Arnold Schwarzenegger,
Governor

Final Report for Profitability, Quality and Risk Reduction through Energy Efficiency

PIER FINAL PROJECT REPORT

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Prepared By:
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Prepared By:
Dr. Robert Hammon
Building Industry Institute
Sacramento, CA
Contract No. 400-00-037

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

Martha Brook,
Contract Manager

Ann Peterson,
Program Area Team Lead

Nancy Jenkins,
Office Manager
Energy Efficiency Research Office

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

B. B. Blevins,
Executive Director

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Program and Contract Management: Martha Brook and Nancy Jenkins, California Energy Commission. Eric Stubee, SAIC.

Lead Researchers: Mark Bernstein, RAND. Chris Fennell, NAHBRC. Russell King, ConSol. *Subcontractors to these researchers are noted at the start of each project section.*

Public Advisory Committee (PAC):

Craig Wray Lawrence Berkeley National Laboratory Berkeley, CA
John Proctor, Proctor Engineering Group, San Rafael, CA
Karl Brown, CIEE/University of CA, Berkeley, CA
Marshall Hunt, Pacific Gas and Electric, San Francisco, CA
Ren Anderson, National Renewable Energy Laboratory, Golden, CO
Rob Ferguson, PMI, Inc., Poway, CA
Thomas Hamilton, CHEERS, Chatsworth, CA
Tony Pierce, P. E., Southern California Edison, Irvindale, CA
Saeed Bekam, Gouvis Engineering, Newport Beach, CA

Technical Advisory Groups (TAG):

Element 5 TAG Members: Mike Beam (Bassenian and Lagoni), Charles Curtis (Centex), Bill Dakin (Davis Energy Group)

Additional Support:

Meyers Group
Builder Partners

- The Brehm Companies
- Centex Homes
- Shea Homes

Building Industry Institute (BII)
Home Buyers Warranty
Fannie Mae

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 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

What follows is the final report for the Profitability, Quality and Risk Reduction through Energy Efficiency, 400-00-037, conducted by the Building Industry Institute. The report is entitled, Final Report for Profitability, Quality and Risk Reduction through Energy Efficiency. This project contributes to the Buildings End-Use Energy Efficiency program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

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ABSTRACT

The *Profitability, Quality and Risk Reduction through Energy Efficiency Program* is comprised of four research projects that focus on integrated design topics to save energy and improve construction quality.

Improved Energy Efficiency, Comfort, and Quality Construction through Reduced Warranty Calls focused on improving energy efficiency in new production homes using the non-energy benefits of quality and comfort, and their impact on profit, to motivate builders to change their building practices. The existing data was insufficient to support an analysis of reasons for callbacks. Alternative sources were examined with the same results. A survey process was implemented to derive qualitative data on callback costs.

Value of Quality, Comfort, and Energy Efficiency in New Homes examined the relative importance of comfort, quality, and energy efficiency in the home buying decision. The existing data was insufficient to support an analysis of consumer value of energy efficiency, comfort, and quality. Alternative sources were explored with limited results.

Increased Energy Efficiency through Improved Mortgage Products identifies ways to increase energy efficiency in new production homes, using the non-energy benefits of quality and comfort, and their impact on the mortgage, sales and profit, to motivate builders to change their building practices. The existing data was not sufficient to determine foreclosures associated with energy costs. Further work on this project was cancelled.

Increased Energy Efficiency through Improved HVAC Tools focused on improving the current state of computer tools and the design methods used to size and locate HVAC systems so that new California homes will demand less energy.

Some of this program's key products are:

- Computational Fluid Dynamics Study
- HVAC Design Guide

Keywords: productivity, energy efficiency, HVAC, quality, comfort, energy efficiency, computational fluid dynamics, design guide

EXECUTIVE SUMMARY

Introduction

This report summarizes the work performed between March 2001 and June 2004 as part of the Profitability, Quality and Risk Reduction through Energy Efficiency Program. This research was supported by the California Energy Commission's (Commission) Public Interest Energy Research (PIER) Program.

The overall goal of the Profitability, Quality and Risk Reduction through Energy Efficiency program was to develop new builder profit incentives to encourage energy-efficient construction. The program explored increasing profit incentives through reducing warranty costs, improving mortgage products, and raising the consumer value of energy efficiency by linking it to quality and comfort. The program also sought to develop improved analytical tools for designing residential HVAC systems. The program consisted of four research elements:

Element 2. Improved Energy Efficiency, Comfort, and Quality Construction through Reduced Warranty Calls led by Mark Bernstein, RAND.

Element 3. Value of Quality, Comfort, and Energy Efficiency in New Homes led by Christopher Fennell, NAHB Research Center.

Element 4. Increased Energy Efficiency through Improved Mortgage Products led by Chris Fennell, NAHB Research Center.

Element 5. Improved HVAC Design Mechanisms led by Russell King, ConSol

Element 2 - Improved Energy Efficiency, Comfort, and Quality Construction through Reduced Warranty Calls

This element focused on improving energy efficiency in new production homes, predominately in inland areas, using the non-energy benefits of quality and comfort, and their impact on profit, to motivate builders to change their building practices. Improved design and construction practices, which may cost more initially, could be cost-effective when warranty costs are considered. Improvements in home building construction can contribute to reduced calls, reduced energy use, and reduced first costs. Element 2 originally included the following three projects:

- Project 2.1. Warranty and Builder Call-Back Data Analysis
- Project 2.2 Improved Construction Protocols
- Project 2.3 Builder Costs and Benefits of Improved Construction Practices

Element 2 Objective

The overall goal was to develop a cost-neutral improvement in energy efficiency, comfort, and quality through savings derived from reduced builder warranty and callback costs. Specific goals included:

1) Identify specific categories of warranty calls and builder callbacks that could be avoided through higher quality construction that would result in increased energy efficiency,
2) Determine the changes in construction practices that would be needed to improve the quality, comfort, and energy efficiency,
3) Develop quality construction protocols for builders to use to improve quality, comfort and energy efficiency, and reduce warranty costs,
4) Determine the costs to the builder of the changes in construction practices that would be needed to implement the quality construction protocols, and
5) Determine the profit potential to the builder if the improved practices are implemented into future home building construction.

Project 2.1 Warranty & Builder Call-Back Data Analysis

This project was designed to identify specific categories of warranty calls and builder callbacks that could be avoided through higher quality construction, resulting in increased comfort and energy efficiency. Costs to fix these construction problems would be determined, as well as the additional impacts on builder profit due to these construction defects.

Findings & Conclusions

- *Home warranty data is insufficient in detail to support an analysis of reasons for callbacks*. The Home Buyers Warranty (HBW) database was examined to determine reasons for warranty callbacks. However, the HBW data did not include the type of information that was needed for this analysis. Complaint categories were too general (HVAC, drywall, electrical, etc.) with no detailed descriptions of problems or their resolutions. Often, callbacks go directly to subcontractors with no follow-up at the corporate builder level. This leaves builders with no way to track these complaints or their associated costs.
- *Alternative data sources yielded a similar lack of detail as the HBW data.* A builder database was examined for callback causes and costs. General callback costs were available but not specific costs. The attributes tracked by the builder did not include the details of the problem or its resolution. Set-asides for callbacks costs seemed to be based on general experience. It was not clear that the builder had sufficient information to tailor training to impact comfort and quality in his training program. The builder that shared its corporate data with the research team was in the process of building a new database to

support this need, but the new database had not yet evolved to the point it could be used to address the research questions.

- *Using a survey/interview process, HVAC system problems, a clear energy-related issue, was revealed as a primary callback complaint.* A survey/interview process was implemented to derive qualitative data on callback costs. Representatives from several California builders were interviewed using a pre-planned questionnaire. The interviewees included executive level representatives from the Sales and Marketing, Construction, and Purchasing organizations of large production building companies.
- *Further research in this area will be unsuccessful without better quality information on the causes and resolution of callbacks.* The methods currently used by production homebuilders to document warranty calls and builder callbacks are not sufficient to identify potentials for energy efficiency improvements. While the currently available data are insufficient for this research, at least one of the builder partners has identified the need for such detailed information and is implementing a system to collect it. Future research efforts will benefit greatly from this investment. In the future, effort should be invested in understanding how this information impacts business and construction practices.

Outcomes

- The project identified typical warranty and callback issues at three representative California builders, which are documented in the "Warranty and Callback Builder Survey" report (Appendix, Report IV).
- Builder survey results focused this research on the development of an HVAC Design Guide useful to the entire production home industry. The primary callback complaint revealed during the survey process was HVAC system problems, a clearly energy-related issue. As a result of this survey information, Element 5 of this program became more focused on the development of an HVAC Design Guide that would be useful from site planning through construction and occupancy.
- Because a definitive link between the number and types of builder callbacks and energy efficiency could not be established, efforts to develop improved construction protocols in Projects 2.2 and 2.3 were discontinued.

Element 3 - Value of Quality, Comfort, and Energy Efficiency in New Homes

This element focused on understanding the role of comfort, quality, and energy efficiency in consumer buying decisions, and developing an improved home rating system which could drive sales of energy-efficient homes. Element 3 originally included the following three projects:

- Project 3.1. Consumer Value of Quality, Comfort and Energy Efficiency (QCEE)
- Project 3.2. QCEE Rating System

- Project 3.3. Consumer Value of QCEE with Rating System

Element 3 Objective

The overall goal of this research was to clarify the relative importance of comfort, quality, and energy efficiency in the home buying decision. This was to be obtained through further, focused analyses of existing data from marketing groups. Specific goals included:

1) Document current consumer value of energy efficiency, as well as the ancillary benefits of comfort, and quality, in new production homes. Determine how consumers currently evaluate these illusive home attributes,
2) Increase the ability of homebuyers to compare the quality, comfort and energy efficiency of new homes, through the development and assessment of an improved home rating system,
3) Document the consumer value of energy efficiency, comfort and quality once there is a rating for these home attributes, which are normally not tangible to the consumer.

Project 3.1 - Consumer Value of QCEE

This project was designed to determine the consumer value of home energy efficiency, comfort and quality. This value was to be compared to the other factors typically considered in home buying decisions, such as location, floor plan, amenities and price. The ability of home ratings to define and influence consumer opinions would then be judged.

Findings & Conclusions

- Existing homebuyer preference data was insufficient in detail to support an analysis of consumer value of home energy efficiency, comfort, and quality. The Meyers Group database (Visions 2000) was examined to determine the key factors involved in the homebuyer's purchase decision. The Visions database did not contain the data needed to make any determination associated with home energy efficiency. Alternative data sources yielded results similar to the Visions database. All were fairly broad surveys, not specific to the research questions. The alternative surveys investigated used vaguely worded questions that made drawing appropriate inferences difficult, revealing the need for consistent definitions of quality, comfort and energy efficiency. Definitions for these terms were developed that could generate useful data in future surveys on the topic.
- Although consumer value of home energy efficiency, comfort and quality cannot be determined from existing data sources, this remains a viable area for future research. A conjoint analysis using a web-based consumer audience has been proposed by the NAHBRC to assign value to the attributes of quality, comfort, and energy efficiency. The consumer survey that generates

the Visions 2000 database is also available for enhancements to capture this information.

Outcomes

Because existing data could not support an analysis to establish the consumer value of quality, comfort, and energy efficiency, work to develop a new QCEE rating system in Projects 3.2 and 3.3 was discontinued.

Element 4 - Increase Energy Efficiency through Improved Mortgage Products

This focus of this program element was to have builders work together with the mortgage market to find new avenues to make increased energy efficiency cost-effective. Element 4 originally included the following technical projects:

- Project 4.1. Risk Analysis of Foreclosures
- Project 4.2 Foreclosure Risk Reduction
- Project 4.3 New Mortgage Guidelines

Element 4 Objective

The goal of this research element was to increase energy efficiency in new production homes, predominately in inland areas, using the non-energy benefits of quality and comfort, and their impact on the mortgage, sales and profit, to motivate builders to change their building practices. Specific goals included:

1) Determine the correlation between construction defects (specifically those that reduce quality, comfort and energy efficiency) and home foreclosures;
2) Prove that foreclosure risk can be reduced by increasing home quality, comfort and energy efficiency; and
3) Produce new mortgage guidelines that will promote quality, comfortable, energy-efficient new homes.

Project 4.1 - Risk Analysis of Foreclosures

The objective of this research project was to determine the frequency of foreclosures related to construction quality, comfort, and energy use attributes. To the extent possible, the construction problem categories identified from the warranty and callback analysis would be used here as well.

Findings & Conclusions

- *The available data was insufficient in detail to support an analysis of reasons for foreclosure*. Despite the Fannie Mae participation, their data was never made available to the NAHBRC for complete analysis. Alternative data sources were unsuccessfully investigated. While there was an anecdotal suggestion that energy cost could be a significant contributor to foreclosure, there was no rigorous data made available to support that proposition.

- *While Fannie Mae has made improvements since this program was designed, there are still problems with existing Energy Efficient Mortgages (EEMs).* Fannie Mae's improvements to its EEM program have streamlined the underwriting process, making EEMs accessible electronically. Loan-to-value evaluation now adds the present-value of the energy efficiency to the sales price and loan amount which allows borrowers to purchase upgrades for their new homes in the amount of the present-value of the energy efficiency savings without an increase in the loan-to-value ratio. Borrowers are then able to pay for these upgrades over the life of the mortgage. The actual monthly energy savings are added to the gross household income, improving the front-end lending ratio so more homebuyers are able to qualify. However, as the mortgage amount is increased by the present value of the energy savings, the loan-to-value increases, increasing the mortgage insurance. This increase in cost is typically greater than the monthly utility savings of these improvements. This loan-to-value mortgage insurance cost increase causes the borrower to have to re-qualify for a larger loan amount. The result is that the borrower will need to put more money down or may no longer qualify.

Outcomes

Because available mortgage data could not establish a link between mortgage foreclosures and construction defects that reduce quality, comfort, and energy efficiency, the efforts to develop new mortgage guidelines in Projects 4.2 and 4.3 were cancelled.

Element 5 - Improved HVAC Design Mechanisms

Element 5 Objective

The overall goal of this research was to improve the current state of computer tools and to improve the design methods used to size and locate HVAC systems so that new California homes will demand less energy. Specific goals included: 1) Develop improved calculation methods and a design guide for an improved software tool for ACCA HVAC system design that included factors for standard and tight-duct installations, 2) Develop improved software specifications for HVAC design that included separate input for window SHGC and U-values, and improved output for installers and raters, 3) Develop a design manual to help builders and designers understand trade-offs between different register locations as well as forced air unit locations. This program element's work scope included the following technical projects:

- Project 5.1. Software Specifications for Improved HVAC Sizing
- Project 5.2. HVAC System Design Alternatives

Project 5.1 - Software Specifications for Improved HVAC Sizing.

The objective of this project was to develop software design requirements for improved version of ACCA Manual J and D calculations. Design requirements include methods, variables, and values for additions such as standard vs. tight duct installations, separation of U-value and SHGC in the heat gain calculations, multiple orientation operations for Manual D, and improved software reporting for raters and diagnosticians.

Findings & Conclusions

- *ACCA Manual J, Version 8, released at the outset of the program, is a substantial improvement from the previous version.* During the course of the program initiation, a new version of ACCA Manual J, Version 8, was released affecting the intended deliverables of this project. A review of ACCA Manual J Version 8 versus best practice found that this version contained the improvements that were originally proposed to be addressed by this research project.
- *There are many opportunities for improving user interfaces in software which implements ACCA Manual J calculations.* The first version of the ACCA Manual J, Version 8 software was released implementing only a portion of the new calculations; the changes are quite extensive and will require a significant investment in training on the part of the users. There are many more inputs required by the user through a tedious interface. One of the needs identified was a "standard" set of inputs that would provide the user with a set of nominal values for many of the required inputs, allowing them to focus on the non-standard features.
- *In general, the current HVAC design practice is based on rule-of-thumb methods and is not adequate for good design of residential HVAC systems.* These methods need to be discouraged and methods based on engineering calculations need to be more fully implemented to avoid poor-performing systems that waste energy and do not maintain comfort. As part of this research program, best practices for HVAC system design in California production home building were incorporated into an HVAC Design Guide applicable during the entire development process, from site planning through construction and occupancy.

Outcomes

The project identified and documented current practices and best practices for handling windows, ducts and multiple building orientations in residential HVAC designs. This information was included in the HVAC Design Guide developed in Project 5.2.

Project 5.2 - HVAC Systems Design Alternatives

The objective of this project was to demonstrate the differences in the delivery and energy efficiency of residential HVAC systems with different FAU and register locations. This research included documenting the effects of register boxes and register types on airflows within different rooms throughout the house. Materials and labor cost comparisons were completed. This research resulted in a design manual that builders, HVAC subcontractors, and HVAC designers can use to understand the comfort and energy efficiency differences between these HVAC system alternatives

Findings & Conclusions

- Computational Fluid Dynamics simulation results indicate that in-wall registers are the most energy efficient and also provide effective thermal comfort and air quality. The best performing location for the return, ceiling or low-wall, depends on whether the home is in a heating- or cooling-dominated climate.
- The two story results indicate that two, centrally located returns, one upstairs and one downstairs, provide improved air mixing and reduced the frequency of the on/off cycling of the HVAC system. The most effective location for the thermostat was centrally located upstairs.

Outcomes

- The project developed an HVAC Design Guide that supports an integrated design process and simplified design methods essential to improved usage, increased HVAC design quality, and reduced HVAC energy consumption. The HVAC Design Guide is applicable during the entire development process, from site planning through construction and occupancy. It addresses topics particularly important to California and specific to new-construction production homes. It is not intended to replace design methodologies such as those provided by ACCA, but to supplement those methodologies and encourage wider use by making them more consistent with best practices in the construction of California production homes.
- Members of the HVAC Guide's intended audience (builders, architects, HVAC designers/engineers, and HVAC contractors involved in the development of production homes) reviewed the Design Guide, with very positive feedback.

Estimated Energy Impacts

The potential market for the HVAC Design Guide includes all production home building in California. An estimated 20% of the HVAC currently being designed uses some form of Manual J. The remaining 80% use alternative methods and this is the target audience.

An estimated 60% of residential HVAC subcontractors in California rely heavily on the "square feet per ton" rule. Depending on the climate zone, common values range from 400 ft^2/ton to 500 ft^2/ton. Using 500 ft^2/ton, a 2500 square foot house would require a 5-

ton system. However, with good envelope design a house this size might be adequately cooled with a 3-ton system, thereby saving 2-tons of HVAC system over-design.

In addition to the energy savings from over-design, registers in-wall would potentially eliminate one duty cycle/hour of run time. CFD simulations predict, for cooling, approximately 8 minutes of On-Time would be saved due to better mixing, with no loss of comfort or air quality.

1.0 Introduction

This report presents the results of research performed between March 2001 and June 2004 as part of the *Profitability, Quality and Risk Reduction through Energy Efficiency Program.* This research was supported by the California Energy Commission's (Commission) Public Interest Energy Research (PIER) Program.

The *Profitability, Quality and Risk Reduction through Energy Efficiency Program,* managed by the Building Industry Institute (BII), focused on building-related energy efficiency advances. The program consisted of one administrative element and four technical elements:

- Element 1. Program Administration
- Element 2. Improved Energy Efficiency, Comfort, and Quality Construction through Reduced Warranty Calls
- Element 3. Value of Quality, Comfort and Energy Efficiency in New Homes
- Element 4. Increase Energy Efficiency through Improved Mortgage Products
- Element 5. Improved HVAC Design Mechanisms

Each element contained multiple projects, and each project contained one or more tasks.

The four research elements in this program were designed to fill gaps in the existing body of building science knowledge, and address topics that have long been recognized as having untapped potential to save energy, improve the quality of construction, reduce foreclosures due to energy-related costs through improved mortgage products and improve HVAC design practices through design tools and guidelines.

1.1. Background and Overview

The overall goal of the *Profitability, Quality and Risk Reduction through Energy Efficiency* program was to develop new profit incentives that would encourage energy-efficient construction. The profit incentives were to be generated through reduced warranty costs, increased sales through improved mortgage products, improved builder and consumer value of energy efficiency through its association with quality and comfort. The program would also provide builders with improved analytical tools that will better demonstrate HVAC sizing differences, and their associated cost savings, due to quality installations. The program included consumer market analyses of all program results, as well as builder analyses for practicality, cost, and marketability.

1.2. Team

The program team members are as follows:

Program Director	- Rob Hammon (BII)
Program Coordinator	- Faith Shimamoto (ConSol)
Program Element Leads	- Mark Bernstein (RAND), Chris Fennell (NAHBRC), Russ King (ConSol)
Key Contributors	- Meyers Group, Builder Partners (The Brehm Companies, Centex Homes, Shea Homes)
Home Buyers Warranty	
Fannie Mae	

A special partnership with California builders was a unique feature of this research program. The builder partners were tasked with ensuring that the procedures and technologies suggested in the research projects were reasonable in terms of construction and that they would improve sales and/or profits. The builders chosen for this task represent diverse viewpoints within production builder companies. They are all influential individuals within large production builder companies.

1.3. Research Elements

The program management/market connections were managed by the Building Industry Institute. The program's four research elements leaders are shown below:

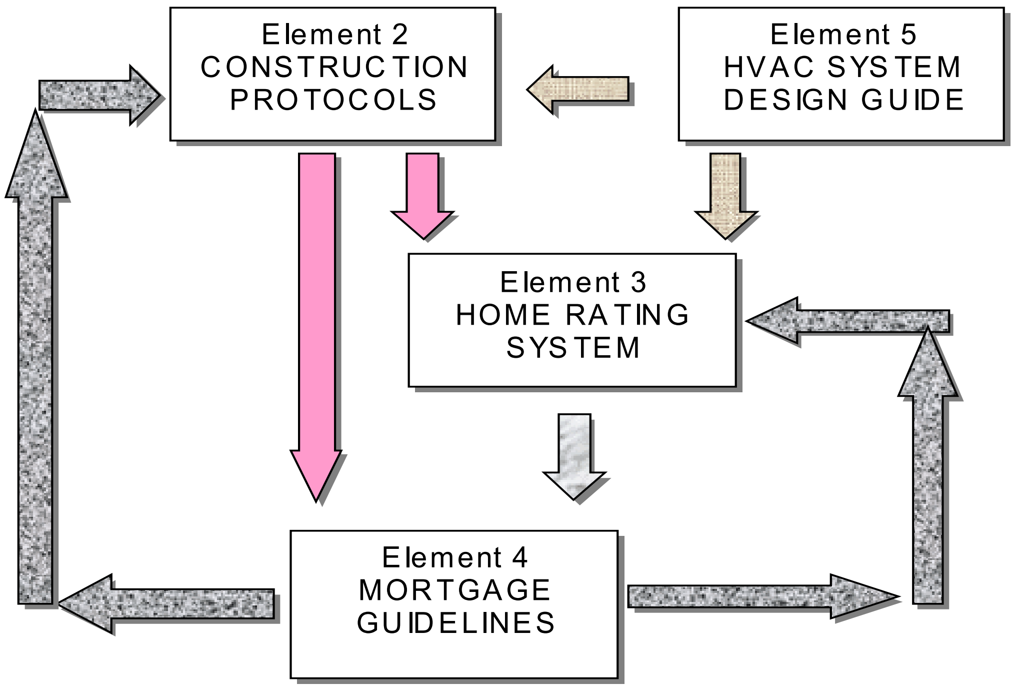
Element 2. *Improved Energy Efficiency, Comfort, and Quality Construction through Reduced Warranty Calls* (Element 2), was led by Mark Bernstein, RAND

Element 3. *Value of Quality, Comfort, and Energy Efficiency in New Homes* (Element 3), was led by Christopher Fennell, NAHB Research Center

Element 4. *Increase Energy Efficiency through Improved Mortgage Products* (Element 4), was led by Christopher Fennell, NAHB Research Center

Element 5. *Increased Energy Efficiency through Improved HVAC Tools* (Element 5), led by Russell King, ConSol

Figure 1 illustrates the linkages between the elements of this research program. Research Elements 2 and 5 are both key to development of the rating system, which was anticipated to be the most important result of this research project. The rating system would encourage use of the construction protocols and HVAC improvements; it would also encourage homebuyers to request higher quality, more energy efficient homes, as well as provide a tool for builders to assess the quality and energy efficiency of their products. Through improved mortgage products, the rating might also help homebuyers buy the higher quality, more energy-efficient homes.



	The HVAC System Design Guidelines will be incorporated into the Construction Protocols and the Home Rating System.
	The Construction Protocols will be incorporated into the Home Rating System and the Mortgage Guidelines.
	The Home Rating System will be the basis for the new Mortgage Guidelines.
	During the development of the Mortgage Guidelines, the Construction Protocols and the Home Rating System will be reviewed and modified, if necessary, to ensure that these tools reduce the risk of home foreclosures.

Figure 1 Program Element Linkages

1.4. Organization Chart

A team of energy efficiency and building science experts and researchers managed the program. Figure 2 shows the structure of the research program and responsibilities for major elements and management.

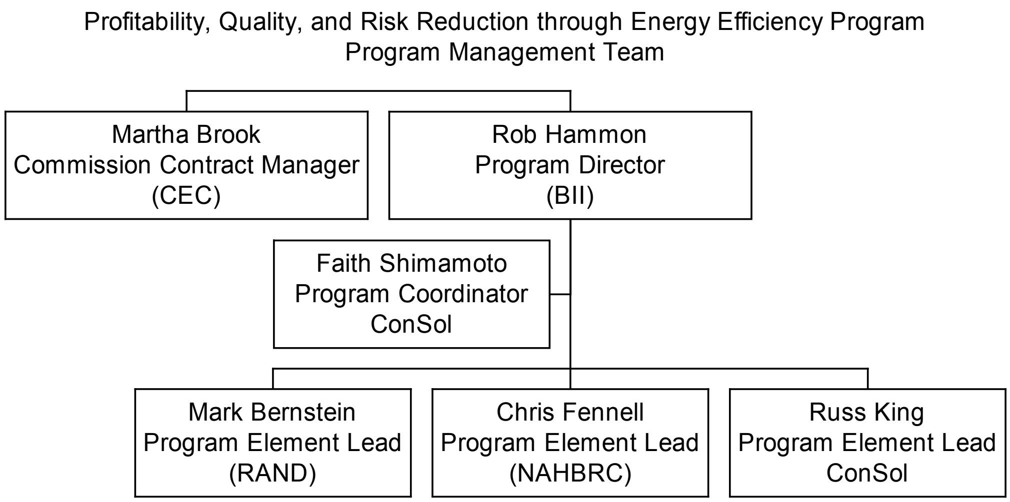


Figure 2 PIER Program Team Organization Chart

1.5. Report Organization

Each Element in this program investigated a distinct topic related to advancing our knowledge of building science. Accordingly, this report is organized in four distinct sections, one for each technical Element.

The Element sections contain a summary of the Element objectives, followed by the approach and technical outcomes for each project. Market connections, conclusions, recommendations and energy impact estimates are described at the end of each Element's section. The research results in the form of guidelines and technical reports are attachments to this report.

The report is organized by the four program research elements:

Section 2.0	Improved Energy Efficiency, Comfort, and Quality Construction through Reduced Warranty Calls,
Section 3.0	Value of Quality, Comfort, and Energy Efficiency in New Homes,
Section 4.0	Increase Energy Efficiency through Improved Mortgage Products, and
Section 5.0	Improved HVAC Design Mechanisms.

The key research products in the form of guidelines and technical reports are as follows

Appendix I.	Causes of Foreclosure
Appendix II.	Categories of Foreclosures
Appendix III.	Costs of Foreclosures
Appendix IV.	Warranty and Callback Builder Survey
Attachment A1	Residential CFD Study
Attachement A2	HVAC Design Guide

2.0 Element 2: Improved Energy Efficiency, Comfort, and Quality Construction Through Reduced Warranty Calls

2.1 Introduction

This research element focused on improving energy efficiency in new production homes, predominately in inland areas, using the non-energy benefits of quality and comfort, and their impact on profit, to motivate builders to change their building practices. Improved design and construction practices, which might cost more initially, could be cost-effective when warranty-call costs are considered. Improvements in home building construction could contribute to reduced calls, reduced energy use, and reduced first costs.

