climate zones.

Outcomes

1. The researcher developed the logic code for the controller. Simulation studies indicated the code successfully tracked the day and nighttime temperatures.
2. The researcher programmed the logic code into a laptop computer. The computer was programmed to record and store test data.
3. The project built and instrumented two identical test cells simulating the characteristics of typical California slab-on-grade houses. One cell was the experimental cell, the other the control cell. The test cells had a 4 by 8 foot area, were 8 feet high, and were properly insulated, and had a south-facing window. The two cells were set side by side and identically oriented to the sun. Cement brick laid on the floors of the cells simulated the slab. The cells were evaluated using California Energy Code, Title 24 and found to properly characterize slab on grade buildings. A calibrations sequence proved the two cells had similar thermal behavior.
4. The results of a series of experiments run in a pair of full-height test cells validated the original feasibility premise. The results led to the following insights:
    a. Ventilation controlled with an intelligent ventilation controller can improve the thermal comfort inside homes with medium thermal mass (slab on grade floors) typical of single-family dwellings in many California climates. Both the maximum indoor temperatures and the number of overheated hours were shown always to be less than in a building without this intelligent ventilation controller.
    b. Increasing the air change rate increases the performance of the system. The experimental data shows when the air change rate is increased from 3.9 to 15 air changes per hour the maximum temperature was reduced by at least 2.7^{o} F compared to the control cell.
    c. Dropping the lower limit of the comfort zone from 70° F to 65° F (at night) significantly reduces the number of hot daytime hours and the maximum temperature inside the cell. This is probably the single most important factor that should be considered in any system that uses natural ventilation for cooling.
5. The researcher evaluated operation of the new type of thermostat/fan controller in other climate zones using an expanded version of the UCLA building performance simulation model. The researcher expanded the program to include a model of the intelligent ventilation controller within the thermostat, and calibrated the model using experimental data.
6. Using the modified computer program simulation, the researcher calculated the annual energy costs for a 2000 square-foot California code-compliant slab-on-grade house in each climate zone. The house model included a whole-house ventilation fan, as well as a furnace and an air conditioner, so that comfort levels were not compromised. The computed outputs tabulated in Appendix A show a typical savings of about $450 a year, with minor shifting of

electrical energy costs to gas heating costs. There were no significant savings in only 3 of the 16 zones.

Conclusions

1. The logic code for the intelligent ventilation controller was successfully developed.
2. The researcher transferred the code to a laptop computer.
3. The researcher built two test cells that served as proxies for a California house. One cell was equipped with the equipment to be tested and the other was used as an experiment control cell. The test cells were calibrated and proved to perform identically.
4. When one test cell was outfitted with the intelligent ventilation controller, it always had lower maximum temperatures than the control test cell and fewer hours of overheated conditions.
5. Using the logic code and the data developed in the experimental tests, the researcher was able to successfully model an intelligent ventilation controller, as it would be integrated into an existing furnace and air conditioner controller to assure comfort is maintained.
6. Using the model, the researcher found the intelligent ventilation controller could reduce the cost of household energy in 13 of California's 16 climate zones.

Use of an intelligent ventilation controller measuring both outdoor and indoor air temperatures to control a whole-house fan can save energy and reduce indoor temperatures without assistance of a mechanical cooling system in climates with cool night temperatures. Experimental results showed in all cases this system produced cooler indoor comfort conditions than an identical building without such a controller. Therefore energy costs for cooling can be reduced. Energy savings could quickly repay the cost of the new controller once the controller can be mass-produced.

Benefits to California

There is no thermostat controller on the market today that uses both indoor temperature and outdoor temperature to control ventilation with a whole-house fan in addition to temperature with an air conditioner and furnace. The potential size of the market for this device appears to be quite large. This new product may have the greatest appeal to homeowners in those California climate zones where this strategy can completely eliminate the need to install an air conditioner. Once field experience grows, the intelligent controller could prove to be cost effective in hundreds of thousands of California homes.

Air conditioning represents the second largest category of electricity consumption in California homes, consuming an estimated 0.3 Quads per year. If this new product leads to the elimination or disuse of just one air conditioner per thousand homes it could save over 87,000 MWh per year statewide. This product should have a significant impact on grid demand during daytime hours when California's electric utilities experience their peak loads. Thus it will help 'shave the peaks'. Because this system consumes electricity at night when utilities have their lowest demand, it helps to 'spread the load', increasing system utilization efficiency. Consequently this new product targeting the large residential market will benefit both ratepayers and utilities alike.

Recommendations

The researcher proved the feasibility of the intelligent ventilation controller. Many steps remain before this proven concept can result in ratepayer benefits. The PA recommends the researcher

engage one or more companies selling house heating and cooling controls. A company in that business can assess the costs to reduce the innovation to practice and the potential market size. In addition, such a company may assume significant development costs to implement the product into a small wall-mounted box that will sell for a competitive price. Additional public monies may be required to perform a statewide test of a prototype product once it is available. Collecting and analyzing data from all sixteen (16) climate zones may form the basis for successful market introduction.

Stages and Gates Methodology

The California Energy Commission utilizes a stages and gates methodology for assessing a project's level of development and for making project management decisions. For research and development projects to be successful they need to address several key activities in a coordinated fashion as they progress through the various stages of development. The activities of the stages and gates process are typically tailored to fit a specific industry and in the case of PIER the activities were tailored to be appropriate for a publicly funded energy research and development program. In total there are seven types of activities that are tracked across eight stages of development as represented in the matrix below.

Development Stage/Activity Matrix

	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8
Activity 1								
Activity 2								
Activity 3								
Activity 4								
Activity 5								
Activity 6								
Activity 7								

A description the PIER Stages and Gates approach may be found under "Active Award Document Resources" at: http://www.energy.ca.gov/research/innovations and are summarized here.

As the matrix implies, as a project progresses through the stages of development, the work activities associated with each stage needs to be advanced in a coordinated fashion. The EISG program primarily targets projects that seek to complete Stage 3 activities with the highest priority given to establishing technical feasibility. Shaded cells in the matrix above require no activity, assuming prior stage activity has been completed. The development stages and development activities are identified below.

Development Stages:	Development Activities:
Stage 1: Idea Generation & Work Statement Development	Activity 1: Marketing / Connection to Market
Stage 2: Technical and Market Analysis	Activity 2: Engineering / Technical
Stage 3: Research & Bench Scale Testing	Activity 3: Legal / Contractual
Stage 4: Technology Development and Field Experiments	Activity 4: Environmental, Safety, and Other Risk Assessments / Quality Plans
Stage 5: Product Development and Field Testing	Activity 5: Strategic Planning / PIER Fit - Critical Path Analysis
Stage 6: Demonstration and Full-Scale Testing	Activity 6: Production Readiness / Commercialization
Stage 7: Market Transformation	Activity 7: Public Benefits / Cost
Stage 8: Commercialization	

Independent Assessment

For the research under evaluation, the Program Administrator assessed the level of development for each activity tracked by the Stages and Gates methodology. This assessment is summarized in the Development Assessment Matrix below. Shaded bars are used to represent the assessed level of development for each activity as related to the development stages. Our assessment is based entirely on the information provided in the course of this project, and the final report. Hence it is only accurate to the extent that all current and past work related to the development activities are reported.

Development Assessment Matrix

Stages / Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

The Program Administrator's assessment was based on the following supporting details:

Marketing/Connection to the Market

The researcher has not discussed any connection with any company that could take this technology into the marketplace. There is no evidence of any marketing effort to determine consumers' needs or expectations of such a product. The PA believes the developed technology has a strong connection to the market. When fully developed the intelligent fan controller could automate and optimize a process that clever, diligent homeowners have performed manually for a number of years.

Engineering/Technical

This project proved the feasibility of using an intelligent fan controller to utilize cool outside air to cool a house at night, thus reducing daytime air-conditioning demand. The researcher proved the concept using small research cells. Additional testing is needed in real houses in candidate climate zones once a prototype controller has been developed.

Legal/Contractual

The researcher plans to publish all technical information in the public domain. He does not intend to seek patent coverage. There is no evidence that the researcher has a contractual relationship with any other party with respect to the developed technology.

Environmental, Safety, Risk Assessments/ Quality Plans

Quality Plans include Reliability Analysis, Failure Mode Analysis, Manufacturability, Cost and Maintainability Analyses, Hazard Analysis, Coordinated Test Plan, and Product Safety and Environmental**.** Any company taking this concept to market as a product will have to complete the plans noted above. There is no evidence that any of these plans has been completed.

Strategic

This product has no known critical dependencies on other projects under development by PIER or elsewhere

Production Readiness/Commercialization

The researcher has not indicated any connection with a company that could take the intelligent fan controller to market. Since the concept can be easily grasped, any of the current thermostat manufacturers could fit the proven concept into their product line. If a company were to adopt this technology, it could be available to ratepayers in a very short period of time, probably less than two years. A commercializing company will have to devote some effort to incorporate the control logic and sensor data into a current or expanded thermostat product.

Public Benefits

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system
- Increased reliability of the California electricity system
- Increased affordability of electricity in California

The primary benefit to the ratepayer from the application of this research is the increased affordability of electricity resulting from reduced consumption by vapor-compressor air conditioners. The proven concept should significantly reduce the amount of electricity that households use to cool their dwellings. More extensive testing on real houses will be required before an accurate estimate of the total impact can be made.

Program Administrator Assessment

After taking into consideration (a) research findings in the grant project, (b) overall development status as determined by stages and gates, and (c) relevance of the technology to California and the PIER program, the Program Administrator has determined that the proposed technology should be considered for follow on funding within the PIER program.
Receiving follow on funding ultimately depends upon (a) availability of funds, (b) submission of a proposal in response to an invitation or solicitation, and (c) successful evaluation of the proposal.

Appendix A: Final Report (under separate cover)

Appendix B: Awardee Rebuttal to Independent Assessment (none submitted)

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

EISG FINAL REPORT

VENTILATION COOLING CONTROLLER STRATEGIES

EISG AWARDEE
Murray Milne, Research Professor
Department of Architecture and Urban Design
UCLA
405 Hilgard Avenue
Los Angeles, CA 90095
Phone: (310) 454-7329
Email: milne@ucla.edu

AUTHORS
Murray Milne, Principal Investigator
Pablo La Roche, Staff Research Associate

Grant #: 51394A / 99-28
Grant Funding: $74,895
Term: March 2000 – January 2002
PIER Subject Area: Residential and Commercial Buildings
End Use Efficiency

Legal Notice

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

Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

TABLE OF CONTENTS

Abstract…… 1

Executive Summary…….. 2

1. Introduction……. 4

1.1 The Opportunity …… 4
1.2 The Alternatives …… 4
1.3 The Research Question ……. 5

2. Project Objectives……... 6

2.1 Survey the Literature for Comparable Work……. 6
2.2 Develop the Controller's Logic and Define the Variables…….. 8

2.3. Test the Prototype Design Controler Logic in a test cell…… 8

3. Project Approach…….. 9

3.1 Thermostat Prototype and Thermistors…… 9
3.2 Test Cells……. 10
3.3 Ventilation System……. 12
3.4 Controller Logic…….. 14

4. Project Outcomes…….. 16

4.1 Experimental Series…… 16
4.2 Experimental Results……. 30
4.3. Simulation Series…….. 37

5. Conclusions…… 39

6. Recommendations…….. 42

7. Public Benefit to California …….. 43

7.1 Making this New Product Available……... 43
7.2 Market Impact……. 43
7.3 Additional Spin-off Products…….. 44
7.4 Dissemination: Product Delivery Mechanism…… 44

8. Development Stage Assessment…… 45

8.1 Work Completed Before this Project Began……. 45
8.2 Work Completed under this EISG Funded Project…… 46
8.3 Development Assessment Matrix…….. 47

9. References…….. 48

Appendices……. 50

LIST OF FIGURES

Figure 3.1. The Experimental System
Figure 3.2. Data Logger-Controller and Computer
Figure 3.3. Plan view of the test cell
Figure 3.4. Photograph of the test cells
Figure 3.5. Photograph of exhaust systems in the test cells
Figure 3.6. Control System Logic
Figure 4.1. Measured average daily temperatures in the experimental and control cell and predicted values for the experimental cell
Figure 4.2. Measured and predicted hourly values subtracting the adjustment factor (0.58 C) from the experimental cell.
Fig 4.3. Temperatures and Air Change rate in series 1.
Fig 4.4. Hot, Comfortable and Cold Hours in series 1.
Figure 4.5: Stratification in the Experimental Cell in Series 1
Fig 4.6. Temperatures and Air Change rate in series 2
Fig 4.7. Hot, Comfortable and Cold Hours in series 2.
Fig 4.8: Temperatures and air change rate in series 3
Fig 4.9. Hot, Comfortable and Cold Hours in series 3.
Fig 4.10. Series 4. Temperatures and air change rate in series 4.
Figure 4.11. Hot, Comfortable and Cold Hours in series 4.
Fig. 4.12. Air temperature and air change rate in series 5.
Fig 4.13: Placement of the fan
Fig 4.14: No stratification in Series 5 with the fan on
Fig 4.15. Hot, Comfortable and Cold Hours in series 5
Fig 4.16. Air temperature and air change rate in series 6.
Fig 4.17. Hot, comfortable and cold hours in series 6
Fig 4.18. Hot, comfortable and cold hours in series 7
Fig 4.19. Air temperatures and air change rate in series 7.
Fig 4.20. Hot, Comfortable and Cold Hours in series 7.
Fig 4.21. Temperatures and air change rates in series 8.
Fig. 4.22:Percentage of Overheated hours in the experimental and control cells and outdoors.
Fig. 4.23: Percentage reduction of the overheated hours in the experimental cell compared to the control cell.
Fig. 4.23: Average Maximum temperatures and swing during the different series

LIST OF TABLES

Table 4.1. Series that are performed in 2001 and presented in this report.
Table 4.2. Percentage of Hot, Comfortable and Cold Hours in series 1.
Table 4.3. Percentage of Hot, Comfortable and Cold Hours in series 2.
Table 4.4. Percentage of Hot, Comfortable and Cold Hours in series 3.
Table 4.5. Percentage of Hot, Comfortable and Cold Hours in series 4.
Table 4.6. Percentage of Hot, Comfortable and Cold Hours in series 5.
Table 4.7: Percentage of Hot Comfortable or Cold Hours in Series 6
Table 4.8. Percentage of Hot, Comfortable and Cold Hours in series 7.
Table 4.9. Percentage of Hot, Comfortable and Cold Hours in series 8.
Table 4.10: Percentage of hot hours in the series
Table 4.11: Maximum Average Temperatures in the Different Series after eliminating days with maximum temperatures below 25 C.
Table 4.12: Performance of the Cells in the Different Series adjusted for days with maximum temperatures above 25 C.

ABSTRACT:

This project demonstrated the feasibility of a new kind of intelligent ventilation controller that can minimize cooling energy costs for California homeowners.

The greatest potential source of FREE cooling energy in most California climates is outdoor air. Typically in much of California, summer daytime temperatures are too hot but night temperatures are quite comfortable. This controller knows how much night-time air should be brought in to cool down the building's interior mass so that it can 'coast' comfortably through the next day. The need for air conditioning can often be greatly reduced or even eliminated, particularly if the home is carefully designed to prevent excess solar gains or infiltration. Experiments showed this controller always reduced the peak indoor temperatures and the number of overheated hours.

This controller is similar to a conventional programmable thermostat, but with the addition of an outdoor temperature sensor and a larger microprocessor to hold the expanded control logic. The house needs to have a whole-house exhaust fan and a strategy for operating windows or air inlets, and as much internal mass as possible but at least a slab floor.

No such controller is on the market today. The barriers to commercialization include the added task of installing the outdoor air sensor and the whole-house fan control, plus some additional complexity of the user interface. The payoffs are the reduction or even elimination of the air conditioning costs, and the potential increase in comfort ventilation cooling and indoor air quality.

EXECUTIVE SUMMARY

Introduction: The goal of this project is to demonstrate the feasibility of an intelligent ventilation controller that can minimize cooling energy expenditures for California homeowners. The greatest potential source of free cooling energy in most California climates is outdoor air, especially at night. There is no thermostat on the market today that measures outdoor air temperature and incorporates it into an intelligent strategy to optimally control a whole-house fan.

Fortunately, even during the periods when daytime temperatures are too hot, in most inland California climate zones the night-time temperatures fall into the comfort range. The controller's task is to bring in the optimum amount of night-time air in order to cool down the building's interior mass so that it can 'coast' comfortably through the next day's heat. In many California climates, the need for air conditioning can be greatly reduced or even completely eliminated if the home is carefully designed and if a smart controller can 'harvest' this free resource.

Project Objectives: The first task was to design the logical structure of the controller. The variables it needs to measure are indoor and outdoor temperature, plus it needs to be told the occupant's upper and lower limits of comfort temperature, and time of day. The controller also needs to know whether it is the heating or cooling season, however our simulation studies imply that this can be calculated on the basis of average temperatures during the prior few days. Next a prototype microprocessor thermostat was constructed. A laptop computer was used to control the execution of each experiment, and to store the results.

Project Outcomes: The results of a series of experiments run in ha pair of full-height test cells validated the original premise, and also lead some new insights:

1. Ventilation controlled with an intelligent microprocessor/thermostat that measure outdoor air temperature can improve the thermal comfort inside homes with medium thermal mass (slab on grade floors) typical of single family dwellings in many California climates. Both the maximum indoor temperatures and the number of overheated hours were shown to always be less than in a building without this intelligent ventilation controller.
2. Increasing the air change rate increases the performance of the system. The experimental data shows that when the air change rate is increased from 3.9 to 15 air changes per hour the maximum temperature was reduced by at least 2.7 F compared to the control building.
3. Increasing air recalculating inside the space reduces stratification and increases the convective gains and losses from the thermal mass, as well as through the walls and roof surfaces of the building. This can be achieved with a ceiling paddle fan or small portable floor fan. Note that when there is a limited amount of mass available inside the home, increasing indoor air recirculation will reduce the heat sink capacity, or discharge the 'coolth' from mass too rapidly, rather than spreading it effect throughout the day. The experimental results show that best results are achieved if the recirculating fan is operated only when the ventilation (night flushing) fan is turned on. Note that whenever the indoor recirculating fan is operating, the occupant's sense of being comfortable (comfort cooling) will also increase even though air temperatures are not reduced.
4. Dropping the lower limit of the comfort zone from 70 F to 65 F, significantly reduces the number of hot hours and the maximum temperature inside the cell. This is probably the

single most important factor that should be considered in any system that uses natural ventilation for cooling. Even with a medium mass slab on grade building, a lower temperature at night makes a big difference in the capacity of the building to flush out the heat built up inside the building (to store 'coolth'). This 65 F outdoor air temperature is reached at night during the summer in many parts of inland California because of the typically large day-to-night temperature differences, especially in the deserts.

5. Careful building design is a precondition to the application of any ventilation cooling strategy. The home should minimize the heat gains by radiation through windows, and the heat gains and losses by conduction through the building envelope, so that the ventilation rate, regulated by the intelligent controller, is the main mechanism of heat transport. Shading the windows, insulating the building envelope and minimizing infiltration can do this.

Recommendations: The use of an intelligent thermostat that measures both outdoor and indoor air temperatures, will save energy and reduce indoor temperatures without assistance of a mechanical cooling system in climates with cool night temperatures. Experimental results showed that in all cases this type of system always produced cooler indoor comfort conditions than an identical building without such a controller. From a building design point of view, more comfortable indoor conditions will occur if solar gains into the building are be reduced by shading the windows, using insulation in the building envelope, and providing an amount of mass at least equivalent to a concrete slab on grade.

Public Benefit to California: There is no thermostat on the market today that reads both indoor and outdoor temperature and that uses a microprocessor to control a whole-house fan in addition to an air conditioner and furnace. This means that the potential size of the market is conjectural. It seems clear that this new product will have the greatest appeal to homeowners in those California climate zones where this strategy can completely eliminate the need to install an air conditioner. Once field experience grows, the potential market is huge. It should prove to be cost effective in hundreds of thousands of California homes.

Air conditioning represents the second largest category of electricity consumption in California homes. If residential air conditioning in California uses roughly .3QBtu (Quads), and if this new product leads to the elimination of just one air conditioner in a thousand, then it could save over 100,000 Mwhr per year. It is also worth noting that this product will have a significant impact during the of the day hours when California's Electric Utilities are experiencing their maximum peak loads, in min-afternoon on the hottest days of the year, thus it will help 'shave the peaks'. Because it also runs at night to 'night flush' the home, when the utilities have their lowest load factor, it will help to 'spread the load', increasing system utilization efficiency. Thus this new product, targeted for this potentially huge residential market, will benefit both ratepayers and utilities alike.

1. INTRODUCTION

The objective of this project is to test the feasibility of an intelligent ventilation controller that can minimize cooling energy expenditures for California homeowners. The greatest potential source of free cooling energy in most California climates is outdoor air. There is no thermostat on the market today that measures outdoor air temperature and incorporates it into an intelligent building control strategy.

When cool outdoor air is available during the daytime to flush overheated buildings the problem is trivial. More difficult is the situation where daytime temperatures are too hot. Fortunately, even during the hottest periods in most California climate zones the night-time temperatures are quite comfortable. The controller's task is to know how much night-time air should be brought in to cool down the building's interior mass so that it can 'coast' comfortably through the next day and not need heating the following night. The controller must also know if natural ventilation is available, or if it is using more fan energy then it is recovering in cooling. Our studies have shown that the need for air conditioning can often be completely eliminated if the home can be carefully designed and if a smart controller can be developed to 'harvest' this free resource.