Improved construction practices that would both reduce warranty calls and increase energy efficiency, possibly producing a net improvement in the overall cost-effectiveness of new home construction were to be identified and put into a form that would be useful to the builder and subcontractors. Protocols previously developed by members of the research team would serve as a template for these new quality construction practices.

Production builders' consumer calls would be analyzed to segregate calls into groups, such as structural, HVAC, and moisture. The resulting groups of calls would be correlated with the costs of the warranty calls, and possible energy-related improvements in construction techniques and or improvements in energy-related features in the homes

2.1.1 Element 2 Objectives

- Identify specific categories of warranty calls and builder callbacks that could be avoided through higher quality construction that would result in increased energy efficiency.
- Determine the changes in construction practices that would be needed to improve the quality, comfort, and energy efficiency.
- Develop quality construction practices (protocols) for builders to use to improve quality, comfort and energy efficiency, and reduce warranty costs.
- Determine the costs to the builder of the changes in construction practices that would be needed to implement the quality construction practices.
- Determine the profit potential to the builder if the improved practices are implemented into future home building construction.

2.2 Warranty & Builder Call-Back Data Analysis

2.2.1 Introduction

The objective of this project was to identify specific categories of warranty calls and builder callbacks that could be avoided through higher quality construction, resulting in increased comfort and energy efficiency. The direct costs to fix these construction problems would be determined, as well as the additional impacts on builder profit due to these construction defects.

2.2.2 Approach and Outcomes

The original project scope was to develop a database of construction problems and, where possible, relate these problems to alternative construction techniques that would eliminate the problem, improve energy efficiency, and reduce cost. It was anticipated that a sufficient number of construction problems, linked with cost and energy-related solutions would be developed to improve builder profit if the alternative construction practices were adopted.

Sufficient quantitative data was not available to support this project as originally planned. Section 2.2.2.1 provides a summary of the data sources that were examined. None of these sources revealed causes and costs of callbacks as related to comfort, quality, and energy efficiency. The sources and findings are provided for information purposes.

However, there was general agreement within the team and advisory committee that identification of categories, costs, and impacts on profit could be gathered from key builders in California, serving the ultimate purpose of the project. Therefore, instead of relying on builder callback data and home warranty data, as described in the original scope of work, this information was collected through a series of structured interviews with California production home builders. This process is described below in Section 2.2.2.2. A detailed report on the process and results is included in the Appendix, Report IV.

2.2.2.1. Gather Data and Construct Database

Several potential sources of data on construction and equipment defects that might relate to QCEE concerns (see section on QCEE framework) were identified. Ideally, particular causes for action would be associated with the QCEE attributes previously defined; their frequencies, dispositions, and costs would be assessed; and construction practices that reduce their incidence would be determined. None of the potential data sources proved to have adequate data for this task.

Table 1 is a summary of the findings for each of the data sets examined.

Table 1 Potential Sources Of Data On Construction And Equipment Defects

2-10 Home Buyers Warranty
2-10 HBW provides structural warranty protection for over one million houses nationwide. They collect little data on complaints. A small number of complaints go to claims, for which more information is recorded, but these are not necessarily representative of all complaints. Defect codes are sometimes entered with claims, but they identify defect types only crudely, e.g. "workmanship," "design," and "heating." These data are not readily called up from an electronic database. Some aggregate data was provided on their activity in the last decade This data shows that numbers of warranty enrollments have increased while the numbers of first/second-year complaints and claims have declined. As HBW enrollments are not a random sample of new homes it is not evident whether building quality has improved in general or whether there has been some selection of higher quality homebuilders for coverage. 2-10 HBW tracks defect codes and year of complaint for only the ten-year structural component of the warranty; they do not track workmanship or systems defect codes, nor the costs of callbacks. Their customer service and claims departments are not sufficiently integrated to connect complaints data with cost data. They have published a pamphlet entitled "Top 10 Callback Items and How Can You Avoid Them" [http://www.2-10.com/whatsnew/pdf/top 10 callback items all together.pdf], but were unable to provide us with the data that support this list.
NAHB ToolBase Hotline
The NAHB Research Center ToolBase is a clearinghouse for home construction information. Its Hotline receives calls on a wide variety of building concerns, many of which concern construction defects that trigger warranty calls. Although the Hotline records do not include data on costs, they might provide information on relative frequencies and consequences of various construction concerns, and aid in interpreting claims data. The Hotline database extends back to 1996. The Hotline database is a four-level hierarchy, with each entry classified by: • Industry Topic (27 codes) • Subject 1 (8 codes) • Subject 2 (55 codes) • Construction Standards Institute (CSI) Level (16 codes) Within each level, many of the codes may relate to QCEE concerns. A small sample (twelve) of promising threads were identified in this database, and copies of all of the corresponding database entries were requested. These queries yielded approximately 200 entries from the 2000 and 2001 databases; of these, no more than seven explicitly mentioned a construction defect, two of those seven appeared to concern houses new enough to be under warranty, and neither of those was clearly energy-efficiency related. Numerous other shortcomings in the data collection render this database unsuited to our purposes.
Builders

Many large builders cover their own warranties, and likely collect detailed complaints and claims data, although they may be reluctant to fully disclose their numbers and costs. Our contact at The Meyers Group helped us identify potential data providers in these companies. One California production builder was particularly responsive and provided access to their customer services department in a Southern California division. The builder's database is a Fox-based product called Service Tract, designed specially for homebuilders. They installed it in early 1999, and it is complete since February 2000. Earlier data are entered only if a new call arrives for the same house. The software had not yet functioned properly, and was very slow and unstable. A sample query of the database revealed that the problem descriptions are too cursory (e.g., “air conditioning not working”) to allow for flagging as a build quality or energy efficiency concern with any certainty. Furthermore, the costs field is entered as zero if the call falls within the one-year limited warranty or a trade is at fault and absorbs the cost of mitigation. Even if the data were complete, unambiguous, and easy to query, they still reflect only a few thousand houses over two years. Absent any indication that other builders have a considerably more complete, refined, and accessible database, this approach does not appear fruitful.
Fannie Mae
Fannie Mae maintains detailed records of mortgage foreclosures, which include codes for energy costs and possibly for construction defects. The NAHB contact sought to determine whether these records are suited to inferring energy costs associated with construction defects, and concluded that they were not. Fannie Mae did not provide any direct communication on this matter.
Other Potential Data Sources
A search of the literature produced no public documentation of housing defects, nor any further references to proprietary information. Other organizations that might be concerned with housing defects and in a position to collect such data were investigated. The following candidates were contacted: the American Society of Home Inspectors (ASHI), the American Association of Home Inspectors (AAHI), the Foundation of Real Estate Appraisers (FREA), the California Real Estate Inspection Association (CREIA), and the Council of American Building Officials (CABO/ICC). None of these groups collect such data.

In summary, no sources of data adequate to the stipulated task were identified, and it is likely that no such sources currently exist. It was not practical to conduct a primary data collection process to acquire the sort of data that needed. A more qualitative analysis of expert knowledge of construction defects was proposed. This analysis was pursued in the Project 2.1 Revised Work Statement, Section 2.2.2.2.

The remaining tasks in this project as originally planned were canceled.

2.2.2.2. Project 2.1 Revised Work Statement

It appeared that a qualitative analysis of expert knowledge of construction defects and associated costs, along with their understanding of consumer demand for comfort, quality, and energy efficiency could provide the information needed. The detail descriptions of this process and results are contained in the Appendix, Report IV.

Executives from KB Home, Pardee Home, and Pulte Homes—each a homebuilder with operations in California—agreed to participate in a survey. These participants were selected from companies that are industry leaders, differ in business strategy and market targets, and together represent a substantial share (approximately twenty percent) of the home building market in California. Participants represented more than one hundred years of professional experience and knowledge developed in the home building industry in California.

A discussion protocol was developed (see Report IV, Appendix 4) from the initial review of the literature and available data. Interviews were conducted with more than a dozen executives and high-level staff, as well as selected trade contractors that do business with our selected builders and others in California. Interview discussions formed the basis of several generalizations, and in some cases, certain specific relevant examples also emerged.

Along with estimates of construction problems and costs, and a review of consumer values, builders' insights into the production home industry, the housing market, builder practices, and profitability as they relate to energy efficiency of new homes in California were compiled. These insights suggest an important role played by builders at critical decision points during the home building process, and also some important constraints faced by builders related to promoting energy efficiency in new homes.

Out of this process emerged three general observations that have implications for promoting energy efficiency in new homes in California. These are detailed in Section 2.3.1.

Few specific energy efficiency construction defects were identified. The primary callback complaint, clearly energy-related, was HVAC system problems. As a result of the survey information, Element 5 of this program became more focused on the development of an HVAC Design Guide that could be used in the entire production home building process, from site planning through construction and occupancy.

2.3 Conclusions and Recommendations

2.3.1 Conclusions

Out of the survey process emerged three general observations that have implications for promoting energy efficiency in new homes in California:

The greatest challenge for promoting energy efficiency in new homes is in the market for first-time homebuyers, for the largest, most comfortable homes that they can afford. Information and resources to invest in energy-efficient options are least available to this group of homebuyers.

There is evidence that some design and construction measures may be taken to reduce cost to builders and improve energy performance of a home, but the greatest incentives to builders to control costs are for problems least associated with energy efficiency.

Motivating builders through increased profit to promote energy efficiency in their home products may be more likely achieved by aiding their marketing and sales efforts in order to increase revenue, rather than by informing design and construction practices in an effort to decrease costs. Builders' marketing and sales teams can sell energy efficiency to homebuyers, with the credible information and risk-reduction options available to them.

The survey results focused this research on the development of an HVAC Best Practices Guide useful to the entire production home industry. The primary callback complaint revealed during the survey process was HVAC system problems, a clearly energy-related issue. As a result of this survey information, Element 5 of this program became more focused on the development of an HVAC Best Practices Guide that would be useful from site planning through construction and occupancy.

Further research in this area will be unsuccessful without better quality information on the causes and resolution of callbacks. The building community does not currently collect the kind of data that will support this type of analysis. The methods currently used by production homebuilders to document warranty calls and builder callbacks are not sufficient to identify potentials for energy efficiency improvement.

While the currently available data is not adequate for our research, at least one of the participating builder partners has identified the need for such detailed information and is implementing such a system. Future research efforts will benefit greatly from this investment. Future effort should be invested in understanding how this information impacts business and construction practices.

Improvements to construction practices in production homes is limited by the lack of definitive data on the connections between energy efficiency and the number and type of builder callbacks. Construction protocols that address energy efficiency, comfort and quality were not developed in this project because the necessary correlations with callback data were never established.

2.3.2 Recommendations

The following five recommendations, at various stages of the home building process, will help to promote energy efficiency. These are described in greater detail in Section 5 of the Appendix, Report IV. All of them highlight the role of the builder in achieving greater energy efficiency in new homes.

- Improve construction protocols and worker training, specifically to address HVAC design and framing problems such as bowed walls.
- Better educate homeowners on basic HVAC use.

- Investigate performance and reliability of promising new technologies for homes, and support their use.
- Identify options for cross-selling energy efficiency upgrades according to their promises of greater comfort and quality.
- Pursue strategies for promoting energy efficiency through builders that also reduce risk to those builders.

Because these interventions are linked to potentially greater builder profit, builders may be more inclined to implement them. Government support is likely necessary to catalyze builders' initial response to these.

2.3.3 Benefits to California

Improved construction protocols addressing energy efficiency, comfort and quality were not developed in this project because the necessary correlations with callback data were never established. The survey process did reveal a primary callback complaint was HVAC system problems, a clearly energy-related issue, that could be addressed through improved practices. Lack of cost data did not allow us to establish a monetary impact that would translate into a specific profit motivation for builders to change their building practices.

However, these results focused this research on understanding current and best practices in HVAC system design and development of an HVAC Design Guide that would be useful to the entire production home industry. If followed, these practices will results in reduced callbacks and improved energy efficiency.

3.0 Element 3: Value of Quality, Comfort and Energy Efficiency in New Homes

3.1 Introduction

It is well known that the primary concerns of new-home buyers include location, floor plan, and amenities. It is also known that new-home buyers will include quality, comfort and energy efficiency in their list of important issues; indeed, these qualities are at least partially responsible for the buyers choosing a new home rather than an existing home. Research is needed to clarify the relative importance of comfort, quality, and energy efficiency in the buying decision. This can be obtained through further, focused analyses of existing data from marketing groups.

The Meyers Group performs on-going market research to determine how and why people buy new homes. As one of the largest real estate information services companies in California, they have extensive data from homebuyer surveys that will be used in this research element to evaluate consumer-buying decisions. Their existing databases were reanalyzed to determine the relative value of quality, comfort, and energy efficiency, as compared to location, amenities, floor plans, etc., to new-home buyers.

3.1.1 Element 3 Objectives

- Document current consumer value of energy efficiency, as well as the ancillary benefits of comfort, and quality, in new production homes. Determine how consumers currently evaluate these illusive home attributes.
- Increase the ability of homebuyers to compare the quality, comfort and energy efficiency of new homes, through the development and assessment of an improved home rating system.
- Document the consumer value of energy efficiency, comfort and quality once there is a rating for these home attributes, which are normally not tangible to the consumer

3.2 Consumer Value of QCEE

3.2.1 Introduction

The objective of this project was to determine the consumer value of home energy efficiency, comfort and quality. This value would be compared to the other factors typically considered in home buying decisions, such as location, floor plan, amenities and price. The ability of home ratings to define and influence consumer opinions could then be evaluated.

3.2.2 Approach and Outcomes

The existing data was insufficient in detail to support an analysis of consumer value of home energy efficiency, comfort, and quality. Alternative data sources were examined. Section 3.2.3.1 provides details and findings of the data sources that were explored.

The NAHB Research Center team proposed an alternative data collection process using a survey process based on conjoint analysis[1] to capture decision making trade-offs in the home buying process. However, the Commission decided not to pursue this research avenue.

Due to the lack of appropriate data, this remainder of this project was terminated.

3.2.2.1. Gather Data and Construct Database

There are no available detailed data on homebuyers' expressed preferences for QCEE. Two large-scale surveys of general preferences yield some scattered data that relate to

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1 Conjoint analysis is concerned with understanding how people make choices between products or services or a combination of product and service, so that businesses can design new products or services that better meet customers' underlying needs. Conjoint analysis has been found to be an extremely powerful of way of capturing what really drives customers to buy one product over another and what customers really value. A key benefit of conjoint analysis is the ability to produce dynamic market models that enable companies to test out what steps they would need to take to improve their market share, or how competitors' behavior will affect their customers.

these attributes, but not in a consistent manner that lends itself to firm conclusions. Other findings are more anecdotal, or from surveys that might not be available to us. Survey methodologies vary and are sometimes unclear, so that it is difficult to compare or synthesize results across surveys. There is also a large body of empirical literature on homebuyers' implicit valuations of various attributes (i.e., revealed willingness-to-pay); EE is treated explicitly in many studies, but other attributes examined are not identified as Q or C. (See Table 2 and Table 3.)

Table 2 Survey - Stated Preferences

The Meyers Group
The Meyers Group conducts ongoing exit surveys of prospective buyers of builder homes in the Southwest; they also collect builder data on new housing developments. The latest survey, published as Vision 2000, reflects the responses of 1900 prospective consumers of the homes of 20 builders, in April–May 2000. The survey was quite broad, and many questions address housing and builder attributes that could relate to QCEE (depending on the construal of QC and on respondents' interpretations). Three of the questions are somewhat more pointed. Respondents assigned influence weights to each of eight purchase decision attributes, four of which might be regarded as embodying QCEE: builder's reputation (Q), warranty/customer service (Q), large number of options (QCEE), and short commute (CEE). The survey questions are all very brief, with no explication of the intended meanings of the response options. Many buyers might construe "builder's reputation" to be a reputation for quality (of workmanship and materials), but some might interpret it as a reputation for low cost or for housing development amenities. Warranty and customer service seems less open to interpretation. Options may reflect all three attributes of interest (especially considering the vagueness of C). Another question asks, "what determines the quality of workmanship?" Respondents chose their top two selections from a list of eleven options, six of which relate to EE: materials/structure/construction, flooring quality, windows, features/options, appliances, and other. This question is ambiguously worded for the research purposes, with at least two likely common interpretations: "in which of these areas is quality of workmanship most important to you?" and "which of these areas best reflects a builder's overall quality of workmanship?" The only questions that speak directly to energy matters concern preferences for gas or electric appliances, by appliance type. Respondents do not indicate the reasons for their preferences (QCEE or otherwise). They are asked if they would "spend more for a home that provided efficient natural gas appliances;" it is not clear whether the appliances in question are (a) natural gas and therefore implicitly "efficient" or (b) both gas and more efficient than some comparison baseline.

Table 3 Econometric Analyses—Revealed Preferences

Homebuyers reveal their implicit valuations of various home attributes by their purchasing behavior. New builder homes are increasingly being offered with explicit options schedules; with data from cooperating homebuilders on options purchases the relative valuations of QCEE attributes may be assessed; this type of analysis is being discussed with The Meyers Group. An extensive literature addresses consumer valuations of home energy efficiency (with respect to both the thermal efficiency of the building shell and the efficiency of appliances and fixtures). Much of the analysis concerns whether consumers place a rational value on the financial returns (in lower utility bills) to investments in energy efficiency; that is, do they apply a consistent discount rate? While not an exhaustive literature search, there appears to be an emerging consensus that improvements in building thermal efficiency are fairly valued (see, e.g., Rick Nevin, Christopher Bender, and Heather Gazan, "More Evidence of Rational Market Values for Home Energy Efficiency," The Appraisal Journal, October 1999, pp. 454–460, available at www.natresnet.org/herseems/APJ_99_10.pdf), while new, energy efficient appliances and fixtures are not (see, e.g., Chris Bataille and John Nyboer, "How do Consumers and Firms Purchase Equipment That Consumes Energy?" Canadian Industrial Energy End-use Data and Analysis Centre, 2001, available at www.cieedac.sfu.ca/reports/OtherReports/BehLit2001.pdf). This discrepancy is attributed largely to differences in perceived investment risk. Some of these analyses discuss ancillary benefits of energy efficiency investments, such as higher quality energy services and greater comfort from reduced draftiness, noise, and air pollutants. Unfortunately, any empirical valuations of these benefits, or any thoroughgoing discussion of their interrelationships have not been uncovered.

Summary of Findings

The data available was not adequate for the stipulated analysis. An analytical framework was constructed (described in section 3.2.2.2) that would allow for suitably targeted data gathering. This framework includes:

- Definitions of the terms of interest
- Interrelationships among QCEE attributes
- Identification of key (high value) data missing from existing surveys
- A body of empirical studies of valuation of EE

3.2.2.2. Quality Comfort and Energy Efficiency Framework

There was a need for a consistent definition of quality, comfort and energy efficiency. Comfort and quality are nebulous terms. The team developed definitions of these terms that could be used to generate useful data and questions in future surveys on the topic.

What Is Meant by Quality, Comfort, and Energy Efficiency?

Energy efficiency can be defined usefully (if not always easily) in terms of thermal efficiency, i.e., joules of fuel (latent heat) or kWh of electricity per unit of useful output (e.g., lumen-hrs, gallons of boiled water). For consumer preference data, these metrics can be translated into more readily understood and comparable metrics (e.g., kW-hrs per day for an 18 cu. ft. refrigerator), or into costs. Home EE consists in passive, active, and behavioral. Passive measures (such as high R-value insulation in the attic) provide for lower energy consumption for the same level of energy services delivered to the occupant, no matter how the occupant behaves. Active measures (such as compact fluorescent lighting) themselves consume energy in delivering a service, but less so than alternative measures. Behavioral measures (such as window louvers), conversely, require that the occupant engage in some particular behavior in order to reduce energy consumption.

Quality and *Comfort* are more elusive concepts, ones which are all familiar and recognized when seen. While there may be generally accepted *dimensions* of *Quality* and *Comfort* (as pertains to housing), valuations along those dimensions are highly subjective. For example, most people would concede that ambient temperature is an important dimension of comfort, but *how* the level of comfort varies with room temperature depends on individual preferences. This subjectivity must be kept in mind when considering consumer preferences and valuations.

Quality entails those aspects of home construction and design that perform their intended functions well and that bespeak care and attention on the part of the builder (considered to include the architect, engineer, construction workers, and others). *Quality* inheres in both materials and workmanship; these dimensions are not orthogonal, as quality materials lend themselves to quality workmanship. Attributes of *Quality* in a new home include fit and finish, durability, efficiency, ease of maintenance, and safety. Many elements that most buyers would likely agree are *Quality* attributes are difficult for them to assess, because they lack expertise or because the elements are not readily observable (e.g., plumbing joins, grounding of electrical conduits).

Comfort entails those aspects that provide the occupants with physical, aesthetic and psychical satisfaction. *Quality* itself may be a *Comfort* attribute, as it can provide peace of mind and satisfaction. But *Quality* and *Comfort*, as subjective matters, are not necessarily coincident; a carefully laid slate floor may be widely regarded as high *Quality* (and is commensurately expensive), but many consumers dislike hard flooring and prefer plush wall-to-wall carpeting, which may be allergenic, nondurable, and otherwise of low "objective" *Quality*. Nonetheless, slate and cut pile carpeting are two points on *Comfort* dimensions such as flooring texture and sound absorption—identifying these dimensions does not require imposing subjective valuations. In a similar vein, consider these somewhat abstracted *Comfort* attributes (which would have to be made more specific for survey questions) of a new home, including the structure, appliances, and fittings, but not such easily altered and personalized features such as furniture and window treatments. (The attributes are grouped by the component of the building or its environment in which they are manifest.) Examples of *Comfort* attributes are listed in Table 4.

Table 4 Comfort Attributes

- Air
  - Odor
  - Temperature
  - Humidity
  - Electrostatic charge
  - Freshness/ventilation
  - Movement
- Sound
  - Exterior sounds
  - Interior transmission
    - Noise suppression
- Lighting
  - Color
  - Intensity
  - Dispersion
  - Efficacy
  - Day lighting
- Structure
  - Basic design type (e.g., split-level ranch, Tudor)
  - Layout aesthetics
    - Ceiling heights
    - Room proportions
    - Room layout
    - Doorways
    - Windows
- Mobility/Access
  - Stairs
  - Hallways
  - Exterior doors
  - Indoor/outdoor connections: decks, porches, patios, walkways
- Surface Aesthetics
  - Exterior surface materials/colors
  - Flooring
- Sustainable Features
  - Low embodied energy (recycled materials?)
  - Durability
- Materials that don't emit indoor pollutants

An implicit hypothesis of this study was that home energy efficiency is positively associated with *Quality* and *Comfort*. There are several main association pathways:

- Quality in materials and workmanship provides a good thermal envelope, preventing uncontrolled infiltration of air, moisture, noise, and pollutants.
- By the same token, it reduces heating, cooling, and dehumidifying loads (in most California climates).

- Energy efficiency allows for greater control over the interior environment.
- Energy efficient design and construction in itself requires care and attention, and so compels quality.
- Energy efficient ventilation reduces cooling loads and indoor pollutant levels. It also feels good, both physically and psychologically.

These relationships are abstracted in Figure 3.

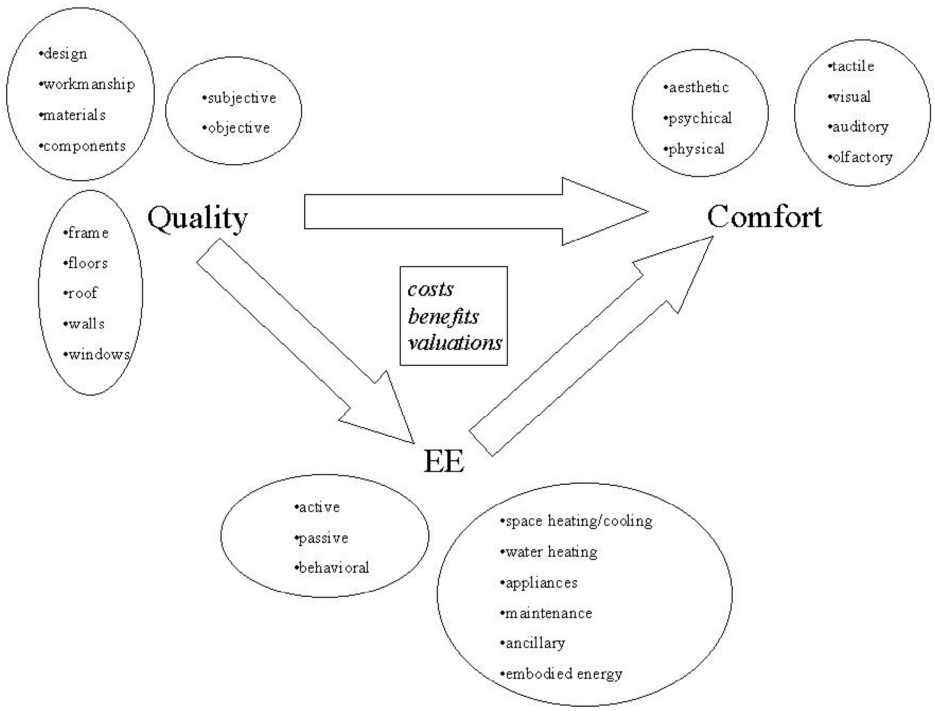

Figure 3 Relationships Between Quality, Comfort, And Energy Efficiency

3.3 Quality, Comfort and Energy Efficiency Rating System

3.3.1 Introduction

The objective of this project was to develop a quantitative rating of new home quality, comfort and energy efficiency. This rating would be based on current HERS, augmented by the improved construction protocols completed in Element 2. This research project would incorporate all relevant findings from Element 5 on optimal HVAC sizing, distribution and unit locations. Finally, the rating developed would include the consumer value information gathered in Project 3.1.

This rating system would be relatively simple for the builders to implement, and for consumers to understand. The challenge would be to achieve a successful degree of simplicity while quantifying the comparatively nebulous home attributes of quality and comfort

3.3.2 Approach and Outcome

3.3.2.1. Research Other Rating Methods

Three existing home energy-rating systems were identified: Consumer Home Energy Efficiency Rating System (CHEERS), Florida Energy Gauge Program, and Energy Rated Homes of America (EHRA) for initial evaluation. Focus was placed on those accredited through Mortgage Industry National Home Energy Rating System Accreditation Standard.

Different methods for presenting rating systems were examined. Research was done on different visual methods of presenting ratings of products: numbers, stars, graphs, multi-dimensional graphs, circles, etc. Of note, JD Powers most notable rating is for consumer satisfaction. Several major builder builders tie executive bonuses to the JD Powers rating of the company for their division.

Due to the lack of data from Project 3.1, the remainder of this project scope was terminated.

3.4 Conclusions and Recommendations

3.4.1 Conclusions

While there is no existing data measuring consumer value of energy efficiency, comfort and quality, a data collection process could be implemented to gather the necessary data. A conjoint analysis using a web-based consumer audience has been proposed by the NAHBRC to assign value to the attributes of quality, comfort, and energy efficiency. The consumer survey that generates the Visions 2000 database is also available for enhancements to capture this information

3.4.2 Recommendations

Improved information to consumers regarding the many values of energy-efficient construction would likely increase consumer demand for homes built above code. We recommend that alternative methods be pursued to determine consumer value of energy efficiency. Improved understanding of consumer value would likely lead to improved tools for consumers to evaluate home's efficiency, comfort, and quality.

4.0 Element 4: Increase Energy Efficiency through Improved Mortgage Products

4.1 Introduction

For ten years there has been an Energy Efficiency Mortgage (EEM) that is of no value to builders and buyers of new homes in California. The EEM provides for a 2% stretch beyond the standard lending ratios for homes that meet the Model Energy Code (MEC). Lenders typically stretch several points beyond the standard ratios to qualify buyers anyway, negating the value of the EEM. Additionally, all new homes in California exceed the MEC by meeting the more stringent California Energy Efficiency Standards, so the EEM does nothing to increase the energy efficiency of California homes.

Prior to this research, Fannie Mae and Freddie Mac developed procedures to allow buyers to qualify for more money based upon the energy efficiency of the new home as demonstrated in a home energy rating (HERS). These HERS-based EEMs are still in draft form. Although some pilots are being developed, so far the tool has yet to be used by new-home builders, primarily because the Freddie Mac product has not been promoted to builders or lenders and the Fannie Mae product is brand new.

An analysis of foreclosures and of new home lending practices would be performed to determine if lenders' risks can be reduced by including the quality of construction, the expected comfort of the occupants, and the energy efficiency of the new home in the mortgage product.

If significant correlations of home quality, comfort, and energy efficiency problems to home foreclosures were found, the research team would develop a mortgage product that reduces the risk of foreclosures. This program element would use the improved home construction practices developed in Element 2, and the home rating system developed in Element 3, to provide a new quality construction mortgage that is relevant to California homes.

4.1.1 Element 4 Objectives

The goal of this research element was to increase energy efficiency in new production homes, which are predominately in inland areas, using the non-energy benefits of quality and comfort, and their impact on the mortgage, sales and profit, to motivate builders to change their building practices.

The key steps of this task are:

- Determine the correlation between construction defects (specifically those that reduce quality, comfort and energy efficiency) and home foreclosures;
- Prove that foreclosure risk can be reduced by increasing home quality, comfort and energy efficiency;
- Produce new mortgage guidelines that will promote quality, comfortable, energy-efficient new homes.

4.2 Risk Analysis of Foreclosure

4.2.1 Introduction

The objective of this research project was to determine the frequency of foreclosures related to construction quality, comfort, and energy use attributes. To the extent possible, the construction problem categories identified from the warranty and callback analysis would be used here as well.

4.2.2 Approach and Outcomes

Sufficient quantitative data was not available to support this project as planned. Despite Fannie Mae participation, their data was never made available to the NAHBRC for complete analysis. Alternative data sources were unsuccessfully investigated. The following subsections provide a summary of the data sources that were examined and the findings. None of these sources correlated energy cost as a cause of foreclosure. Due to the lack of appropriate data, further work on this project was terminated. .

4.2.2.1. Gather Data and Construct Database

The evidence suggests that the poor are the most likely to suffer foreclosure caused by excessive maintenance or utility costs. The poor, about one-third of which are homeowners, spend proportionately more of their incomes on housing costs and therefore have little income left over for unexpected costs, such as maintenance or high utility bills. A detailed report is available in the Appendix, Report I.

4.2.2.2. Identify Categories of Foreclosures

There is a significant body of literature evaluating the probability of default based on loan characteristics, borrower characteristics, property characteristics, and crisis events. Most are studies evaluating risk factors of foreclosure, for use as a tool to mortgage underwriters for evaluating mortgage loan risk. A detailed report is available in the Appendix, Report II.

4.2.2.3. Determine Costs of Foreclosures

According to the Mortgage Insurance Corporation of America (MICA), many expenses make up the cost of foreclosure to lenders, which are approximately 15% of the original loan amount. A detailed report is available in the Appendix, Report III.

4.3 Conclusions and Recommendations

4.3.1 Conclusions

New mortgage guidelines promoting quality comfort and energy efficiency were not developed due to the lack of data correlating home foreclosures with construction defects that reduce quality, comfort, and energy efficiency. Due to lack of available data on mortgage foreclosures associated with energy costs, the remainder of this element was canceled. Data promised by Fannie Mae was not available. Numerous other sources were probed.

While the data most likely exists, the research question posed could not be fully answered. .

However, during the course of this research, several changes took place in the Energy Efficient Mortgage arena, providing some promising changes. Fannie Mae expanded and improved its Energy Efficient Mortgage program.

The initial underwriting guidelines for Energy Efficient Mortgages required cumbersome and time-consuming manual underwriting and offered extremely limited loan product options. Fannie Mae now allows Energy Efficient Mortgages on all of their loan products. Fannie's Delegated Underwriting system has also been enhanced so that Energy Efficient Mortgages can be underwritten electronically, thereby eliminating considerable waste of resources and enhancing lender efficiencies and productivity. These developments make it much more likely that Fannie Mae-approved lenders will offer Energy Efficient Mortgages for buyers of eligible properties.

One of the even more significant changes made by Fannie Mae is in their approach to qualifying guidelines. Fannie Mae-approved lenders add the present value of the energy efficiency to the sales price and loan amount (up to 5% of the less of the original sales price or appraised value before adding present value), which enables borrowers to purchase upgrades for their new homes in the amount of the present value of the energy efficiency savings without an increase in the loan-to-value ratio. The borrowers are then able to pay for these upgrades over the life of the mortgage.

More homebuyers are able to qualify using Energy Efficient Mortgages because the front-end lending ration (the "housing expense" of principal, interest, property taxes and hazard insurance relative to gross household income) is reduced as a result of the monthly energy savings. The actual monthly energy savings are added to the gross household income. If Congress approves the proposed tax credit for Energy Efficient Mortgages, the appeal of these loans should increase even more[2].

While addressing many of the previously existing problems with Efficient Mortgages, there is still a loan-to-value mortgage insurance issue that needs addressing. As the mortgage amount is increased by the present value of the energy savings, the loan-to-value increases, increasing the mortgage insurance. This increase in cost is typically greater than the monthly utility savings of these improvements. This loan-to-value mortgage insurance cost increase causes the borrower to have to re-qualify for a larger loan amount. The result is that the borrower will need to put more money down or may no longer qualify.

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2 Home Energy Magazine, "The Easier Efficient Mortgage", July/August 2003 Issue, p6

Based on verbal communication with our builder partners, they are not using this loan (at least not yet). This suggests a need for both builder and sales agent training. Builders need training on the value of the mortgage to their sales and profit. Sales agents need training on the existence and use of these mortgages. Understanding and communicating how the mortgage works and why it is a benefit to the consumer can translate higher value into higher profit.

In addition to builder and sales training, consumers need to be aware of this loan opportunity. Consumer awareness has the potential of creating demand for the product and for energy efficiency. Fannie Mae can better advertise the existence and value of EEMs, thereby generating greater consumer demand.

4.3.2 Recommendations

There is an identified need for both Builder and Sales Agent training on the how the EEM works and why it is a benefit to the consumer, builder, and sales staff. Understanding and communicating how the mortgage works and why it is a benefit to the consumer can translate higher value into higher profit.

The lending community can create consumer demand for the EEM and for energy efficiency through consumer education opportunities. Fannie Mae and the lender community can better advertise the existence and value of EEMs, generating greater consumer demand.

Additional work is still needed to keep loan mortgage insurance manageable. There is an opportunity to address this issue up-front, in the EEM loan structure. Loans need to be structured initially so the qualifying amount takes the additional cost for mortgage insurance into account. Alternatively, lending guidelines would need thoughtful modification so the loan ratio remains at the pre-EEM amount, keeping mortgage insurance manageable.

5.0 Element 5: Improved HVAC Design Mechanisms

5.1 Introduction

Two clearly identified quality construction, comfort, and energy efficiency objectives are tight ducts and a properly designed and sized HVAC system. The typical duct system in a California house leaks approximately 25% and was not installed pursuant to a mechanical design. The most recent version of California's Residential Building Energy Efficiency Standards includes credits for tight ducts and system design (Air Conditioning Contractors of America – ACCA – Manual J and D).

Unfortunately, the Manual J, Version 7 (loads) procedure assumes that there is no duct leakage. While the ACCA methods will permit a designer to increase or decrease loads for other reasons (e.g., the recommendation within Manual S to oversize by 15%), there are no clear methods for consistent changes in duct and equipment size as a function of duct leakage. As a result of the inability to calculate the increase in loads and decrease in system efficiency due to duct leakage, there was no consistent method for designers to downsize air conditioners for systems with tight ducts as opposed to those with leaky ducts. Downsizing for spectrally selective glass, as compared to clear glass was also a problem with Manual J, Version 7 method. This method combined a U-value and a shading coefficient to generate a heat gain multiplier. This research element sought to make the necessary ACCA software changes to improve calculations for both tight ducts and spectrally-selective windows.

This research element also included a study of register location, and the resulting differences in system efficiency and comfort. There are various schools of thought within the HVAC and the larger building industry regarding placement of registers. Some HVAC installers believe that registers should be placed near windows, which substantially increases the length of a duct run compared to a register near or over an entrance to a room.

The location of the forced air unit (FAU) is another important energy-related issue in the design of a home. Currently, FAUs are often located in the attic, whereas 10-15 years ago they were typically in the garage. This research analyzed comparative designs for several homes, in different climate zones, placing the FAU in the garage, in the attic, and inside the home to compare costs and energy losses associated with FAU placement.

5.1.1 Element 5 Objectives

- Develop improved calculation methods and a design guide for an improved software tool for ACCA HVAC system design that will include factors for standard and tight-duct installations.
- Develop improved software specifications for HVAC design that will include separate input for window SHGC and U-values, and improved output for installers and raters.
- Develop a design manual to help builders and designers understand trade-offs between different register locations as well as forced air unit locations.

- Provide tools for builders and HVAC designers and subcontractors to shorten duct runs and reduce system sizes as appropriate, to reduce energy consumption and save materials and equipment costs

5.2 Software Specifications for Improved HVAC Sizing

5.2.1 Introduction

This project objective was to develop software design requirements for improved version of ACCA Manual J and D calculations. Design requirements will include methods, variables, and values for additions such as standard vs. tight duct installations, separation of U-value and SHGC in the heat gain calculations, multiple orientation operations for Manual D, and improved software reporting for raters and diagnosticians.

5.2.2 Approach and Outcomes

During the course of the program initiation, a new version of ACCA Manual J, Version 8, was released affecting the intended deliverables of this project. The updated version was evaluated and contained the improvements that were proposed to be addressed by this research project.

The first version of the ACCA Manual J, Version 8 software was also released. This first version implemented only a portion of the new calculations. These changes are quite extensive and require a significant investment in training on the part of the users. There are many more inputs required by the user through a tedious interface. One of the needs identified was a "standard" set of inputs that would provide the user with a set of nominal values for many of the required inputs, allowing them to focus on the non-standard features. This was not considered appropriate for this research project to pursue.

Best Practices in HVAC Design were documented, capturing the current and best practices in California production home building. This document covered best practices for windows, distributions systems, and orientation. In general, the current HVAC design practice is based on rule-of-thumb methods and is not adequate for good design of residential HVAC systems, resulting in poor performing systems that waste energy and do not maintain comfort.

The differences between Version 7 and Version 8 were compared and provided in a detail form as an appendix to the Best Practices report, which was an interim deliverable under this project. As part of this research program, best practices for HVAC system design in California production home building were incorporated into an HVAC Design Guide (Attachment 3 to this report) applicable during the entire development process, from site planning through construction and occupancy.

5.3 HVAC System Design Alternatives

5.3.1 Introduction

This project demonstrated the differences in the delivery and energy efficiency of residential HVAC systems with different FAU and register locations. This research included documenting the effects of register boxes and register types on airflows within different rooms throughout the house. Materials and labor cost comparisons were completed. This research resulted in a design manual that builders, HVAC subcontractors, and HVAC designers can use to understand the comfort and energy efficiency differences between these HVAC system alternatives.

5.3.2 Approach and Outcomes

5.3.2.1. Determine Energy and Comfort Impacts of FAU location, Register Location and Register Type

A study, using a commercial computational fluid dynamics (CFD) modeling, was used to compare register placement in a three-bedroom, single story home. The study compared three register placements and two return locations. Cooling and heating efficiency, comfort, and air quality were analyzed. Comfort impacts were evaluated using the ASRAE 55-1981 standard.

These simulation results indicate that in-wall registers are the most energy efficient and also provide effective thermal comfort and air quality. The report discusses the details of this study and the impacts of register location and type on comfort and energy efficiency. Air animations and comfort analyses are included in the full report, Attachment 2 to this report.

Figure 4 shows a static, single frame from an airflow animation for cooling with in-wall supply registers and a low-wall return. This image show the type of information generated from the CFD simulation. The air particle movement and temperature are tracked over time. This helps to visualize the airflow and mixing from the various combinations we examined.

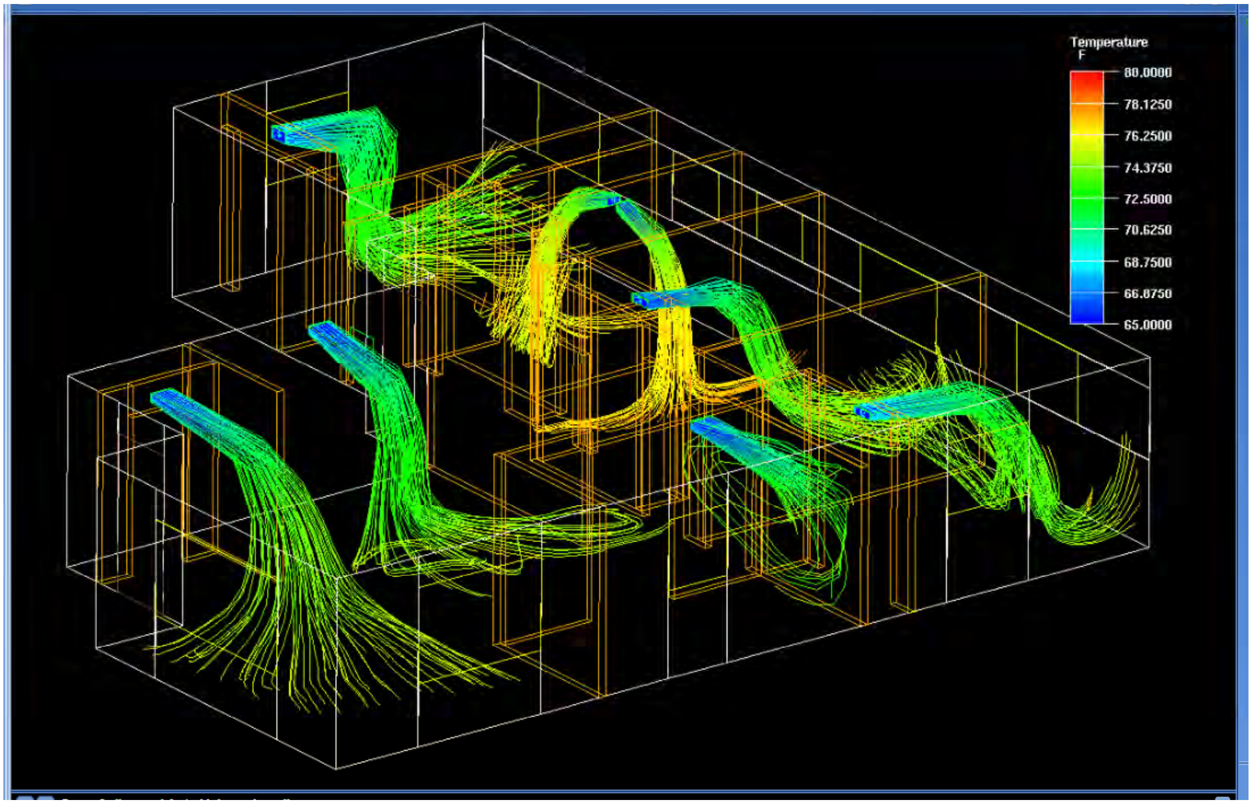

Figure 4 Example Airflow Animation For Cooling Case

Figure 5 is a static, single frame from an example Predicted Mean Vote (PMV) animation. PMV is just one of the air quality and comfort indicators that are provided as part of the CFD analysis. PMV is an index for thermal sensation of the occupants, represented as a seven-point scale ranging from +3 (very hot) to –3 (very cold). This animation shows that, based on this scale, most individuals would be comfortable. If the airflow animation and these results are analyzed together, the "cooler" (blue) areas are where the conditioned air from in-wall supply is dispersed.

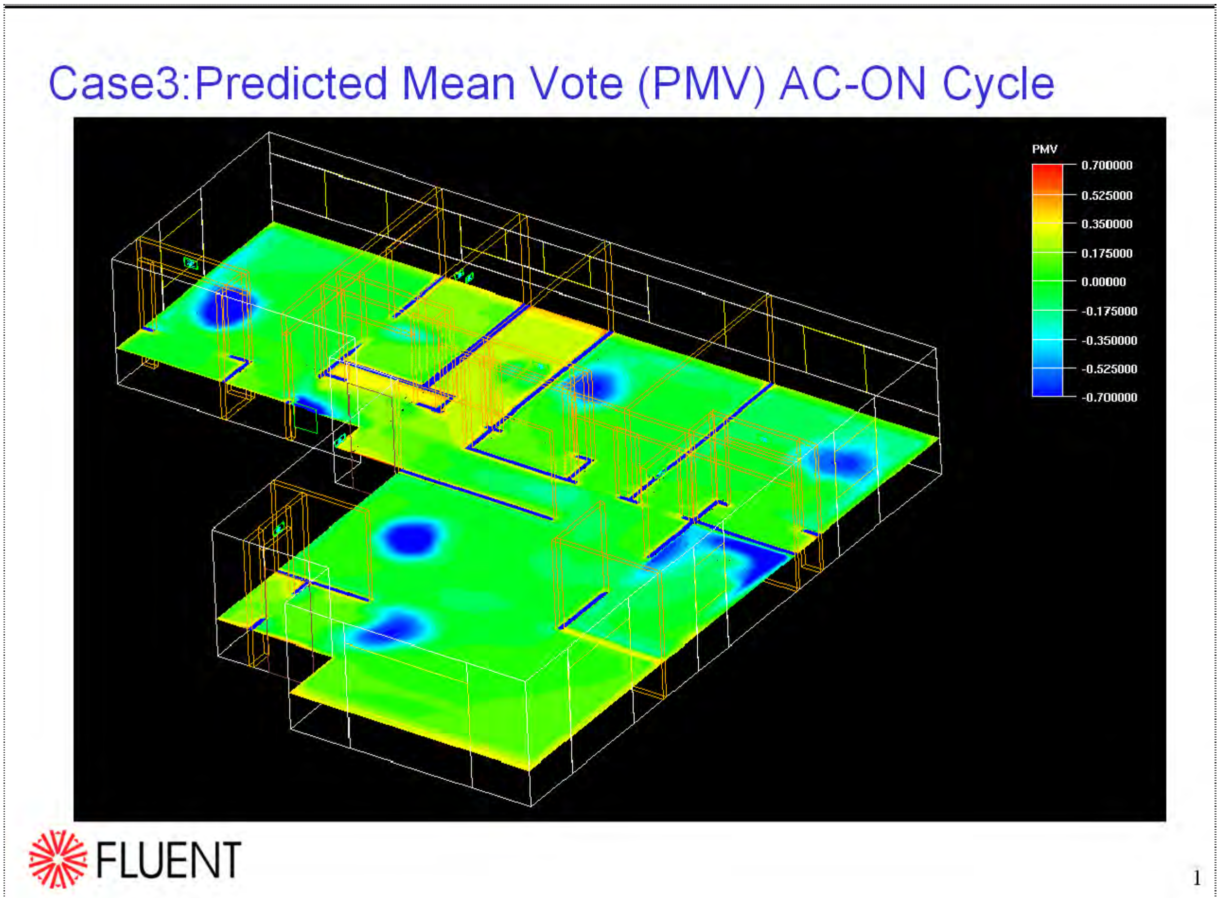

Figure 5 Example of Predicted Mean Vote during the AC ON cycle

Figure 6 shows an example of the duty cycle output for three cooling cases with differing register configurations and a ceiling return. The simulation showed that the in-wall supply registers provided the longest cycle times with the shortest HVAC ON duty cycle. The airflow animations for these cases indicate that the in-wall supply configuration provides the best mixing, which results in good occupant comfort and reduced overall run times.

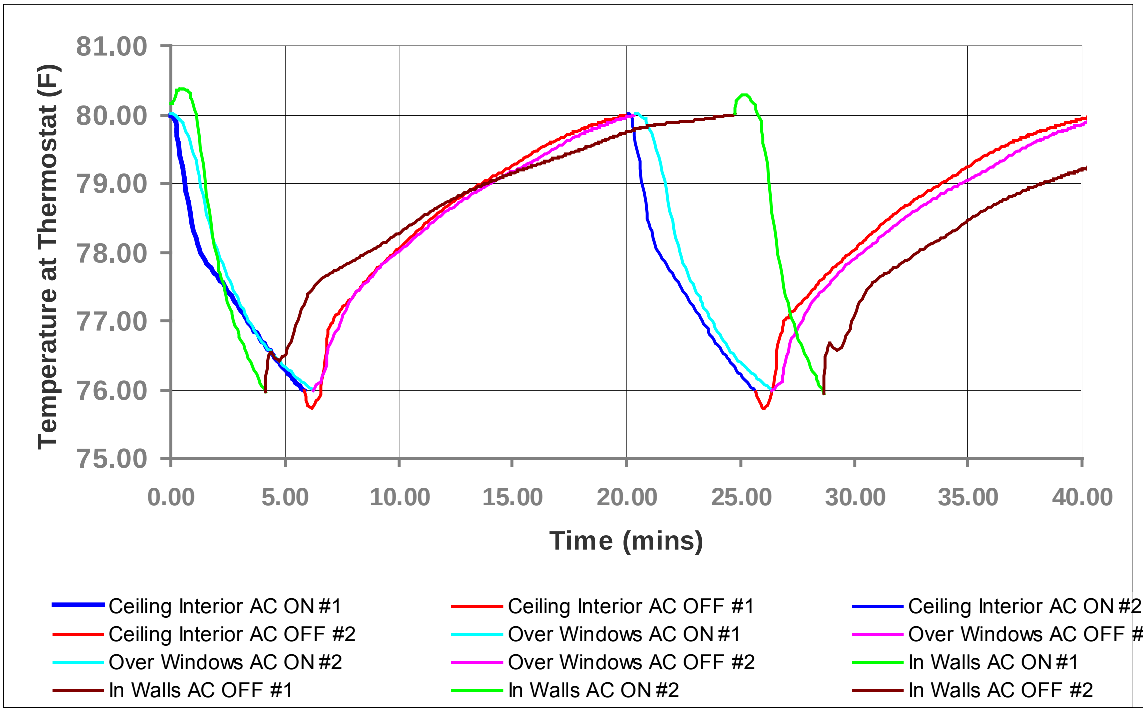

Figure 6 ON/OFF Run Times With Ceiling Return For Three Cooling Configurations
(supply register interior ceiling, ceiling over windows, and in-wall)

Figure 7 is an example showing the impact of the ceiling return for the in-wall supply in the heating case. The duty cycle is slightly longer for the ceiling return but the actual HVAC ON time is shorter for the low-wall return. Also note that the transient temperatures seen at the thermostat are erratic for either return, probably due to buoyancy. For heating, the combination of the wall supply and low-wall return provides a slightly more energy efficient design in terms on total ON-time. The length of low-wall return duty cycle is very close to the ceiling return duty cycle. However, the percent of ON-time for the low-wall return is smaller, likely due to a better mixing. The HVAC unit would cycle slightly more often with the low-wall design and this study does not consider that impact on the lifetime of the HVAC unit.

Since HVAC system in production homes are not built with both a high and low positioned return system, the designer will need to decide whether heating or cooling takes precedence and design accordingly.

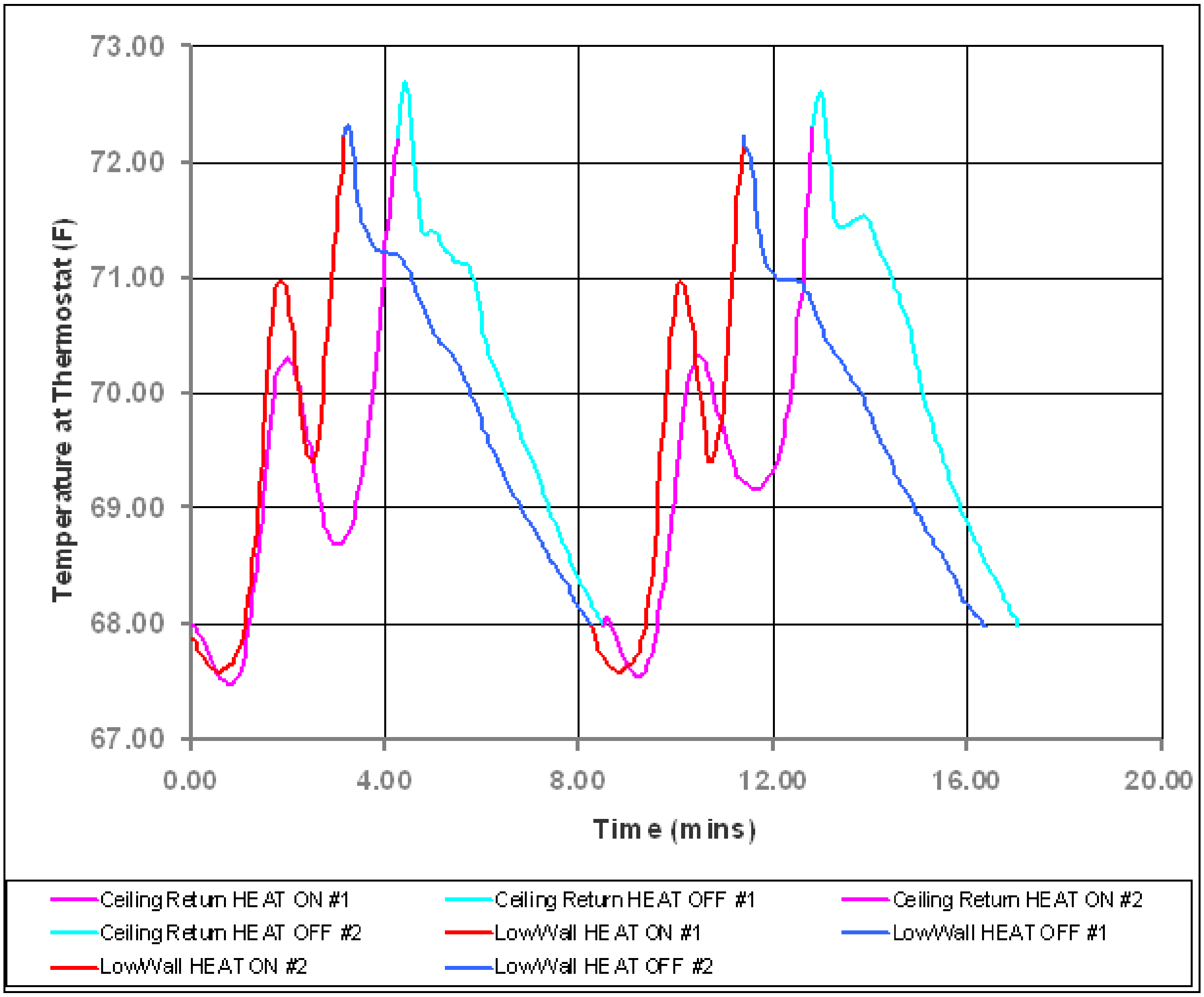

Figure 7 Ceiling Return vs Low-Wall Return for Heating (in-wall supply registers)

Based on input from the TAG, a second, follow-on study was conducted using CFD modeling to examine a two-story home. Two-thirds of the new homes built in California are two storied and many of the complaints in new homes are from heating and cooling problems in these homes. This study examined variations in the number and location of returns and the placement of the thermostat. Results and recommendations from this study are included as an addendum to the HVAC Design Guide. These study results are included in Attachment 2 to this report.

The two story results show that two, centrally located returns, one upstairs and one downstairs, provide improved air mixing and reduced the frequency of the on/off cycling of the HVAC system. The most effective location for the thermostat was centrally located upstairs. Figure 8 compares the temperatures and cycle times for the three cooling cases studied. In these cases, occupant comfort was comparable but system cycling was significantly different and would have negative impacts on equipment life.