1.1 THE OPPORTUNITY:

In California's climates, the greatest single source of free cooling energy for homeowners is outdoor air. Unfortunately, most homes are not designed to effectively 'harvest' this resource.

Proof of this is the common situation where a home's air conditioner is running when outdoor air temperature is quite pleasant. Or in spite of cool temperatures the night before, the house is now overheating. The problem clearly has something to do with the way that particular home is designed and operated.

The basic physics involved are all well known and well understood. Unfortunately, there are no controllers on the market that know how to utilize all these cooling resources in order to minimize residential cooling costs.

1.2 THE ALTERNATIVES:

On one level ventilation cooling seems to be a trivial problem; "If you are hot and it is cool outside, open the window!" But the reality is more complex. In fact there are at least three quite different ways ventilation cooling can increase comfort and reduce energy cost for California's consumers, and each has different control strategies and different building design implications:

<u>Night Flushing:</u> In California climates with hot days but cool comfortable nights, this strategy involves moving large volumes of cool night air through the house to remove the heat from the day before and storing this 'coolth' in the building's interior mass to allow it to 'coast' through the next day. This can be done either by manually opening and closing windows at the correct time or with a whole-house fan if a smart enough controller is developed. In this case the building's economizer ventilation capacity must be sized to match the thermal mass. The classic California adobe buildings had earthen floor and sixteen inch thick adobe walls. Modern

buildings may have much less mass, usually a slab floor with gypsum board walls and ceilings. Adding clay time floors, a brick fireplace, and even concrete block walls would help to increase internal thermal mass. Given enough mass, this ventilation strategy has the potential to completely eliminate the need for air conditioners in California climates that have large diurnal (day to night) temperature swings.

Economizer Cooling: When a home's interior is too hot but outdoor temperatures are comfortable, ventilating with 100% outdoor air can restore comfortable conditions without the need for air conditioning. This can be accomplished by natural ventilation if wind resources are adequate, or can be fan-forced if an appropriate controller is available. Even in homes with large internal loads from appliances or large solar radiation gains this cooling strategy is often adequate to eliminate the need for an air conditioner in many California climates. If this is the only form of ventilation cooling, then lower mass buildings have an advantage.

Comfort Cooling: In hot-humid climates where daytime and nighttime temperatures are almost the same (which rarely occur in California), it is possible to increase occupant comfort by simply increasing the rate of air flow. This increases the effectiveness of the sweat evaporation from the skin, thus cooling by evaporation. Increased air motion also produces a measurable increase in the psychological sense of cooling. It is important to note that in this case the dry bulb temperature does not fall, but instead the increased air motion increases the effective comfort range. Sometimes it may be more effective to simply increase indoor air circulation, perhaps with a ceiling paddle fan, depending on the temperature and humidity of indoor versus outdoor air. This strategy does not depend on an air conditioner to achieve cooling by reducing dry bulb temperature, but instead depends simply on natural or fan-forced ventilation managed by an intelligent controller.

This project does not address the particular problems of large commercial buildings which typically have complex computer controlled HVAC systems that can be programmed to use an economizer cycle for free outdoor cooling. But still we all have experienced commercial buildings that run air conditioning all year around. Thus, even for professional building managers, harvesting this free resource is a bit more complex then it seems at first glance.

1.3 THE RESEARCH QUESTION:

The research question we believe we now have answered is: Can an controller be developed that effectively manages residential ventilation cooling, including night flushing and economizer cooling, and as a "proof of concept" can that controller’s performance be validated in a large scale instrumented test cell.

2. PROJECT OBJECTIVES

The approach as originally proposed changed slightly during the course of the project to place greater emphasis on the development of the prototype thermostat and on the experimental validation of its performance, and less emphasis on the computer simulation and modeling aspects.

2.1 SURVEY THE LITERATURE FOR COMPARABLE WORK

2.1.1. Relevant Literature: How this Work will Extent the Existing Knowledge Base

There are four recent research and development projects discussing the need for a “smart” residential-scale thermostat. However, this project is the only one that has actually built a microprocessor based programmable thermostat, and used it to test various control strategies in a matched pair of experimental test cells.

The literature shows a project at UC Berkeley (G. Brager Principal Investigator, 1988-1991) addressed the comfort of hotel occupants and laid out the control logic for a proposed intelligent thermostat that was to be called a "comfortstat". They also proposed to use an infrared occupancy sensor, door switch, radiant temperature sensor and special control logic to optimize room comfort conditions.

In the currently on-going Alternatives to Compressor Cooling (ACC) project, the Davis Energy Group proposes to interest developers in building test houses in two different California climates in order to demonstrate the savings possible with nocturnal cooling (www.davisenergy.com/acc). One is to be in a milder climate that should completely eliminate the need for compressor cooling (air conditioner), and the other is to be in a hot climate that should result in reduced air conditioner sizing. As part of this project they are developing the user interface for a thermostatic control. Their web site reports a preliminary test on two houses, but does not give any information on how the fan was controlled or on the details of the experimental design

A "Web-enabled" home is currently under construction by John Picard in Manhattan Beach, California. It will contain a building automation system that will talk to the National Weather Service. Presumably this would allow the house to better anticipate major changes in local weather. However our own research has not shown any cases where information on longer term trends would have improved our controller's fast response ability to maintain indoor comfort temperatures. This type of knowledge would be most useful if it could give 24 hour advance notice when the building will go from needing cooling to heating.

A fourth project at Purdue University, lead by Dr. James Braun, is mentioned as part of a large PIER funded portfolio of programs managed by Architectural Energy Corporation (AEC) (http://aes1.archenergy.com/cec-eeb/docs/). The objective of this effort was to focus on algorithms for night-time ventilation that can be integrated into controllers, however no results from this effort have yet been published. It is assumed that these are non-residential scale applications.

There is a great deal of research work available on fans and the design of ventilation systems, but that was not the focus of this project.

2.1.2. How This Controller/Thermostat Compares with Existing Products

There is no controller on the market today that can intelligent control a whole-house fan by sensing both indoor and outdoor temperature. The prototype microprocessor/thermostat that we have developed should be relatively straight forward to manufacture, in part because all the required sensors and actuators are currently commercially available.

There are many programmable thermostats on the market that range from the simple night-setback type to more sophisticated models with up to four different programs per day and seven different programs per week. The EPA Energy Star web site lists over two dozen different products from over a dozen different manufacturers, but none of them measures outdoor air temperature and incorporates it into the control logic (www.epa.gov/appdstar/hvac/prodtherm.html). There are apparently three thermostats that sense outdoor air temperature, but two (Honeywell and Johnson) only use it to display outdoor temperature, and the other (Carrier) uses it only to adjust humidity settings to reduce condensation on windows (www.dulley.com: bulletin 453, and www.johnsoncontrols.com). Many thermostat manufacturers including Honeywell and Johnson are already including simple microprocessors in their residential products, so expanding that capability should be easily feasible.

Differential temperature controllers are required for solar hot water systems. These special-purpose controllers measure multiple temperatures (at least collector surface and storage tank temperature) and decide when to turn on and off the water pump. However, these controllers are not programmable and they cannot also control a home heating and cooling system (www.thermotechs.com and www.goldline.com).

Another class of highly experimental home thermostats are connected to the local utility via a phone line or the Internet. The objective is to let the utility control the home's air conditioner in order to reduce their total system load (load shedding). They can adjust the home's setpoint temperature by 2 to 6 degrees, and the homeowner presumably saves money on their electric bill (www.carrier.com and www.energycite.com). There is growing interest by the utilities in peak load pricing, and some type of remotely monitored and controlled thermostat will be essential to make such a system feasible.

Contributing to lack of progress in the area of intelligent multi-function thermostats is the fact that there is no trade group or lobbying constituency pressuring for new code requirements in this area, which would quickly help to ‘make a market’. Up to now no one has figured out a good way to make a profit by offering a product of this type, however the economics of this market are now seem to be changing rapidly.

It should be noted that this project does not address the particular problems of large commercial buildings which typically have complex computer controlled building energy management systems (EMS) that sense temperatures at many points throughout the building and send control

signals to many different types of equipment. However the cost and complexity of these systems puts they far beyond the reach of homeowners. We all have seen buildings that use massive amounts of air conditioning on days when night flushing or economizer cooling could easily be utilized. Thus, even for professional building managers, harvesting this free resource for large commercial buildings is a bit more complex then it seems at first glance.

2.2 DEVELOP THE CONTROLLER'S LOGIC AND DEFINE THE VARIABLES THE TO BE MEASURED:

The first task was to design the logical structure of the controller. The variables the controller will need to measure include indoor and outdoor temperature, upper and lower limits of comfort temperature, and time of day. The controller also needs to know whether it is the heating or cooling season, however our simulation studies imply that this can be calculated on the basis of average temperatures during the prior few days.

If in the future natural ventilation is to be controlled, then additional variables need to be measured including winds speed, wind direction, window opening position, and it may be that pressure differences will need to be measured. Because of the potential for highly irregular and rapid oscillations, natural ventilation has a high potential for system instability. This implies that some sort of damping strategy might be required. However, the current system assumes that air motion is fan forced.

2.3 TEST THE PROTOTYPE CONTROLLER DESIGNS IN AN INSTRUMENTED TEST CELL:

In order to determine the preferred controller logic design, a series of test were run in the full-height test cells at the Department of Architecture Energy Lab, at UCLA. The results of these experiments (described below) are the basis for the final recommended "Proof of Concept".

3. PROJECT APPROACH (DESIGN OF THE EXPERIMENTAL SYSTEM)

The experimental system consists of a Data Logger/Controller Microcomputer with thermistors to measure air temperature and a Laptop computer connected to the Microcomputer, which contains the control programs and collects and stores experimental data. There are also two test cells with ventilation systems, which consist of single 4-inch openings for the intake of air and on the outlet side a four-inch opening with a constantly running fan and a cone reducer. The damper in the outlet opening of the experimental cell is opened and closed by a signal from the microcomputer, and on the control cell is fixed in the "closed" position. This "closed" position permits the same amount of controlled infiltration in each cell.

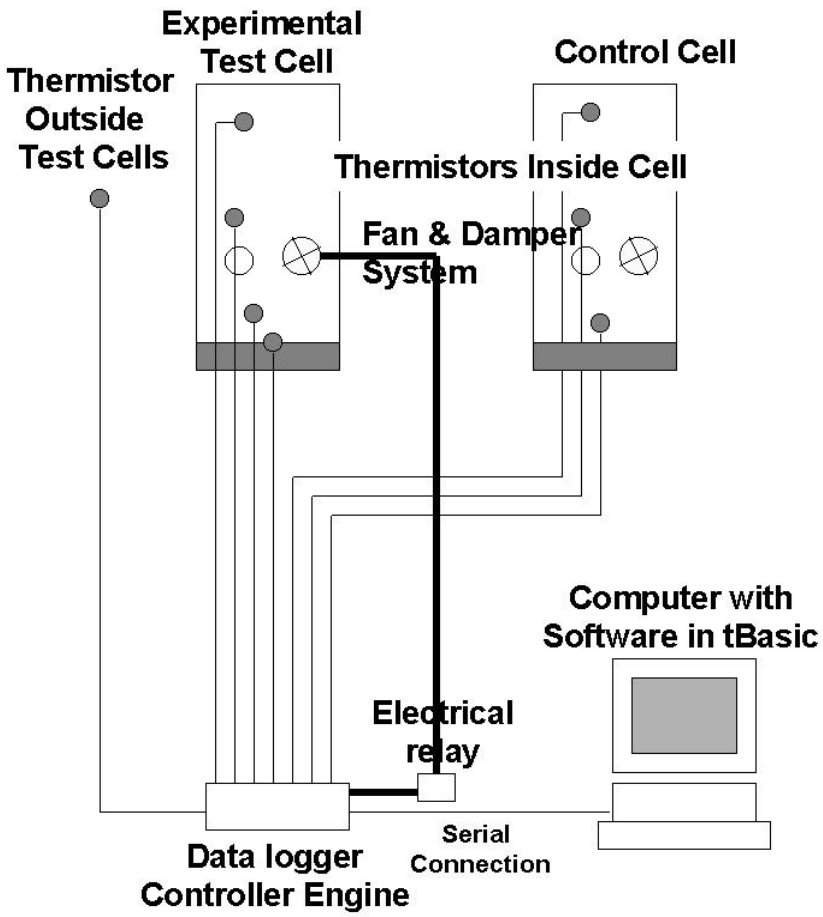

Figure 3.1. The Experimental System

3.1. THERMOSTAT PROTOTYPE AND THERMISTORS

The Data Logger-Controller Engine is a microcomputer "Tattletale TFX-11"model built by Onset Computer Corporation. It has a 68HC11 main processor with PIC 16LC62A coprocessor and 8 analog channels. It is programmable using a version of Basic called TFBasic, has 128 k RAM capacity, a hardware real time clock, and a 472 K flash EEPROM capacity. A computer is connected to this datalogger through the serial port and is running DOS.

The temperature sensors that are used in the experiment are thermistors built by ONSET and have a range of –0°C to +100 °C (-40 °F to 212 °F) with an accuracy of ± 0.5 °C at +20 °C (± 0.9 °F at 70 °F). The length of the wires is 50 ft.

There are four thermistors in the experimental cell, three thermistors in the control cell and one thermistor outside in the shade. In each cell they are placed in the center of the cell at different heights, to measure air temperature, one above each other. The lowest one is 2" above the bricks of the floor, the middle one at 54" and the highest one at 91" or 5" below the ceiling. The experimental cell has the same three thermistors plus an additional thermistor that measures the temperature of the mass. The outdoor thermistor measures outdoor air temperature in the shade.

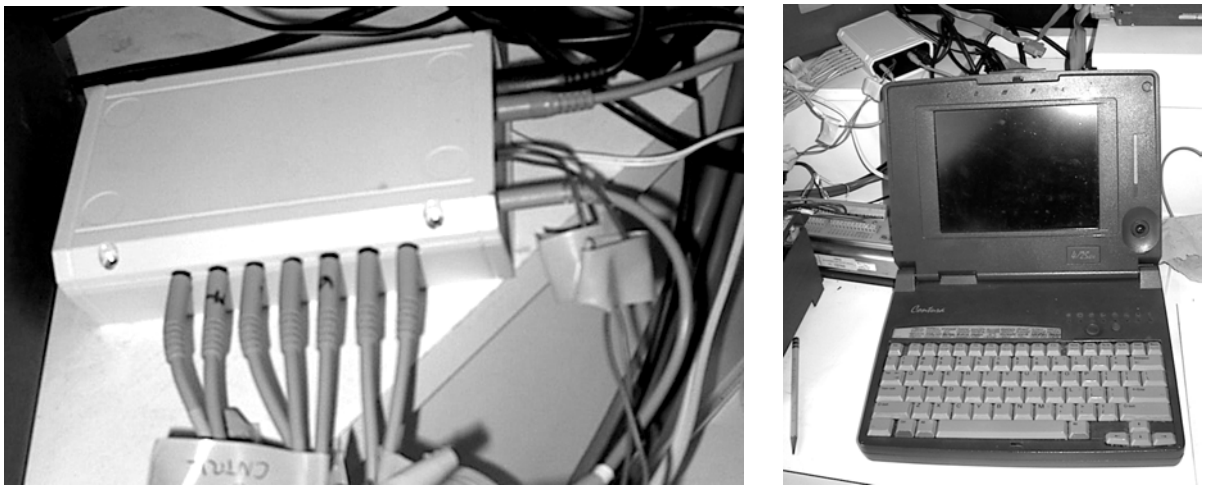

Figure 3.2. Microprocessor Thermostat/Controller (2" by 3") and Laptop Data Acquisition System

3.2. TEST CELLS

Two identical test cells were built simulating the characteristics of typical California slab-on grade houses. They are 4 ft wide by 8 ft long and 8 ft high and are oriented with the longest facade towards the east and west. The cells have 3" foam R12 insulation on the outside and ¼" gypsum inside the walls and roofs. The floor is hardboard placed on top of an insulation panel and the roof has two layers of insulation, one on top of each other for R24. There is a 2 x 2 ft (4 f^2) double pane window on the south side with a Solar Heat Gain Coefficient of 0.72 and a U value of 0.75. The ratio of the glazing to floor area is about 12.5 %. The east and west walls are shaded by another layer of insulation separated by about 3 inches from the wall, to generate an air chamber in between the two layers and block the influence of morning and afternoon sun. The walls and windows are carefully sealed so that infiltration is controlled only by the fan and damper system.

In all of the simulations, each test cell has 106 cement bricks distributed evenly in the floor simulating a concrete slab. The bricks are 4" x 8" x 2.5". The height of the bricks above the floor is 2.5" and they are spread evenly over the surface of the floor.

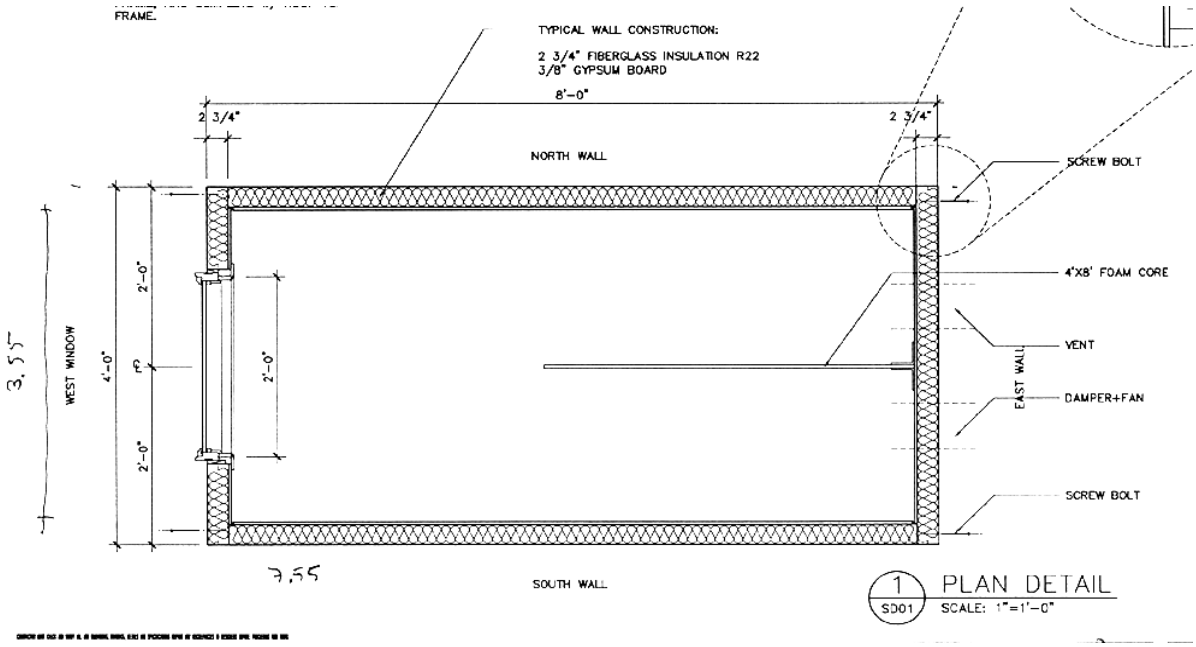

Figure 3.3. Plan view of the test cell

One way to quantify thermal mass in the building is defined in the California Energy Code, Title 24. According to the code, to be characterized as a slab on grade building it should have a minimum Interior Mass Capacity determined by the following equation:

IMC= 2.36 * Ground Floor Area. (1)

IMC = Interior Mass Capacity
Agf = Area of the Ground Floor

Applying this equation for the cells:

2.36 * 26.25 = 61.95

61.95 is the minimum IMC value that the cell must have to qualify as slab on grade according to the energy code.

To determine IMC in the cell:

$IMC = (Area_1 * UIMC_1) + (Area_2 * UIMC_2)\ldots.. (Area_3 * UIMC_3)$(2)

UIMC = Unit Interior Mass Capacity of mass material which is the amount of effective heat capacity per unit of thermal mass, taking into account the type of mass material, thickness, specific heat, density and surface area.

The UIMC for 2.5" concrete bricks is 3.9 so the IMC of the cell is:

1.9 * 26.25 = 102.375

Because 102.38 > 61.95 the cell qualifies as slab on grade building.

To check that the cells are not heavy-mass buildings we use the same code. Even though this index is used mainly to determine heating storage potential in buildings in the winter, it can be a useful indicator of the amount of mass a building needs to qualify as a high-mass building. To qualify as a heavy-mass building the cell must have an IMC larger than:

IMCmass = 35.9 * Asg. (3)

Asg = Area of south glazing

IMCmass = 35.9 * 4 = 143.6

Since 143.6 > 102.4, the building does not qualify as a heavy mass building.

Figure 3.4. Photograph of the Full Height Test Cells

3.3. VENTILATION SYSTEM

Exhaust systems are easy to install in houses or small buildings using whole house fans. These are central-exhaust ventilation systems in which a fan, generally located in the ceiling or uppermost story, is used to blow air out of the house, which is replenished with fresh air from the outdoors that penetrates through random holes or deliberate inlets. If the temperature outside is lower than inside, these systems can be used to cool a house in the summer. If there are no other pressures acting on the building, this results in an equal volume of air passively infiltrating wherever it can to make up for the air being exhausted. A controlled system such as this one is

necessary in the experimental setup to determine the effects of the air change rate on the internal air temperature.