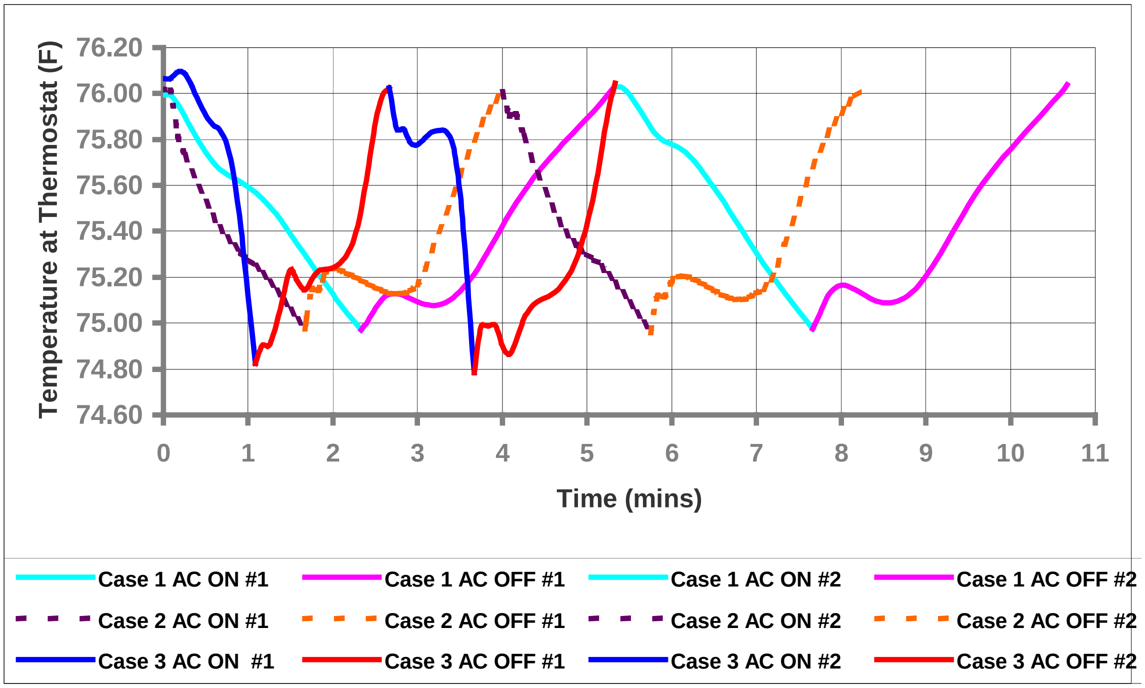

Figure 8 Comparison of Two-Story HVAC Cycle Time (Return Upstairs and Downstairs, Return Upstairs Only, Thermostat Downstairs)

5.3.2.2. Determine Builder and Building Impacts of Register and FAU Location

The different costs for materials and installations for the different cases with different register locations and/or different FAU locations were estimated by HVAC sub-contractors. These differential costs can be compared to the predicted differences in airflows and comfort for each design to further evaluate the cost-benefits of a particular design. Builder costs and impacts are included in the CFD case study, Attachment 2.

The design and installation costs for 4 cases along with calculated AC ON time/Hr were provided below comparisons. (Note: Framing cost information is not included and would be dependent on the applications.)

The short-duct run times are from the ceiling return cases. The long-duct run times are from the low-wall return cases. Based on input from our HVAC subs, the cost differences between short and long ducts are primarily the duct material length. Again, these would depend on the specific installation.

In discussion with the HVAC contractor, the most significant cost differences between wall mounted registers and other applications is the cost of the wall register boot (sheet-metal fixture).

Current installation practice in California production homes is to place the registers in the ceiling, centered in the room or over the windows, depending on the shortest duct length, to minimize initial installation costs. The "Incremental Cost" shown in Table 5 is the increased cost over registers in the ceiling, centered in the room.

Table 5 Design and Installation Costs

FAU Location	Register Location	Incremental Cost	Calculated AC ON Time/Hr (seconds)
Attic (Short duct run)	Ceiling-Mounted Registers	Baseline Cost	17.7
Attic (Short duct run)	Registers Over Windows	$3000	17.3
Attic (Short duct run)	Wall-Mounted Register	$3400	9.5
Garage (Long duct run)	Ceiling-Mounted Registers	Not costed	16.0
Garage (Long duct run)	Registers Over Windows	$3400	17.7
Garage (Long duct run)	Wall-Mounted Register	$3800	11.9

5.3.2.3. Develop HVAC System Design Manual

An HVAC Design Guide was produced which includes the CFD Study results and the previously documented best practices. The HVAC Guide was reviewed by a variety of users (TAG members, as well as other builders, architects, HVAC designers/engineers, and HVAC contractors) with very positive feedback. The CFD results are included to help explain, in a graphical way, the impact of register placement. This guide is included as Attachment 3.

5.4 Conclusions and Recommendations

5.4.1 Conclusions

The new version of ACCA Manual J, Version 8 contains the improvements of interest to this research element. The newest version of the Version 8 software implements a preliminary set of these calculations. The changes require more input by the user and can be tedious and time-consuming. The added complexity is a serious barrier to use of the new software, even though it has substantial accuracy and implementation benefits.

The requirement for "short ducts" involves twice the effort in the design stage. To receive credit, two steps are required. First, a normal system is designed. Then, the design is redone with the short duct system. This two-step process is costly to the designer and usually results in a small credit and is not a significant motivator.

The incorporation of best practices in the design and construction of HVAC systems in California production home building would have a significant impact on home energy use. The best practices identified in this research are not currently used by a significant part of the home building industry. Wider adoption of these methods would have a significant impact on energy use. It is estimated that only 20% of new construction uses some form of Manual J. The remainder use "rule-of-thumb" or alternative methods that are described in this research. A best practice design (and construction) process that includes system design by a qualified design consultant, communication of the design, construction, and verification is recommended to increase the energy efficiency.

5.4.2 Recommendations

One of the needs identified in the latest Version 8 software was a "standard" set of inputs that would provide the user with a set of nominal values for many of the required inputs, allowing them to focus on the non-standard features. Expanded capability and ease-of-use would have a positive effect on the adoption of the tool.

One of the most common practices in California production home building is to place the supply registers in the ceiling and to locate the return in a hallway ceiling. While cost-effective for the builder, the CFD results show this to be the least energy efficient design, particularly in a cooling dominated climate zone. This practice should be discouraged and one of the alternative methods should be considered.

Use of the HVAC Design Guide would improve energy efficiency and we recommend that it be made easily available and accessible. There are opportunities to make it available through the BII website and through the Building America Program. It could also be provided to interested parties during the BECT training sessions.

5.4.3 Benefits to California

While many designers own a copy of ACCA Manual J, only about 20% of new construction uses some form of Manual J. Of those using Manual J, we estimate that about 75% are using the latest version. Version 8 is more accurate but does not necessarily result in a substantially different design. However, using ACCA results in an energy credit of 0.5-1.5 kbtu/sf/yr, depending on home design and climate. If Manual J were more widely used, energy benefits would be substantial.

The HVAC Design Guide includes recommendations based on the CFD studies that show potential energy savings through register and return placement. Based on study results, improved practice (wall register/ceiling return) vs. common practice (ceiling register/ceiling return) translates to over 8 minutes/hr of run time in energy savings. Proper use of the methodologies, described in this design guide, will save energy.

In 2005, the projected number of California new homes (per CIRB -- Construction Industry Research Board) is 146,000. This is projected to increase 1-2% in 2006 and 2007 (CIRB) and remain flat through 2010 (according to NAHB). The 2005 expected market penetration for this program is 20-25% through efforts of ConSol, through their design services and consulting/training HVAC contractors who do their own designs, including those who participated in this program and others. The market penetration is expected to increase at a projected rate of 2-4% per year through 2010.

A potentially higher level of market penetration is probable based on the Builder Energy Code Training (BECT) Program. This program's total market impact for 2005 is estimated to be 15% with a potential mechanical systems impact of 5%. With continued funding, market impact is anticipated to increase 5% during 2006 and to continue to increase at 1-2% per year while the contract is in place.

GLOSSARY

Acronyms	Term
ACCA	Air Conditioning Contractors of America
BII	Building Industry Institute
EEM	Energy Efficiency Mortgage
FAU	Forced Air Unit
HBW	Home Buyers Warranty
HERS	Home Energy Rating Systems
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
MEC	Model Energy Code
NAHBRC	National Association of Home Builders Research Center
PAC	Program Advisory Committee for this PIER contract
PIER	Public Interest Energy Research
QCEE	Quality, Comfort and Energy Efficiency
SHGC	Solar Heat Gain Coefficient

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LIST OF APPENDICES

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APPENDIX I

CAUSES OF FORECLOSURE

Report on Causes of Foreclosures

Task 4.1.1 Gather data on foreclosures

This report summarizes the data sources we examined to determine the causes of foreclosure as related to comfort, quality, and energy efficiency. The evidence suggests that the poor are the most likely to suffer foreclosure caused by excessive maintenance or utility costs. The poor, about one-third of which are homeowners, spend proportionately more of their incomes on housing costs and therefore have little income left over for unexpected costs, such as maintenance or high utility bills. Moreover, ability to pay energy bills is not only constrained by level of income, but also by the stability of the income source: if the pay is regular and can be increased in times of need (Power, 1999).

Background

The Foreclosure Process

After a borrower is delinquent on paying a loan for a certain amount of time (length of time varies with lender), the borrower is considered in default. Once in default, the lender chooses to work with the borrower to avoid foreclosure, or to initiate the foreclosure process. Therefore, data on delinquency cannot easily be translated into foreclosure data. Once the foreclosure process is initiated, there is a considerable amount of borrowers who are reinstated or who sell their homes pre-foreclosure (Capone, 1996*)*. Lenders are reluctant to foreclose on loans because the cost to the lender is significant. In years 1991, 1992, and 1993, HUD reported that 65%, 61%, and 57% of defaulted loans were reinstated and only 22%, 18%, and 11% of foreclosures were completed, respectively.

Foreclosure Rates

In the years 1984-1993, the delinquency rate in California was consistently lower than the rate in other parts of the U.S. (Capone, 1996). FHA and VA loans consistently have a higher rate of foreclosure than conventional loans.

Housing Conditions

In *Beyond Poverty, Extended Measures of Well-Being* (U.S. Bureau of the Census, 1995), almost 10 percent of non-poor people reported living conditions bad enough that the person reported a desire to move. Of the poor, over one-quarter reported the same, and over one-third of families receiving Aid for Families with Dependent Children (AFDC).

According to the *State of the Nation's Housing, 2000*, 2.1% of very low-income owner households (out of 12,820,000 total) live in severely inadequate housing—defined as having severe problems in plumbing, heating, electrical systems, upkeep, or hallways. Of these 12.8 million households, over one-third pay more than half of their income on housing, leaving little if any for maintenance costs.

Gyourko and Linneman (1993) state that reduced income, in constant dollars, of low-skilled workers is leading to an increased probability of deferred maintenance and, hence, a substantial drop in the quality of affordable existing homes over the past 15 years.

According to Fluhr and Thomas (2000), about one percent of new homes will experience major structural damage in 10 years, at an average repair cost of $30,000. This cost is significant, although no data was found linking structural repair costs to foreclosures.

In a 2001 study, Listokin and Listokin report that about one in twenty homes in the U.S. require substantial rehab and one in ten need moderate rehab. Substantial rehab involves removing all interior walls and mechanical equipment and installing a new space plan. Moderate rehab includes extensive improvements such as new wiring or replacement of mechanical systems.

Housing Cost Burden

As a percentage of monthly income, the cost burden of housing expenses (mortgage, taxes, and utilities) in California greatly exceeds the national average when it comes to cost burden. Of the owner-occupied units, 29% expend 30% or more of their monthly income on housing costs, compared to the 19% nationally who spend more than 30% on housing costs.

The *2001 Advocate's Guide to Housing and Community Development* (National Low Income Housing Coalition, NLIHC) reports that homebuyers today pay substantially smaller down payments than buyers in the 1980s, leaving them more in debt, having lower loan-to-value ratios, and more susceptible to economic downturns.

Maintenance Cost Burden
The NLIHC also reports that low income homeowners—defined as having 80% or less of area mean income (AMI)—have additional challenges. Low income homeowners typically live in older homes requiring more maintenance and in neighborhoods with less potential for property value increases. Approximately half of low income homeowners are elderly or disabled and, of the elderly, approximately 80% are single females. Therefore, the potential for do-it-yourself home repair or maintenance is low, further increasing maintenance costs.

In its report, *Low Income Housing Profile*, NLIHC reports that 27% of low income home owners had either moderate or severe housing problems. A moderate housing problem is defined as a cost burden between 30% and 50% of income, occupancy of housing with moderate physical problems, or overcrowding (more than one person per room). Severe housing problems are defined as a cost burden greater than 50% and with serious physical problems.

Listokin and Listokin (2001) showed that the very low income, the group most unable to pay for home improvements, are disproportionately living in homes that are in need of moderate or substantial rehab. Eighteen percent of very low income occupants were found to live in homes (or apartments) needing moderate or substantial repair, compared with twelve percent of high income occupants. The study clearly demonstrated that the cost burden on the poor is extreme: 58% of very low income occupants have pre-rehab (excessive is defined as by the researchers as housing costs greater than 40% of income), while 71% would have excessive housing costs if rehab costs were included. For the high-income group, the percentage of people who would incur excessive cost burdens pre- and post-rehab are 2% and 3%, respectively.

Utility Cost Burden
According to the U.S. Department of Housing and Urban Development, utility bills provide a disproportionate burden on the poor, comprising 19% of income on average in compared to 4 percent for families of median income.

A significant portion of payment problems occur with people who make between 150% and 200% of poverty level, an income level which is high enough that the families are unable to receive most forms of assistance, but not high enough to be able to meet monthly payment obligations.

Lending and Foreclosures

The ability to borrow money and the cost of mortgage instruments available to low income homeowners places a financial burden upon the low income population and increases foreclosure risk.

Pine (2001) states that predatory lending costs consumers $9.1 billion per year. There are two types of predatory lending. In equity stripping, exorbitant fees are charged and incorporated into the loan, such as a prepayment penalty on subprime loans, which results in less equity when the loan is refinanced or home sold. (Subprime lending refers to the practice of lending to people considered high-risk, usually with associated high fees or interest rates.) The second predatory lending practice is risk-rate disparity that occurs when the borrower charges a higher interest rate than the risk justifies. Risk-rate disparity is estimated to cost low-income borrowers $2.9 billion per year in excess interest.

In general, subprime loans with predatory terms are thought to be more likely to end in foreclosure than conventional loans, although no statistics were given to justify this hypothesis.

Prioritization of Utility Bill Payment

Energy is a very high priority for low-income households, to the point that people have been known to cheat on baby formula to pay utility bills, the “heat or eat” dilemma. (Benfield, personal communication). A Boston City Hospital study reported that emergency visits by underweight children underweight children increased by 30% after the coldest months of the winter—demonstrating the heat or eat dilemma for low-income families (Ribadeneira, 1996).

A 1989 Washington Natural Gas study looked at how customers prioritize bill payment. Thirteen percent of respondents said they would pay their heating bill before rent or mortgage. (Baker, 1989)

A 2000 Iowa study (Mercier, et. al.) surveyed 10,000 applicants to the Low-Income Housing Energy Assistance Program (LIHEAP). When faced with unaffordable home energy bills:

- 12 percent went without food at times to pay their home heating bill
- More than 20 percent went without medical care in order to make utility bill payments
- Overall, 7.4 percent reported not paying rent or house payment in order to afford the heating bill (12.9% of wage-earner households and 10.9% of households with young children opted to pay utility bills in lieu of rent or house payment, 3.1% of seniors reported doing so [probably low because 84% of seniors own their homes mortgage free—U.S. Bureau of the Census, 1995])
- Almost 30 percent reported not paying other bills, or incurring debt, in order to pay utility bills.

A 1999 study by Energy Cents Coalition discovered that, of low income families with children in Minnesota, over one-third could not pay their full rent or mortgage because of the cold winter and high fuel costs.

A 1993 Washington Post study revealed that between 2.5 million and 4.9 million elderly Americans suffer "food insecurity" caused by utility bill payments, this included skipping meals (from Universal Electric Service Fund website, www.uesfacts.org).

A 1988 Penn State Study found that 63% of Pennsylvania consumers expressed a “great deal of concern” over winter heating costs, while only 48% expressed the same level of concern over mortgage or rent.

Although the previous studies may not apply to a more temperate climate such as California where heating is not a life-or-death decision, they describe the importance many place on paying utility bills in relation to mortgage payments and other bills.

The Urban Institute’s 1999 National Survey of American Families shows that California ranks above the national average in percent of homes reporting difficulty paying mortgage, rent, or utility bills. Fourteen percent of all California households (25% of those having income less than 200% of the poverty level and 9% of those having incomes higher than 200% of poverty level) reported having difficulty paying mortgage, rent, or utilities. In comparison, the national levels were 11.4% (all income levels), 23.1% (below 200% poverty) and 7.1% (above 200% poverty). Of those nationwide who reported having difficulty paying mortgage, rent, or utilities, 8.8 percent reported moving in with other people (even temporarily) because they could not afford to pay their bills.

Link between Utility Termination and Homelessness

A Philadelphia study showed that people who had utilities disconnected sought shelter in city-funded homeless shelters in almost 8% of cases (however, only 1.5% were confirmed to be the same person by name and address matching, others were simply determined by name matching) (Robinson, 1991). Regardless, since city-funded shelters are often considered a last resort (after friends, family, and private shelters), this is a distressing statistic. The same study showed that, over the five year period between 1986 and 1991, 32 percent of homes had been abandoned within one year of electric service termination and 22.4 percent of homes had been abandoned within one year of gas service termination. Due to incomplete records, abandonment caused by water shutoff was not analyzed.

The Coalition on Homelessness in Pennsylvania surveyed emergency shelter providers about the cause of homelessness in their regions. Utility terminations were cited 7.9% of the time (Robinson, 1991).

A Minnesota study (Copeland, 1997) revealed that over one-quarter of evictions were caused by electric and gas termination; 40 percent were caused by water shutoff.

According to the U.S Bureau of the Census (1995), more than one-quarter of the poor reported not being able to pay their full rent or mortgage, one-third reported not being able to pay their full utility bill, 8.5 percent had gas or electric service turned off, and 2.1 percent were evicted.

While none of this information gives statistical data about people foreclosing on their homes on the basis of unaffordable energy bills or substandard living conditions, it does paint a picture of the situation to lend credibility to the theory that these factors can lead to foreclosure.

Causes of Foreclosures—Sources Examined

As mentioned, we found little data on causes of foreclosures. However, we examined numerous avenues. Here, we report on those sources examined, so that the reader has knowledge of where data is not available. According to Quercia and Stegman, data is not collected at the time of default, leaving causes up to speculation.

Private Lending Institutions
Private mortgage lenders were unwilling to divulge data on mortgage default rates. Foreclosure cost data, however, can be ascertained from financial statements of publicly-owned companies.

Freddie Mac
Data may be available through Freddie Mac, however we were unable to obtain any. We spoke with John Hemschoot of Freddie Mac, who merely suggested we can 800-FREDDIE and ask to speak to the non-performing loans department. The person at 800-FREDDIE was not able to help us find this department.

Office of Federal Housing Enterprise Oversight, Department of Risk Analysis.
This office appears to conduct risk analysis of foreclosure.

Louisiana Mortgage Lenders Association
Expressed recent interest in durability and foreclosures based Formosan termite cases. They do not track the statistics, however, for termite or other durability issues tied to foreclosures.

Mortgage Bankers Association.
Conducts an annual delinquency survey which reports rates of delinquency by a variety of demographics. However, reasons for delinquency are not tracked. In addition, they conduct an annual analysis of income and costs associated with one to four-unit residential mortgage loans. The cost study does not segregate foreclosures in the reporting.

Mortgage Insurance Companies of America.
Trade association of the Private Mortgage Insurers. Washington, DC. The association does not track data.

National Mortgage News Daily.
Publishes the Mortgage Industry Directory which includes information, by lender, about the rate of delinquencies. They have no other relevant statistical data for this task.

Housing Statistics of the United States
Reports default rates for various types of loans (FHA, conventional, etc.) but does not give reasons for loan default.

Energy Star mortgage providers. Of the four providers of Energy Star mortgages listed on the energystar.gov website, two were wrong numbers and one (Loanz.com) was not available on the website. Messages left at the phone number for Loanz.com (which did not appear to be a business, from the recorded message) and at the fourth lender went unanswered.

Fitch International Rating Agency Mortgage Default Model (awaiting return call on FRM Loan Loss Database).

Loan Performance
A Jersey City, NJ based company that tracks loan performance data and sells it for a fee. A call left with the DC-based sales person went unanswered.

Foreclosure Prevention Efforts
There are many agencies that help homeowners reduce the risk of foreclosure, generally through credit counseling or financial assistance. Several organizations offer both weatherization services and foreclosure prevention services, although we could not find any who track reduced risk of foreclosure through weatherization services.

Low Income Housing Energy Assistance Program (LIHEAP)
LIHEAP administers emergency funds for energy bills and conducts some weatherization services. They do not track data on foreclosure or how LIHEAP funds affect one's risk of foreclosure.

Ginny Mae referred to FHA for any data.

Associations that do work related to energy and housing:
National Consumer Law Center (Washington, DC)
Energy Cents Coalition (St. Paul, Minnesota)
Urban Institute (Washington, DC), conducts the National Survey of American Families which asks about inability to pay utility bills.
Association for Energy Affordability (New York)
Economic Opportunity Studies (Washington, DC)
Center for Law and Social Policy
Energy Coordinating Agency (Philadelphia)

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APPENDIX II

CATEGORIES OF FORECLOSURES

Report

Task 4.1.2 Identify Categories of Foreclosures

There is a significant body of literature evaluating the probability of default based on loan characteristics, borrower characteristics, property characteristics, and crisis events. Most are studies evaluating risk factors of foreclosure, for use as a tool to mortgage underwriters for evaluating mortgage loan risk.

Fannie Mae Data

The data obtained by Fannie Mae includes reasons for *delinquency*, which is not necessarily the same as foreclosure.

The reasons for delinquency used by Fannie Mae in their database include the following:

1. Death of Principal Mortgagor
2. Illness of Principal Mortgagor
3. Illness of Mortgagor's Family Member
4. Death of Mortgagor's Family Member
5. Marital Difficulties
6. Curtailment of Income
7. Excessive Obligations
8. Abandonment of Property
9. Distant Employment Transfer
10. Property Problem
11. Inability to Sell Property
12. Inability to Rent Property
13. Military Service
14. Other
15. Unemployment
16. Business Failure
17. Casualty Loss
18. Energy-Environment Costs
19. Servicing Problems
20. Payment Adjustment
21. Payment Dispute
22. Transfer of Ownership Pending
23. Fraud
24. Unable to Contact Borrower
25. Incarceration

The codes that are at least partly relevant to this task include:

Property Problem, which is defined as “delinquency [that] is attributable to the condition of the improvements or the property (substandard construction, expensive and extensive repairs needed, subsidence of sinkholes on property, impaired rights of ingress and egress, etc.) or the mortgagor's dissatisfaction with the property or the neighborhood."

Energy-Environment Costs, defined as "delinquency [that] is attributable to the mortgagor's having incurred excessive energy-related costs or costs associated with the removal of environmental hazards in, on, or near the property."

The servicer is instructed to report only one code—the primary contributing factor to the delinquency. Therefore, energy costs or repairs related to housing quality may not be transparent in the data, if they are only compounding causes.

However, both categories are sufficiently broad in scope as to make it impossible to determine if a delinquency is actually caused by energy costs or poor quality construction.

Causes of Foreclosure in the Literature

The central problem with understanding causes of foreclosure is that information is collected by lenders at the time of loan origination but is not collected at the time of default. Data regarding borrower information is estimated from data taken at the time of loan origination.

Quercia and Stegman reviewed the literature on residential mortgage default and divided their findings into three types of studies: first, second, and third generation studies. The importance of home equity in the default decision was evident in these early studies. Other factors in the early studies found to increase the risk of default include term of the loan (a longer term increases risk), the age of the loan (up to 3-4 years, after which risk declines), and the presence of secondary financing.

The first generation studies also examined borrower-related factors in the default decision. Borrower age, marital status, and number of dependents did not have an effect on default risk. Payment-to-income ratios of more than 30 percent were found to significantly increase the risk of default. Borrowers having occupations with variable incomes (such as salesman) were also found to be more likely to default.

The first generation studies also found location to be an important factor. Loans made in suburban locations were less risky than central-city loans, areas with high unemployment had higher default rates, and mortgage interest rate premiums (hence costlier loans) were found in areas with poor conditions of property and neighborhood.

Later first generation studies expanded the factors analyzed to type of mortgage instrument (e.g., adjustable rate mortgage), ratio of loan to value at time of default decision, and crisis events.

Beginning in the late 1970s, second generation studies modeled the behavior of individual households in making the default decision. The models are optimization models to determine borrower choice at the time of mortgage payment: make scheduled payment, delay payment (delinquency), stop payment (default), or prepay the mortgage. Basically, these studies examined this option as merely a financial decision (if home equity is negative after all costs and benefits are weighed, borrowers will choose to default). However, this theory is incomplete, as borrowers might not have the information they need to make the default decision (e.g., the total cost of foreclosure). One study showed the borrowers do not exercise the default option consistently, even if foreclosure costs are zero and the borrower has negative equity in the home. Another study which looked at transaction costs and crisis events showed that net equity and the difference between market value of the home and value of the mortgage have significant effects on the default decision (if the home is worth less than the mortgage balance, a borrower is more likely to walk away, provided they do not have significant equity in the home).

Another second generation study examined the effect of self-employment on default, and found that being self-employed increases default risk 14 times more than increasing the loan-to-value from 75 to 95 percent.

A third generation of studies began in the late 1970s and early 1980s as a result of the high rates of default seen during this time. The studies, like second generation studies, viewed default as an option, with net equity being the major factor in the decision. However, the studies have not reached consensus on whether the default decision is purely related to net equity, with no consideration of transaction costs or crisis events.

Overall, Quercia and Stegman showed that loan characteristics (mainly home equity) influences the default decision while the influence of transaction costs remains unknown. The main problem in understanding default risk is the lack of data at the time of foreclosure.

We reviewed recent literature on probability of default and came up with the following factors as affecting the likelihood of default:

- Loan-to-value (biggest single predictor according to Case and Shiller)
- Adjustable rate mortgages
- Homeowner equity
- Years at current residence
- Expectations regarding equity and future value
- Interest rate
- Ratio of mortgage payment to income
- Occurrence of a crisis event (divorce, death)
- Unemployment
- Risk posture (consumer debt, personal savings)
- Neighborhood effects (race and mean income)

Data from other Institutions

Family Housing Fund
This organization provided housing and some financial assistance to over 4000 homeowners in Minneapolis and St. Paul from July 1, 1991 through June 30, 1997. Of this population, 59% stated that job loss or reduction in income was the causal factor for mortgage default; 38% from emergency home repairs; 28% for health-related problems; and 19% attributed to divorce or separation. Further explanation about the type of emergency home repairs was not disclosed.

Vermont Housing Finance Agency
Data not available.

Alaska Housing Finance Agency
Data not available.

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APPENDIX III

COSTS OF FORECLOSURES

Report

Task 4.1.3 Determine cost of foreclosures

According to the Mortgage Insurance Corporation of America (MICA), many expenses make up the cost of foreclosure to lenders, which are approximately 15% of the original loan amount:

- Interest during the period of delinquency and during the foreclosure process (which can be up to one year or more)
- Legal fees
- Maintenance and repair expenses
- Real estate broker fees
- Other closing costs
- Losses from sale at less than original sales price

The cost to lenders of foreclosure, an important factor in a lender's decision to foreclose rather than renegotiate a loan, is affected by laws in the state. Costs of foreclosure are lower in states where:

- Nonjudicial foreclosure is allowed (court supervised foreclosure is not required);
- There is no statutory right of redemption (where borrowers can redeem their properties after the foreclosure sale for the amount paid at the sale);
- Deficient judgment is allowed (lenders can recover costs directly against borrower's personal assets); and
- Foreclosure and redemption periods are shorter (the period of time borrowers have to exercise right of redemption).

In California:

- Nonjudicial foreclosure is allowed.
- Lenders may not obtain a deficiency judgment against the borrower under certain circumstances (e.g., if the foreclosure is nonjudicial).
- A borrowers right ot redemption is terminated when a deficiency judgment is waived or prohibited.
- The borrower may redeem 12 months after the sale if the lender seeks a deficiency in a judicial foreclosure; otherwise, the redemption period is three months.

Therefore, foreclosures in California may be more expensive than those in other states.

Fannie Mae

Year	**Average Loss per Real Estate Acquired:**
1990	$29,166

1991	$27,557
1992	$25,254
1993	$21,087
1994	$29,661
1995	$26,275
1996	$20,385
1997	$15,854
1998	$12,670
1999	$7,396
2000	$6,188

* The drastic decline in cost per foreclosure starting in 1996

Freddie Mac Financial Statements

Year	Average Loss per Real Estate Acquired:
1998	$13,686
1999	$12,550
2000	$9,127

FHA Case Studies

Losses from foreclosed MMI Fund loans averaged about $24,400 per property between 1975 and 1993[1]. In 1997, the average national loss on FHA foreclosures was $28,000[2].

Department of Veteran's Affairs

Department of Veteran's Affairs in North Dakota, South Dakota, and Minnesota had an average loss per foreclosed loan of $10,600 in 1998[3].

Private Mortgage Insurer

United Guaranty Corporation had an average loss of $17,300 per foreclosed loan in 1997[4].

Literature

According to the Family Housing Fund, the average cost of reinstating a mortgage—providing counseling and financial assistance—that is at risk of default is $3,300[5]. Costs, if the house is allowed to go into foreclosure, are significantly higher. Under one

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1 Information on Foreclosed FHA-Insured Loans and HUD-Owned Properties in Six Cities, GAO/RCED-98-2, United States General Accounting Office.
2 Mortgage Foreclosure Prevention: Program and Trends, December 1998. Family Housing Fund, Minneapolis, MN. www.fhfund.org/research
3 Ibid.
4 Ibid.
5 Cost Effectiveness of Foreclosure Prevention, Summary of Findings, 1995. Family Housing Fund, Minneapolis, MN. www.fhfund.org

scenario, in which the house becomes vacant and boarded and the city rehabilitates the house for sale, the cost to[6]:

Homeowner:	$7,200
Lender:	$1,500
FHA/HUD:	$26,500
Servicer:	$1,100
The City:	$27,000
Neighbors:	$10,000

In scenario 2, the house is sold and is insured by private mortgage insurance. The cost in this scenario is[7]:

Insurer:	$16,000
Lender:	$2,300
Servicer:	$1,100
Homeowner:	$7,200

A HUD report to congress listed itemized the "typical" costs of foreclosure in the following manner:[8]

Values at Loan Origination	
House Price	$ 100,000
Loan Amount	80,000
Values at Loan Default (36 months after origination)	
House Value (after rehabilitation)	100,000
Loan Amount (9%, 30 yr., fixed rate loan)	78,200
Gross Equity	21,800
Expenses That Are Independent of Holding Period	
Property Rehabilitation (8% of full house value)	8,000
Attorney, Title, and Transfer Fees (3.2%)	3,200
Realty Commission on Final Sale (6%)	6,000
Contribution Toward Buyer Closing Costs (3%)	3,000
Total Cost	20,200
Add Expenses That Vary With Holding Periods	
Minimum holding period: 5 months from delinquency to foreclosure, 3 months from foreclosure to property disposition	

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[6] Ibid

[7] Ibid

[8] U.S. Department of Housing and Urban Development, 1996. Providing Alternatives to Mortgage Foreclosure: A Report to Congress.

Lost interest	4,692
Property taxes, hazard insurance, and maintenance (0.21%/mn)	1,680
Holding Period Costs	6,372
Total Cost	26,572
Loss on Foreclosure	**4,772**

Average Holding Period: 10 months from delinquency to foreclosure, 5 months from foreclosure to property disposition

Lost interest	8,798
Property taxes, hazard insurance, and maintenance (0.21%/mn.)	3,150
Holding Period Costs	11,948
Total Cost	31,148
Loss on Foreclosure	**10,348**

Long Holding Period: 18 months from delinquency to foreclosure, 7 months from foreclosure to property disposition

Lost interest	14,663
Property taxes, hazard insurance, And maintenance (0.21%/mn.)	5,250
Holding Period Costs	19,913
Total Cost	40,113
Loss on Foreclosure	**18,313**

APPENDIX IV

WARRANTY AND CALLBACK BUILDER SURVEY

Preface

California is one of the largest producers of homes in the nation—with over 100,000 new homes built each year across the state. Yet the housing market continues to favor sellers as desperate home buyers drive prices out of reach for most of those seeking home ownership in California. Increasingly, home buyers are turning to new housing developments in inland valleys, where land is available and housing more affordable, but also where energy use, especially for summertime cooling, is greater.

Even with the recent energy crisis fresh in their minds, most California home buyers continue to demand larger homes with "comfort" and "quality" amenities (e.g., countertop and flooring upgrades) that appear to equate to clearer investment value than do energy efficiency features sold explicitly as such (e.g., denser insulation). To remain profitable in a highly competitive industry, home builders seek to develop strong customer relationships by responding to specific consumer preferences—especially for comfort, quality, and affordability—while already following some of the nation's strictest building and energy codes.

Promoting residential energy efficiency remains an important pursuit in California given projected growth in less temperate regions of the state and the increasing consumer demand for larger, more comfortable homes. But, given the perceptions and motivations reflected in the process of constructing, selling, and buying homes, taking further steps to promote energy efficiency is a "tough sell" to builders and consumers alike. In this report, RAND researchers seek additional ways to promote energy efficiency by shedding some light on the following question:

What can be done to address the state's interest in increasing energy efficiency in residential construction, while respecting individual consumer demand for affordability and investment value, and increasing the profit of production home builders in California?

In 2001, the Building Industry Institute (BII) partnered with the RAND Corporation, the National Association of Home Builders (NAHB) Research Center, and ConSol to conduct research under the California Energy Commission's Public Interest Energy Research (PIER) program. The research program, Profitability, Quality, and Risk Reduction through Energy Efficiency, endeavored to understand the relationship between comfort, quality, and energy efficiency; how homes are built; and the ability of builders to earn a profit. This report compiles a review of the literature, various consumer survey and customer-service data sets, and insights revealed in a series of interviews with executives of leading home building companies that have operations and experience in California.

Findings are presented within a broader framework describing the home building process, and identify some possible interventions that could achieve greater energy efficiency in new California homes. This report is intended especially to help energy policymakers better understand how market pressures affect home buyers' purchase decisions related to energy efficiency, and the important role that builders play in facilitating these decisions.

RAND Science and Technology

RAND is a nonprofit institution that helps improve policy and decisionmaking through research and analysis. RAND Science and Technology (S&T), one of RAND's research units, assists government and corporate decisionmakers in developing options to address challenges created by scientific innovation, rapid technological change, and world events. RAND S&T's research agenda is diverse. Its main areas of concentration are science and technology aspects of energy supply and use; environmental studies; transportation planning; space and aerospace issues; information infrastructure; biotechnology; and the federal R&D portfolio.

For more information about RAND S&T, see our website at http://www.rand.org/scitech/index.html.

Building Industry Institute

The Building Industry Institute (BII) was founded in 1993 by the California Building Industry Association (CBIA) to develop, implement and administer research and educational programs for home builders, developers, and the general public. The CBIA is a statewide trade association and represents over 6,000 construction related firms involved in both residential and light commercial construction. CBIA members produce nearly 80 percent of all new homes in California each year. The BII works cooperatively with a variety of state and federal agencies, local governments, utility companies, universities and private, not-for-profit organizations to provide information and research which facilitates the construction of quality homes for consumers. For more information about BII, see their website (http://www.thebii.org/).

Contents

Tables

Summary

Overview

The RAND Corporation, the Building Industry Institute (BII), the National Association of Home Builders (NAHB) Research Center, and ConSol were funded by the California Energy Commission (CEC) to conduct a research program that aimed to understand the relationship among comfort, quality, and energy efficiency as valued by consumers, how homes are built, and issues of home builder profit.

RAND's assignment in this research program was to explore the possibility that home features associated with home owner comfort and quality may also be associated with energy efficiency in the home. Further, RAND researchers explored the relationship of energy efficiency to builder profit through cost control. Both of these lines of inquiry were hoped to return insights for promoting energy efficiency in new California homes.

First, we reviewed the literature describing concepts and measures of comfort, quality, and energy efficiency in homes, and relationships among these notions (See Appendix 1 for further discussion of these). Second, we reviewed several available data sources describing both stated and revealed preferences by home buyers for comfort, quality, and energy efficiency in homes (See Appendix 2). Third, we reviewed data collected by home warranty companies, and elsewhere in available literature, looking especially for evidence that certain amenities or construction practices characterized as more energy efficient may also be associated with reduced costs of fixing problems in the home that are covered under warranty (See Appendix 3).

After this third step, we determined that we could not differentiate consumer values for comfort, quality, and energy efficiency using available data, nor could we conduct a rigorous quantitative analysis of warranty calls and associated costs to builders. However, it appeared that a qualitative analysis of expert knowledge of construction defects and associated costs, along with their understanding of consumer demand for comfort, quality, and energy efficiency could provide the information we needed.

In the summer and fall of 2003, we turned to executives of KB Home, Pardee Home, and Pulte Homes—each a home builder with operations in California—for some help with our assignment. Although not exhaustive in number (there are thousands of construction firms in California), participants were selected from companies that are industry leaders, differ in business strategy and market targets, and together represent a substantial share (approximately twenty percent) of the home building market in California. Together, participants represented more than one-hundred years of professional experience and knowledge developed in the home building industry in California.

We developed a discussion protocol (see Appendix 4) from our initial review of the literature and available data. Interviews were conducted with more than a dozen executives and high-level staff, as well as selected trade contractors that do business with our selected builders and others in California. Interview discussions formed the basis of several generalizations, and in some cases, certain specific relevant examples also emerged. In this report, interview statements are not attributed directly to individuals or their companies.

Along with estimates of construction problems and costs, and a review of consumer values, this report compiles builders' potentially useful insights into the production home industry, the housing market, builder practices, and profitability as they relate to energy efficiency of new homes in California. These insights suggest an important role played by builders at critical decision points during the home building process, and also some important constraints faced by builders related to promoting energy efficiency in new homes.

Findings

We have grouped our findings in three general areas. First, we describe the markets in which the home buyers and builders participate. Second, we describe effects on builder profit due to construction problems that increase builders' costs. Third, we take a broader look at builder profitability and describe some emerging options that may increase revenue (hence profit) to builders while also increasing energy efficiency in new homes.

Characteristics of new home markets in California, with respect to comfort, quality, and energy efficiency

- More affordable new-home opportunities are increasingly occurring in the inland valleys of California, where energy use, especially for summertime cooling, is greater.

- "Wow" features that are associated with greater comfort or quality (e.g., countertop and flooring upgrades) are perceived by most home buyers to secure greater resale value more than features promising greater energy efficiency (e.g., denser insulation).

- Two home features for which additional cost and risk to the home buyer and builder discourage promoting energy efficient options are heating, ventilating, and cooling (HVAC) systems and insulation. "Split HVAC" systems (either in the form of two smaller HVAC units, or as a single unit capable of cooling multiple zones), for example, promise greater comfort and energy efficiency, but are more expensive to purchase than conventional systems, and the newest of these are unproven.

- Builders seek long-term customer satisfaction. While builders are in a position to influence home buyers' decisions on certain home features, they have difficulty convincing home buyers (particularly first-time home buyers) of the additional benefit in upgrading features to a higher level of energy efficiency relative to the additional cost of doing so. The risk of customer disappointment in making energy-efficient choices threatens a lasting customer relationship and overall reputation of the builder.

The effect of warranty calls on builder profits, and their energy-efficiency implications

- Builders maintain active customer-service departments. Customer-service and warranty budgets typically amount to about ten percent of builders' after-tax profits.

- Builders review customer-service records and seek to improve practices that lead to the highest frequency and most costly problems in their homes. However, warranty calls with greatest frequency and costs are for "fit and finish" problems in the home (e.g., paint, walls, trim, flooring, and cabinetry), not for items with obvious energy-efficiency implications.

- The number of warranty calls for HVAC problems increases during summer months, but the effect of these calls on profit is small.

- HVAC systems that use wall registers appear to simultaneously satisfy consumer demand for comfort, reduce warranty callbacks to builders, and increase energy efficiency.

- Split-AC systems may also simultaneously satisfy consumer demand for comfort, reduce warranty calls to builders, and increase energy efficiency.
- Using green lumber (i.e., lumber that has not been dried in a kiln before use) may cause bowing of walls, which compromises the building envelope, especially in hotter, drier areas of the state. This problem appears to be infrequent, but may be emerging.

Opportunities for selling energy efficiency

- Energy efficiency in the home has broad marketing appeal that invites home buyers to consider builders that offer energy-efficient options, whether these options are ultimately selected in a new home purchase or not.
- Consumer values, home ownership experience, and equity drive decisions related to energy efficiency in home purchases, but the builder plays an important role in finalizing these decisions.
- Energy efficiency may be bundled with comfort and quality during sales, but options to do so need further review.
- The risks of buying and selling energy-efficient options need to be removed from the builder-home buyer transaction.

Emerging Policy Issues and Options

Out of our findings emerge three general observations that have implications for promoting energy efficiency in new homes in California:

- The greatest challenge for promoting energy efficiency in new homes is in the market for first-time home buyers looking inland, for the largest, most comfortable homes that they can afford. Information and resources to invest in energy-efficient options are least available to this group of home buyers.
- There is evidence that some design and construction measures may be taken to reduce cost to builders and improve energy performance of a home, but the greatest incentives to builders to control costs are for problems least associated with energy efficiency.
- Motivating builders through increased profit to promote energy efficiency in their home products may be more likely achieved by aiding

their marketing and sales efforts in order to increase revenue, rather than by informing design and construction practices in an effort to decrease costs. Builders' marketing and sales teams can sell energy efficiency to home buyers, with the credible information and risk-reduction options available to them. Making even a "tough sell" is what a trained salesperson is in the best position to do.

With these observations in mind, we present five interventions at various stages of the home building process that promote energy efficiency, and which are described in greater detail in Section 5. All of them highlight the role of the builder in achieving greater energy efficiency in new homes.

- Improve construction protocols and worker training, specifically to address HVAC design and framing problems such as bowed walls.
- Better educate home owners on basic HVAC use.
- Investigate performance and reliability of promising new technologies for homes, and support their use.
- Identify further options for cross-selling energy efficiency upgrades according to their promises of greater comfort and quality.
- Pursue strategies for promoting energy efficiency through builders, that also reduce risk to builders doing so.

Because these interventions are linked to potentially greater builder profit, builders may be more inclined to implement them. Government support is likely necessary to catalyze builders' initial response to these.

Organization of This Report

This report is organized as follows:

Section 1	describes the objectives for, and approach taken in, this study.
Section 2	examines consumer demand for comfort, quality, and energy-efficiency features in California homes.
Section 3	describes findings related to warranty calls, and their implications for builder profit and energy efficiency.
Section 4	explores possible roles for energy efficiency in home builders' business strategy, particularly as it relates to marketing and sales.

Section 5 summarizes emerging issues and suggests directions for policy development.

Appendix 1 presents concepts and measures of comfort, quality, and energy efficiency.

Appendix 2 reviews consumer valuations of comfort, quality, and energy-efficiency features of homes, and provides some guidelines for future market-survey instruments.

Appendix 3 describes an initial review of available warranty-call data, with emphasis on calls that have potential energy-efficiency implications.

Appendix 4 includes a discussion protocol for interviews with home builders.

Acknowledgments

We gratefully acknowledge several executive and management staff that participated in this study, and who shared valuable insights and information. We are especially thankful to Bruce Karatz, Eric Kough, Todd Baker, Tom DiPrima, and Matt McLaren of KB Home; Randy Myers, Doug Cazin, and Joyce Mason of Pardee Home; David Beck of Pulte Homes; Lori Duran of Shea Homes; Brad Tunby of WesPac; Steve Branson of Arden Lumber and Truss; and Stephen Smiley of The Meyers Group.

We are also grateful for the guidance and support of Rob Hammon, Director of the *Profitability, Quality, and Risk Reduction through Energy Efficiency* research program, of which RAND's project components were a part, and to Martha Brook and Eric Stubee of the California Energy Commission for their oversight and guidance of this evolving effort.

1. Introduction

The RAND Corporation, the Building Industry Institute (BII), the National Association of Home Builders (NAHB) Research Center, and ConSol were funded by the California Energy Commission (CEC) to conduct a research program that aimed to understand the relationship among consumer values, how homes are built, energy efficiency, and the ability of builders to earn a profit in markets for new homes in California.

In this program, RAND sought to:

- Understand the relationship between comfort, quality, and energy efficiency; how consumers value these characteristics of a new home; and how builders respond to consumer demand for these.
- Understand and identify categories of warranty call items—items that require home owners to call builders, and builders to fix problems in the home that are covered under warranty—and estimate the direct costs to address these problems.
- Determine whether some of these costs could be avoided through different construction techniques that could also result in increased quality, comfort, and energy efficiency in the home.
- Determine whether there are additional opportunities that simultaneously address the state's interest in maximizing energy efficiency in residential construction, while also serving individual consumer demand for investment value and increasing the profit of California home builders.

Approach

First, we reviewed the literature describing concepts and measures of comfort, quality, and energy efficiency, and relationships among these. Second, we reviewed several available data sources describing both stated and revealed preferences by home buyers for comfort, quality, and energy efficiency. Third, we reviewed data collected by home warranty companies, and elsewhere in available literature.

After this third step, we determined that a clear understanding of consumer values for comfort, quality and energy efficiency was not to be gained from available data. We also determined that a rigorous quantitative analysis of warranty calls and associated costs to builders was not possible. However, we suggested that a qualitative analysis of expert knowledge of construction problems and associated costs, and consumer values reflected in markets for new homes more generally, could be quite useful.

In the summer and fall of 2003, we turned to executives of KB Home, Pardee Home, and Pulte Homes—each a home builder with operations in California—for some help with our assignment. Our discussion protocol is included in Appendix 4. Although not exhaustive in number (there are thousands of construction firms in California), participating companies were selected from companies that are industry leaders, differ in business strategy and market targets, and together represent a substantial share (approximately twenty percent) of the home building market in California. The participants represent more than one hundred years of professional experience and knowledge developed in the home building industry. Participants included corporate executives and managers in architecture, construction, marketing, and customer-service divisions. In addition, we consulted with subcontractors that specialize in heating, ventilating, and cooling (HVAC) system design and installation; and framing. In combination with the literature we reviewed, this report compiles results of discussions with more than a dozen executives and high-level staff in these companies, as well as selected trade contractors that do business with these and other builders in California.

In this report, statements are not attributed to individuals or companies, and this intent was made clear to participants in an effort to elicit candid responses. Interview results were considered according to builder characteristics (e.g., size, target markets, etc.) so that generalizations could be drawn, and specific examples better understood. These interviews provided us with overall estimates of frequency and costs of construction problems, efforts to improve design and construction related to these, and several specific insights into additional opportunities to promote energy efficiency in homes.

The Home Building Process and the Role of the Builder

Findings of this study have implications for interventions at various stages of the home building process. According to Hassell et al (2003), this process is defined by the following stages, with each characterized by several steps:

- Land Development: Acquisition, use planning and subdivision, rough grading, and infrastructure construction.
- Design: Floorplan, lot layout, basic specifications and options, basic cost analysis.
- Pre-construction: Selection of home builder, selection of trade contractors, sequencing and scheduling, selecting and ordering materials.
- Construction: Excavation; foundation; structure; HVAC, plumbing, electrical, etc.; finishing (interior and exterior); certificate of use and occupancy.
- Post-construction: Purchase by owner, financing and insurance, purchasing durables and consumables, use by owner, warranty claims and customer service, operation and maintenance.

The above summary illustrates that the home building process is complex, and involves several specialized participants in various steps. The builder typically enters the process around the design and pre-construction stages and is often involved in the several stages that follow, including the final sale of the home to the owner. Although the owner typically enters the process at the post-construction stage, consumer preferences influence builder decisions and actions at earlier stages of the process, including design and pre-construction.

Importantly, we see that larger home building companies often coordinate information, decisions, and actions at almost all stages of the process. Builders are in a position to promote worker training that can influence performance at pre-construction and construction stages. Builders are also in a position to present information and options that can influence consumer decisions at the post-construction stage. Purchase decisions, facilitated by the builders themselves, can feed back to builders' design and construction decisions as well.

Specialized departments of home building companies are variously devoted to design, construction, marketing and sales, as well as warranty claims and customer service. These departments are staffed by experienced employees that are trained to facilitate and influence this complex process to achieve business goals. Overall, business strategy is motivated chiefly by profitability—either through increased revenue or decreased costs to home builders. Increasing revenue is tied largely to marketing and sales efforts, which generally follow opportunities defined by consumer demand. Decreasing costs are tied to achieving more efficient operations, customer service (e.g., handling warranty calls and claims), and production (i.e., home design and construction). Business strategy reflects, and shapes, markets too. Decisions and actions of individual builders that reveal a profitable business strategy tend to ripple through the market to other builders. Interactions between builders' sales and customer-service staff are often described, by word of mouth, to other consumers.

In all, builders as individuals and in aggregate, amongst themselves and in relation to consumers, emerge as important stakeholders in the effort to promote energy efficiency in new California homes. And profitability is an essential motivator of their decisions and actions.

2. The Market for Comfort, Quality and Energy Efficiency in New California Homes

Creating equity through home ownership remains a desirable investment strategy, yet the possibility of home ownership remains out of reach for more than three-quarters of Californians.[1] While housing supply continues to increase in California,[2] demand growth is even greater and fuels a strong sellers market. Demand has created strong pressure to build affordable new homes on available land, increasingly in California's inland valleys.[3] Affordability is especially important to first-time home buyers.

Consumer demand for homes has created various housing market niches across four dimensions:

- Location
- Price
- Consumer perceptions of investment value
- Home ownership experience

Builders target home buyers in one or more niches as reflected in their respective business strategies. Competing well in their niches is essential to builders' profit goals and their survival in a highly competitive industry. Market pressures, especially in markets for first-time home buyers, have important implications for residential energy efficiency.

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[1] According to the California Association of Realtors, 23 percent of households in California were able to afford a median-priced home in December 2003. The minimum household income needed to purchase a median-priced home at $404,520 in California in December was $94,730, based on a typical 30-year, fixed-rate mortgage at 5.82 percent and assuming a 20 percent down payment. By comparison, 57 percent of households across the U.S. were able to afford a new home in December 2003; the minimum household income needed to purchase a median-priced home at $173,200 in the U.S. was $40,560.

[2] The California Association of Realtors reports 123,864 new single-family housing units built in 2002, up from 73,812 built in 1991.

[3] When comparing costs of comparable houses, the most affordable regions in 2003 were (in order): High Desert, Sacramento, Central Valley, and Riverside/San Bernardino.

Pressure to Build Inland, and to Build Big

Differences in home price are tied primarily to the price of land (which varies by location), and secondarily to floor area and amenities of the home. In coastal areas and in the largest metropolitan areas (i.e., Los Angeles and the Bay Area), location can account for the vast majority of a home's value.

Land is generally more available and homes are more affordable in the inland areas of the state, creating new opportunities to generate investment value in lower price ranges by upgrading the home itself. Consumers often seek to increase value of a home on a given plot of land by building two stories and/or upgrading amenities. Builder strategies to increase their own profit largely follow consumer demand for value.

Perceptions of Investment Value in New Homes

Appendix 3 provides further discussion of both stated and revealed preferences of consumers for comfort, quality, and energy efficiency in homes. When prioritizing home features according to their perceived investment value, consumers tend toward greater floor area, and "wow" amenities tied to appearance of greater comfort and quality (e.g., countertop and flooring upgrades), before energy-efficiency features sold explicitly as such (e.g., denser insulation).

According to a recent article[4] provided by one builder we interviewed, and echoed in most of our discussions, the top five "splurge" items from a consumer standpoint are windows, refrigerator, stove, flooring, and insulation. Interestingly, these are items with relatively greater energy-efficiency implications as well, yet their design, appearance, and durability—not energy performance—are most important to consumers. Besides heating, ventilating, and cooling (HVAC) systems, comfort-related features that appear to have the greatest energy-efficiency implications include water heaters, windows, insulation, and patio trellises. But consumers do not frequently demand upgrades for these that increase energy efficient performance beyond their desired level of comfort.

The implication is that if energy efficiency can be uncoupled from comfort and quality, home buyers generally will purchase comfort and quality, before energy efficiency, especially on items that that have identified as luxury items that they

[4] Farnsworth, C.B. 2003. "The Right Stuff." *Builder*. May.

would have to spend more on. That energy efficiency is inextricably tied to comfort and quality in many instances, however, is an important opportunity that will be explored further in Section 4.

The Influence of Experience on Home Buyer Preferences

Home buyers move between housing market niches as their purchasing power increases (largely through growth in equity of their previous home purchase) and as their lifestyles, perceptions, and experiences dictate. Thus a useful way to look at the housing market is through the eyes of first-time buyers and "move-up" buyers purchasing their second or third homes.

Some builders target home buyers in these groups separately; others target home buyers in both, and look to build an ongoing relationship with their customers, selling them both their first and subsequent homes. Differences between these consumer groups have important implications for residential energy efficiency.

First-time home buyers

Whether to and how to purchase a home is the defining decision of first-time home buyers. Qualifying for a home loan, paying closing costs on the purchase, and affording mortgage payments are the most important concerns of this group.

Also important to the first-time home buyers is creating investment value that allows them to "move-up" to their second home purchase, generally about five years after their first home purchase. Thus further considerations in their purchase are related to fetching a high price and quick turnaround on the resale market, which as described above are driven mostly by location, floor area, and "wow" amenities, if they can be afforded.[5] Energy efficiency itself may be important to this group, if only as a stated ideal, but generally not revealed over these other factors in their first-home purchase.

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[5] One interesting, recent shift in demand related to amenities in medium- to lower-priced homes is the separation of stove and over. Demand for more "gourmet" kitchen design specifies separate stovetop and oven appliances, yet because of increased cost of venting separate devices, they are less likely to be available as gas-powered appliances in lower-priced homes. Thus less efficient electrical stoves and ovens are generally selected to satisfy this demand.

"Move-up" buyers

With more equity to invest in their next home, often more experience with paying high energy bills, and an intention to stay in their next homes for longer periods of time, the importance of energy efficiency becomes more important to "move-up" buyers. Preferences for energy-efficient features are revealed to a greater extent in their investment decisions, even when such features represent greater initial cost.

Preferences for greater comfort and quality also follow move-up buyers in their next home purchases, and sometimes these preferences are tied to greater energy efficiency. According to one builder, home buyers purchase low-emissivity ("low-e") windows not only for increased energy efficiency performance, but because these windows provide greater protection of their furniture and drapes.

Implications for Energy Efficiency in California's New-Home Market

Demand for larger, more comfortable, yet more affordable homes in inland valleys creates an energy-efficiency challenge:

- Inland areas of California are hot in summer months. All else being equal, homes built in these areas require greater energy for cooling to achieve a given comfort level for home owners.
- Home owners differ in the way they use their homes, making it more difficult for builders to design HVAC systems to achieve a given comfort level throughout the home, while also maximizing energy efficiency. Two-story homes are particularly difficult to cool evenly.

There appear to be technology solutions that can achieve greater comfort and energy efficiency, even in larger, two-story homes. "Split-AC" systems—consisting either of two separate, smaller HVAC units for different parts of the house, or newer multi-zone systems—can be effective in simultaneously addressing summer cooling needs, increasing comfort, and perhaps also increasing energy efficiency. Using such systems allows potentially greater control over cooling only the areas needed, or differentially cooling areas according to different levels of comfort required by different occupants in different parts of the home.

Two challenges for cooling remain, and are greatest in the context of a home sale to a first-time home buyer:

- Split-AC options require a larger initial investment. The additional purchase cost, even for potentially increased comfort and energy savings, is less attractive to the first-time home buyer than are lower closing costs, or other value-creating options such as countertop or flooring upgrades.
- The performance and reliability of multi-zone HVAC systems are not yet proven, thus builders are more hesitant to promote them to their customers and potentially jeopardize the customer relationship.