The ventilation system in these cells consists of a fan, a damper and ducts in the exhaust side and a 4” hole on the intake side.

The flow rate is adjusted to 13.21 cfm when the damper is open in the experimental cell and 2.4 cfm when the damper is closed. Since the internal volume of the cells is 202.4 cubic feet, this is equivalent to 3.9 air changes per hour when the damper open and 0.7 air changes per hour when the damper is closed. In the control cell the damper is kept closed and the airflow rate is also fixed to 2.4 cfm (0.7 air changes per hour). Another series is performed with a maximum air change rate of 15-air changes hour in the experimental cell and a minimum air change rate of 0.5 air changes per hour. The maximum air change rate of 3.9 changes/hour is much lower then the rate that can be achieved in small homes with a high capacity whole-house fan. For example a 5.000 cfm fan in a 10000 cubic feet building (about 1.000 square feet) would generate 30 air chages per hour.

Air velocity is measured with a Kestrel-2000 thermo-anemometer, which has a small electronic rotating vane anemometer and a light weight impeler. It has an air velocity measuring range from 0.3 m/s to 40 m/s and an on axis accuracy of the greater of ±3 % of the reading or 0.1 m/s.. The exhaust snout in the test cells has been designed to fit snugly with the anemometer and is always perpendicular to the wind.

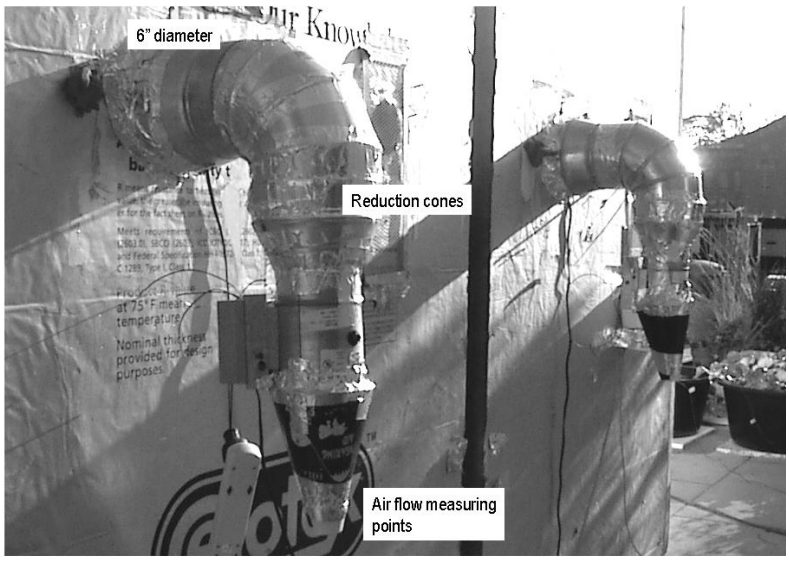

Figure 3.5. Photograph of exhaust systems in the test cells

The fan and damper both work with 110 Volts AC. The fan runs continuously and the 4” diameter damper is in the open position (3.9 AirChanges/hour) when it receives an electrical current and springs back to a closed position without the current. The damper is set up so that in the closed position there is still an air flow rate of 2.35 cfm which amounts to 0.7 air changes per

hour and simulates infiltration. The controller signal output is 9 V DC, which is transformed in a solid state relay to 110 V AC and opens and closes the damper.

3.4. CONTROLLER LOGIC

The temperature inside the building is affected by how the building modifies the climate variables. The main building factors that affect its thermal performance are the U Value of the Envelope, the window design, the air change rate and the amount of mass in the building. In these series, only the ventilation rate is modified, which is controlled by the computer program.

The objective of all the controller programs is to optimize the use of the available ventilation and mass to achieve comfort with minimum energy consumption. The quantity of heat exchanged between the outside and inside is what ultimately defines indoor air temperatures and heating and cooling loads. Since both cells are built identically, performance can be evaluated by comparing the results of the experimental cell with the control cell.

Several series were performed in the summers of 2000 and 2001. Several versions of the control program were tested in which different parameters were modified to determine which was more effective in cooling. As a general rule they all compare a set of conditions inside the test cell with outdoor conditions and generate an electrical signal to activate the damper if a prescribed set of conditions as determined by sets of rules is met.

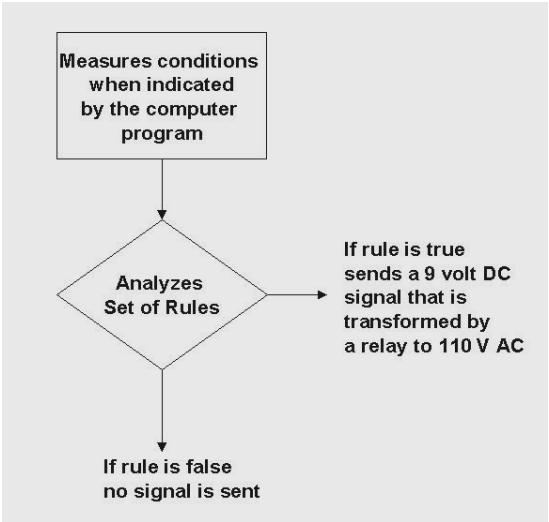

Figure 3.6. Control System Logic

1. The controller programs are simple enough so that they can be built into a thermostat and any homeowner will be able to understand how to use them. The main components of these rules are:

2. Comparison of an interior temperature, which can be either mass or air, with outdoor temperature to determine if the damper will open or not. If the indoor temperature is higher than the outdoor temperature the airflow rate should increase (damper open) so that a larger amount of cool air enters the building. If the indoor temperature is higher than the outside temperature, the airflow rate should be reduced (damper closed) so that the warmer outside

air does not enter the building. This rule can be combined with one or both of the following other rules.

3. Comparison of interior air temperature with a given minimum value. If the air temperature is below this value the air flow rate will be reduced to avoid overcooling of the building. This value can be called comfort low because it is a comfort control for low temperatures.

4. Comparison of interior air temperature with a given maximum value. If the air temperature is above this value the damper will close to avoid overheating by ventilation of the building. This option can be linked to a mechanical cooling system (air conditioner) so that if the indoor temperature is above this value the mechanical cooling system is activated. This variable is called comfort high because it is a comfort control for high temperatures. It can also be the maximum value, above which introducing air from the outside is of any cooling use.

The previous options can be grouped together in different configurations and using different values for comfort low and comfort high, which can be adjusted by the user. The advantage of using a rule-based system is that the ventilation rate is adjusted according to the predetermined rules. Traditional ventilation systems are based on simpler fixed options, such as predefined hours or only the value of the internal temperatures.

4. PROJECT OUTCOMES

4.1. EXPERIMENTAL SERIES

Several control and test series were performed during the summer of 2000 and thirteen series were performed during the summer of 2001. The calibration and eight series are described in this report and summarized in table 4.1. They are explained in more detail in the next sections.

Table 4.1. Series that are performed in 2001 and presented in this report.

Series Number & Name	Date	Comfort Low	Comfort High	Minimum Air Changes per Hour	Maximum Air Changes per Hour	Destrat-ification Fan
Series 1: Basic Comfort Configuration	Aug 9-17	21.1 °C (70 °F)	25.5 °C (78 °F)	0.7	3.9	None
Series 2: Reduced Comfort Low	Aug 18-22	18.3 °C (65 °F)	25.5 °C (78 °F)	0.7	3.9	None
Series 3: Reads Mass Temperature	Aug 32-28	21.1 °C (65 °F)	25.5 °C (78 °F)	0.7	3.9	None
Series 4: No comfort high & 15 air changes/hour	Aug 30 - Sept 4	21.1 °C (65 °F)	none	uncontrolled	15	None
Series 5: Comfort Configuration, Destratification Fan & 3.9 air changes / hour	Sept 12-17	21.1 °C (70 °F)	none	0.7	3.9	Yes
Series 6: Reduced comfort low	Sept 23-27	15.6 °C (60 °F)	none	0.7	3.9	Yes
Series 7: Destratification Fan controlled by Ventilation System	Sept 28 - Oct 1	15.6 °C (60 °F)	none	0.7	3.9	Yes coupled with controller
Series 8: Higher air change with no Destratification Fan	Oct 2-8	15.6 °C (60 °F)	none	uncontrolled	15	None

4.1.1. Calibration Series.

This series compares results in both cells, to be sure that they have similar thermal behavior. Their performance was analyzed during a six-day series, with an equal fixed infiltration rate of 0.7 air changes/hour in both cells. The eastern cell (experimental cell) had slightly higher values, especially at peak hours of the day. Several regression equations were developed to determine a factor that would relate the temperature differences in the two cells (figure 1). A value of 0.58 °C relates the value in one cell to the other. When 0.58 is subtracted from the measured temperature in the experimental cell is always within 0.20 °C of the measured value in the control cell (Fig 4.1, 4.2). From this point on this value is always subtracted from the temperature in the experimental cell.

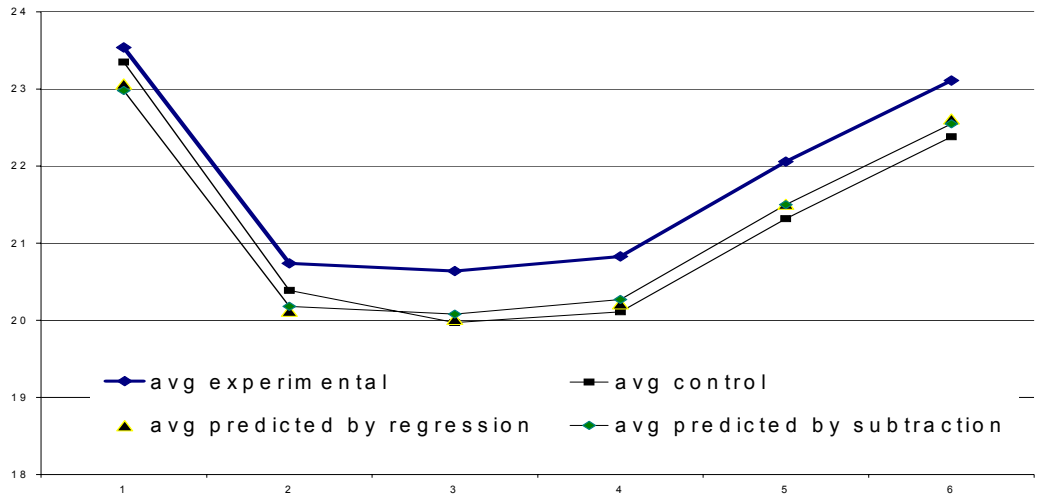

Figure 4.1. Average daily temperatures in celld and predicted values for experimental cell

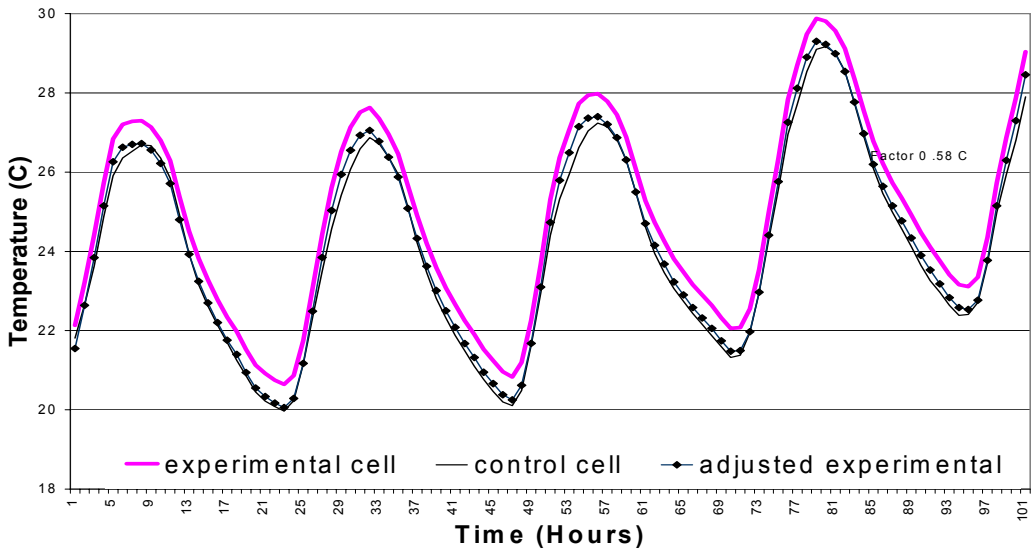

Figure 4.2. Measured and predicted hourly values after subtracting the adjustment factor

4.1.2. Series 1: Basic Comfort Zone Configuration

This first series is set so that the system will shut off whenever conditions are outside the traditional comfort zone of 70-78F. The fan controller mechanism is programmed to increase the air change rate to 3.9 air changes/ hour whenever the indoor temperature is between comfort low, 21.1C (70 °F) and comfort high, 25.5 °C (78 °F) and when the outdoor temperature is lower than the indoor temperature. This rule is in the following form:

If $t_o < t_i$ and $t_i > Cf_low$ and $t_i < Cf_high$ *then* activate fan

t_o: Temperature outside
t_i: Temperature inside
C_{f_low}: Comfort low
C_{f_high}: Comfort high

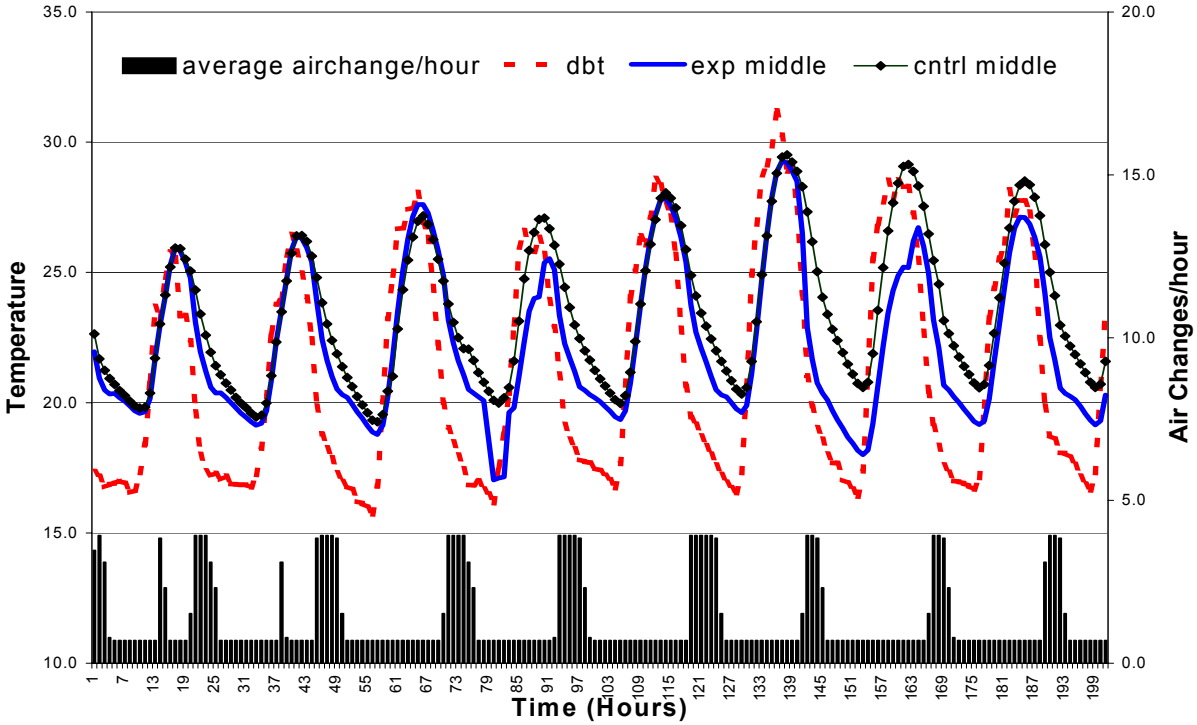

Fig 4.3. Temperatures and Air Change rate in series 1.

Figure 4.4. is a matrix made up of 24 rows that represent each hour of the day and a number of columns equal to the number of measured days in the series. Each of these cells indicates the temperature of one hour for each day. These temperatures are compared to the comfort zone (70-78 °F) and if it is below 70 °F the rectangle is colored light gray, because the temperature is cooler than the comfort zone; if it is between 70 and 78 °F it is shaded medium gray which indicates that it is comfort; and if it is above 78 °F it is shaded dark gray which indicates that it is warmer than comfort.

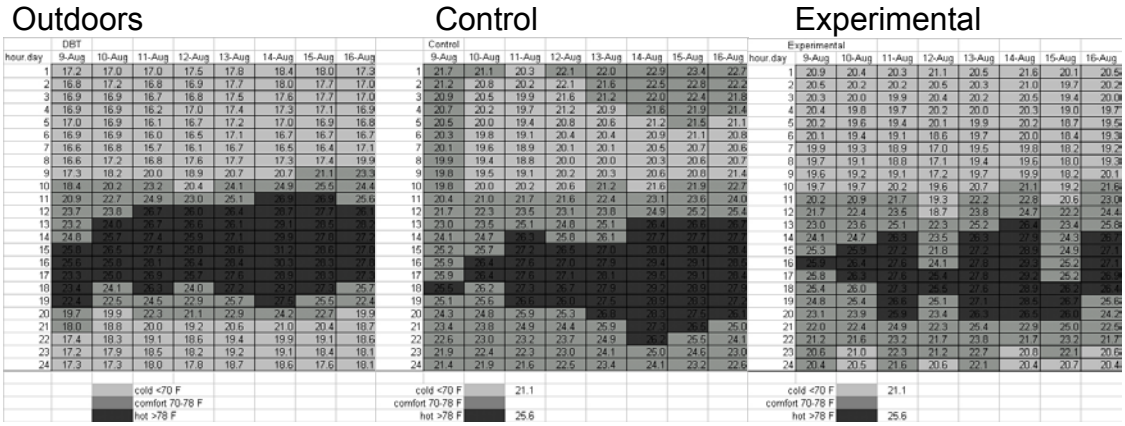

Fig 4.4. Hot, Comfortable and Cold Hours in series 1.

In this series (Fig 4.4, table 4.2) there are more hours in comfort inside both cells than on the outside, probably because of the flattening effect that the mass has on the air temperature. The number of overheated hours in the control cell is slightly lower than the number outdoors, but is reduced by about 24% in relation to the test cell and 32% in relation to the outdoor temperature. Since the fan is set to turn off when the cell temperature is above 78 °F (overheated), the system could be connected to a mechanical cooling system, which would be activated at this moment, eliminating the overheated hours altogether.

Table 4.2. Percentage of Hot, Comfortable and Cold Hours in series 1.

	Hot	Comfortable	Cool
Outdoor DBT	27.6	18.3	54.1
Control Cell	24.5	40	35.5
Experimental Cell	18.8	34.5	46.7

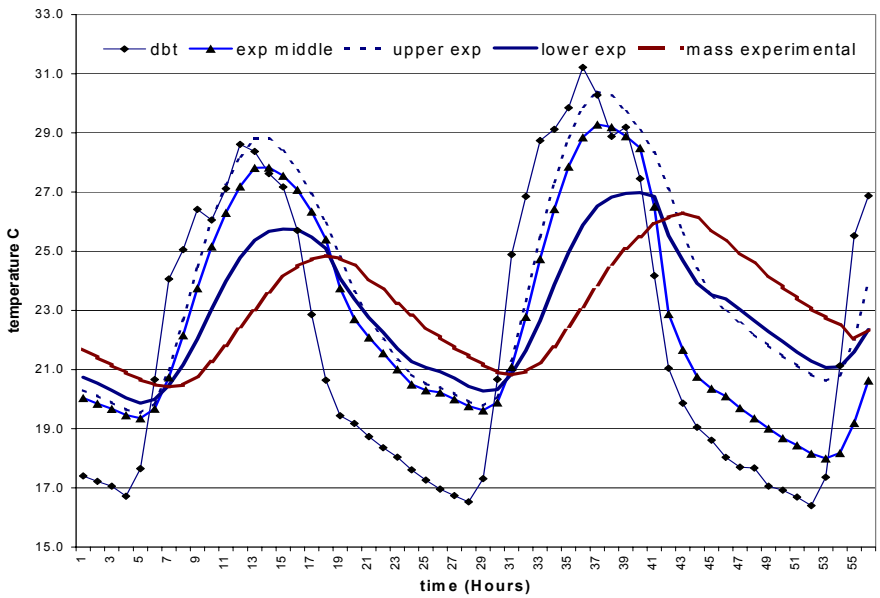

Figure 4.5: Stratification in the Experimental Cell in Series 1

Figure 4.5 gives an idea of the temperature distribution inside the test cell. The temperature difference between the upper and lower levels in the cell is accentuated during the peak mid afternoon hours when the solar gain increases and the ventilation system is turned off. At this point the temperature at the upper level of the test cell is higher than the temperature in the lower level by about 5 C this phenomenon in which the temperature is not distributed evenly in the building, with the warmer air in the upper portion and the cooler air in the lower portion, is called stratification. During the night, if the system is working, the temperatures at all heights are closer together.

4.1.2. Series 2: Reduced Comfort Low

Comfort low is reduced to 18.33 °C (65 °F) to increase the heat sink capacity of the mass. The fan is activated at several times of the day and for different amounts of time (Fig 4.6.), which is an advantage over a ventilation system that is activated at fixed hours. The fan system is

activated during longer periods than in the previous series because it now also operates when the outdoor temperature is between 70 and 65 °F.

The number of overheated hours in the experimental cells has been reduced by 54% when compared with the control cell and 31% when compared with outdoor temperatures (Table 4.3).

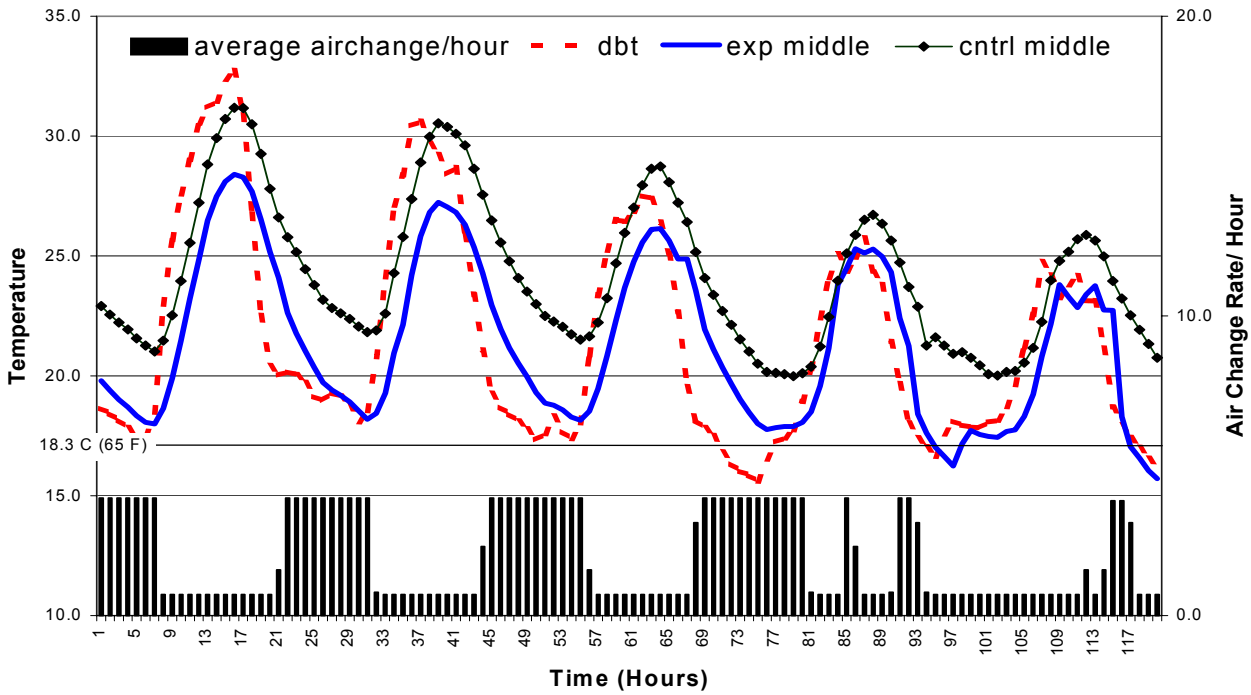

Fig 4.6. Temperatures and Air Change rate in series 2

Table 4.3. Percentage of Hot, Comfortable and Cold Hours in series 2.

	Hot	Comfortable	Cool
Outdoor DBT	21.7	25.5	55.8
Control Cell	32.5	40	27.5
Experimental Cell	15	31.7	53.3

Lowering the value of comfort low reduces the amount of overheated hours but also increases the amount of cooled hours, which occur mostly between 11 PM and 10 AM of the next day (Fig 4.3). Even though these cool hours are technically below the comfort zone, they occur in the summer nights and mornings when it is not necessarily uncomfortable.

OUTDOORS

	DBT				
hour.day	18-Aug	19-Aug	20-Aug	21-Aug	22-Aug
1	18.7	19.2	17.8	16.0	18.1
2	18.4	19.0	17.3	15.9	18.0
3	18.2	19.3	17.6	15.6	17.9
4	17.8	19.2	18.3	16.5	17.8
5	17.4	18.8	17.7	17.3	18.1
6	17.5	18.1	17.4	17.4	18.2
7	18.5	18.5	18.0	17.8	18.7
8	23.0	20.8	20.9	18.9	19.6
9	25.7	24.1	23.4	20.3	21.2
10	27.6	27.1	25.2	22.4	22.6
11	29.0	28.4	26.5	24.1	24.8
12	30.5	30.4	26.4	25.1	24.2
13	31.2	30.6	26.9	24.4	23.3
14	31.4	29.7	27.5	25.0	23.8
15	32.4	29.2	27.4	25.8	24.2
16	32.7	28.4	26.4	24.3	23.2
17	30.9	28.7	25.1	23.8	23.1
18	26.7	25.9	22.7	21.4	21.2
19	22.5	23.4	19.6	19.7	18.7
20	20.4	21.1	18.1	18.0	18.0
21	20.0	19.3	17.8	17.4	17.4
22	20.2	18.7	17.5	17.1	17.0
23	20.1	18.4	16.8	16.6	16.6
24	19.7	18.1	16.3	17.6	16.2

cold <70 F
comfort 70-78 F
hot >78 F

CONTROL

	Control				
	18-Aug	19-Aug	20-Aug	21-Aug	22-Aug
1	22.9	23.8	20.0	21.5	20.9
2	22.6	23.2	19.3	21.0	21.0
3	22.2	22.8	18.9	20.5	20.8
4	21.9	22.6	18.8	20.2	20.4
5	21.6	22.4	18.6	20.1	20.1
6	21.3	22.1	18.3	20.1	20.0
7	21.0	21.8	18.1	20.0	20.2
8	21.5	21.9	18.5	20.1	20.2
9	22.5	22.6	19.5	20.4	20.6
10	24.0	24.3	20.8	21.2	21.2
11	25.6	25.8	22.3	22.5	22.3
12	27.2	27.4	23.7	24.0	24.0
13	28.8	28.9	24.8	25.1	24.8
14	29.9	30.0	25.6	25.9	25.2
15	30.7	30.5	26.1	26.5	25.7
16	31.2	30.4	26.1	26.7	25.9
17	31.2	30.1	25.7	26.4	25.7
18	30.5	29.6	24.9	25.7	25.0
19	29.3	28.6	24.9	24.7	24.0
20	27.8	27.6	23.6	23.7	23.2
21	26.6	26.5	21.9	22.9	22.5
22	25.8	25.6	21.1	21.3	21.9
23	25.2	24.8	20.3	21.6	21.3
24	24.5	24.1	19.7	21.3	20.8

cold <70 F
comfort 70-78 F
hot >78 F

EXPERIMENTAL

	Experimental				
hour.day	18-Aug	19-Aug	20-Aug	21-Aug	22-Aug
1	19.8	20.4	20.0	19.0	17.4
2	19.4	19.7	19.3	18.5	16.9
3	19.0	19.4	18.9	18.0	17.9
4	18.7	19.2	18.8	17.8	18.4
5	18.3	18.9	18.6	17.9	18.3
6	18.1	18.5	18.3	17.9	18.2
7	18.0	18.2	18.1	17.9	18.1
8	18.6	18.4	18.5	18.1	18.4
9	19.9	19.3	19.5	18.5	18.5
10	21.5	21.0	20.8	19.6	19.0
11	23.2	22.1	22.3	21.2	19.9
12	24.9	24.2	23.7	22.9	21.5
13	26.5	25.8	24.8	23.7	22.9
14	27.5	26.8	25.6	24.1	24.5
15	28.1	27.2	26.1	25.1	24.0
16	28.4	27.0	26.1	25.3	23.6
17	28.3	26.8	25.7	25.0	24.1
18	27.7	26.3	24.9	24.3	24.5
19	26.5	25.4	24.9	22.4	23.5
20	25.2	24.3	23.6	21.3	23.4
21	24.1	23.0	21.9	18.4	19.0
22	22.6	22.0	21.1	15.7	17.8
23	21.8	21.2	20.3	14.9	17.3
24	21.1	20.5	19.7	15.2	16.8

cold <70 F
comfort 70-78 F
hot >78 F

Fig 4.7. Hot, Comfortable and Cold Hours in series 2.

4.1.3. Series 3: Read Mass Temperature

In this series the operation of the cooling system is determined by the relationship of the outside air temperature with the mass temperature inside the building, which is the actual storage medium of the 'coolth'. 'Coolth' cannot really be stored in the building structure, what happens is that the heat stored in the mass is flushed outside, so that it has more potential for storing heat and thus keep the space cool. 'Coolth' storage is the summer equivalent of heat storage by the mass in the winter. The mass temperature probe is located in between two bricks about one inch from the surface. The airflow rate is increased when the outdoor temperature is lower than the mass temperature, while the air temperature is used as a comfort control, shutting off the system whenever the indoor temperature is above or below the comfort zone. In this series comfort low is set at 65 °F (18.33 °C) and comfort high at 25.2 °C (78 °F). Thus, the mass temperature is an indicator of the amount of heat that can be stored, while the air temperature controls comfort. When the indoor air temperature reaches the maximum comfort value, natural ventilation will be reduced and the mechanical cooling system could have been activated because it is no longer possible to maintain comfort using only the venting system. The rule is in the following form:

If $t_{to} < t_{mass}$ and $t_i > C_{cf_low}$ and $t_i < C_{cf_high}$ *then* activate fan

$t_{o:}$ Temperature outside
$t_{mass:}$ Temperature of the mass inside the test cell
C_{f_low}: Comfort low
C_{f_high}: Comfort high

There are 27.6% less overheated hours in the experimental test cell than in the control cell, but slightly more than outdoors. The experimental cell has more cool hours than the control cell or outdoors.

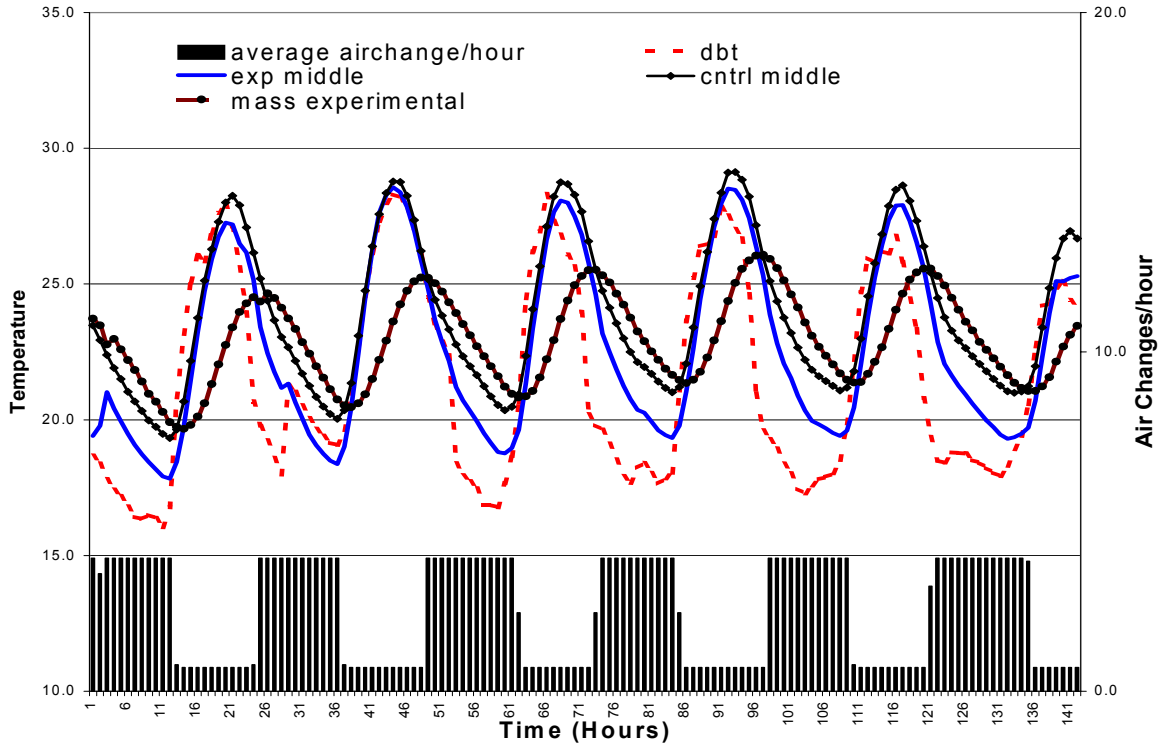

Fig 4.8: Temperatures and air change rate in series 3

OUTDOORS

hour.day	DBT 24-Aug	25-Aug	26-Aug	27-Aug	28-Aug	29-Aug
1	16.8	21.0	18.0	17.7	17.5	18.8
2	16.4	20.5	17.7	18.2	17.3	18.5
3	16.3	20.1	17.5	18.4	17.6	18.4
4	16.5	19.7	16.9	18.0	17.8	18.2
5	16.4	19.4	16.9	17.6	17.9	18.1
6	16.0	19.2	16.8	17.8	18.0	17.9
7	16.8	19.1	17.7	18.1	18.5	18.3
8	20.8	19.6	18.7	21.1	19.9	18.9
9	23.2	21.0	20.6	23.7	22.2	19.4
10	25.1	22.7	24.5	25.2	24.7	20.6
11	26.1	24.6	26.2	26.4	26.0	22.7
12	25.8	26.1	26.9	26.5	25.8	24.2
13	26.9	27.3	28.3	26.8	26.2	24.3
14	27.6	28.0	27.3	27.9	26.1	24.9
15	28.0	28.3	26.8	27.5	26.8	25.1
16	27.1	28.2	26.1	27.0	25.8	24.4
17	25.6	27.8	25.7	26.7	24.5	24.1
18	24.0	27.0	24.0	24.6	23.3	22.7
19	20.7	26.1	20.2	21.0	20.8	19.9
20	19.8	24.5	19.8	19.6	19.4	18.5
21	19.2	23.5	19.6	19.3	18.5	18.1
22	18.6	22.9	19.1	18.9	18.4	17.8
23	18.0	22.4	18.5	18.4	18.8	17.4
24	21.3	18.4	17.9	18.0	18.8	18.1

CONTROL

	Control 24-Aug	25-Aug	26-Aug	27-Aug	28-Aug	29-Aug
1	21.0	22.2	20.7	22.5	22.7	22.6
2	20.7	21.7	20.3	22.1	22.2	22.3
3	20.3	21.3	20.0	21.9	21.8	22.1
4	20.0	20.8	19.5	21.7	21.6	21.8
5	19.7	20.5	19.2	21.4	21.4	21.5
6	19.5	20.2	18.8	21.2	21.3	21.3
7	19.3	20.0	18.8	21.0	21.1	21.1
8	19.6	20.4	19.0	21.2	21.2	21.0
9	20.7	21.4	19.6	22.1	21.8	21.0
10	22.2	23.1	21.3	23.4	23.0	21.2
11	23.8	24.8	23.4	24.9	24.6	22.0
12	25.1	26.4	25.1	26.2	25.8	23.4
13	26.3	27.6	26.6	27.4	26.8	24.9
14	27.3	28.4	27.7	28.4	27.9	26.0
15	28.0	28.8	28.1	29.1	28.5	26.7
16	28.3	28.8	28.0	29.1	28.6	27.0
17	27.9	28.3	27.5	28.8	28.1	26.7
18	27.1	27.4	26.8	28.2	27.3	26.1
19	26.2	26.2	25.8	27.2	26.4	25.3
20	25.2	25.2	24.6	26.0	25.4	24.3
21	24.4	24.4	23.2	25.1	24.5	23.5
22	23.7	23.8	22.5	24.4	23.8	22.9
23	23.1	23.3	21.9	23.8	23.3	22.4
24	22.7	22.8	21.3	23.2	22.9	22.0

EXPERIMENTAL

hour.day	Experimental 24-Aug	25-Aug	26-Aug	27-Aug	28-Aug	29-Aug
1	19.5	20.6	20.7	20.8	20.9	20.9
2	19.1	20.1	20.3	20.4	20.3	20.6
3	18.7	19.5	20.0	20.3	20.0	20.3
4	18.4	19.1	19.5	19.9	19.8	20.0
5	18.2	18.7	19.2	19.6	19.7	19.7
6	17.9	18.5	18.8	19.4	19.5	19.5
7	17.8	18.4	18.8	19.3	19.4	19.3
8	18.5	19.0	19.0	19.8	19.6	19.4
9	19.7	20.5	19.6	21.0	20.5	19.5
10	21.5	22.5	21.3	22.6	22.0	19.7
11	23.3	24.5	23.4	24.4	23.8	20.7
12	24.7	26.3	25.1	25.8	25.2	22.3
13	25.9	27.6	26.6	27.1	26.4	23.9
14	26.7	28.3	27.7	28.0	27.4	25.1
15	27.3	28.6	28.1	28.5	27.9	25.1
16	27.2	28.4	28.0	28.5	27.9	25.2
17	26.5	27.8	27.5	28.1	27.3	25.3
18	26.2	27.0	26.8	27.4	26.5	23.6
19	25.2	25.9	25.8	26.4	25.6	21.9
20	23.4	24.8	24.6	25.3	24.3	20.6
21	22.4	23.7	23.2	23.9	22.9	19.8
22	21.8	22.9	22.5	22.8	22.1	19.2
23	21.2	22.2	21.9	22.1	21.6	18.7
24	21.3	21.2	21.3	21.5	21.3	18.5

cold <70 F
comfort 70-78 F
hot >78 F

Fig 4.9. Hot, Comfortable and Cold Hours in series 3.

Table 4.4. Percentage of Hot, Comfortable and Cold Hours in series 3.

	Hot	Comfortable	Cool
Outdoor DBT	21.5	25.7	52.8%
Control Cell	32.6	35.4	32%
Experimental Cell	23.6	34	42.4%

4.1.4. Series 4: No Comfort High and 15 air changes/hour

The same set of rules as in the previous series are applied, but the maximum air change rate is increased from 3.9 to 15 air changes per hour, while the minimum air change rate, the infiltration, is not determined because the fan is turned off so it is free floating. The temperature of the air inside the cells follows the temperature of the outside air very closely, and is lower than the mass temperature.

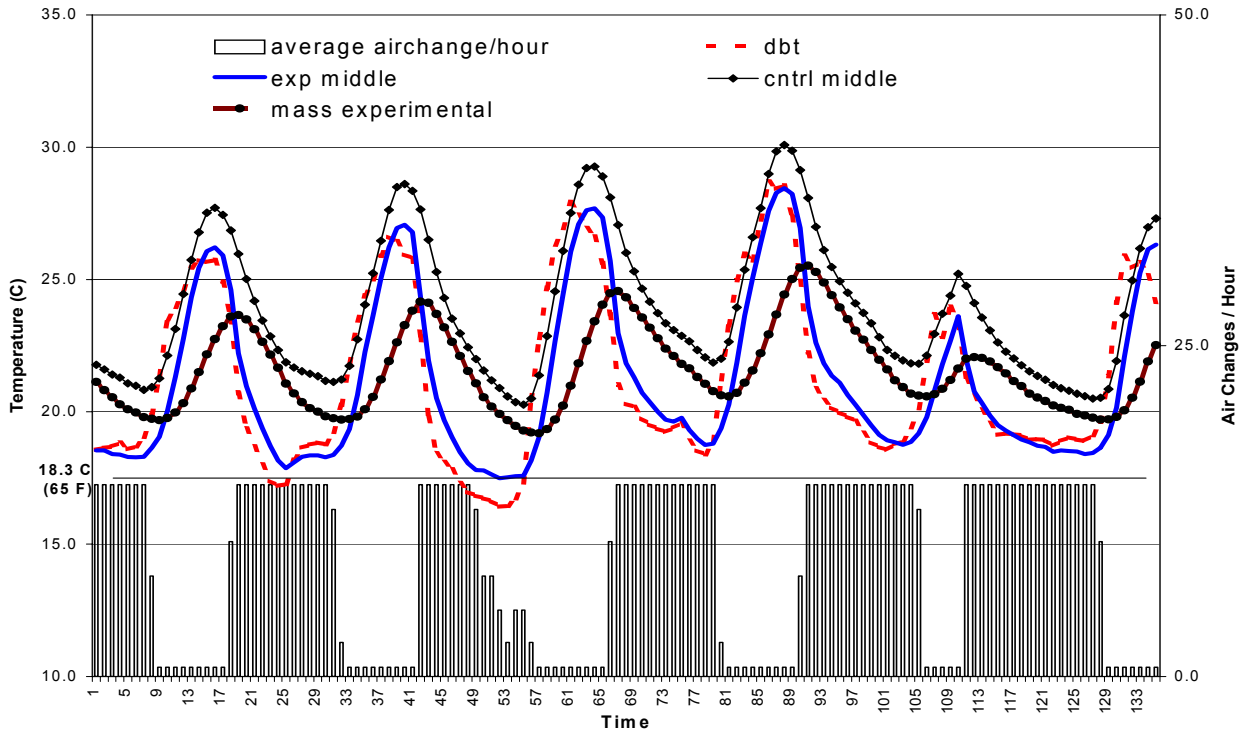

Fig 4.10. Series 4. Temperatures and air change rate in series 4.