Nonetheless, builders' sales staff are uniquely positioned to present and explain energy-efficient options, whether for cooling, or for other energy-demanding services (e.g., water and space heating, lighting.) Equipped with credible information and the necessary incentives to reduce profit risks to the builder and investment costs of the home buyer, the builder is more likely to make a sale on a more energy-efficient home.

3. Effects of Warranty Calls on Builder Profit and Implications for Energy Efficiency

Important environmental conditions in California include seismicity, heat and wind in the inland valleys, and moisture in the northern part of the state. These conditions, along with various demands of consumers, create challenges for the builder in the design and construction of new homes. Sometimes difficulties in meeting these and other challenges are reflected in the home's performance, and home owners register complaints with the company that handles the home's warranty. We reviewed several potential sources of data on construction and equipment defects that may be related to quality, comfort, and energy efficiency, but none of the sources proved to have adequate data to support rigorous analysis (see Appendix 3 for a summary of this review). Thus, we turned to several California builders for their expert opinion on these issues.

In our sample, the building companies handled their own warranties, and complaints from home owners were directed to builders' customer-service departments. How customer-service departments in our sample of builders were organized and the methods by which they served customers varied. Yet two general principles that relate warranty calls to profitability emerged:

- Customer-service records inform builders' design and construction practices, thus warranty calls potentially influence production and associated costs.
- Prompt, effective customer service is a priority of successful builders and an important part of overall marketing and sales efforts, which rely on word-of-mouth advertising and seeks to lock-in repeat customers.

Warranty-Call Data for New Homes: Type, Frequency, and Costs

Warranty-call data describe calls from home owners registering complaints about problems in their homes, and that potentially require fixing at builders' expense. In this study, we include problems identified during the "walkthrough"[6] as well as problems identified during the warranty period. Warranty periods vary for different items according to state law, such as two to four years for patent defects (e.g., "fit-and-finish" items such as cabinetry, flooring, paint, and trim), and ten years for latent defects (e.g., structural problems).

According to the builders we interviewed, the highest frequency categories of warranty calls (expressed as a percent of total customer-service calls) accounted for nearly all warranty call items as follows:

- Paint and drywall (25−35%)
- Stucco (10−20%)
- Flooring (10−20%)
- Plumbing (10−20%)
- Electrical (5−15%)
- HVAC (up to 10% in summer, in certain areas)
- Soil/grading (less than 5%)

The vast majority of warranty calls are for fit-and-finish items: About half of these are for paint and drywall problems, about one-quarter for stucco problems (minor cracks of aesthetic nature only), and another quarter for flooring problems—mostly scratches, stains, and problems with carpet seams. About ten to twenty percent of calls are related to leaky plumbing—mostly at the fixtures. About five to fifteen percent are related to electrical systems—mostly broken switches. Almost five percent are related to soil grading issues—primarily in certain clayey areas, where surface water can accumulate after irrigation.

In general, budgets for handling customer calls amounted to approximately one-half to one percent of the sales price of a new home product, which amounts to five to ten percent of the after-tax profit from a new home. Costs related to warranty calls often get passed on, through subcontract agreements, to subcontractors. Costs for subcontractors likely correspond to about one percent of their billed work. Few problems were reported to go beyond customer-service departments to legal ends, but some small-claims and class-action lawsuits have been made.

[6] The "walkthrough" describes the final inspection by the home owner at the time of sale.

These data, along with the experience of their executives, inform builders' design and construction practices. At the pre-construction and construction stages, in particular, the builders interviewed address known problems through training and supervision efforts. Throughout the industry, it was noted, important factors related to construction problems appear to be variability in available subcontractors and, more generally, worker turnover. Not surprisingly, builders' training and supervision efforts focus on the highest-frequency and highest-cost warranty-call items, which are generally not energy-efficiency related.

Energy-Efficiency-Related Warranty Calls

Very few warranty call items are obviously related to the energy performance of the home. The largest category of calls with obvious energy-efficiency implications regarded HVAC—accounting for up to ten percent of calls in certain inland areas, in summer months. Summertime HVAC calls from home owners in the state's warmest areas, and water intrusion calls at any time of year from home owners statewide, are the warranty holders' top callback response priorities.

Another problem identified in our interviews that has energy-efficiency implications was associated with bowed walls that result from using green lumber in home construction in some areas of the state.[7] This problem appeared to be infrequent, but may be emerging.

HVAC calls

A typical call for an HVAC problem is that the HVAC unit is not cooling the home sufficiently, or that cooling is uneven. This can mean that the HVAC unit itself needs to be adjusted, or that registers need to be adjusted. Sometimes additional dampers and returns must be added, which can be more costly, but significant and costly HVAC reconfigurations are rare.

The underlying problem is one of design—HVAC systems are not customized for the house and particular consumer behaviors, such as preferences for setting window blinds and opening and closing doors. It appears to be well known among builders and their HVAC subcontractors that larger, two-story structures, with more windows and larger kitchens, family rooms, and master suites create

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[7] Green lumber has not been dried in a kiln, and tends to warp as it dries out during home construction.

a greater heating and cooling challenge. While state code provides some guidance on standards and modeling, it is impossible to fine-tune HVAC systems for particular customers until after they have lived in their home for at least one complete heating and cooling season.

Although the builder's customer-service department takes the initial call from the home owner, responsibility for addressing HVAC problems typically lies with the HVAC subcontractor. To the builder, the average cost of handling customer calls reporting HVAC problems appears to be less than 0.25 percent of the after-tax profit on the sale of a new home.[8] Costs to the subcontractor may be slightly greater, but these problems appear to be resolved in the first two years, generally by simple adjustment of the HVAC unit or registers, and educating the home owner on how to use the HVAC system.

An interesting trend in consumer demand for HVAC is the preference for lower, wall registers instead of ceiling registers. This preferences appears to be for aesthetic reasons. Modeling of ceiling versus wall register placement elsewhere in this research program has also demonstrated more efficient cycling of air, as well as greater thermal comfort of occupants, when wall registers are assumed. In this case, consumer demand for comfort and quality appears to coincide naturally with greater energy efficiency and possibly reduced calls from customers.

None of the interviewees suggested that split-AC systems increase the frequency or cost of responding to warranty calls. From a customer-service standpoint, such systems may decrease warranty calls to the builder due to increased comfort and flexibility for the home owner.

Bowed walls

Another issue mentioned in our interviews with energy efficiency implications was that of bowed walls. The problem results when lumber used to frame the home warps, and the finished wall bows out (or in) from an otherwise flat, vertical plane. When this occurs near a window, part of the frame can pull away from the window and compromise the building envelope, resulting in a less energy-efficient home.

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[8] This assumes that HVAC related calls take place in summer (one-quarter of the year), that these account for up to ten percent of calls at that time, and that total warranty calls account for ten percent of after-tax profit on home sales.

The problem is exacerbated when green lumber is used for construction in hot, dry areas such as the inland valleys of California. While green lumber is approximately five to ten percent less expensive than dried lumber, one framing subcontractor we interviewed suggested that the savings on lumber is almost certainly lost to the builder when the additional construction labor involved in stud straightening[9] is considered.

This problem occurs infrequently, likely in less than a few percent of all new homes, and is apparently limited to homes with more energy-efficient design. Existing construction practices appear generally to address this problem,[10] but it persists as a practical challenge in building new homes in the hottest, driest areas in California, where new development is occurring, and as more energy-efficient homes are built. The possible roles of further builder training, supervision, and construction planning as they relate to this potentially emergent problem warrant further attention.

Energy-Efficiency Related Warranty Calls and Builder Profit

With the exceptions of HVAC system problems and possibly issues surrounding bowed walls, evidence that energy-related construction problems are responsible for substantial costs to builders is not compelling. In an effort to control costs, builders in our sample already address the highest frequency callback items in their construction practices, and the majority of these appear not to be energy-efficiency related. Energy-efficient construction doesn't appear to generate substantially greater builder profit through warranty-cost control.

However, in reviewing builders' customer-service efforts, we continue to see an important connection between home owners and builders through the builders' commitment to customer satisfaction and efforts to build lasting relationships with home owners. Word-of-mouth advertising between customers and builders seeking repeat customers through exceptional customer service emerge as common strategies and goals in the production-home industry. Promoting

[9] "Stud straightening" describes a process of either "felting" concave portions of the framing studs, or "planning" the convex portions of studs to achieve a flat surface that can receive interior drywall or exterior surfaces. According to one framing subcontractor we interviewed, stud-straightened homes constructed with green lumber require about twenty percent more labor than homes framed with dried lumber; the savings to the builder using dried lumber for framing can be several hundred dollars per home.

[10] The majority of homes in Northern California, where this problem is less likely to occur, use green lumber. Dried lumber is almost exclusively used in Southern California already.

energy efficiency through builders' marketing and sales efforts to achieve builder profit shows potentially greater promise.

4. Opportunities for Selling Energy Efficiency

Offering energy-efficient options appears to have broad marketing appeal, and acts to invite consumers to consider particular builders, even though home buyers may not choose more energy-efficient options in their purchase decision. One builder we interviewed sells only energy-efficient homes, and competes well in California's housing market, but admitted that the first-time home buyer remains the most challenging target market they face.

In keeping with their profit interests, builders consider new revenue-generating opportunities, but in keeping with customer-satisfaction interests—especially for building trust in first-time buyers—they recognize that energy-efficient upgrades must be presented in ways that demonstrate value in the home purchase. As described in Section 2, value appears to be secured by purchasing features satisfying demands for comfort and quality before energy efficiency.

The Builder-Home Buyer Relationship and the Challenge of Promoting Energy Efficiency in New Homes

Because customer satisfaction is important to marketing and sales efforts, builders are less inclined to promote energy efficiency beyond specific consumer demand. An important obstacle in convincing buyers to purchase energy-efficient options is that energy savings are difficult to prove; they vary greatly with consumer use and energy prices. To save money with energy-efficient appliances, for example, the appliances need to be used; yet energy bills often encourage consumers to conserve energy (e.g., turn off the air conditioning). Builders are hesitant to recommend options when their value is questionable.

We were presented with examples of first- and second-time home buyers who purchased energy-efficiency upgrades and were disappointed with the extent to which these upgrades delivered performance relative to their additional first cost. In one housing tract, where the same builder offered energy-efficient homes along with standard homes, more customer complaints arose from owners of the energy-efficient product. In this case, however, the builder believed that the increased incidence of complaint was due to some unique characteristics of these home owners and their home owner association, rather than the home product itself.[11]

In another example, when one builder offered a denser insulation option that supposedly provided additional soundproofing, more calls were received from disappointed home owners claiming that the insulation didn't work well enough with respect to soundproofing, relative to the additional cost they paid for it. Whether it improved energy-efficiency appeared to be irrelevant to these home owners. These examples indicate that energy efficiency is a "tough sell" to consumers, but perhaps an even tougher sell to builders seeking customer satisfaction and profitability.

But the fact remains that consumers often turn to builders for advice on certain features—including HVAC and insulation—that have clear energy efficiency implications. Note too that in a highly competitive market, builders appear willing to pursue novel revenue opportunities, which includes selling higher-priced energy-efficient options on the basis of consumer demand for comfort and quality.

Bundling Energy Efficiency with Quality and Comfort in New Home Sales

It appears difficult to sort out consumer preferences as they relate to comfort, quality and energy efficiency, especially as they are tied to costs. A builder trying to establish a trusting relationship with a home buyer is unlikely to speculate on savings or value of energy efficiency for a particular home owner, especially as the builder seeks a repeat customer on their next home purchase, or favorable word-of-mouth advertising to other consumers.

Above were illustrated two disappointing examples in builders' efforts to promote energy efficiency in new home sales. But at least three promising examples of "cross-selling" energy efficiency on the promise of greater comfort and quality also emerged from our discussions:

[11] In this tract, the type and frequency of warranty calls associated with the energy-efficient home did not differ substantially from those of the standard home.

- Customers often choose low-e windows for the additional UV protection they provide, especially to reduce fading of drapes and furniture.
- Patio trellises create additional attractive living areas. Plants can be added at a later time to provide additional shading, and as the home owner can afford to do so. Specially designed trellises can support solar panels, which can be installed at a later time as well.
- New technologies, such as multi-zone HVAC systems and tankless water heaters, promise greater energy efficiency and comfort than existing options.

Adding these items to the home sale increases builder profit through increased revenue, can add significant value to the home buyers' purchase, and has the potential to increase the energy efficiency of the home. According to one builder, offering solar panels on trellises, rather than on rooftops, reduced the potential for roof leaks (and potentially costs of warranty calls) as well as consumer hesitance to consider solar panels. Also, while a trellis that can receive solar panels may not achieve increased energy efficiency right away, it gives the builder another sale item, and the consumer an option that may have resale value with or without the solar panels installed at time of purchase.

Further research and demonstration of the reliability of some new technologies, notably multi-zone HVAC systems and tankless water heaters, is needed. These technologies promise greater energy efficiency and comfort, and potential for builder profit, but builders hesitate to offer them because they are new. Successfully promoting these items will require greater proof of their reliability and value to the home buyer before they can be incorporated effectively into the builders' sales pitch.

5. Options for Policy Development

Findings of this study suggest that there are some opportunities simultaneously to increase builder profit, customer satisfaction, and energy efficiency in new homes. In this section we present some options and interventions at various stages of the home building process that our findings support. These interventions emerge from three general observations that have implications for promoting energy efficiency in new homes in California:

- The greatest challenge for promoting energy efficiency in new homes is in the market for first-time home buyers looking inland, for the largest, most comfortable homes that they can afford. Information and resources to invest in energy-efficient options are least available to this group of home buyers.
- There is evidence that some design and construction measures may be taken to reduce cost to builders and improve energy performance of a home, but greatest incentive to builders to control costs are for problems least associated with energy efficiency.
- Motivating builders through increased profit to promote energy efficiency in their home products may be more likely achieved by equipping their marketing and sales efforts to increase revenue, rather than by informing design and contruction practices in an effort to control warranty costs. Builders' marketing and sales teams can sell energy efficiency to home buyers, with the credible information and risk-reduction options available to them. Making even a "tough sell" is what a trained salesperson is in the best position to do.

With these observations in mind, we present five interventions at various stages of the home building process that promote energy efficiency. All of them highlight the role of the builder in achieving greater energy efficiency in new homes. Because their implementation is linked to potentially greater builder profit, builders may embrace these interventions as well. Government support is likely necessary to catalyze builders' initial response to these.

Improve protocols and worker training, specifically to address HVAC design and framing problems such as bowed walls.

The nature of the construction industry—with relatively high turnover and variable availability of trade contract labor—makes worker training a continuing challenge. The builders we interviewed already analyze their customer-service records, with the intention of reducing the highest frequency customer complaints and otherwise controlling costs through better construction practices. These highest-frequency complaints and costs, however, are not energy-efficiency related. Of all problems occurring in new homes, addressing HVAC design and framing problems (i.e., bowed walls around windows) are most likely to have an effect on energy efficiency in homes.

Addressing HVAC and framing problems through better worker training and improved construction protocols may reduce some warranty calls and their associated costs to builders, but additional incentives and assistance are likely necessary to motivate builders. Incentives could include government sponsored rebates, tax incentives, and credit support for builders that extend their current efforts beyond "fit and finish" items to include HVAC and framing problems as well.

Better educate consumers on basic HVAC use.

Many new home owners simply do not know how to use their new HVAC system. In most cases, complaints related to cooling the home are simple to address, and require only adjustment of the registers or HVAC unit itself. Customer-service representatives often provide simple instructions on thermostat adjustment over the phone.

Better understanding of basic system operation, perhaps through improved documentation for home owners, may conserve energy, as well as reduce the number of calls and associated costs to builders. This information could also be provided through existing consumer-education programs.

Investigate performance and reliability of promising new technologies for homes, and support their use.

Business decisionmakers may entertain some risk when doing so may yield substantial profits or competitive advantage, but most builders are risk averse. Builders are hesitant to promote certain technological options to consumers, such as multi-zone HVAC systems and tankless water heaters, because they are relatively new and their reliability is unproven. The fear is that these options may require not only greater up-front costs for home buyers, but incur greater warranty costs to builders, and customer dissatisfaction further jeopardizes ongoing client relationships or the builder's reputation. Yet these two particular technologies appear to promise greater energy efficiency and comfort in homes, and selling them introduces new revenue opportunities for builders.

More information is needed on these technologies and others, which could be provided to builders for use in their marketing and sales efforts. Useful information would describe performance results of further testing of these technologies under real operating conditions. Additional warranty support for newer technologies may also be necessary.

Identify further options for cross-selling energy efficient upgrades according to promise of greater comfort and quality in new homes.

Consumers seek value in making investments. While energy efficiency doesn't appear to weigh heavily in home buying decisions until home ownership experience and purchasing power increase—as in the second home purchase—the value of comfort and quality to consumers is apparently evident to all home buyers.

Certain energy-efficient home features such as low-e windows are often purchased for reasons other than energy efficiency (e.g., protection of furnishings from sun exposure.). There may be other energy-efficient amenities (e.g., multi-zone HVAC systems, tankless water heaters, and trellises that can support solar panels) that also have marketable consumer value in terms of comfort and quality.

Identifying these options, and making them even more attractive with additional incentives to builders and consumers, would present builders with additional revenue-generating options, increase customer satisfaction, and increase energy efficiency. The necessary dollar value of these incentives could be established through application of an appropriate survey methodology and analytic method (Appendix 2 presents more detailed guidelines on these).

Pursue risk-reduction strategies for selling energy efficiency through builders.

The builders' sales teams are nearest to the critical decision to purchase an energy-efficient upgrade in a new home, or not. Equipped with credible information and the necessary incentives (for both consumer and builder), experienced salespersons can make even a "tough sell." A variety of existing information and incentive approaches focus on the consumer to make more energy-efficient decisions, but few incentives for builders encourage these decisions. Builder incentives can be in the form of government-sponsored rebates, tax incentives, credit support, warranty support or otherwise focus on reducing risks to the builder when promoting energy efficiency in a home sale.

One approach may be through a government-backed price support system for the builder, allowing the builder to offer to the home buyer:

> *If this energy-efficient upgrade (e.g., for HVAC, insulation, or windows) doesn't save you X dollars on your energy bill, relative to the energy bills of others who purchase our standard product, we'll credit you the difference when you purchase your next home with us. Or you can pass the credit to a friend or family member who buys a home from us. You can't lose, even if we do.*

Then the government assumes this risk the builder takes through a builder-government agreement and pays the builder as necessary. The consumer is left out of this last transaction. The government may pay out in some cases, but is in a much better position to distribute risk across builders and markets than are individual builders and home buyers.

Such an approach takes advantage of the unique relationship the builder has, especially with the first-time buyer, and encourages builders to incorporate energy efficient options in their sales strategies. Such a guarantee gives the builder a revenue opportunity of an energy efficiency upgrade, and potentially strengthens returns from word-of-mouth referrals by home owners. In the case of a builder that targets both first-time and move-up buyers, such an approach potentially locks in a repeat customer.

Appendix 1: Quality, Comfort, and Energy Efficiency in New Homes—Concepts and Measures

The relationships among quality, comfort, and energy efficiency (QCEE) are conceptually central to this research program. In this appendix we seek to define these notions and consider relationships among them as they apply to homes.

The terms "quality," "comfort," and "energy efficiency" are not equally obscure. While its precise interpretation varies with the context, we have a clear notion of what energy efficiency entails and how to measure it. Quality and comfort are both more intimately familiar and more difficult to explain, and are more subjective than energy efficiency; as such they do not as easily lend themselves to quantification and rigorous valuation. Association pathways among quality, comfort and energy efficiency in new homes are gaining wider recognition, but the difficulty of measurement and valuation of these associations is at least as great as their component parts.

Energy Efficiency: Concepts and Measures

The construct of energy efficiency is well understood, and is readily quantified, for a device, a system, or a process, as the output of a good or service per unit input of energy.

Energy efficiency can be realized through *active measures* (such as compact-fluorescent lighting), which themselves consume energy but more efficiently than alternatives; through *passive measures* (such as high R-value insulation), which allow for less energy consumption in delivering energy services to the building occupant, without any intention on the occupant's part; and *behavioral measures* (such as adjustable window louvers), which require that the occupant engage in some particular behavior in order to reduce energy consumption.

Home energy efficiency may be achieved in space and water heating, in gas and electric appliances, in proper maintenance of the building's structure and systems, and in the materials and processes used in construction. With regard to residential construction, the principal energy efficiency concerns are for space conditioning, water heating, and appliance and fixtures energy consumption. One home is regarded as more energy efficient than another if it can provide the same services with a lower level of energy consumption. However, unless the homes are identical in all palpable respects, they cannot be said to provide the same services to the occupants.

The outputs can be compared only to the extent that they provide similar quality of services, to achieve the same degree of occupant comfort. In this case, energy efficiency is often confused with energy conservation. Improving the energy efficiency of, say, a central air-conditioning unit will translate into energy conservation only insofar as the user maintains his comfort (room temperature) at the same level; if the user cares to increase his comfort for the same energy expenditures, he will take back some or all of the potential gains from energy conservation. The size of this effect for different energy uses is a matter of some dispute as is how to value increased comfort in determining the value of energy efficiency.

Measures of energy efficiency

Energy efficiency is measured at many different levels of aggregation. Standards institutes and professional associations establish units, measurement procedures, and performance standards for the energy efficiency of components and materials, such as heating elements and insulating fibers, and more integrated devices and processes, such as windows and air conditioning. Many of these standards are quality related as well.

Most useful for our purposes are methodologies for determining whole-house energy efficiency, such as Home Energy Ratings Systems (HERS). HERS entail comparing a rated home to a computer model of a reference home of the same size and shape and which meets the Council of American Building Officials Model Energy Code. A certified energy rater inspects the home and measures its energy characteristics, such as insulation levels, window efficiency, wall-to-windows ratio, heating and cooling system efficiency, solar orientation, and water heating system. The rater also conducts diagnostic testing, such as blower door for air leakage and duct leakage. The reference home is given a score of 80 out of 100; every five percent decrease in energy use earns the rated home a one-point rating increase. The widely used EPA Energy Star rating is given to homes scoring at least 86.

Quality: Concepts and Measures

Quality is a more elusive construct than energy efficiency, and discussions of quality tend to the metaphysical more than the physical. Yet a transcendent approach that poses quality as a metaphysical ideal is of little practical use to this effort. We consider the following more relevant approaches to assessing quality in new homes:

- *Product-based approach*. This approach holds that quality inheres in the quantity of one or more product attributes; e.g., the quality of a light bulb derives from its expected lifetime, color, temperature, etc.

- *User-based approach*. This approach holds that quality is contextual and subjective—that a quality product is suited to the uses to which it is put; this approach includes its value for money.

- *Manufacturing-based approach*. This approach finds quality in the degree to which a product conforms to specifications; it assumes optimal values of quality measures, rather than the open-ended positive scales of the product-based approach, and is most suited towards mass manufacturing, where consistency and interchangeability are paramount.

- *Value-based approach*. This approach shies away from superlative notions of quality, so that a satisficing product is adjudged to be of higher quality than a better performing but more costly alternative.

All of these approaches may be useful in considering QCEE for new homes. For the relationship between quality and energy efficiency, the product- and manufacturing-based approaches are likely best, as they are embodied in industry codes and standards. As comfort is more subjective and determined by the home occupant, a user-based approach should better capture the relation to quality.

Within any of the approaches to quality there are, to varying degrees, eight dimensions of quality, as described in Garvin (1984):

- Performance

- Features

- Reliability

- Conformance

- Durability
- Serviceability
- Aesthetics
- Perceived Quality

Features, conformance, and durability provide the most compelling links to energy efficiency. Indeed, the data-gathering effort summarized in Appendix 3 and also described in Section 3 largely entailed finding data on the instances of poor reliability and durability in new home construction. The Partnership for Advancing Technology in Housing (PATH) Program on Improving Durability in Housing (1999), for instance, takes a pragmatic and scientific approach, measuring the expected lifetime of housing components under standard use and care, as determined by accelerated testing to failure.[12] While comfort may derive from all of these dimensions of quality, the most direct manifestations that the occupant appreciates are in performance, features and aesthetics.

Any of the conventional structural elements of a home (i.e., frame, foundation, floors, roof, windows) can be of greater or lesser quality, independently in their design, workmanship, and materials or components. For instance, a roof can be well designed so as to shed snow, require little maintenance, and be attractive, but the skill and attention of the roofer and the choice of a roofing-materials supplier can either realize the quality of the design or render it moot. Similarly, a poorly designed roof could be laid precisely according to the specifications with very high quality slate, but not perform well by any of the occupant's criteria.

Measures of quality

As with energy efficiency, the housing industry and other interested parties have developed a wealth of operational measures of quality. International Standards Organization (ISO) 9000 is concerned with quality in the manufacturing process (interpreted as adherence to standards), which is expected to yield quality in outcomes. NAHB, PATH, and the Wood Truss Council have undertaken a pilot program to bring ISO 9000 certification to the framing industry, which is to yield tools including a framing quality manual; use-of-materials documents for basic materials, connectors, and hardware; training materials; job site inspection

[12] See also Uniacke, M. 1996. "Creating Quality in New Construction: A Practitioner's Perspective." *Home Energy Magazine*. January/February.

procedures and lists; methods to track and monitor quality; and contract templates that assign responsibilities and acceptance criteria. The NAHB Research Center National Housing Quality Award is similarly concerned with construction processes rather than explicitly with outcomes.

The NAHB Residential Construction Performance Guideline is a collection of industry standards covering all aspects of home building, and is regarded as the only authoritative body of information on how new homes should behave under warranty. Industry standards and codes are inherently manufacturing-based approaches to quality.

Comfort: Concepts and Measures

Comfort may be perceived as an aesthetic judgment, through the physical senses, or as psychical well-being. Comfort is perhaps even more difficult than quality to measure and attribute—"comfort is not a condition, but a state of mind" (Goldman, 1999). As such, while surveys and experimental observation can yield normative measures of comfort, positive directives for comfort are less successful—if I insist that I am comfortable in a damp, 55 °F room, the fact that very few other people would find it comfortable does not have any bearing on my judgment.

Most of the comfort research literature relates to thermal comfort, which has external determinants that are more easily measured than other aspects of comfort and which is strongly associated with health outcomes, as well. This research has found that people tend to take notice of discomfort, rather than comfort; above some threshold, incremental improvements in comfort are not appreciated, while below the threshold discomfort is quite sensitive to improvements. Across a broad range of comfort attributes, it has been found that the subject's ability to control his personal environment (temperature, lighting, etc.) to his liking contributes heavily to the perceived level of comfort. Those housing comfort measures that have been developed do not strictly pertain to houses, but to their occupants; comfort rating schemes should be able to make use of these personal comfort measures.

The experience of comfort is a combination of aesthetic, physical, and psychical perceptions. While aesthetic judgments of quality can affect comfort perceptions (e.g., a well designed and installed window may be lend a higher comfort rating to a room's lighting than a lower-quality window that admits precisely the same natural light), physical perceptions of comfort are a more apt focus for this research program. All five of the senses (sight, hearing, touch, smell, and taste) can contribute, to varying degrees, to comfort perceptions. As noted earlier, thermal comfort is the best studied, and is also the most important to home QCEE considerations, which focus on space conditioning concerns.[13]

As we have seen with quality, there is a matrix of responses of comfort senses to comfort attributes. Consider how a forced air register and its operation may affect the comfort of a room's occupant. Her comfort likely depends most strongly on the temperature of the air about her, but also on the distribution of temperature in the room (temperature gradients create discomfort). The air's smell and relative humidity (and associated electrostatic charge) likewise influence her comfort. Research has found that air velocities that would constitute a comfortable warming breeze outdoors (or through a room opening) are generally regarded as uncomfortable coming from an indoor source (Baker, 2000). The air motion induced by a fan is perceived as comfortable, while that from an air conditioning vent is not.

The air register also contributes to the occupant's acoustic comfort, from the sound of the air motion itself, the noise from the register grille, and HVAC system noise transmitted through the ductwork. The design quality of the register opening and grille, its location in the room, and the furniture layout dictated by its location all contribute to aesthetic comfort perceptions, as well. While we should not expect a comfort rating to account for all of these interactions, it must be kept in mind that a high comfort score along one dimension is not necessarily associated with high scores in other dimensions.