OUTDOORS

hour.day	DBT 30-Aug	31-Aug	1-Sep	2-Sep	3-Sep	4-Sep
1	18.6	17.3	16.8	19.2	19.7	18.9
2	18.6	18.2	16.7	19.4	19.2	18.7
3	18.7	18.7	16.6	19.6	18.9	18.9
4	18.8	18.8	16.4	18.9	18.7	19.0
5	18.6	18.9	16.5	18.6	18.6	19.0
6	18.7	18.8	16.7	18.4	18.8	18.9
7	19.1	19.2	17.3	18.9	18.9	19.1
8	19.9	20.3	20.5	21.2	19.4	19.6
9	21.4	21.8	22.8	23.3	20.1	21.4
10	23.5	23.5	24.7	25.0	21.9	24.1
11	24.0	24.4	26.3	26.0	23.7	25.9
12	24.6	25.0	26.9	25.7	22.8	25.4
13	25.5	25.9	27.9	27.3	24.0	25.7
14	25.7	26.6	27.5	28.7	23.3	25.2
15	25.7	26.5	27.0	28.4	21.3	24.2
16	25.7	26.0	26.6	28.6	20.6	0.0
17	24.9	25.8	25.6	27.4	20.1	0.0
18	23.5	22.9	23.7	24.9	19.6	0.0
19	20.7	19.8	21.0	22.2	19.1	0.0
20	19.4	18.4	20.3	20.9	19.2	0.0
21	18.7	18.1	20.2	20.5	19.2	0.0
22	18.0	17.8	19.8	20.2	19.1	0.0
23	17.4	17.3	19.5	20.0	19.0	0.0
24	17.2	17.0	19.4	19.8	19.0	0.0

cold <70 F
comfort 70-78 F
hot >78 F

CONTROL

	Control 30-Aug	31-Aug	1-Sep	2-Sep	3-Sep	4-Sep
1	21.8	21.9	17.8	23.4	24.1	21.2
2	21.6	21.7	17.8	23.1	23.7	21.0
3	21.4	21.5	17.6	22.9	23.4	20.9
4	21.3	21.4	17.5	22.7	22.8	20.8
5	21.1	21.3	17.5	22.3	22.3	20.7
6	21.0	21.2	17.6	22.1	22.1	20.6
7	20.8	21.1	17.6	21.9	21.9	20.5
8	20.9	21.2	18.2	22.0	21.8	20.5
9	21.3	21.7	19.0	22.6	21.8	20.9
10	22.1	22.7	20.7	23.9	22.1	21.9
11	23.1	24.1	22.7	25.4	22.9	23.6
12	24.5	25.2	24.4	26.6	23.7	25.0
13	25.7	26.5	26.1	27.7	24.4	26.2
14	26.8	27.6	27.1	29.0	25.2	27.0
15	27.5	28.5	27.6	29.8	24.8	27.3
16	27.7	28.6	27.7	30.1	24.1	0.0
17	27.4	28.4	27.4	29.9	23.6	0.0
18	26.9	27.7	25.7	29.1	23.1	0.0
19	26.0	26.5	23.0	28.1	22.6	0.0
20	25.0	25.3	21.8	27.0	22.3	0.0
21	24.2	24.3	21.3	26.1	22.0	0.0
22	23.5	23.5	20.7	25.5	21.8	0.0
23	22.9	23.0	20.4	24.9	21.5	0.0
24	22.3	22.4	20.0	24.5	21.4	0.0

cold <70 F
comfort 70-78 F
hot >78 F

EXPERIMENTAL

hour.day	Experimental 30-Aug	31-Aug	1-Sep	2-Sep	3-Sep	4-Sep
1	18.5	17.9	17.8	19.7	20.3	18.7
2	18.5	18.1	17.8	19.6	19.9	18.5
3	18.4	18.3	17.6	19.8	19.5	18.5
4	18.4	18.4	17.5	19.3	19.1	18.5
5	18.3	18.4	17.5	19.0	18.9	18.5
6	18.3	18.3	17.6	18.8	18.9	18.4
7	18.3	18.4	17.6	18.8	18.8	18.5
8	18.6	18.7	18.2	19.4	18.9	18.6
9	19.1	19.3	19.0	20.3	19.2	19.1
10	20.0	20.6	20.7	21.9	19.8	20.2
11	21.3	22.3	22.7	23.6	20.8	22.1
12	22.8	23.6	24.4	25.1	21.8	23.8
13	24.3	25.1	26.1	26.4	22.7	25.3
14	25.4	26.2	27.1	27.6	23.6	26.1
15	26.1	27.0	27.6	28.3	22.0	26.3
16	26.2	27.1	27.7	28.5	20.8	0.0
17	25.9	26.8	27.4	28.2	20.3	0.0
18	24.6	24.4	25.7	26.9	19.9	0.0
19	22.2	21.9	23.0	24.0	19.5	0.0
20	21.0	20.5	21.8	22.6	19.3	0.0
21	20.1	19.7	21.3	21.8	19.1	0.0
22	19.4	19.0	20.7	21.4	19.0	0.0
23	18.7	18.5	20.4	21.1	18.9	0.0
24	18.2	18.1	20.0	20.6	18.7	0.0

cold <70 F
comfort 70-78 F
hot >78 F

Figure 4.11. Hot, Comfortable and Cold Hours in series 4.

Table 4.5. Percentage of Hot, Comfortable and Cold Hours in series 4.

	Overheated	Comfort	Cool
Outdoor DBT	14.8	22.2	63
Control Cell	24.4	55.6	20
Experimental Cell	14.8	23.7	61.5

4.1.5. Series 5: lower comfort adjusted to comfort zone, destratification fan and 3.9 air changes / hour

In this series comfort low is increased, as in series 1, to the lower limit of the conventional comfort zone, 21.1 °C (70 °F) and there is no comfort high. The maximum air change rate is reduced from the previous series and a fan rated at 560 cfm is installed sitting on the floor of the test cell, pointing at the ceiling, to generate an air current that will eliminate air stratification and reduce the resistance of the air film on the surface of the mass. This fan is called a destratification fan because it mixes the air inside the cell, reducing temperature differences.

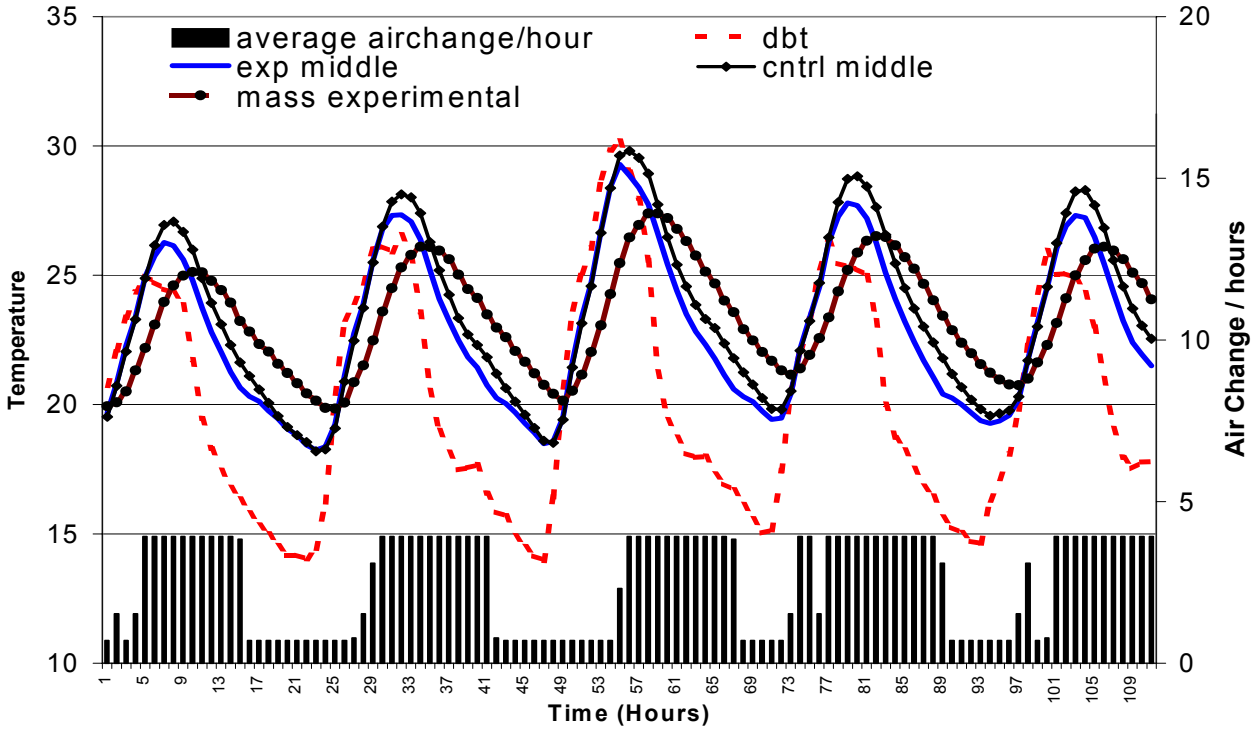

Fig. 4.12. Air temperature and air change rate in series 5.

With the fan inside the cell, stratification has been reduced compared to the other series in which there is no fan inside the cells (fig 4.14 compared to fig 4.5). The number of overcooled hours is also reduced in comparison to the previous series. Air movement should reduce the resistance of the air film on the surface of the mass and increase its admittance, but this strategy does not seem to help reduce the indoor maxima as compared to other series. Since the air temperature inside the experimental cell is rarely above 28 °C, the velocity that is generated inside the test cell is sufficient to bring conditions to comfortable levels by physiological cooling.

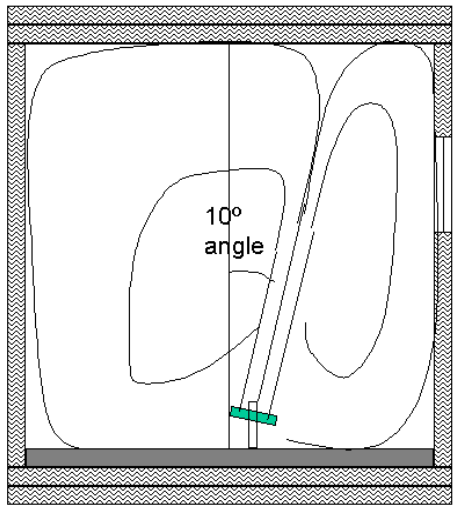

Fig 4.13: Placement of the fan

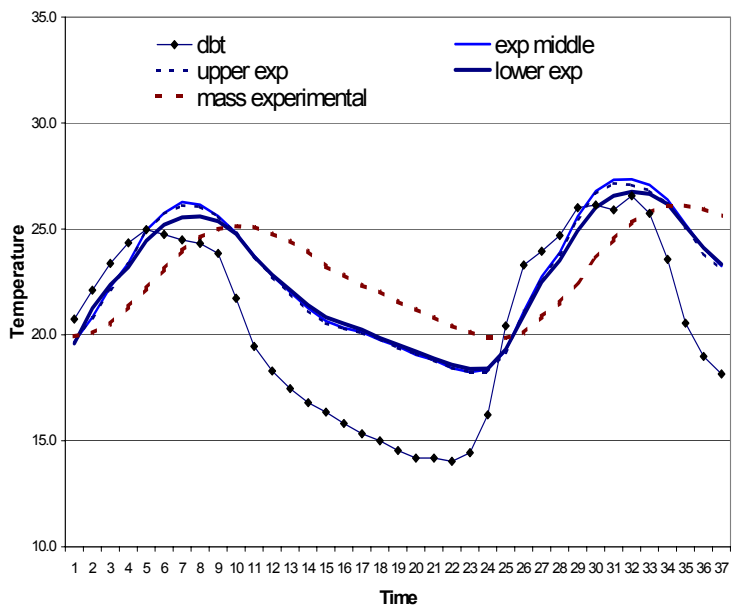

Fig 4.14: No stratification in Series 5 with the fan on

Table 4.6. Percentage of Hot, Comfortable and Cold Hours in series 5.

	Hot	Comfortable	Cool
Outdoor DBT	14.6	32.3	53.1
Control Cell	27.1	26	38.6
Experimental Cell	53.1	46.9	37.5

OUTDOORS

	DBT					
hour.day	12-Sep	13-Sep	14-Sep	15-Sep	16-Sep	4-Sep
1	0.0	15.3	16.6	17.3	15.7	0.0
2	0.0	15.0	15.9	17.0	15.3	0.0
3	0.0	14.5	15.7	16.7	15.1	0.0
4	0.0	14.2	14.9	16.1	14.7	0.0
5	0.0	14.2	14.5	15.6	14.7	0.0
6	0.0	14.0	14.2	15.0	16.3	0.0
7	0.0	14.4	14.0	15.2	17.1	0.0
8	0.0	16.2	16.4	17.4	18.1	0.0
9	20.7	20.4	20.7	20.6	19.8	0.0
10	22.1	23.3	23.7	22.1	22.4	0.0
11	23.4	24.0	25.1	23.3	24.3	0.0
12	24.4	24.7	26.0	25.3	26.0	0.0
13	25.0	26.0	28.8	26.4	25.0	0.0
14	24.7	26.1	29.8	25.5	25.1	0.0
15	24.5	25.9	30.2	25.3	24.9	0.0
16	24.3	26.6	29.0	25.3	24.3	0.0
17	23.9	25.7	28.0	25.0	23.0	0.0
18	21.7	23.6	25.6	23.2	21.0	0.0
19	19.5	20.6	21.3	20.0	19.1	0.0
20	18.3	19.0	19.4	18.7	18.0	0.0
21	17.5	18.2	18.7	18.2	17.5	0.0
22	16.8	17.5	18.1	17.5	17.8	0.0
23	16.4	17.6	18.0	16.9	17.8	0.0
24	15.8	17.7	18.0	16.5	17.5	0.0

cold <70 F
comfort 70-78 F
hot >78 F

CONTROL

	Control				
	12-Sep	13-Sep	14-Sep	15-Sep	16-Sep
1	0.0	20.6	20.8	23.0	21.8
2	0.0	20.1	20.3	22.4	21.2
3	0.0	19.6	20.0	21.8	20.7
4	0.0	19.1	19.7	21.3	20.2
5	0.0	18.8	19.3	20.8	19.8
6	0.0	18.6	18.9	20.3	19.6
7	0.0	18.2	18.5	19.8	19.7
8	0.0	18.3	18.6	19.8	19.8
9	19.5	19.1	19.5	20.5	20.3
10	20.7	20.9	21.6	22.1	21.7
11	22.1	22.5	23.4	23.2	23.0
12	23.3	23.7	24.7	24.7	24.6
13	24.9	25.5	26.7	26.5	26.3
14	26.2	26.9	28.4	27.8	27.4
15	27.0	27.9	29.3	28.7	28.2
16	27.1	28.1	28.9	28.8	28.3
17	26.7	28.0	28.4	28.4	27.7
18	26.0	27.4	27.7	27.6	26.8
19	24.9	26.3	26.6	26.6	25.6
20	23.9	25.2	25.4	25.5	24.6
21	23.1	24.3	24.4	24.5	23.7
22	22.3	23.3	23.5	23.7	23.1
23	21.6	22.7	22.8	23.0	22.5
24	21.1	22.3	22.3	22.4	22.3

cold <70 F
comfort 70-78 F
hot >78 F

EXPERIMENTAL

	Experimental				
hour.day	12-Sep	13-Sep	14-Sep	15-Sep	16-Sep
1	0.0	20.1	20.8	21.8	20.4
2	0.0	19.8	20.3	21.2	20.3
3	0.0	19.5	20.0	20.6	20.0
4	0.0	19.1	19.7	20.3	19.7
5	0.0	18.8	19.3	20.1	19.4
6	0.0	18.4	18.9	19.7	19.3
7	0.0	18.2	18.5	19.4	19.4
8	0.0	18.4	18.6	19.5	19.6
9	19.7	19.3	19.5	20.4	20.2
10	20.8	21.1	21.6	22.2	21.8
11	22.3	22.8	23.4	23.4	23.2
12	23.4	23.9	24.7	24.6	24.6
13	25.0	25.6	26.7	26.3	26.1
14	25.8	26.8	28.4	27.3	26.9
15	26.3	27.3	29.3	27.8	27.3
16	26.1	27.3	28.9	27.7	27.2
17	25.6	27.1	28.4	27.2	26.5
18	24.8	26.4	27.7	26.3	25.5
19	23.8	25.2	26.6	25.1	24.4
20	22.8	24.1	25.4	24.1	23.3
21	22.0	23.3	24.4	23.2	22.4
22	21.3	22.5	23.5	22.4	21.9
23	20.7	21.8	22.8	21.7	21.5
24	20.3	21.4	22.3	21.1	21.0

cold <70 F
comfort 70-78 F
hot >78 F

Fig 4.15. Hot, Comfortable and Cold Hours in series 5

4.1.6. Series 6: Reduced Comfort Low

In this series the comfort low is reduced to 15.6 °C (60 °F) and the destratification fan is working all the time to maintain air movement inside the cell. There are less overheated hours than in the previous series, when the comfort low value was set at 70 °F. The exhaust fan is also turned on for longer periods because value of comfort low is reduced and there is no comfort high, extending the range of operation.

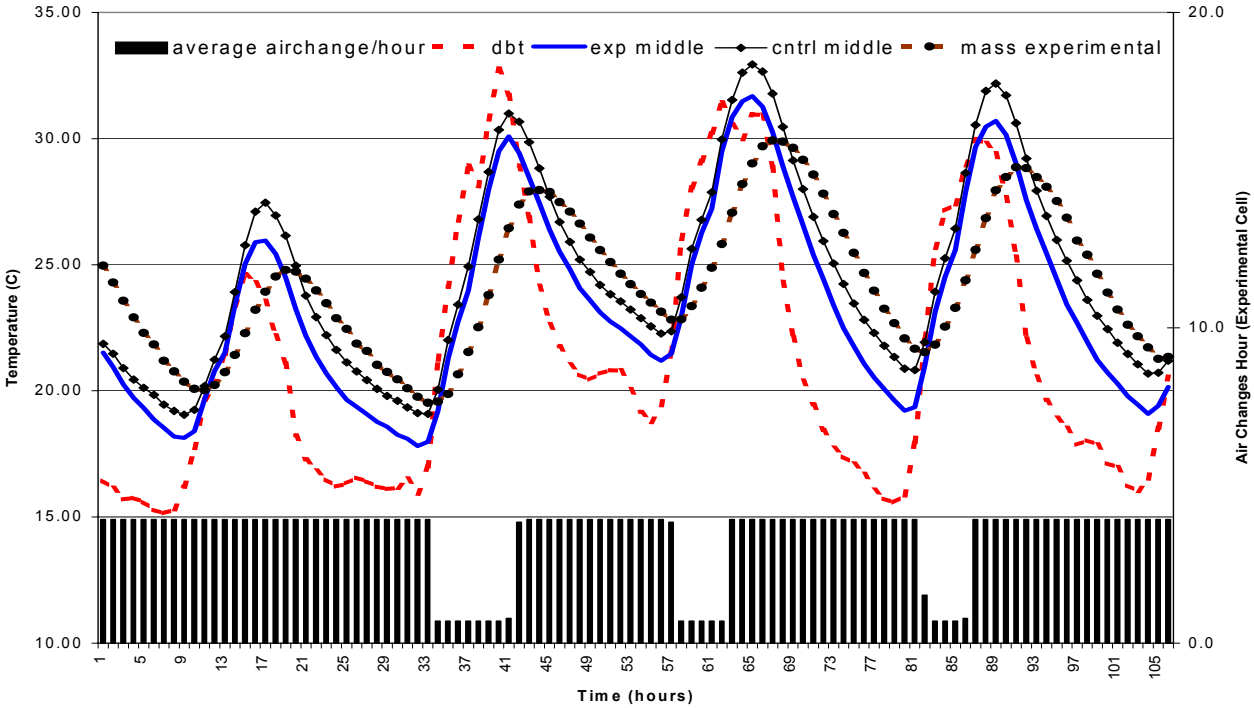

Fig 4.16. Air temperature and air change rate in series 6.