Measures of comfort

There do not appear to be any existing operational measures of comfort that can be applied to a whole house or even to a major system. Subjective comfort measures typically relate to an individual in an environment, and depend on the individual's behavior and condition, and so are multidimensional. For example, the optimally comfortable relative humidity varies by individual with the ambient temperature, clothing, and level of activity. The population distributions for this optimal humidity, furthermore, will vary by age and sex (Meier, 1994). With this variation, optimal comfort may not be the most appropriate measure; widely appreciated acceptable comfort may be the best that can be achieved.

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[13] See Hackett, B. and B. McBride. 2001. *Human Comfort Field Studies Report*. California Energy Commission. Contract no. 500-98-024.

Many measures for thermal comfort have been adduced (Nicol et al., 1995). The most widely used standard, developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) is ASHRAE 55-1992R, Thermal Environmental Conditions for Human Occupancy, which focuses on workplace rather than residential environments. Visual comfort measures generally concern glare and daylighting (Sick, 1995.)

QCEE Associations

There are many association pathways among the quality, comfort, and energy efficiency attributes that we've considered and described above. These associations are gaining wider recognition; for instance, "ASHRAE's latest research programs attempt to link its thermal comfort concepts to incorporate effects of noise, odor, and other elements in indoor environmental quality (IEQ), and to link comfort with changes in such human behavior as productivity," (Goldman, 1999) and the similar efforts with regard to lighting (e.g., Veitch and Newsham, 1998).

The literature of consumer valuations (as opposed to perceptions) of quality, comfort, and energy efficiency is skewed heavily towards energy efficiency. While not conclusive, some rigorous analysis of revealed preference data from home sales suggests that energy efficiency investments in existing houses are fairly valued in the resale market (see Appendix 2). Yet it is not clear how these findings relate to new home sales. As noted elsewhere, very little is known about valuations of quality and comfort, and collective measures of QCEE associations do not appear to exist, likely because of the difficulty in measuring their component parts.

Appendix 2: Review of Consumer Value of Quality, Comfort, and Energy-Efficiency Data Sets

According to home builders, there is growing customer interest in energy efficiency and a perception that new homes are more energy efficient than resale homes. We are not aware of any rigorous analysis of how these perceptions of energy efficiency shape home buying behavior, let alone any that relates consumer preferences for quality, comfort, and energy efficiency (QCEE). In this section, we consider valuation data that reflect expressed preferences of home buyers, as from responses to surveys or interviews, and revealed preferences of home buyers, as from controlled experiments or econometric analysis of consumption data.

Meyers Group Exit Survey Data

The Meyers Group conducts ongoing exit surveys of prospective buyers of builder homes in the Southwest; they also collect builder data on new-housing developments. The latest survey, published with Meyers' partners in The Vision Group (2000), reflects the responses of 1900 prospective buyers of the homes of twenty builders, in April and May 2000. The survey is quite broad, and many questions address housing and builder attributes that could relate to QCEE (depending on our construal of quality and comfort and on respondents' interpretations). Three of the questions are somewhat more pointed, and are discussed below.

Respondents assigned influence weights (four-point scale) to each of eight purchase-decision attributes, four of which might be regarded as embodying QCEE:

- Builder's reputation (Q)
- Warranty/customer service (Q)
- Large number of options (QCEE)

- Short commute (CEE).[14]

The survey questions are all very briefly stated, with no explication of the intended meanings of the response options. Many buyers might construe "builder's reputation" to be a reputation for quality (of workmanship and materials), but some might interpret it as a reputation for low cost or for housing-development amenities. "Warranty/customer service" seems less open to interpretation. "Large number of options" may reflect all three attributes of interest (especially considering the vagueness of "comfort").

The responses to all the purchase decision attributes are shown in Table 1; the figure in brackets is a weighted composite score of "strong impact" and "some impact" responses.[15]

Table 1. Purchase decision attributes, with composite scores

Anticipated price appreciation	[159]	Warranty/customer service	[138]
Builder's reputation	[144]	Large number of options	[127]
Interest rates	[140]	Master-planned community	[98]
Size of lot	[140]	Shorter commute	[96]

Source: The Meyers Group

The question methodology makes it difficult to test for statistical significance of differences in buyer valuations of these attributes; it seems clear, nonetheless, that buyers care most about the investment value of the house, and secondarily about other attributes.

Another question asks, "what determines the quality of workmanship?" Respondents chose their top two selections from a list of eleven options, six of which might relate to energy efficiency or comfort:

- Materials/structure/construction
- Flooring quality
- Windows
- Features/options

[14] To the extent that a shorter commute reduces transportation energy use, the household becomes more energy efficient.

[15] Weighted composite score represents 2 x "strong impact" + 1 x "some impact."

- Appliances
- Other

The responses to all options are shown in Table 2; the figure in brackets is the percentage of respondents naming that attribute.

Table 2. Determinants of quality of workmanship, with percent citing in top two choices

Details/finish/edges	[51]	Windows	[14]
Materials/structure/construction	[45]	Features/options	[13]
Builder reputation	[43]	Fixtures	[12]
Cabinetry/cupboards	[25]	Appliances	[8]
Doors/molding/walls	[22]		
Flooring quality/squeaks	[16]		

Source: The Meyers Group

This question is ambiguously worded for our purposes, with at least two likely common interpretations: "in which of these areas is quality of workmanship most important to you?" and "which of these areas best reflects a builder's overall quality of workmanship?" A question worded explicitly to elicit the former interpretation would be more useful to our purposes, but the "builder reputation" option is inconsistent with that formulation, so perhaps Meyers intended the latter.

In any event, it seems evident that buyers *represent* that quality detailing and the overall structure are more important than any particular features. Empirically, however, buyers may take greater note than they are aware of features such as windows and fixtures, or they may be aware of their preferences but feel it less superficial to say that they value materials and construction quality. To the extent that comfort derives from a general satisfaction with one's house or from aesthetic appreciation, then all of the attributes (except, in the latter case, dealer reputation) relate to comfort; as noted above, many of the construction attributes may relate to energy efficiency, but it is not evident how to make analytical use of these data. (It is also curious and unfortunate that quality of workmanship was not one of the items in the prior question on purchase decision attributes.)

The only questions that speak directly to energy matters concern preferences for gas or electric appliances, by appliance type. Respondents do not indicate the reasons for their preferences (QCEE or otherwise). The responses are shown in Table 3; the figure in brackets is the percentage of respondents preferring gas.

Table 3. Preferences for gas appliances, in percent of respondents

Water heating	[94]
Stove	[91]
Space heating	[89]
Clothes dryer	[86]
Oven	[74]

Source: The Meyers Group

Note that this survey was conducted before the 2000–01 electricity crisis; preferences for gas were actually lower than in the 1999 survey. Even so, this survey does not indicate why gas is preferred—energy efficiency as such, expected lower operating costs (due to efficiency and relative fuel prices), or performance characteristics. Additional questions find that 88 percent of respondents say that they notice whether appliances are gas or electric, and that 74 percent would "spend more for a home that provided efficient natural gas appliances." This latter question does not ask how much more the respondent would be willing to spend for which sorts of benefits, nor is it clear whether the appliances in question are (a) natural gas and *therefore* implicitly "efficient" or (b) natural gas *and* more efficient than some baseline standard (i.e., would the responses differ if the characteristics of fuel type and energy efficiency were made independent?).

The foregoing questions address buyers' stated preferences; as suggested above, these may differ from their revealed preferences through two effects. Respondents may be aware of their (revealed) behavior and its implications but choose to answer differently, or they may answer truthfully according to their misunderstanding of the questions or their own behavior. To the extent that we are concerned with the ultimate goal of improving the energy efficiency of new housing stock, it is not necessarily important that stated and revealed preferences align, so long as the corresponding attributes are correlated. A contrived example: if buyers were to say that they preferred energy efficiency in washing machines, but they actually preferred quiet operation (comfort) and durability (quality), it would not matter for our purposes so long as the more energy- efficient appliances were also quieter and longer lasting. This is not a merely theoretical point; The Meyers Group collects detailed data on new-home offering characteristics, including features and pricing. It may be possible from these data to extract some measures of willingness to pay for QCEE attributes, but not with the specificity that this task requires.

Other Survey Data

National Association of Home Builders

NAHB (2001) conducted a survey of about 1,200 recent or intended home buyers nationwide (of new builder homes and otherwise), with detailed questions on preferences. While few relate explicitly to QCEE, some may be useful.

Questions on building materials ask which are preferred and for what reason, some of which could be construed as quality valuations. The responses vary strongly by region and price range, but the stated reasons for the preferences vary less: appearance, low maintenance, and strength/durability all rank much higher than cost. Even so, we again confront the difficulty with interpreting quality; many respondents might construe visually attractive materials necessarily to be of high quality, whereas for our purposes strength and durability may be more apt indicators.

Seventy percent say they are very concerned about structural materials, and twenty-eight percent are somewhat concerned. This question may be the most closely related to quality—why else be concerned about (hidden) structural materials? (As with many others, this question is briefly worded and broadly interpretable: We might expect that most respondents would construe structural materials to include frame, foundation, and roofing, and possibly drywall, insulation, flooring, etc.)

The survey asks how each of eighty-nine designs and features would affect the purchase decision (on a four-point scale). The only explicitly energy-efficiency features are multipane windows; double-pane windows ranked as the tenth most-essential feature (twenty-one percent), and as the sixth most essential (thirty-five percent) in the West region. The only other features that relate directly to energy are energy-*in*efficiency features, such as whirlpool tubs and fireplaces, which few buyers find essential. Many options could be construed as quality or comfort attributes: construction materials, kitchen counter materials, bathroom fixtures, etc.

There are no questions about appliances. (Some might argue that appliances are easily replaced and should not factor as heavily in a purchase decision as more immutable features like fireplaces and basements, but the survey does include features such as exterior lighting and a fenced yard.) A separate question asked about the importance of an energy management system (it is not evident that any explication was provided); fifteen percent hold it to be very important and thirty percent somewhat important.

The survey asked how concerned were buyers about the "environmental impact" of their new-home decision. Ten percent were not concerned, twenty-six percent were concerned but it was not a factor in their purchase decision, fifty percent wanted to reduce the environmental impact but were not willing to pay for it, and fourteen were willing to pay (an unspecified amount). Results in the West region do not differ significantly from those nationwide. As elsewhere, this question is too vaguely worded to be especially useful; it is not clear how prominent energy efficiency is in buyers' conceptions of the environmental impact of houses, but we might speculate that it is among the top few factors.

Respondents were asked how much they would be willing to pay upfront to save $1,000 per year in utility costs; the median response is between $5,000 and $7,000 (for an implicit real discount rate of about twenty percent); willingness to pay skews somewhat higher in the West, and is not significantly different for new builder homes. This result is certainly an upper bound on the actual willingness to pay, and is somewhat higher than other surveys have found. Questions of this sort are problematic, as some respondents may overstate their willingness to pay in order to appear environmentally conscious, and many are unable to make an abstract calculation that reflects their true personal discount rate.

A 1999 NAHB survey reported that eighty-eight percent of consumers indicate that builders and developers should build more energy-efficient homes and equip them with energy-saving appliances. But a 2000 NAHB study asked prospective buyers if they would pay less than $1,000 in the purchase of their next house in order to save $1,000 every year in utility costs; about two-fifths said they would. An NAHB economist observed that people actually want "wow" features that will impress their friends, and will say with one breath that they want an energy-efficient house, and with the next that they want a host of energy consuming comfort features (Salant, 2002). Another 2001 NAHB report similarly finds that ninety-six percent want energy efficiency.

Cahners Business Information

The Cahners publishing group reported in *Professional Builder* the results of an online 2001 survey of potential home buyers, conducted in partnership with the Partnership for Advancing Technology in Housing (PATH), the U.S. Green Building Council, builders, and appliance makers.[16] Ninety-four percent of buyers claimed that energy efficiency features were among the three most important home upgrades—the number-one response. Respondents said they would pay an average of $2300 up front for energy-efficiency upgrades that would reduce their monthly energy bills (the survey question did not specify the monthly savings, so we cannot infer a discount rate from these data); two percent said they were unwilling to pay any more up front. A separate question finds that respondents on average expect a four-year payback time on energy efficiency upgrades, compared with three years in the 2000 survey. The energy-efficiency features that respondents most want to have as standard are insulation above code (83%), high efficiency heating devices (83%), passive solar (76%), Energy Star certification (61%), ceiling fans (60%), and sealed combustion HVAC equipment (51%).

One question tangentially relates quality and comfort attributes to energy efficiency: among the perceived benefits of "green buildings" seventy percent cite quality, fifty-two percent durability; and sixteen percent quiet. Possibly illuminating the NAHB questions about environmental impact, eighty-seven percent of respondents cite saving energy as the foremost environmental issue with green buildings, up from seventy-eight percent in 2000.

Pulte Homes

The Tucson Division of Pulte Homes (a builder of 5-Star homes) conducted a survey of its buyers in 2001. Fifty-five percent said that energy efficiency was very important in their decision to buy a Pulte home, and two percent said it was not important. Eighteen percent would be willing to spend $1500–2000 to save $300 per year in energy costs, sixty-seven percent would be willing to spend $1200–1500, and twelve percent would not be willing to spend anything.

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[16] The methodology likely suffers from a high degree of selection bias, as respondents were among those visitors to housing related web sites who followed a link for a green building survey.

California Energy Commission/Washington State University

The California Energy Commission and Washington State University are conducting a study of residential electricity use in California, and have surveyed nearly 2000 households and interviewed several hundred of those in greater depth (preliminary results in CEC, 2002). The questions concern respondents' electricity consumption and conservation behavior and related beliefs, but none address valuations of building energy efficiency.

Data from other organizations

A 1997 National Family Opinion Research survey of recent new-home buyers found that eighty-nine percent reported wanting energy-efficiency upgrade options. A 2000 Realtors National Market Institute survey of realtors on buyers' wants had realtors saying that energy features were important in the buying decision for ninety-four percent of their clients. A 1998 survey by the Portland Cement Association (PCA) claimed that home builders underestimate how much buyers are willing to pay for energy efficiency. Earlier research had suggested that fifty-one percent of home buyers would be willing to pay five percent more for a home that offered twenty-five percent lower energy costs, whereas thirty percent of builders thought that home buyers would be willing to spend an additional five percent.[17]

Econometric Analyses—Revealed Preferences

Home buyers reveal their implicit valuations of various home attributes by their purchasing behavior. New homes are increasingly being offered with explicit options schedules; with data from cooperating home builders on options purchases we may be able to assess relative valuations of QCEE attributes.

A modest literature addresses revealed consumer valuations of home energy efficiency (with respect to both the thermal efficiency of the building shell and the efficiency of appliances and fixtures). Much of the analysis concerns whether consumers place a rational value on the financial returns (in lower utility bills) to investments in energy efficiency; that is, do they apply a consistent discount rate to all investments?

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[17] In fact, the figures cited neither prove nor disprove the PCA contention; more detailed response distributions are required to assess whether builders properly estimate buyers' willingness to pay.

There appears to be an emerging consensus that improvements in building thermal-efficiency are fairly valued by resale home buyers (Nevin, Bender, and Gazan, 1999) while new, energy-efficient appliances and fixtures are not (Bataille and Nyboer, 2000). This discrepancy is attributed largely to differences in the perceived riskiness of the investments (Howarth and Sandstad, 1995). With funding from the U.S. Environmental Protection Agency (EPA) and the Housing and Urban Development Department (HUD), ICF Consulting analyzed detailed data (from the U.S. Census Bureau's American Housing Survey) on 55,000 homes and found that, on average, an annual savings of $100 in utility bills from energy-efficiency upgrades translates into a $2000 increase in a home's value; these now widely cited results were published in Nevin and Watson (1998) and Nevin, Bender, and Gazan (1999). When accounting for the costs of the energy-efficiency upgrades, the increased home valuations reflect a twenty-three percent return on investment (Perkins, 2001a). These studies contend that the home appraisal industry has been slow to recognize the resale value of energy efficiency investments, an argument rejected by many appraisers (Perkins, 2001b).

The prior studies concern investments in energy-efficiency upgrades to existing houses. Horowitz and Haeri (1990) report on a study of new homes that were required to meet higher thermal-efficiency standards, and find that the real-estate market operates efficiently in capitalizing the value of energy savings into sales prices, with an implied discount rate of eight percent (at the time of the study, mortgage rates were about nine percent). Their review of the existing literature on consumer discount rates for energy efficiency finds values from seven to 378 [sic] percent; they attribute this discrepancy to measurement error in indirect measures of energy savings and costs. While comfort and quality attributes are not included in the econometric specification, the authors note that if a household discount rate for energy-efficiency investments is found to be lower than the prevailing mortgage rate, it might indicate that home owners view "the added expenditures as consumers as well as investors, finding additional, non-quantifiable benefits in the efficiency measures, such as decreased draughtiness or noisiness" (p. 128). While other analyses discuss such ancillary benefits of energy-efficiency investments, we have not discovered any empirical valuations of these benefits or any thoroughgoing discussion of their interrelationships.

Guidelines for Future Analyses of Consumer Valuation of Comfort, Quality, and Energy Efficiency

There are scant, largely anecdotal publicly available data on the value that consumers place on energy efficiency in new homes, and likewise for quality and comfort. It is apparent that consumers value quality, comfort, and energy efficiency to varying extents, but existing data are scarce and correspond poorly to the definitions of QCEE that we have elaborated in Appendix 1. We have, however, constructed an analytical framework that will allow for suitably targeted data gathering. This framework includes:

- Definitions of the terms of interest;
- Interrelationships among QCEE attributes; and
- Empirical studies of valuation of energy efficiency.

Based on this framework and on the results from existing surveys, we also provide some guidelines for future market-survey instruments. These guidelines correspond to operational definitions of quality, comfort, and energy efficiency, and provide for consistent comparisons of consumer values within and across the categories of interest.

Doing so rigorously, however, will require a more sophisticated survey methodology than that employed by The Meyers Group and other organizations whose findings we have reviewed. While these survey instruments are no doubt suited to these groups' needs for market research, it is difficult to infer relative preferences and willingness-to-pay for disparate goods from questions that ask for absolute valuations of individual goods. For example, if one randomly assigned set of survey respondents is asked to rate their fondness for apples on a five-point scale, and likewise for oranges and for bananas, and another set is asked to rate their relative preferences for the three fruits, we should not expect the outcomes of the two surveys to correspond. Survey participants are well known to value hypotheticals differently when presented individually or collectively, and commonly express nontransitive preferences. These problems are further magnified when the options are more disparate (e.g., relative preferences for apples, toothpaste, and television programs).

A host of survey methodologies and analytical methods have been developed to address these problems, including two paradigms of stated preference methods (conjoint analysis and discrete-choice modeling) and contingent valuation (widely used for valuation of nonmarket environmental goods). The hedonic pricing method, furthermore, allows for the implicit valuation of components of an aggregated purchase, when only the aggregate expenditure is observable; such an analysis of The Meyers Group builder survey data may reveal buyer valuations of quality, comfort, and energy efficiency attributes. A discussion of these and other candidate methodologies is beyond the scope of this report,[18] but any effort to pursue them should bear in mind several important classes of questions:

- How do home buyers interpret "quality" with respect to new home construction? These questions should be distinct from the relative preference and valuation questions. Likewise, how do they interpret "comfort"?

- What associations do buyers make among quality, comfort, and energy-efficiency attributes and features?

- What relative preferences do buyers have for attributes from among these three classes? (i.e., pose discrete choices *between*, e.g., quality and energy-efficiency attributes.)

- What relative preferences do buyers have for attributes within these three classes?

- What relative preferences do buyers have for the three classes? These last three questions, together, may reveal inconsistent implicit valuations or misinterpretations of the classes and attributes.

These questions should be formulated and interpreted, to the extent possible, in a manner consistent with the definitions and metrics of QCEE as discussed in Appendix 1. We expect that meeting this condition should be challenging; while home buyers have an intuitive feel for quality and comfort and a rudimentary understanding of energy efficiency, the operational definitions and metrics for these attributes are, in the former case, arcane and, in the latter case, highly technical.

Furthermore, as noted above, The Meyers Group survey of builders is a potentially rich source of data on home buyers' implicit valuations of QCEE options in new homes; these data could be subjected to hedonic pricing analysis to yield estimates of willingness to pay for QCEE attributes. If these data (by homes) could be matched with survey data from those homes' respective buyers, then we could determine more rigorously the correspondence between stated and revealed preferences for quality, comfort, and energy efficiency.

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[18] See, e.g., Bateman et al. (2002) and Griliches (1971).

Appendix 3: Review of Warranty-Cell Data Sources

We have identified several potential sources of data on construction and equipment defects that may relate to quality, comfort, and energy efficiency (QCEE) concerns (see also Appendices 1 and 2 on QCEE concepts, measures, and valuations). Ideally, we would like to associate particular causes for action with the QCEE attributes that we have defined, and to assess their frequencies, dispositions, and costs, as well as best construction practices that reduce their incidence. None of the potential data sources proved to have adequate data to support rigorous statistical analysis.

2-10 Home Buyers Warranty

2-10 Home Buyers Warranty (HBW) provides structural warranty protection for over one million houses nationwide. They collect few data on complaints. A small number of complaints go to claims, for which more information is recorded, but these are not necessarily representative of all complaints. Defect codes are sometimes entered with claims, but they identify defect types only generally, e.g., "workmanship," "design," and "heating." These data are not readily called up from an electronic database.

We were provided some aggregate data on their activity in the last decade, which show that numbers of warranty enrollments have increased while the numbers of first- and second-year complaints and claims have declined. As their enrollments are not a random sample of new homes it is not evident whether building quality has improved in general or whether there has been some selection of higher quality home builders for coverage.

2-10 HBW tracks defect codes and year of complaint for only the ten-year structural component of the warranty; they do not track workmanship or systems defect codes, nor the costs of callbacks. Their customer service and claims departments are not sufficiently integrated to connect complaints data with cost data. They have published a pamphlet entitled "Top 10 Callback Items and How Can You Avoid Them,"[19] but were unable to provide us with the data that support this list.

NAHB ToolBase Hotline

The NAHB Research Center ToolBase is a clearinghouse for home construction information. Its Hotline receives calls on a wide variety of building concerns, many of which concern construction defects that trigger warranty calls. Although the Hotline records do not include data on costs, we had thought that they might provide information on relative frequencies and consequences of various construction concerns, and aid in interpreting claims data. The Hotline database extends back to 1996.

The Hotline database is a four-level hierarchy, with each entry classified by:

- Industry Topic (27 codes)
- Subject 1 (8 codes)
- Subject 2 (55 codes)
- Construction Standards Institute (CSI) Level (16 codes)

Within each level, many of the codes *may* relate to QCEE concerns; we identified a small sample (twelve) of promising threads in this database, and requested copies of all of the corresponding database entries. These queries yielded approximately 200 entries from the 2000 and 2001 databases; of these, no more than seven explicitly mentioned a construction defect, two of those seven appeared to concern houses new enough to be under warranty, and neither of those was clearly energy-efficiency related. Numerous other shortcomings in the data collection render this database unsuited to our purposes.

Builders

Many large builders cover their own warranties, and likely collect detailed complaints and claims data, although they may be reluctant to disclose fully their numbers and costs. Our contact at The Meyers Group helped us identify potential data providers in these companies. Shea Homes was particularly responsive, and we visited the customer services department in the San Diego division.

[19] http://www.2-10.com/whatsnew/pdf/top%2010%callback%20items%20all%20together.pdf

Shea's database is a Fox-based product called Service Tract, designed specially for home builders. They installed it in early 1999, and it is complete since February 2000. Earlier data are entered only if a new call arrives for the same house. We made one sample query of the database, which revealed that the problem descriptions are too cursory (e.g., "air conditioning not working") to allow for flagging as a build-quality or energy-efficiency concern with any certainty. Furthermore, the costs field is entered as zero if the call falls within the one-year limited warranty or a trade is at fault and absorbs the cost of mitigation. Even if the data were complete, unambiguous, and easy to query, they still reflect only a few thousand houses over two years, contra the CEC statement of work.

Absent any indication that other builders have a considerably more complete, refined, and accessible database, this approach does not appear fruitful.

Fannie Mae

Fannie Mae maintains detailed records of mortgage foreclosures, which include codes for energy costs and possibly for construction defects. Our contact at NAHB sought to determine whether these records are suited to inferring energy costs associated with construction defects, and concluded that they were not. We were unable to communicate with Fannie Mae directly on this matter.

Other Potential Data Sources

A search of the literature produced no public documentation of housing defects, nor any further references to proprietary information. We sought other organizations that might be concerned with housing defects and in a position to collect such data. We identified as candidates and contacted: the American Society of Home Inspectors (ASHI), the American Association of Home Inspectors (AAHI), the Foundation of Real Estate Appraisers (FREA), the California Real Estate Inspection Association (CREIA), and the Council of American Building Officials (CABO/ICC). None of these groups collect such data.

Conclusion

We have not identified any sources of data adequate to the stipulated task in this research program seeking to associate warranty call types, frequencies, costs, and construction practices that could reduce warranty call occurrences. We are inclined to conclude that no such data exist. While it is impracticable to conduct primary data collection to acquire the sort of data that we had hoped to receive in this research effort, a more qualitative analysis of expert knowledge of construction defects may be quite promising.

Appendix 4: Interview Questions for Home Builders

Background

1. Your company and construction related activities:

    a. How large is your company? (revenue, homes per year, employees, market share)

    b. What are the locations of past developments and future targets? (county, city, or climate zone)

    c. What are the construction-related weather issues in those areas? (temperature, humidity, precipitation)

2. Your product, marketing approach, and competition:

    a. How would you describe your market and product? (e.g., high end, affordable, type, size, price)

    b. Over what market opportunities do you consider that you have a competitive advantage? (e.g. location, type of product, price, other)

3. Please describe your participation in energy-efficiency programs:

    a. Do you participate in Energy Star, Comfortwise, or other programs? (names)

    b. Do you take advantage of available government incentives? (names)

    c. What energy-efficient features do you offer in your homes? (features)

Product and Construction Problems

4. What is your total cost/budget for rework and warranty callback items annually?

5. What are your top-five highest frequency rework or warranty callback items?

a. Can you estimate the percent of frequency and percent of total rework/callback costs for these items?

b. Are there factors that affect the frequency of the top five problems you listed? (e.g. location, price of house, quality of materials). Are there different frequencies for different products?

c. Are there factors that affect the cost of the top five problems? Are there different costs for different products?

d. When addressing these top five problems, do they have an order of priority? What are criteria for prioritizing (cost, frequency, short-term, long-term planning)?

6. Are any of the categories listed below, which are not on your top- five list, also major items? If so, what are their estimated frequency and cost?

   a. Foundation

   b. Frame

   c. Sheathing

   d. Interior finishes (drywall, paint, plaster, nail pops)

   e. Floors (hardwood floor movements, vinyl)

   f. Exterior cladding (siding, roofing)

   g. Insulation

   h. Fenestration (doors, windows, skylights, leaks)

   i. Plumbing (leaks)

   j. Electrical

   k. HVAC

   l. Other (e.g., basement leaks, surface drainage

7. Focusing specifically on HVAC, are there differences in frequency and cost of callbacks in homes with ceiling vs. wall registers? In homes with single-, split-, or dual-AC systems?

8. Are there additional costs that are hidden to the builder because they are in the subcontractor costs? If so, what are they?

9. How does your company respond to consumers regarding these construction problems?

    a. Do you generally defer to home-warranty companies?

    b. Are certain calls (e.g., leaks) responded to with higher priority? Are there significant cost savings associated with doing so?

    c. Have these problems resulted in changes in building practices by your company, or other strategic planning changes? If not, why not?

10. Do you think rework or warranty callbacks affect sales? If so, can you estimate how much?

11. Do insurance and legal fees associated with rework and callbacks affect construction costs? If so, can you estimate by how much?

12. Are there alternative building practices that can minimize the rework and callbacks on highest priority items? If so what are some reasons that you have not employed these practices?