OUTDOORS

	DBT				
hour.day	18-Sep	19-Sep	20-Sep	21-Sep	22-Sep
1	17.6	17.0	17.1	16.4	16.3
2	17.4	16.9	16.6	16.4	16.0
3	17.3	16.8	16.9	16.5	16.0
4	17.1	16.7	16.7	16.4	15.5
5	17.1	16.9	16.5	15.6	15.2
6	17.0	16.9	16.5	15.2	15.6
7	17.1	16.9	16.4	14.5	15.5
8	17.3	17.0	16.5	14.7	15.4
9	17.9	17.6	17.0	15.7	16.0
10	19.2	18.7	17.9	18.6	19.4
11	20.9	20.1	19.6	21.3	22.7
12	22.5	21.8	21.6	21.2	23.9
13	22.6	22.8	22.7	22.5	24.5
14	23.4	24.1	23.1	24.6	24.8
15	23.9	24.3	23.3	25.3	25.8
16	23.9	23.6	23.5	25.6	26.1
17	22.7	23.3	22.6	25.4	25.4
18	21.7	21.8	20.9	22.9	23.6
19	18.8	19.7	18.7	22.2	22.3
20	18.1	17.9	17.3	19.1	19.5
21	17.6	17.4	17.2	18.2	18.0
22	17.4	17.5	17.1	17.7	17.4
23	17.4	17.4	16.6	17.2	16.8
24	17.0	17.4	16.0	16.8	16.8

cold <70 F
comfort 70-78 F
hot >78 F

CONTROL

	Control				
	18-Sep	19-Sep	20-Sep	21-Sep	22-Sep
1	21.9	21.4	23.0	20.7	21.6
2	21.7	21.1	22.6	20.4	21.1
3	21.3	20.7	22.3	20.2	20.6
4	21.1	20.4	22.0	19.9	20.3
5	20.8	20.2	21.7	19.7	19.8
6	20.5	20.1	21.5	19.3	19.5
7	20.3	19.9	21.2	19.0	19.3
8	20.1	19.7	21.0	18.6	19.2
9	20.1	19.6	20.9	18.6	19.0
10	20.2	19.8	20.9	19.1	19.6
11	20.9	20.2	21.2	20.6	21.4
12	22.3	21.4	22.1	21.7	22.8
13	23.5	22.7	23.5	22.7	23.8
14	24.9	24.5	25.4	24.5	25.5
15	26.2	26.0	26.8	26.2	26.8
16	27.2	27.0	27.7	27.4	28.2
17	27.3	27.2	27.8	27.9	28.5
18	26.7	26.7	27.3	27.4	28.0
19	25.6	25.8	26.3	26.6	27.2
20	24.4	24.6	25.1	25.5	26.0
21	23.4	23.5	24.3	24.3	24.9
22	22.7	22.8	23.6	23.5	23.4
23	22.2	22.2	23.2	22.7	22.5
24	21.8	21.9	22.7	22.2	22.5

cold <70 F 21.1
comfort 70-78 F
hot >78 F 25.6

EXPERIMENTAL

	Experimental				
hour.day	18-Sep	19-Sep	20-Sep	21-Sep	22-Sep
1	20.9	19.4	23.1	22.5	21.9
2	20.3	19.1	22.8	21.8	21.2
3	19.7	18.8	22.5	21.1	20.7
4	19.3	18.6	22.2	20.5	20.3
5	18.9	18.3	21.8	20.1	19.8
6	18.5	18.1	21.4	19.6	19.5
7	18.2	17.8	21.2	19.2	19.1
8	18.1	18.0	21.5	19.4	19.4
9	18.4	19.2	22.9	21.0	20.2
10	19.7	21.3	25.0	23.1	20.4
11	20.8	22.8	26.3	24.5	21.7
12	21.5	24.0	27.2	25.6	22.5
13	23.4	26.1	29.5	27.9	23.9
14	25.0	28.0	30.9	29.7	25.1
15	25.9	29.5	31.5	30.5	26.0
16	26.0	30.1	31.7	30.7	26.2
17	25.4	29.4	31.3	30.2	25.8
18	24.5	28.5	30.3	29.0	25.1
19	23.2	27.5	28.9	27.6	24.2
20	22.2	26.4	27.7	26.4	23.2
21	21.4	25.5	26.6	25.5	23.4
22	20.7	24.8	25.4	24.4	23.0
23	20.2	24.1	24.4	23.4	23.0
24	19.7	23.6	23.4	22.7	23.0

cold <70 F 21.1
comfort 70-78 F
hot >78 F 25.6

Fig 4.17. Hot, comfortable and cold hours in series 6

Table 4.7: Percentage of Hot Comfortable or Cold Hours in Series 6

	Hot	Comfortable	Cool
Outdoor DBT	1.7	30.8	67.5
Control Cell	20.8	55	24.2
Experimental Cell	28.3	39.2	32.5

4.1.7. Series 7: Stratification Fan Controlled by Ventilation Fan Signal

As in the previous two series there is an internal fan inside the cell, but this time it is connected to the controller and turns on whenever the system is activated to increase the air change rate. The lower set point, when the system will not be activated, is lowered to 60 °F (15.66 °C). There is no upper comfort limit, so the system will work whenever the indoor temperature is higher than the outdoor temperature and the indoor temperature is above the comfort low. The maximum air change rate is 3.9 air changes/hour.
The rule for this series is in the following form.

If $t_{to} < t_i$ and $t_i > C_{cf_low}$ *then* activate internal fan and air change fan

$t_{o:}$ Temperature outside
$t_{i:}$ Temperature of the air inside the test cell
C_{f_low}: Comfort low

OUTDOORS

hour.day	DBT 27-Sep	28-Sep	29-Sep	30-Sep	1-Oct
1	0.0	17.2	16.4	18.8	18.8
2	0.0	17.1	16.2	18.5	18.9
3	0.0	16.4	15.7	18.4	19.3
4	0.0	15.7	15.6	18.4	19.7
5	0.0	15.2	15.7	17.9	20.6
6	0.0	14.9	15.2	17.6	21.2
7	0.0	15.1	15.1	18.3	22.1
8	0.0	16.9	16.6	19.7	24.1
9	23.5	20.5	20.3	22.8	27.5
10	24.8	23.5	24.3	26.6	31.0
11	24.2	24.2	25.8	28.2	29.8
12	24.4	25.2	26.8	30.5	30.1
13	26.9	26.5	28.1	30.8	31.1
14	28.5	27.4	29.7	31.2	30.9
15	27.7	27.8	30.2	30.5	31.2
16	27.2	26.0	29.4	29.8	30.7
17	26.0	25.4	28.5	26.0	29.5
18	23.4	23.2	25.1	23.9	26.8
19	20.3	20.6	21.7	22.3	22.0
20	19.3	19.4	20.4	21.5	20.6
21	18.8	18.7	19.5	20.9	20.3
22	18.4	17.8	19.0	20.0	19.7
23	17.8	17.5	18.8	19.3	19.2
24	17.3	16.8	19.3	19.0	18.8

		cold <70 F
		comfort 70-78 F
		hot >78 F

CONTROL

	Control 18-Sep	19-Sep	20-Sep	21-Sep	22-Sep
1	0.0	23.0	20.8	23.5	24.6
2	0.0	22.5	20.2	23.1	24.1
3	0.0	22.0	19.6	22.6	23.6
4	0.0	21.4	19.1	22.3	23.3
5	0.0	20.7	18.7	21.9	23.1
6	0.0	20.2	18.3	21.5	23.0
7	0.0	19.8	17.9	21.2	23.0
8	0.0	19.6	18.0	21.2	23.3
9	23.2	20.5	19.4	22.2	24.6
10	23.8	22.4	21.6	24.3	26.8
11	24.8	23.5	23.2	25.6	27.9
12	25.4	24.6	24.3	27.2	28.7
13	27.2	26.5	26.4	29.5	30.2
14	29.1	28.4	28.5	31.3	31.7
15	30.6	30.0	29.7	32.6	32.7
16	31.2	30.5	29.8	32.6	33.1
17	30.9	30.0	29.3	31.4	32.5
18	30.0	29.0	28.4	30.3	31.6
19	28.5	27.7	26.8	29.1	30.3
20	27.1	26.4	25.6	27.9	28.9
21	26.1	25.4	24.6	27.1	27.8
22	25.3	24.6	23.6	26.4	27.0
23	24.5	23.9	22.8	25.7	26.2
24	23.8	23.1	22.3	25.1	25.6

cold <70 F		21.1		
comfort 70-78 F				
hot >78 F		25.6		

EXPERIMENTAL

hour.day	Experimental 18-Sep	19-Sep	20-Sep	21-Sep	22-Sep
1	0.0	21.3	20.8	21.8	22.8
2	0.0	20.6	20.2	21.4	22.4
3	0.0	20.0	19.6	21.0	22.0
4	0.0	19.4	19.1	20.7	21.7
5	0.0	18.8	18.7	20.3	21.6
6	0.0	18.4	18.3	19.9	21.6
7	0.0	18.0	17.9	19.7	21.8
8	0.0	18.1	18.0	19.9	22.2
9	21.3	19.3	19.4	21.2	23.4
10	23.0	21.6	21.6	23.4	25.7
11	24.0	23.0	23.2	25.1	27.3
12	24.5	24.0	24.3	26.5	28.1
13	26.5	25.7	26.4	28.7	29.6
14	28.3	27.4	28.5	30.4	30.7
15	29.4	28.4	29.7	31.0	31.2
16	29.7	28.7	29.8	30.7	31.3
17	29.3	28.1	29.3	29.4	30.6
18	28.2	27.1	28.4	28.4	29.7
19	26.6	25.7	26.8	27.3	28.4
20	25.3	24.6	25.6	26.2	27.1
21	24.3	23.6	24.6	25.4	26.1
22	23.5	22.8	23.6	24.8	25.2
23	22.8	22.1	22.8	24.0	24.5
24	22.0	21.5	22.3	23.4	23.7

cold <70 F		21.1		
comfort 70-78 F				
hot >78 F		25.6		

Fig 4.18. Hot, comfortable and cold hours in series 7

Table 4.8. Percentage of Hot, Comfortable and Cold Hours in series 7.

	Hot	Comfortable	Cool
Outdoor DBT	29.5	17.8	52.7
Control Cell	51.2	32.1	16.7
Experimental Cell	37.5	31.3	31.2

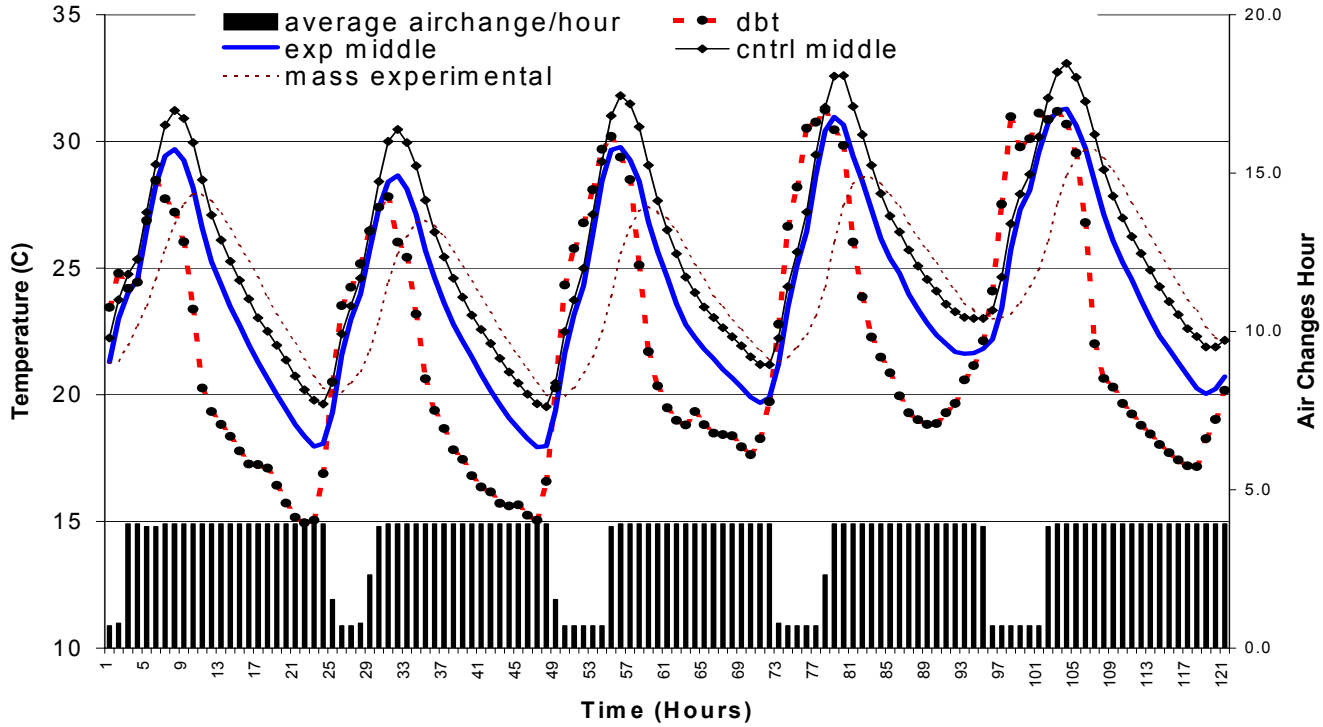

Fig 4.19. Air temperatures and air change rate in series 7.

4.1.8. Series 8: Higher air Change Rate with no Destratification Fan

The maximum air change rate is again increased to 15 air changes/hour and the minimum is undetermined. The airflow rate is increased when the outdoor temperature is lower than the air temperature and above the comfort low, which is set at 60 °F (15.66 °C). Since the comfort low is 60 °F this series permits to determine the effect of combining an increased air change rate with a lower comfort low. There is no upper comfort limit, so the system will work whenever the indoor temperature is higher than the outdoor temperature and the indoor temperature is above the comfort low

The rule for this series is in the following form.

If $t_{to} < t_i$ and $t_i > C_{cf_low}$ *then* increase air change rate

t_o: Temperature outside
t_i: Temperature of the air inside the test cell
C_{f_low}: Comfort low

OUTDOORS

	DBT						
our.day	2-Oct	3-Oct	4-Oct	5-Oct	6-Oct	7-Oct	8-Oct
1	0.0	17.2	18.3	18.3	16.8	17.3	14.86
2	0.0	17.1	18.5	18.1	16.8	17.3	14.66
3	0.0	16.7	18.3	17.9	16.9	17.2	14.45
4	0.0	16.7	18.1	17.8	16.9	17.1	14.16
5	0.0	17.6	18.1	17.7	16.7	17.1	13.9
6	0.0	17.5	18.2	17.8	16.5	17.2	13.92
7	0.0	17.4	18.4	17.8	16.6	17.3	14.02
8	0.0	18.1	18.9	18.2	17.3	17.8	15.93
9	22.7	19.3	20.3	18.7	18.4	19.3	17.53
10	24.3	20.8	22.2	18.6	19.0	20.9	19.08
11	24.4	22.2	23.2	19.2	20.3	20.8	20
12	25.3	23.8	24.0	19.8	21.4	22.1	20.57
13	25.0	25.2	23.9	20.6	22.7	22.6	19.8
14	25.1	25.9	23.6	20.2	22.3	22.8	0
15	26.3	26.1	23.4	20.3	22.1	22.6	0
16	25.4	25.2	23.2	20.8	21.6	21.9	0
17	24.6	23.7	20.9	19.2	20.1	21.0	0
18	22.3	20.1	18.9	17.4	18.1	19.2	0
19	20.0	18.4	18.0	17.1	17.2	17.6	0
20	19.6	18.2	18.0	17.2	16.6	16.7	0
21	19.1	18.1	17.9	17.5	16.0	16.2	0
22	18.7	18.2	18.0	17.7	15.6	15.8	0
23	18.2	18.0	18.3	17.6	16.3	15.5	0
24	17.7	18.0	18.5	17.4	17.0	15.3	0

	cold <70 F
	comfort 70-78 F
	hot >78 F

CONTROL

	Control						
	2-Oct	3-Oct	4-Oct	5-Oct	6-Oct	7-Oct	8-Oct
1	0.0	23.1	18.4	18.5	19.8	20.04	20.04
2	0.0	22.6	18.3	18.8	19.5	19.86	19.65
3	0.0	22.2	18.2	19.0	19.2	19.71	19.22
4	0.0	21.7	18.0	21.0	19.1	19.53	18.82
5	0.0	21.5	17.8	21.0	19.0	19.42	18.43
6	0.0	21.3	17.9	20.8	18.8	19.27	18.13
7	0.0	21.2	17.9	20.6	18.7	19.17	17.85
8	0.0	21.1	18.1	20.4	18.7	19.18	17.91
9	23.0	21.2	18.6	20.4	18.9	19.42	18.28
10	24.3	21.7	19.9	20.4	19.3	20.21	18.95
11	25.2	22.6	21.2	20.6	20.0	21.23	19.95
12	26.0	23.9	22.3	21.0	20.8	22.16	20.8
13	27.6	25.8	23.4	21.6	22.5	24.01	21.03
14	29.0	27.7	23.9	22.2	24.4	25.75	0
15	30.2	29.2	24.1	23.1	25.7	26.99	0
16	30.4	29.6	23.9	23.9	26.1	27.14	0
17	30.0	29.0	22.7	23.6	25.5	26.46	0
18	28.9	27.8	21.1	22.6	24.2	25.36	0
19	27.6	26.2	19.9	21.7	23.0	24.07	0
20	26.5	25.1	19.2	21.0	22.1	23.08	0
21	25.7	24.3	18.8	20.6	21.4	22.3	0
22	25.0	23.6	18.5	20.3	20.7	21.62	0
23	24.3	23.1	18.4	20.1	20.3	20.96	0
24	23.8	22.7	18.3	20.0	20.1	20.47	0

cold <70 F		21.1
omfort 70-78 F		
hot >78 F		25.6

EXPERIMENTAL

	Experimental						
hour.day	2-Oct	3-Oct	4-Oct	5-Oct	6-Oct	7-Oct	8-Oct
1	0.0	18.3	18.4	18.2	16.7	16.7	15.64
2	0.0	18.0	18.3	18.0	16.4	16.7	15.29
3	0.0	17.5	18.2	17.8	16.3	16.6	15.03
4	0.0	17.3	18.0	17.6	16.3	16.4	14.87
5	0.0	17.7	17.8	17.5	16.2	16.5	14.63
6	0.0	17.7	17.9	17.4	16.1	16.5	14.61
7	0.0	17.6	17.9	17.3	16.1	16.6	14.75
8	0.0	17.8	18.1	17.4	16.3	16.7	14.93
9	21.9	18.3	18.6	17.7	16.4	17.1	15.38
10	23.4	18.9	19.9	17.9	16.5	18.0	16.17
11	24.0	19.9	21.2	18.1	16.6	19.3	17.47
12	24.6	21.2	22.3	18.6	17.7	20.3	18.39
13	25.8	23.3	23.4	19.3	20.6	21.9	18.72
14	26.5	25.1	23.9	19.5	21.9	22.8	0
15	27.1	25.6	24.1	20.3	22.2	23.2	0
16	26.7	25.2	23.9	20.6	22.1	22.8	0
17	26.0	24.4	22.7	19.7	21.0	22.0	0
18	24.7	22.5	21.1	18.4	19.6	20.7	0
19	22.9	20.8	19.9	17.7	18.5	19.4	0
20	21.9	19.9	19.2	17.4	17.7	18.4	0
21	21.1	19.4	18.8	17.3	17.0	17.6	0
22	20.3	19.0	18.5	17.2	16.4	16.9	0
23	19.6	18.7	18.4	17.2	16.3	16.4	0
24	19.0	18.4	18.3	17.0	16.6	16.1	0

cold <70 F		21.1
comfort 70-78 F		
hot >78 F		25.6

Fig 4.20. Hot, Comfortable and Cold Hours in series 7.

As in series 4, with a higher air change rate, indoor and outdoor values are closer together when the fan is on.

Table 4.9. Percentage of Hot, Comfortable and Cold Hours in series 8.

	Hot	Comfortable	Cool
Outdoor DBT	3.1	25.8	71.1
Control Cell	12.7	33.3	56
Experimental Cell	0	32.1	67.9

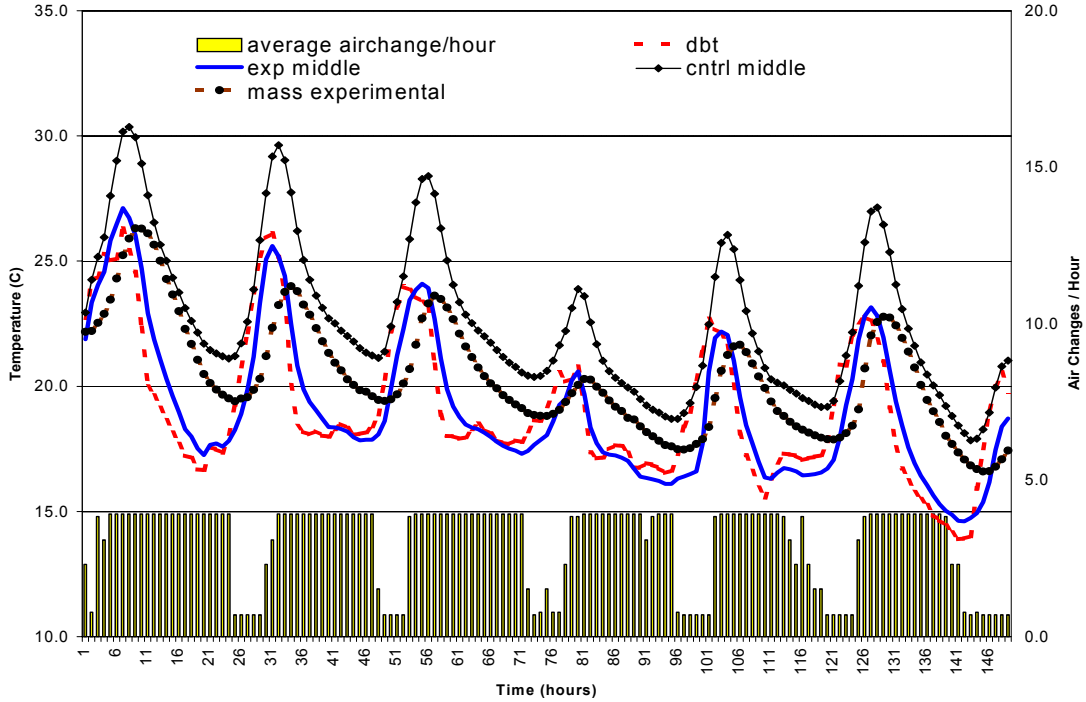

Fig 4.21. Temperatures and air change rates in series 8.

4.2. EXPERIMENTAL RESULTS

Two variables are used to evaluate the performance of the different series: the number of hot hours and the reduction of the maximum temperature. The number of hot, cold and comfortable hours and their distribution during the day permits the examination of the overall patterns inside the cell. The most important of these factors is the number of hot hours in each series because these negatively affect comfort in the summer and require a mechanical cooling system to lower temperatures to a comfortable level. This value is expressed as a percentage of the total number of hours in the series.

The reduction of the maximum temperature, when compared to the swing permits to determine the performance of the series and compare one to another.

4.2.1. Percentage of Hot Hours

The series are compared by the percentage of hot hours in the experimental cell with the control cell (table 4.8 and figure 4.22). The series are discussed with detail in the following paragraphs.

Table 4.10: Percentage of hot hours in the series

	Series 1	Series 2	Series 3	Series 4	Series 5	Series 6	Series 7	Series 8
Outdoor	27.6	21.7	21.5	14.8	14.6	1.7	29.5	3.1
Control Cell	24.5	32.5	32.6	24.4	27.1	20.8	51.2	12.7
Experimental Cell	18.8	15	23.6	14.8	53.1	28.3	37.5	0
Control minus Experimental	5.7	17.5	9	9.6	-26	-7.5	13.7	12.7
Control minus experimental (%)	30.3	116.7	38.1	64.9	49	26.5	36.5	div/0

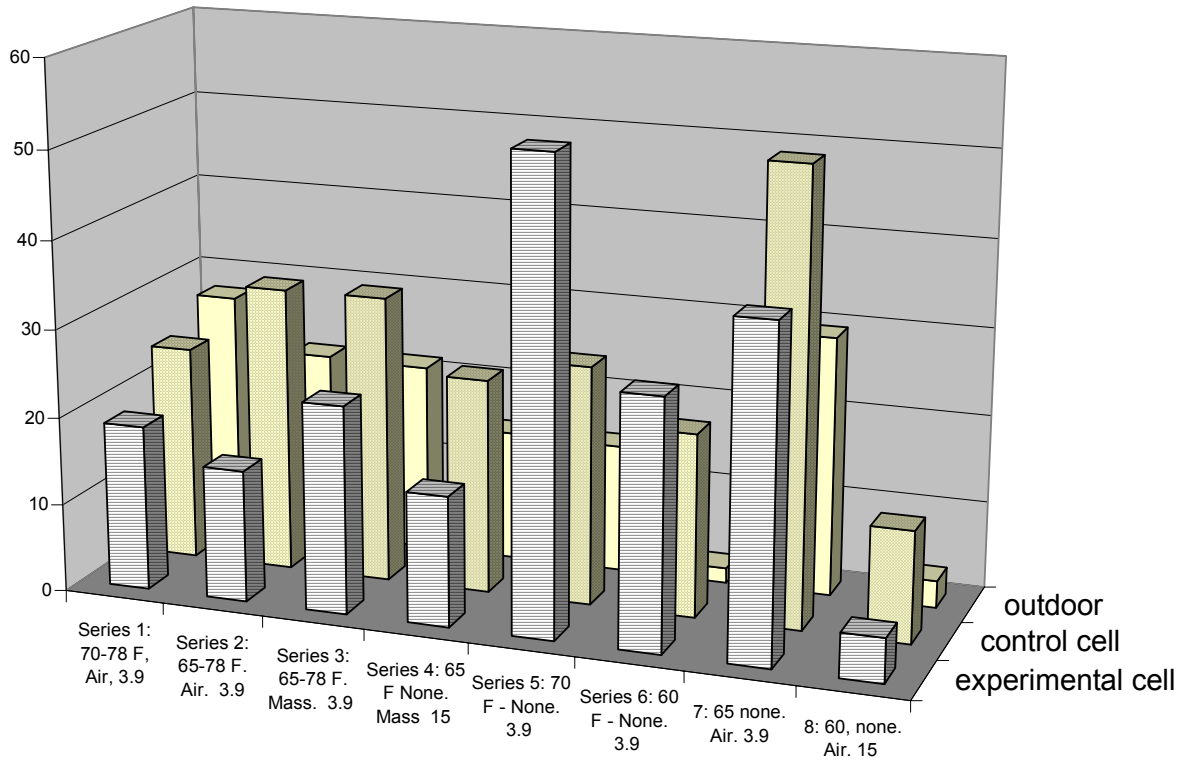

Figure 4.22:Percentage of Overheated hours Outdoors and in the Experimental and Control cells

Series 1 is the basic system configuration with comfort low and comfort high set at the lower and upper limits of the conventional comfort zone (70-78 °F.). The minimum air change rate is 0.7 air changes/hour and the maximum air change rate is 3.9 air changes/hour. This configuration performs better than the control cell, reducing the number of overheated hours from 24.5 % in the control cell to 18.8% in the experimental cell, an improvement of 30.3%. This means that in a typical day with outdoor average maximum temperatures close to 28 °C, 24.5% of the hours are overheated in a typical building compared to 18.8% in the experimental cell with this system operating. The difference between the cells is the potential savings in mechanical cooling.

In series 2, the lower limit of the comfort zone is reduced to determine the cooling effect of a greater outdoor temperature swing in the building. The mass temperature inside the cell will then be lower during the night so that it can absorb more heat during the daytime. To be effective, temperatures during the night should be equal or lower than the comfort low set for the system. With this configuration, the number of overheated hours is reduced from 32.5% in the control cell to 15% in the experimental cell. This is an improvement of 116.7% over the control cell, which is one of the best in all the series. This and results from other series indicate that reducing the value of comfort low (equivalent to increasing the temperature swing) reduces the number of overheated hours.

In series 3 the operation of the cooling system is determined by the relationship of the outside air temperature with the mass temperature inside the building, which is the actual storage medium of the coolth. The analysis of this series permits to determine if it is more efficient to use the

internal mass or the air as the controlling element. The air change rate is increased whenever the outdoor air temperature is lower than the mass temperature, cooling the mass, while the air temperature is used as a comfort control, with the same minimum and maximum values established in the previous series. Even though the experimental cell has less overheated hours than the control cell, the percentage improvement over the control cell (38.1%) is less than in the previous series where the air was the controlling agent (116.7%). Thus, using the mass temperature as the governing criteria for the controller does not seem to be as effective as using the air.

To determine the effect of a higher air change rate, in series 4, the maximum air change rate is increased from 3.9 air changes/hour to 15 air changes / hour. The percentage of overheated hours is reduced from 24% in the control cell to 14.8% in the experimental cell. This is an improvement of 64.9 % over the control series. There is an improvement in the performance of the system when the air change rate is increased but that this not as significant as when the comfort low is reduced.

In series 5 there is no value for comfort high and a fan rated at 560 cfm is placed inside the test cell to generate an air current to destratify the air. The set-up increases the air change rate whenever the air temperature inside the cell is higher than the temperature outside the cell, and above comfort low, which is set at 70 °F.. In this series, the number of overheated hours in the experimental cell is 53.1 %, which is higher than the 27.1% in the control cell. This is an increase of 49% over the control cell and significantly worse than the performance in the first series, which had the same values of comfort low. Two variables were modified in this series, so it is not clear if eliminating the comfort high or increasing the air change rate inside the test cell has a negative effect on the reduction of overheated hours. Both could have a negative effect. The elimination of comfort high permits the entry of hot air at times when the air temperature is above the comfort zone, heating the internal mass. It is preferable to cool the space until the outside air temperature reaches the upper limit of the prescribed comfort zone, after which it should not be permitted to penetrate the building, even if the air temperature inside is higher than outside. When the air temperature reaches the upper limit of the comfort zone, rather than opening the windows, it is preferable to increase the air movement inside the space to increase the comfort sensation or use mechanical cooling. Adding air movement inside the test cell does not reduce the number of overheated hours, probably because the rate of heat loss is also increased and the thermal mass storage space is emptied rapidly.

In series 6 the fan is kept inside the cell and comfort low is also reduced to increase the storage capacity for the heat. There are more overheated hours in the experimental cell than in the control cell by 26.5%. The performance of this series, with air movement inside the test cell, and no upper comfort value is lower than in other series. The performance is better than in the previous series, so lowering comfort low improves the performance of the system, but it is still worse than series 2, so generating continuos air motion and eliminating comfort high seem to have a negative effect on the performance of the system.

In series 7 the internal fan is coupled with the controller system that regulates the air change rate and is only activated when the air change rate of the cell is increased. Now the performance of the experimental cell is better than the control cell by 36.5% which is a significant improvement

over the previous series. Reducing the resistance of the surface of the mass only while cooling the building seems to be an effective way to improve the performance of the system. Modifying the air velocity in contact with the mass when it is being cooled and reducing the air velocity when the mass is not being cooled has a positive effect on the performance of the system.

Series 8 tests the effect of the two variables that seem to be the most effective, increasing the air change rate to 15 air changes hour and reducing comfort low to 65 °F. There is no destratification fan in this series. This is the series with the best performance, and there are no overheated hours in the experimental cell compared to 12.7% in the control cell proving that the combination of a higher air change rate with a reduced comfort low reduces the number of overheated hours. Even though there was no comfort high, this did not affect the performance of the system, probably because the outside air temperature was not very high during this period. Establishing comfort high seems to be a more important factor when the outside temperatures are higher.

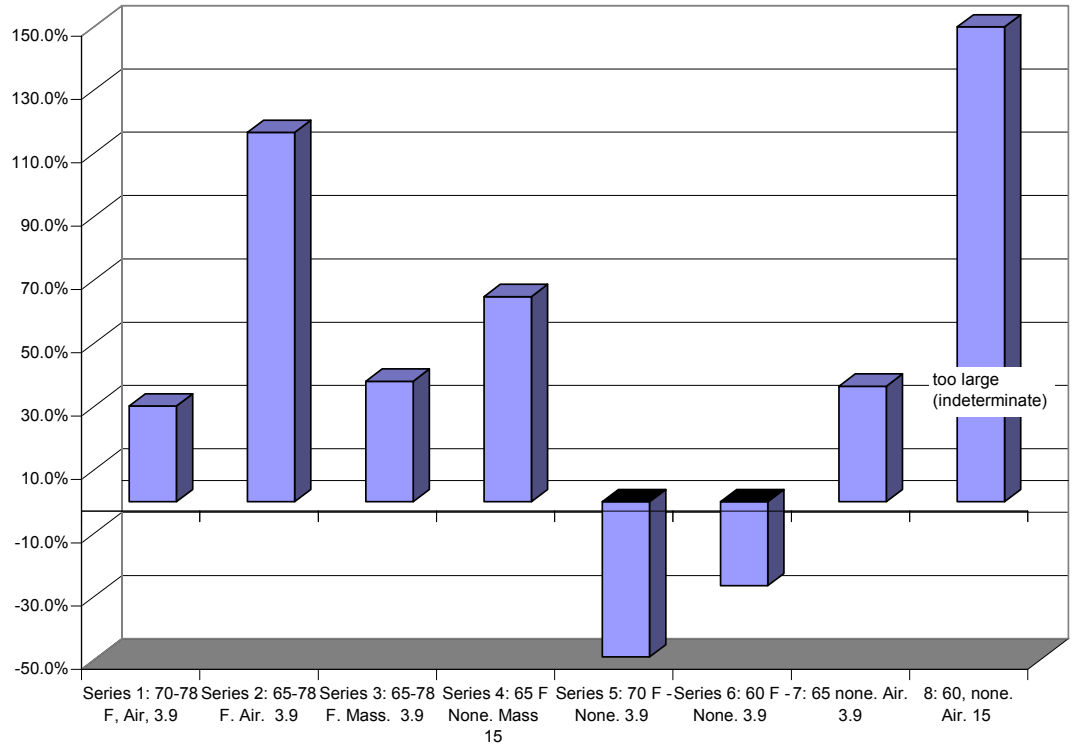

Figure 4.23: Percentage reduction of the overheated hours in the experimental cell compared to the control cell.

After analyzing the different series, the factors that reduce the number of overheated hours and that should be included in the programming of an intelligent thermostat should be:

1. Provide a comfort low and a comfort high. These values should be adjustable by the user and indicate the lower and upper sections of the comfort zone. When the air temperature inside the building is between these values the air change rate with the outdoors should be reduced to the minimum amount necessary for health reasons.

2. Reduce the comfort low to the lowest possible value tolerated by the users. Very good results were achieved with 65 °F. The lowest value of outdoor temperature is also the lowest theoretical value that can be achieved, so comfort lows below this value are useless.
3. Increase the air change rate. Good results were achieved with 3.9 air changes/hour and better results were achieved with 15 air changes/hour. More series have to be performed to determine the optimal air change rate.
4. Use the temperature of the air instead of the temperature of the mass as the controlling element of the system. The rules should use the reference between the indoor and the outside air temperatures to increase or reduce the air change rate.
5. Reduce the surface resistance (e.g. air speed) of the mass while it is losing heat during the cooling process. This will allow the heat to be lost quickly during the cooling process, permitting it to work better as a heat sink.

4.2.2. Reduction of the Maximum Temperature

The reduction of the maximum temperature by itself permits to determine if a system is working well or not, but doesn't permit to compare the series with each other because the weather conditions in during the measurement periods for the different series are different (Fig 4.23 and table 4.9).

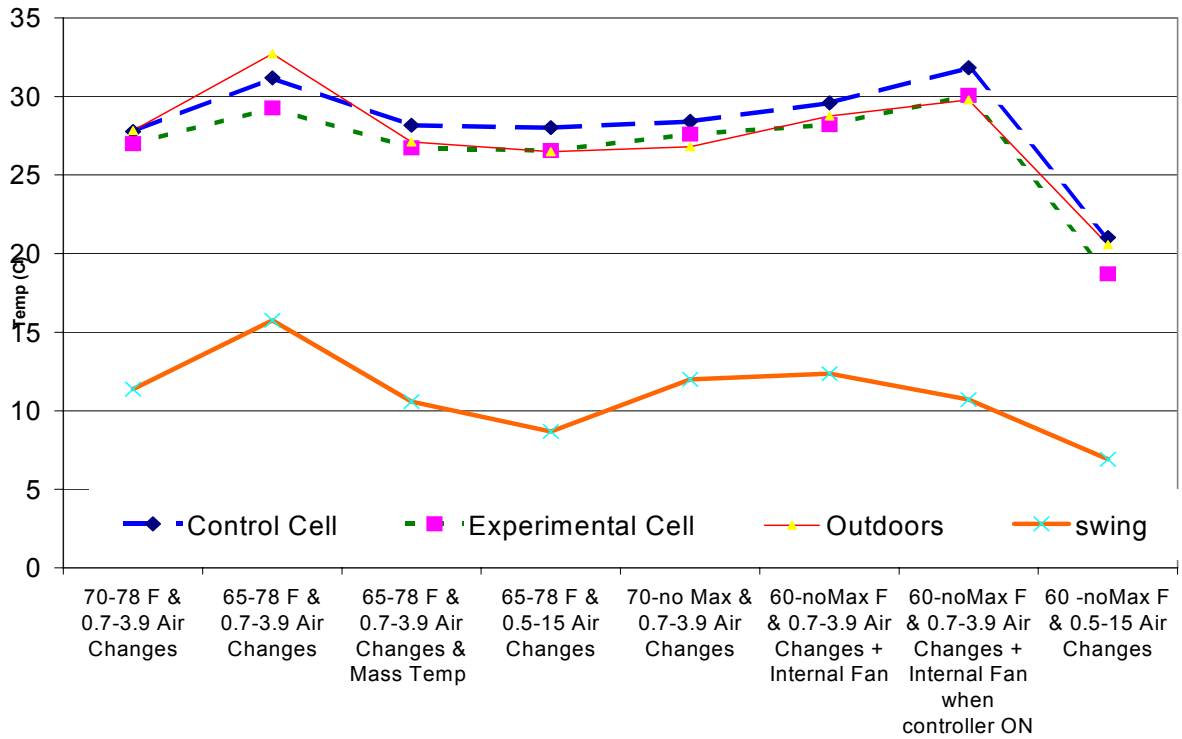

Figure 4.24: Average Maximum temperatures and swing during the different series

Some series are cooler than others are, so in all series, the days with maximum temperatures below 25 °C were discarded because little or no cooling was required on these days. The average maximums after eliminating these cool days are presented in table 4.11.

A simple comparison of the average maximum temperatures inside and outside the cell indicates that all of the configurations of the experimental cell perform better than the control cell, reducing the indoor maximum value by about 6% of the maximum temperature of the control cell. The maximum air temperature inside the experimental cell is not always lower than the maximum outdoor dry bulb temperature but not farther away than 1% of its value.

Table 4.11: Maximum Average Temperatures in the Different Series after eliminating days with maximum temperatures below 25 °C.

Series	**Average Maximum Experimental Cell**	**Average Maximum Control Cell**	**Average Maximum Outside**	**Average Swing**	**Max DBT Minus Experimental Max**	**Max Control Minus Max Experimental**
1: Basic Comfort Configuration	27	27.78	27.84	11.38	0.84	0.78
2: Reduced Comfort Low	27.5	29.3	29.2	12.2	1.7	1.8
3: Reads Mass Temperature	26.73	28.17	27.11	10.58	0.38	1.44
4: No comfort high & 15 air changes/hour	27.1	28.6	27	9.3	-0.1	1.5
5: Comfort Configuration, Destratification fan & 3.9 air changes / hour	27.6	28.43	26.81	12	-0.79	0.83
6: Reduced comfort low	30.8	32	31.4	14.6	0.6	1.2
7: Destratification Fan controlled by Ventilation System	30.07	31.84	29.78	8.9	-0.29	1.77
8: Higher air change with no Destratification Fan	26.37	30	26.21	8.80	-0.16	3.63

The magnitude of the number by itself is not indicative of the performance of a series because of different weather conditions. Only the fact that the experimental configuration reduces the maximum temperature when compared to the control cell is significant. Series 1,2,3,6, and 8 have maximum temperatures lower than outdoors and all configurations have lower temperatures than the control cell.

The different series are analyzed comparing the reduction in the maximum temperature inside the cell with the outdoor temperature swing. A variable which is calculated by determining the average reduction of the maximum temperatures in the each series as a function of the outdoor swing is used to compare the series. This variable is called “performance” and is determined by the following equation:

Performance = Tmaxout - Tmaxin / Tmaxout – Tminout (3)

Where:
Tmaxout: maximum temperature outside
Tmaxin: maximum temperature inside
Tminout: minimum temperature inside

So that:

Performance = reduction of maximum temp / swing

The numerator expresses the reduction of the maximum temperature as compared to the outside maximum, while the denominator is the outdoor swing. In a naturally ventilated building the result can't be higher than the unit and can also be expressed as a percentage. The higher the value, the better the cooling performance of the system. A higher value indicates that there is a larger temperature difference between outdoors and indoors, which is closer to the swing. This performance is calculated for the experimental and control cells and compared. Since some series are cooler than others are, and some had a larger number of cooler days, the days with maximum temperatures below 25 °C were discarded because little cooling was required on these days. The performance of the series with the cooler days discarded is presented in table 4.11. A positive value indicates that the maximum temperature inside the test cell is lower than the maximum outside. A negative value indicates that the indoor maximum is higher than the outdoor maximum. This occurs on clear hot days when the solar radiation gains overwhelm the 'coolth' stored in the mass.

Table 4.12: Performance of the Different Series adjusted for days with maximum temperatures above 25 °C.

Series number & dates	**Comments**	**Performance Experimental Cell**	**Performance Control Cell**	**Numerical Improvement over Control**
Series 1:	Basic Comfort Configuration	7.30%	0.46%	6.84%
Series 2:	Reduced Comfort Low	13.93%	-0.82%	14.75%
Series 3:	Reads Mass Temperature	3.56%	-10.01%	13.57%
Series 4:	No comfort high & higher air changes/hour	-1.08%	-17.2%	16.13%
Series 5:	Comfort Configuration, Destratification fan & 3.9 air changes / hour	-6.58%	-13.46%	6.88%
Series 6:	Reduced comfort low	4.11%	-4.11%	8.22%
Series 7:	Destratification Fan controlled by Ventilation System	-3.3%	-23.1%	19.8%
Series 8:	Higher air change with no Destratification Fan	-1.82%	-43.07%	41.25%

In all series the performance of the experimental cell is better than the performance of the control cell. After adjusting only for days that have maximum temperatures above 25 °C, series 2 has the best performance but series 8 has the best improvement over the control cell. Series 8 and 7, even though have negative values for the performance have a significant improvement over the control cell and series 2,3 and 4 also have significant improvements over the control series.

In the performance analysis and the analysis of the overheated hours, the four best series are the same, numbers 2,4,7 and 8, with number 8 and number 2 as the best. The common denominators in these series that increase the performance of the cells as described in this section are the same factors that also reduce the number of overheated hours: reduction of comfort low, increase in the air change rate, and selective air motion inside the cell.

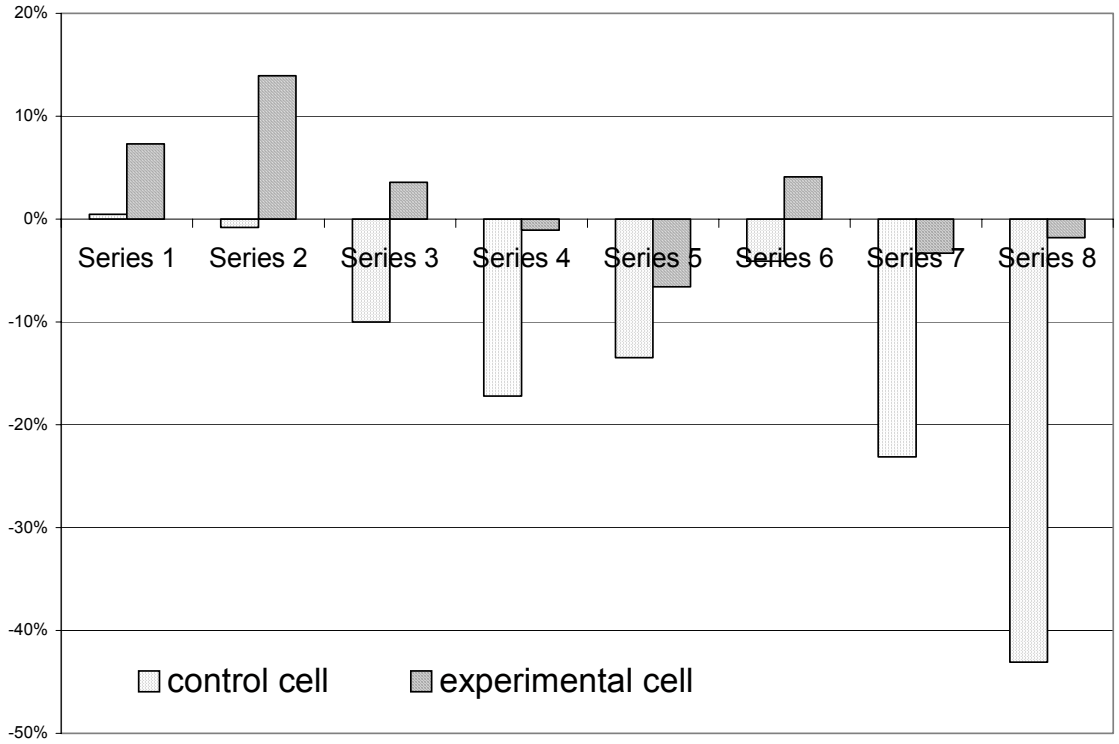

Figure 4.25: Performance in the Control Cell and Experimental cell

4.3 SIMULATION SERIES

California has 16 different climate zones as defined by the California Energy Commission. All these experiments were conducted at the UCLA Energy Lab, which is in Climate Zone 8, close to the boarder with Climate Zone 6. In order to get a rough idea of how this new type of thermostat would function different climates, a series of building performance simulation runs were conducted.

Annual energy costs were calculated for a basic 2000 sq.ft house that meets the California Energy Code in each zone using an energy performance program called HEED. Hourly climate date is available for 14 of California's climate zones. The house is a typical California tract house with a slab on grade, stud and stucco walls, and glass area and glass type as allowed by the Code in each zone. The Series 1 controller logic was used with 0.5 air changes of infiltration, and 1.0 air changes of natural ventilation in the Code Minimum Vented building, and up to 10 air changes in the same building using Smart Thermostat controlling a whole house fan. Both buildings had an air conditioner and a furnace. This meant that daytime comfort conditions (70 to

78 F) were always maintained in these homes. All costs were calculated using the Southern California Edison new 5-Tier rate structure, and the Southern California Gas residential energy rates averaged for the prior year.

	Home with Code Minimum Ventilation			Home with Smart Thermostat and Whole-house Fan			Energy Cost Savings
Climate Zone	**Electricity**	**Gas**	**Total**	**Electricity**	**Gas**	**Total**	**Difference**
01 Arcata	1145	700	1845	1146	701	1847	2
02 San Francisco	1209	338	1548	1110	347	1457	91
04 Sunnyvale	1387	295	1682	1134	296	1431	151
05 Santa Maria	1221	152	1374	1068	272	1340	34
06 Los Angeles LAX	1538	65	1603	1109	65	1174	429
07 San Diego	1652	36	1689	1167	37	1204	485
08 El Toro	1641	44	1689	1811	48	1230	459
09 Thousand Oaks	1845	77	1923	1228	87	1315	508
10 Elsinor	1867	251	2118	1442	254	1697	411
12 Sacramento	1925	179	2105	1314	283	1597	508
13 Fresno	2274	167	2442	1725	259	1984	458
14 Daggett	2811	105	2917	2317	108	2426	491
15 Las Vegas	2868	187	3056	2353	192	2545	511
16 Reno	1623	682	2305	1380	938	2318	-13

The results show that this type of smart whole-house fan cooling strategy saves very little money in the cooler coastal climates (Zones 1,2,5) and in the high mountains (zone 16). It is much more cost effective in all of California's inland climates. Notice that while it reduces electricity consumption, primarily for the air conditioner, it inevitably increases gas consumption of heat slightly.

This analysis shows that there is a better return on investment for many California homeowners to invest in this smart thermostat and a whole house fan, then to put this same amount of money in the best bank certificate of deposit (it would require a $5600 investment at 8% to equal the annual energy savings of this system, which should cost much less than that to install). The utilities should be willing to financially aid homeowners install such systems because it will help to reduce their system peaks on the hottest periods of the year, and also shift more load into the night time hours when the fan is running to flush heat out of the building. In one sense the utility could avoid the cost of installing a peaking generator if enough of their customers install this fan-thermostat system in their homes.

Once such a smart thermostat reaches production, there should be a viable market in many parts of California.

5. CONCLUSIONS

After analyzing the results several conclusions can be stated:

1. Today there is no microprocessor/thermostat on the market that senses both outdoor and indoor temperatures, and uses intelligent logic to control a whole-house fan. This project demonstrated that such a system would allow California homeowners to minimize or even eliminate the need for air conditioning.

2. Ventilation controlled with an intelligent microprocessor/thermostat that measure outdoor air temperature can improve the thermal comfort inside homes with medium thermal mass (slab on grade floors) typical of single family dwellings in many California climates. Both the maximum indoor temperatures and the number of overheated hours can be significantly reduced when compared a building without this intelligent ventilation controller.

3. Because the test cells have a large south glazing to floor ratio (12.5%, twice the code minimum), the large amount of radiation that penetrates through this unshaded window sometimes overwhelms the cooling effect of the ventilation system. A precondition to the application of any ventilation cooling strategy is to minimize the heat gains by radiation through windows, and the heat gains and losses by conduction through the building envelope, so that the ventilation rate, regulated by the intelligent controller, is the main mechanism of heat transport. Shading the windows, insulating the building envelope, and minimizing infiltration can do this.

4. Increasing the air change rate increases the performance of the system. When the air change rate is increased from 3.9 to 15 air changes per hour the maximum temperature was reduced by 1.5 C compared to the control building. More series have to be performed with different air change rates but our results indicate that a typical whole house fan should provide a maximum air change rate similar to the tested rate of 4 air changes/hour. The infiltration rate is a function of health and energy and since health issues were not considered in this project, there is no minimum air change rate proposed. But for energy conservation an air change rate of about 0.8 air changes / hour similar to the tested seems to be sufficient in southern California's climate.

5. There is no evidence to indicate that when the system is controlled by the relationship of the mass temperature with the outdoor air, the performance is better than when it is governed by the air temperature difference. This indicates that even though the mass in the building plays an important role as a storage medium, air temperature inside the cell, which is affected by the thermal mass, is a better control variable for the ventilation system.

6. A potentially negative effect of using natural ventilation for cooling is that night temperatures inside the building might drop below the comfort zone. This will happen if thermostat night flushing temperatures are set below the comfort zone in order to increase the buildings 'coolth' storage capacity during the night and to flush out the heat gained during the day. But since these cool hours occur at night, between midnight and sunrise, it has far

less impact on occupant comfort, especially because many people actually prefer to set back their thermostats to lower night time temperatures.

7. Increasing the movement of the air recirculating inside the space reduces its stratification and increases the convective gains and losses from the thermal mass, as well as through the walls and roof surfaces of the building. This can be achieved by simple means such as a ceiling paddle fan or small portable fans. This interior air movement is most effective when cooling down the mass. However, when there is a limited amount of mass available, increased indoor air recirculation will discharge the 'coolth' from mass too rapidly, rather than spreading its effect throughout the day. Experimental results show that best results are achieved if the recirculating fan is operated only when the ventilation (night flushing) fan has been turned on. Whenever this indoor fan is operating, the occupants' sense of being comfortable (comfort cooling) will also increase even though air temperatures are not reduced.

8. When the lower limit of the comfort zone is lowered to 65 F, there is a reduction in the number of hot hours and the maximum temperature inside the cell. This is probably the single most important factor that should be considered in any passive cooling system that uses natural ventilation. Even with medium mass slab on grade buildings, a lower temperature at night makes a big difference in the capacity of the building to flush the heat stored inside the building (to store 'coolth'). For this system to be effective, night temperatures should reach values below 70 F and close to 65 F. This 65 F outdoor air temperature is reached at night during the summer in many parts of inland California because of our typically large day-to-night temperature differences, especially in the deserts.

9. An advantage of an intelligent thermostat controller that measures outdoor air temperatures, compared to a system that measures only the indoor air temperature, or a system with a fixed timer, is that the intelligent controller increases the air change rate only when it is needed and when resources for cooling are available, rather than at times when it inadvertently heats the building.

10. With an intelligent thermostat controller it is possible to maximize the effectiveness of the mass in a building, to achieve better cooling results with only slab on grade construction, than in a building with more thermal mass that isn't provided with an intelligent controller for natural ventilation cooling.

11. Using hourly climate data for 14 different California climate zones, the building performance simulation study shows that there is a better return on investment for many California homeowners to invest in this smart thermostat and a whole house fan, then to put this same amount of money in the best bank certificate of deposit. The utilities should be willing to financially help homeowners install such systems because it will reduce their system peaks on the hottest periods of the year, and also shift more load into the night time hours. In one sense the utility could avoid the cost of installing a peaking generator if enough of their customers install this fan-thermostat system in their homes. Thus once such a smart thermostat reaches production, there should be a viable market in many parts of California.

12. The most effective rule that would be recommended for an intelligent thermostat is:

If $t_o < t_i$ and $t_i >$ Cf_low and $t_i <$Cf_high *then* activate fan

Where:
$t_{o:}$ Temperature outside
$t_{i:}$ Temperature inside
C_{f_low}: Comfort low = 65 F
C_{f_high}: Comfort high = 78 F

Note: Comfort low and comfort high should be adjustable by the user

6. RECOMMENDATIONS

The use of this new type of intelligent thermostat that measures both outdoor and indoor air temperatures, will save energy and reduce indoor temperatures without assistance of a mechanical cooling system in climates with cool night temperatures. Experimental results showed that in all cases this type of system always produced cooler indoor comfort conditions than an identical building without such a controller. From a building design point of view, more comfortable indoor conditions will occur if solar gains into the building are be reduced by shading the windows, using insulation in the building envelope, and providing an amount of mass at least equivalent to a concrete slab on grade.

7. PUBLIC BENEFIT TO CALIFORNIA

7.1 MAKING THIS NEW PRODUCT AVAILABLE:

There is no microprocessor controlled thermostat on the market today that reads both indoor and outdoor temperature and that can control whole-house fans in addition to an air conditioner and a furnace. This means that the potential size of the market is conjectural. It seems clear that it will have the greatest appeal to homeowners in those California climate zones where this strategy can eliminate the need to install an air conditioner.

The objective of this project is to encourage companies like Honeywell and Johnson, as well as manufacturers of whole-house fans to see this new type of thermostat as a valuable addition to their product line. All the components are 'off the shelf', including thermistors on long leads and microprocessors chips. In fact many programmable thermostats already have microprocessors built in. Examples of thermostats, such as Honeywell's Chronotherm, with user interface designs that could handle the additional information are also already on the market. Initially this innovative new product will appeal to the small market of early adapters, but once field experience grows the potential market is huge. It should prove to be cost effective in hundreds of thousands of California homes.

Cost effectiveness is a complex calculation, especially without knowing the eventual manufacturing or retail cost of this new product. However, a rough estimate is possible, by recalling that the standard residential programmable thermostat is generally thought to have a 1 to 2 year payback, in other words it saves enough money in heating costs to pay for its initial purchase price. Assuming that the additional functionality proposed here would double its cost, and if it saved about as much in cooling cost as it previously saved in heating costs alone, then this new thermostat also would have a 1 to 2 year payback.

7.2 MARKET IMPACT:

Air conditioning represents the second largest category of electricity consumption in California homes. If the thermostat/controller developed in this project reaches the market place, it should prove to be cost effective and could permanently transform an initially small but steadily growing share of California's electricity market.

The potential impact is immense. If residential air conditioning in California uses roughly .3QBtu (Quads), and if this product leads to the elimination of just one air conditioner in a thousand, then it could save over 100,000 Mwhr per year. It is also worth noting that this product will have a significant impact during the hours California's Electric Utilities are experiencing their maximum peak loads, in min-afternoon on the hottest days of the year, thus it will help 'shave the peaks'. Because it also runs at night to 'night flush' the home, when the utilities have their lowest load factor, it will help to 'spread the load'. Thus this new product, targeted for this potentially huge residential market, will benefit ratepayers and utilities alike. It is a win-win situation.

7.3 ADDITIONAL SPIN-OFF PRODUCTS:

Once this product reaches the market, it will in turn create the demand for a number of additional new building products. Quieter, more efficient whole-house fans are needed. Pressure balanced fresh air inlets will improve the overall efficiency of the system. If natural ventilation is to be managed by this controller, then some type of automatically controlled window openers will be needed. There will also be the need for residential-scale inlet air filters. These are examples of possible new commercial products that need to be developed and manufactured, assuming that market demand for this kind of cooling strategy can be generated.

7.4 DISSEMINATION: PRODUCT DELIVERY MECHANISM:

It should be noted again that this proposal is only a feasibility study. Clearly it is in the interest of both the University of California and the California Energy Commission to get innovations like this into the hands of consumers as quickly as possible. The authors of this study stand ready to support the process of helping this product reach California homeowners.

8. DEVELOPMENT STAGE ASSESSMENT

8.1 WORK COMPLETED BEFORE THIS PROJECT BEGAN

1. Marketing: Stage 1. Idea Generation:

There is no intelligent thermostat on the market that reads both indoor and outdoor temperature and can control whole-house fans or operable sun controls, so the potential size of the market is conjectural. It will appeal to homeowners in many California climate zones where this strategy can eliminate the need to install an air conditioner. All the components are 'off the shelf', including thermistors on long leads and microprocessors built into thermostats. Companies like Honeywell and Johnson, as well as manufacturers of the operable sunshades should see this as a valuable addition to their product line. Initially it will appeal to the small market of early adapters, but as field experience grows the potential market is huge. It could prove to be cost effective on hundreds of thousands of California homes.

2. Engineering/Technical: Stage 1. Idea Generation:

We have developed the concept and have assembled the team to demonstrate the technical feasibility. The concept is to develop a controller software that uses both indoor and outdoor temperatures to control a whole-house fan to provide 'free' sources of cooling.

2. Engineering/Technical: Stage 2. Technical and Market Analysis:

We have already conducted a series of similar feasibility experiments. We have surveyed the marketplace and found no similar competing products. The product design and manufacturability should pose no unusual problems, and installation and maintenance should be within the technical capabilities of conventional residential HVAC contractors.

3. Legal/Contractual: Stage 1. Idea Generation:

All our technical information will be published in the public domain. The basic idea does not seem to be patentable because all of the components are generic and interchangeable, and there is probably no royalty potential for PIER program.

4. Risk Assessment/Quality Plans: Stage 1. Idea Generation

There are no known or potential environmental or life safety risks.

5. Strategic: Stage 1. Idea Generation

Because this is a direct benefit to ratepayers, there is a good fit with the PIER Program objectives. It will reduce electrical consumption in California, especially at peak air conditioning times. It has the added advantage of shifting some residential electrical usage to the midnight to 6 AM off peak hours.

6. Production Readiness/Commercialization: Stage 1. Idea Generation:

The potential cost is similar to current high-end thermostats, and the time-to-market could be short because of its use of off-the-shelf components. It is an easily grasped concept that should make commercialization straightforward. It would most naturally fit into the product line of current thermostat manufacturers and as a market expanding option for operable sunshade manufacturers.

7. Public Benefits/Costs: Stage 1. Idea Generation:

This controller should eventually prove to be cost effective on hundreds of thousands of California homes, provided that it eliminated the need to install an air conditioner. It will use much less electricity that the equivalent cooling that would be produced by an air conditioner. Because of the very low power demands it will appeal to people installing photovoltaic systems. The public benefit is that if widely adopted this will reduce the need to increase the number of power plants and to expand the distribution grid.

8.2 WORK COMPLETED UNDER THIS EISG FUNDED PROJECT

2. Engineering/Technical: Stage 3. Research:

This was the main activity of this proposal, the refinement of the technical product specification. Initially we developed the performance criteria and experimental test plan. We then constructed a microprocessor capable of functioning as a full-feature thermostat and fan controller. We wrote the controller logic software that evolved on the basis of the experimental test results.

2. Engineering/Technical: Stage 4. Technology Development:

We tested the components of the prototype system on full-height test cells using fans and dampers controlled by the microprocessor/thermostat. We were able to quantify the performance in terms of the actual indoor air temperatures produced compared to the control test cell. We these tests demonstrated the technical feasibility of the concept, and could lead to detailed technical product specification for a potential manufacturer.

7. Public Benefits/Cost: Stage 2. Technical and Market Analysis

As part of this project originally planned to develop a new simulation component for a large whole-building energy and economic simulation program that we have been developing under another PIER contract administered by Southern California Edison. This program includes California's new 5-tier residential rate structures, so it could accurately compare the cost and thermal performance of typical tract houses in different climates with and without this new whole-house fan controller.

8.3. DEVELOPMENT ASSESSMENT MATRIX

Stages Activity	1 Idea Generation	2 Technical & Market Analysis	3 Research	4 Technology Develop-ment	5 Product Develop-ment	6 Demon-stration	7 Market Transfor-mation	8 Commer-cialization
Marketing								
Engineering / Technical								
Legal/ Contractual								
Risk Assess/ Quality Plans								
Strategic								
Production. Readiness/								
Public Benefits/ Cost								

Legend:

Completed Work	
Projected EISG Funded Work	
Projected Applicant Contribution	

9. REFERENCES

ASHRAE Handbook. (1997). Fundamentals. Inch-Pound Edition. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Auliciems, A., Szokolay S.: Thermal Comfort, PLEA Note 3 Series Design Tools and Techniques, PLEA, 1997. 64 pp.

Bansal, N., Hauser, G., Minke, G. (1994). Passive Building Design: a Handbook of Natural Climatic Control. Elsevier Science. Netherlands. 336 p.

Cook, Jeffrey. 1989. Passive Cooling. Massachussets Institute of Technology. MIT Press.

De Waal, H.B. (1993): New recommendations for building in tropical climates, Building and Environment., Vol. 28. p. 271-285.

Nicol, F., Jamy G, Sykes, O., Humphreys, S. Roaf S., Hancock M: Thermal Comfort in Pakistan U.K.: Oxford Brooks University, School of Architecture.

Givoni B. (1995). Passive and Low Energy Cooling of Buildings. Van Nostrand Reinhold. 262 p.

Givoni B. (1998). Climate Considerations in Building and urban Design. Van Nostrand Reinhold. 464 p.

Givoni, B. (1992): Comfort, Climate analysis and building design guidelines, Energy and Buildings. Vol. 18. N 1. p. 11-23.

Givoni, B. (1995). Passive and Low Energy Cooling of Buildings. Van Nostrand Reinhold.. New York. 263 p

Humphreys, M.A.: Thermal Comfort Requirements, Climate and Energy, Proceedings of the Second World Renewable Energy Congress. Reading, U.K. 1725-1734 pp. 1992.

La Roche, P., Machado, M.,. (1999). Materials and appropriate design strategies for buildings in hot climates. Congress: PLEA 1999, The 16th International Conference on Passive and Low Energy Architecture. p 357-362

La Roche, P. Milne, M. (2001). Smart Controls for Whole House Fans. Cooling Frontiers, The Advanced Edge of Cooling Research and Applications in the Built Environment. October 4-7, 2001. College of Architecture and Environmental Design, Arizona State University.

Murray Milne, Carlos Gomez, Don Leeper, Yoshihiro Kobayashi, Jennifer Zurich, Deborah Weintraub, Hernando Miranda. "A Drag-and-Drop Energy Design Tool", Proceedings of the American Solar Energy Society, April, 2001

Murray Milne, Carlos Gomez, Donald Leeper, and Yoshihiro Kobayashi. "Strategies to Visulaize the Cooling Performance of Buildings" Cooling Frontiers, the Advanced edge of Cooling Research and Applications in the Build Environment, College of Architecture and Environmental Design, Arizona State University, October, 2001

Murray Milne, Carlos Gomez, Don Leeper, Yoshihiro Kobayashi, Jennifer Zurick, Deborah Weintraub, Hernando Miranda "HEED, Home energy Efficient Design", Proceedings of PLEA 2001, the Passive and Low Energy Architecture Association, Florianopolis, Brazil, November 2001

Stein, B., Reynolds, J. Mechanical and Electrical Equipment for Building. Eighth Edition.. John Wiley and Sons, Inc. 1627 p

Download Energy Design Tools at UCLA: http://www.aud.ucla.edu/energy-design-tools

Home Energy Efficient Design (HEED) download page: http://www.aud.ucla.edu/heed