13. Is there a role for construction protocols to help avoid the highest priority problems? If so, where should they concentrate and why?

14. Are there potential cost savings to the home owner, or builder, associated with alternative construction protocols? Would cost reductions occur over the short or long term?

Dimensions of Comfort and Quality Relevant to Construction Decisionmaking

15. What aspects of "comfort" and "quality," or consumer satisfaction more generally, dominate the decisions made as they relate to construction?

    a. When a customer buys a home, what do you believe are the key perceptions that distinguish a home that the buyer might feel has greater "comfort" than another? (aesthetic, physical, psychical)

    b. What features of a home are most important to achieve the comfort of its occupants? (heating, cooling, lighting color and intensity, wall and flooring aesthetics and layout, noise suppression and transmission, etc.)

    c. Is there a relationship between homes that you would consider higher quality and comfort and callback/rework events?

Business Decisionmaking Related to Participation in Energy-Efficiency Programs

16. If you have built energy-efficient homes, how do they differ from your standard product?

17. Are any specific energy-efficiency features more or less prone to further problems compared to standard construction/feature alternatives? In other words is there a relationship between some energy-efficiency measures and callback/rework items?

18. Are there energy-efficiency features that contribute to increasing the quality and comfort of a new home?

19. Regarding participation/non-participation in energy-efficiency programs:

    a. What is your estimate of participation cost to the builder? ($/house, % of sales price)

    b. What is the value of the various incentives you receive? ($/house, % of sales price)

    c. Do you capture the difference in the sales price? (yes, no)

    d. If you do not participate in energy-efficiency programs or take advantage of incentives, why not?

    e. To what extent does consumer interest in energy-efficient homes affect your company's design and construction practices?

    f. What do you believe is the consumer interest in energy-efficient homes relative to interest in comfortable and high-quality homes?

    g. How much are consumers willing to pay for energy efficiency? ($/$ annual savings)

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LIST OF ATTACHMENTS

Attachment Title	Description	Publication Number
Residential CFD Study	A Computational Fluid Dynamics study of one-story and two-story HVAC systems (registers, returns, and thermostat)	A-1
HVAC Design Guide	Residential HVAC design guide	A-2

CALIFORNIA
ENERGY
COMMISSION

RESIDENTIAL CFD STUDY

TECHNICAL REPORT

JULY 2005
CEC-500-2005-118-A1

Arnold Schwarzenegger, *Governor*

Prepared By:
Dr. Robert Hammon
Building Industry Institute
Sacramento, CA
Contract No. 400-00-037

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

Martha Brook,
Contract Manager

Ann Peterson,
PIER Buildings Program Manager

Nancy Jenkins
Office Manager
ENERGY EFFICIENCY RESEARCH OFFICE

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

B. B. Blevins,
Executive Director

DISCLAIMER

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 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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

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

What follows is an attachment to the final report for the Profitability, Quality, and Risk Reduction through Energy Efficiency program, contract number 400-00-037, conducted by the Buildings Industry Institute. This project contributes to the PIER Building End-Use Energy Efficiency program. This attachment, "Residential CFD Study" (Attachment 1), provides supplemental information to the program final report.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Abstract

This "Residential CFD Study" report was produced by the Profitability, Quality, and Risk Reduction through Energy Efficiency program, funded by the California Energy Commission's Public Interest Energy Research (PIER) Program.

Using a commercial computational fluid dynamics package, a single-story three-bedroom home was analyzed for cooling and heating efficiency, comfort, and air quality. These results indicate that wall-mounted registers are not only the most energy efficient but also provide effective thermal comfort and air quality.

Placement of the single story return is dependent on whether the design is dominated by heating or cooling. For cooling, the combination of the wall supply and ceiling return provides good mixing as cold air falls and is drawn up to the return. For heating, the combination of the wall supply and low-wall return provides a slightly more energy efficient design.

The study also examined the placement of the thermostat and returns in a two-story home. The simulations results show that two returns, one upstairs and one downstairs, with the thermostat centrally located upstairs provide the most effective cooling, occupant comfort, and air quality.

PIER Profitability, Quality and Risk Reduction through Energy Efficiency Program

Project 5.2: HVAC System Design Alternatives

Tasks 5.2.1 (Determine Energy and Comfort Impacts of FAU location, Register Location and Register Type)

Executive Summary

The objective of this task was to determine energy efficiency and room comfort conditions based on different register locations, register installations and types. Using a commercial computational fluid dynamics package, a single-story three-bedroom home was analyzed for cooling and heating efficiency, comfort, and air quality. The study was extended to include the effects of return placement. These results indicate that wall-mounted registers are not only the most energy efficient but also provide effective thermal comfort and air quality.

Placement of the single story return is dependent on whether the design is dominated by heating or cooling. For cooling, the combination of the wall supply and ceiling return provides good mixing as cold air falls and is drawn up to the return. For heating, the combination of the wall supply and low-wall return provides a slightly more energy efficient design.

Based on feedback from our Technical Advisory Group, this study was again extended to examine the placement of the thermostat and the number returns in a two-story home. The simulations results show that two returns, one upstairs and one downstairs, with the thermostat centrally located upstairs provide the most effective cooling, occupant comfort, and air quality.

This report discusses the details of this study and the impacts of register location and type on comfort and energy efficiency

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Tables

Method Description

Overview

A three-bedroom, single floor home in climate zone 14 was analyzed using a commercial computational fluid dynamics package designed for HVAC analyses, AirPak by Fluent, Inc. A baseline heating case was used to establish basic model parameters. Heating and cooling modes were analyzed for three supply register configurations and two return configurations. Two different FAU locations were examined.

Additional computation fluid dynamic (CFD) studies were performed to further investigate common questions related to residential HVAC design. The questions to be answered relate to how return air grille location and thermostat location affect temperature distribution in a two-story home that is conditioned by a single HVAC system. These additional studies were undertaken based on feedback from our Technical Advisory Group and our field experience. This feedback indicated that further investigation would greatly improve the value of an HVAC Design Guide if performance in a two-story home could be addressed. The details, results, and recommendations from the two-story study are included as Appendix B.

Method detail

Computational fluid dynamics (CFD) is a computational method that enables the user to study the dynamics of matter that flows. Using CFD, a computational model is built to represents a system or device to be studied. By applying fluid flow physics to this virtual prototype, the software produces a prediction of the fluid dynamics. CFD not only predicts fluid flow behavior, but also the transfer of heat, mass, phase change, chemical reaction, mechanical movement, and stress or deformation of related solid structures. In this study, the CFD predicts the airflow, including heating and cooling, that results from the supply of air to each room from each register, as well as the return of air from the HVAC return register.

Fluent Inc. is a provider of commercial CFD software and services. The company offers general-purpose CFD software for a wide range of industrial applications, along with highly automated, application-focused packages such as AirPak, a highly focused design and analysis tool tailored for ventilation system design and analysis. Airpak lets the user accurately and easily model airflow, heat transfer, contaminant transport and thermal comfort in the ventilation system. For more detailed information, the reader can learn more about the product on-line at http://airpak.fluent.com/.

Data provided

The house used for the analysis was a 3-bedroom, single floor design with a single Forced Air Unit (FAU). The thermal properties of walls, ceilings, floor, doors, and windows were determined for the home to meet 2001 Title 24 requirements, and are documented on the ACCA Manual J form for this house.

The design was provided as a 3-D AutoCAD drawing with walls, doors, and windows placed as in the actual design. **Figure 1** shows a solid model of the house. This view shows the supply registers in the ceiling of each room. The return is not visible in this view but is located low on the hallway wall, adjacent to the garage door.

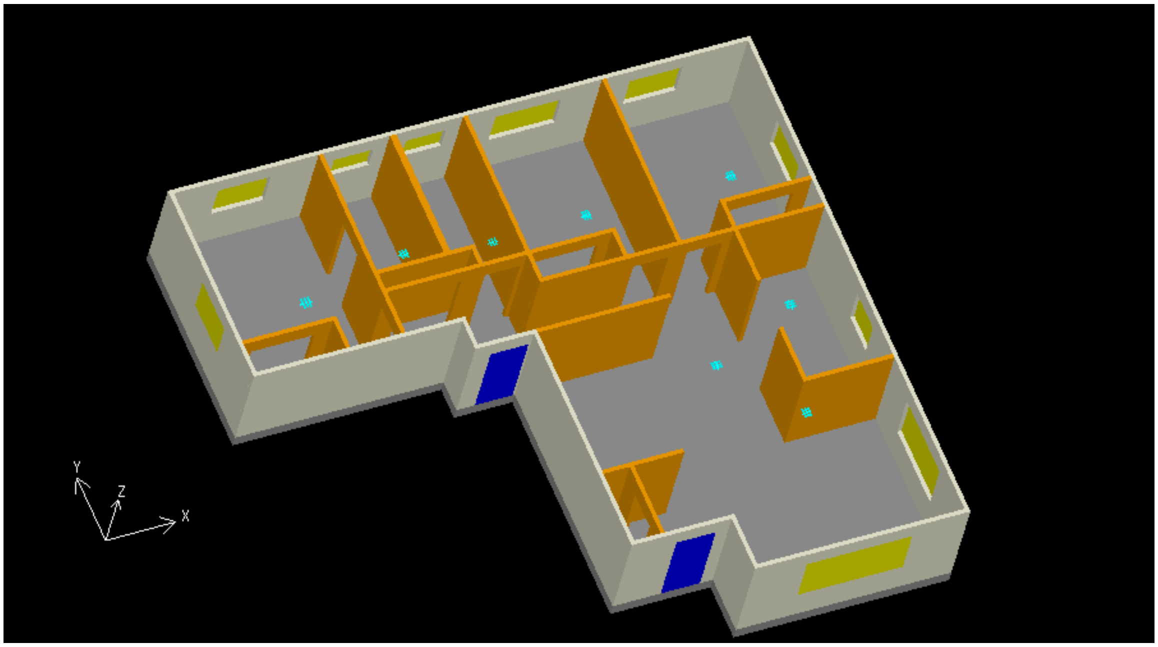


Figure 1: Solid model view of study house

The initial analysis was performed for the heating condition. The temperature of the walls, ceiling and floor were constant. The outside temperature was 20ºF, which is the outdoor heating design temperature for Palmdale, Climate Zone 14, where the home was built.

The airflow rates for the supply registers in each room were taken from the output of the Right Suite software and provided as input to model. An estimate of the temperature leaving the registers was provided, based on equations from 2001 ASHRAE Fundamentals Handbook and air velocities in the ducts from Right Suite software.

The initial heating case was used to work out procedural methods and define the required datasets. This initial case provided the opportunity to evaluate the output from the model and determine what material would be most useful to our analyses. Based upon results of the heating conditions, analyses were performed for both the heating and cooling condition with variations in supply register location and return location. For the cooling case, the appropriate parameters from the design were used, e.g., outside temperature = 103ºF, cooling fan CFM, cooling airflow factor, etc.

Data Sources

The engineering data sources for these analyses are available in Appendix A.

Assumptions

The garage space was not considered. The attic and garage space were assumed to be at the outside temperature, i.e. exposed to outdoor ambient conditions, for the heating case. For the cooling case, the attic temperature was assumed to be 140^{o}F. The temperature of the outside walls was assumed constant with an exterior temperature equal to the heating or cooling design temperature. Interior doors were in the open position. Exterior doors and windows were closed. House leakage was assumed to be negligible. Relative humidity was not included in the computations.

Evaluation of One-Story Designs.

FAU Placement

Design cases with both short and long ducts were computed.. The short duct configuration is shown below in **Figure 2**. The FAU is located in the center of the house.

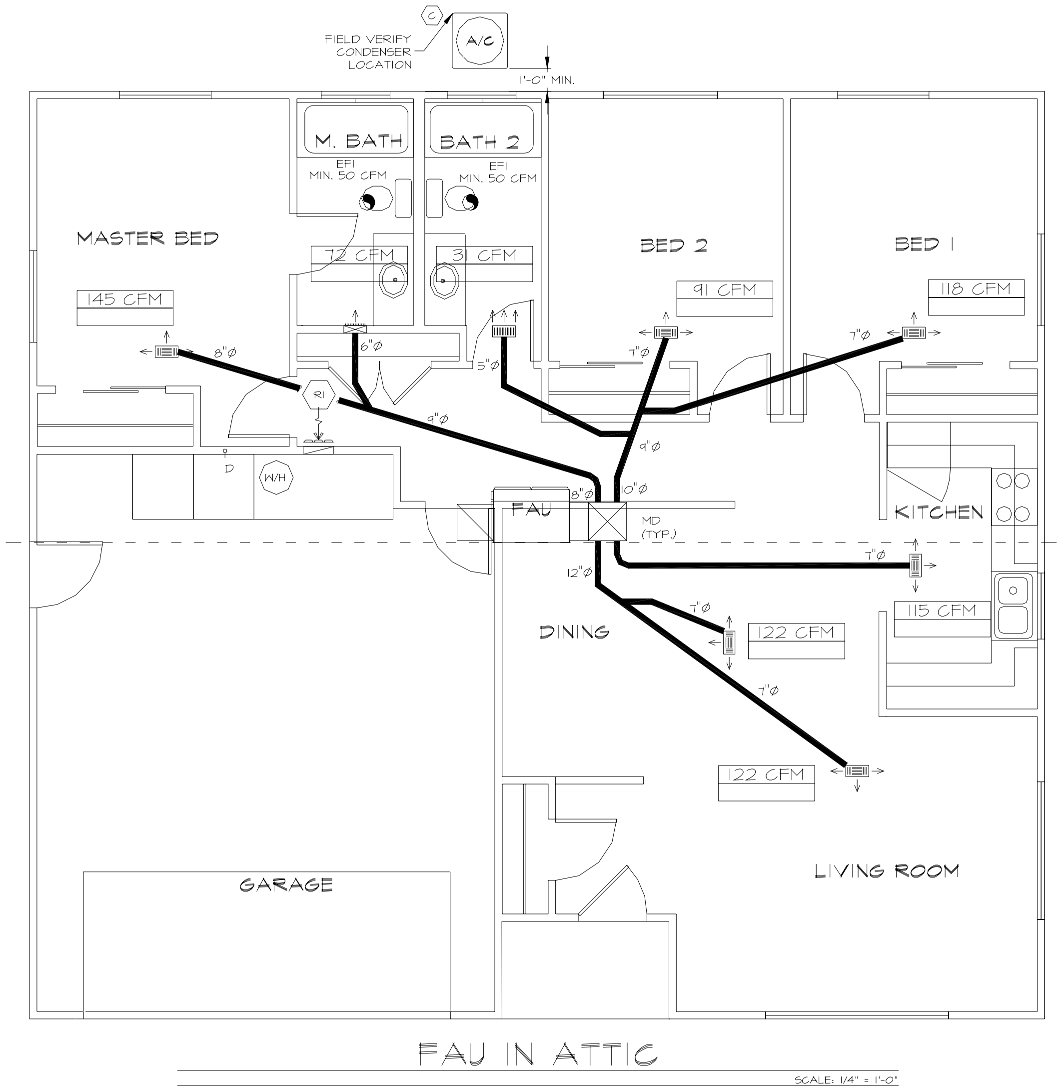


Figure 2: FAU in Attic, Ceiling Registers with Short Duct Runs

The long duct configuration places the FAU in the garage, as shown in **Figure 3**. (Note: the FAU was placed as far away as possible to create a long duct run for this house. This configuration is somewhat impractical given the simplicity of the layout).

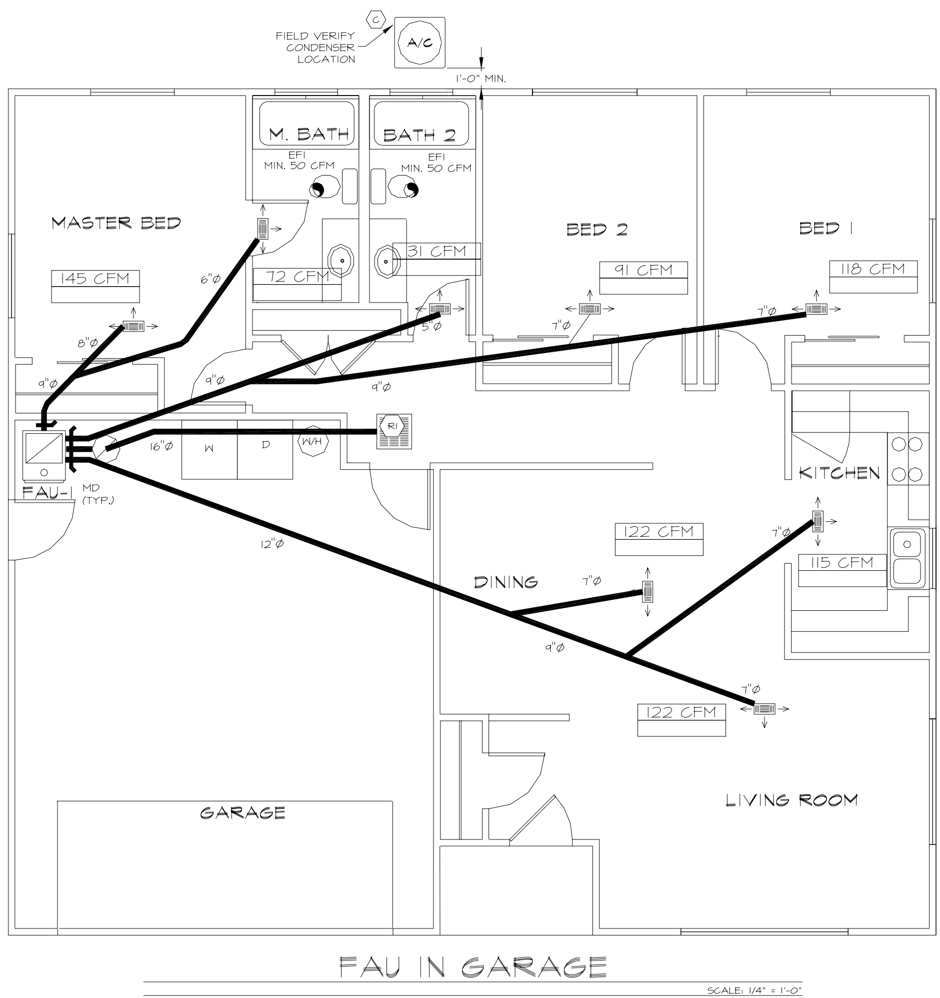


Figure 3: FAU in Garage, Ceiling Registers with Long Duct Runs

Both long and short ducts configurations were analyzed to determine the air supply flow rate and temperatures for each supply register. The design differences for each case resulted in similar CFM rates for each register. The supply temperatures for each location were calculated based on the duct length for each supply register. The temperature differences at the supply register are shown below in **Table 1** for interior ceiling supply registers.

	Heating Register Temp ºF		**Cooling** Register Temp ºF	
FAU Location	Ceiling	Garage	Ceiling	Garage
Living Room	98º	98	59	62
Living Room	102º	99	57	61
Kitchen	103º	97	58	63
Bedroom 1	102º	98	58	62
Bedroom 2	102º	98	57	62
Bath 2	100º	96	59	62
Master Bath	101º	96	63	62
Master Bed	101º	104	59	56

Table 1: Temperature variation at supply registers for long and short ducts

A decision was made to limit the number of CFD runs performed due to resource limits for CFD analyses. Given the register supply locations were considered a more critical design variable for the analysis and that the attic FAU is the most prevalent configuration in California production homes, all the analyses were performed on the short duct configuration. The cost difference for the long duct case due to the increased amount of ducting would need consideration as part of an overall cost-benefit assessment.

Supply Register Location Configurations

Three register location configurations were analyzed. In the first case, registers were ceiling-mounted multidirectional. In the second case, the registers were place over windows on the exterior walls. The third case placed the registers in interior walls. The FAU was placed in the middle of the house.

Return Location Configurations

Two return locations were analyzed. The most common location for the return in California productions home is in a hallway ceiling. In the alternate configuration, the return was place low on the hallway wall.

Analysis of the return locations was not part of the original analysis scope. However, when the first CFD results were analyzed, flow characteristics were noted that required more investigation of the return location.

One-Story Case Summary

Table 2 provides a summary of the return and supply register configurations for the twelve, one-story cases that were analyzed.

Case	Mode	Return configuration	Supply Register configuration
1	Cooling	ceiling	Ceiling interior
2			Ceiling over windows
3			In walls
4	Heating	ceiling	Ceiling interior
5			Ceiling over windows
6			In walls
7	Cooling	Low wall	Ceiling interior
8			Ceiling over windows
9			In walls
10	Heating	Low wall	Ceiling interior
11			Ceiling over windows
12			In walls

Table 2: Summary of One-Story Cases

CASE 1: Cooling, Ceiling Interior Registers, Ceiling return

The register and duct configurations for Case 1 are shown below in **Figure 4**. The inlet air temperature and flow rates for this case are shown in **Table 3**. **Figure 5** shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. The total ON/OFF cycle takes approximately 20 minutes for this case. The HVAC ON cycle takes approximately 6 minutes.

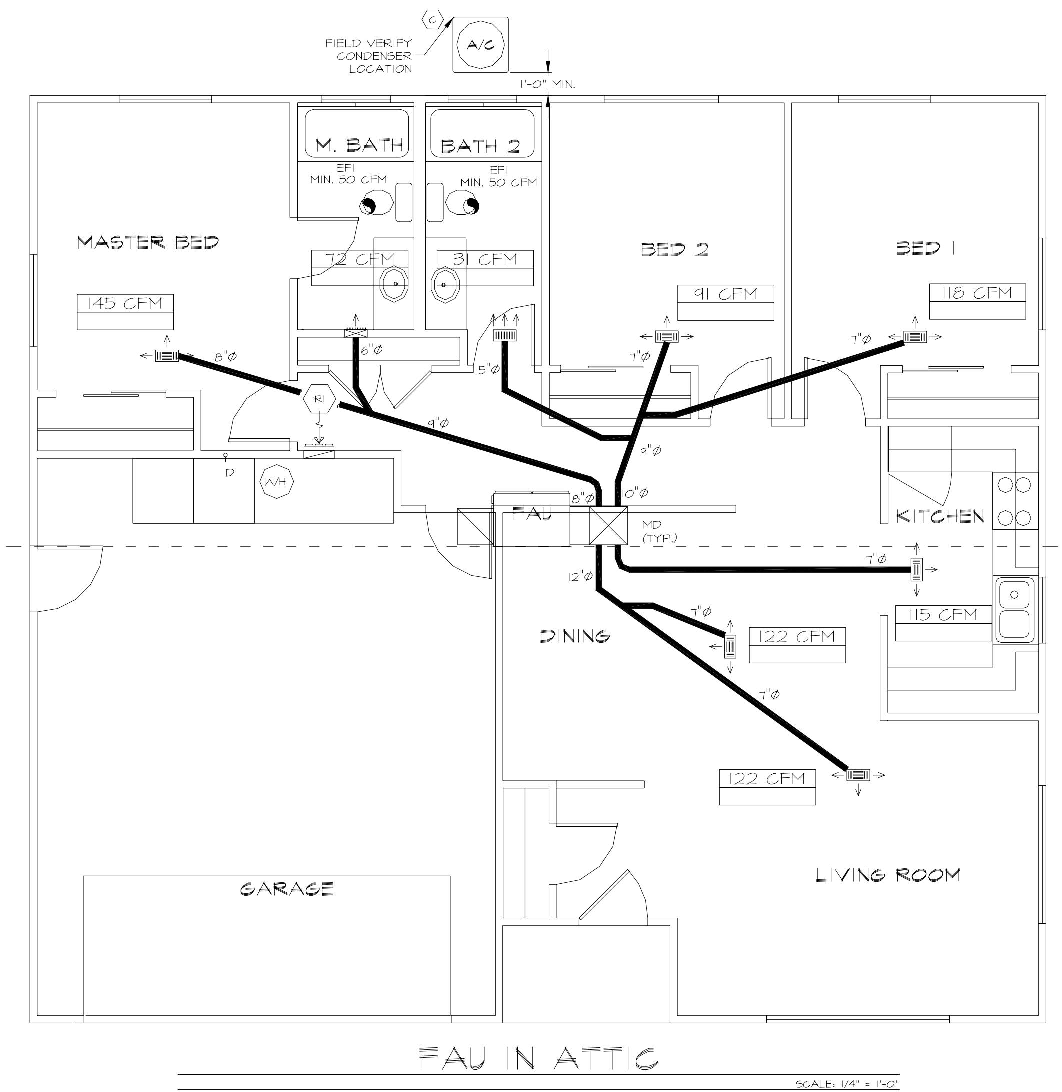


Figure 4: Case 1 – Ceiling Interior Registers

Inlet air temperatures through registers Ceiling Registers, Center of Ceiling, Shoemaker Series 203 Registers			
Room	Duct Length (feet)	Duct flow rate (CFM)	Register Temp (ºF)
Living Room	17	129	59
Living Room	9	129	57
Kitchen	15	120	58
Bedroom 1	16	125	58
Bedroom 2	7	95	57
Bath 2	10	33	59
M Bath	21	33	63
Master Bed	21	152	59

Table 3: Case 1 Inlet air temperature and flow rates

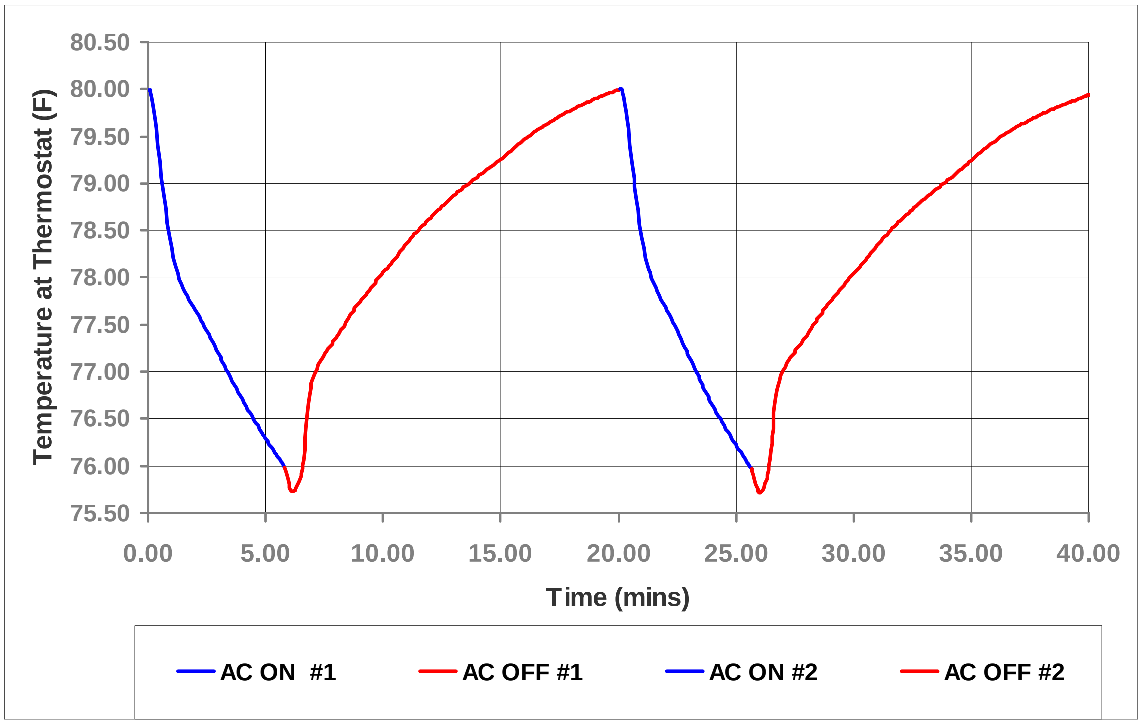


Figure 5: Case 1--Transient Temperature Variation at Thermostat

CASE 2: Cooling, Ceiling Over Window Registers, Ceiling Return

The register and duct configurations for Case 2 are shown below in **Figure 6.** The inlet air temperature and flow rates for this case are shown in **Table 4**. **Figure 7** shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. Each ON/OFF cycle takes approximately 20 minutes for this case.

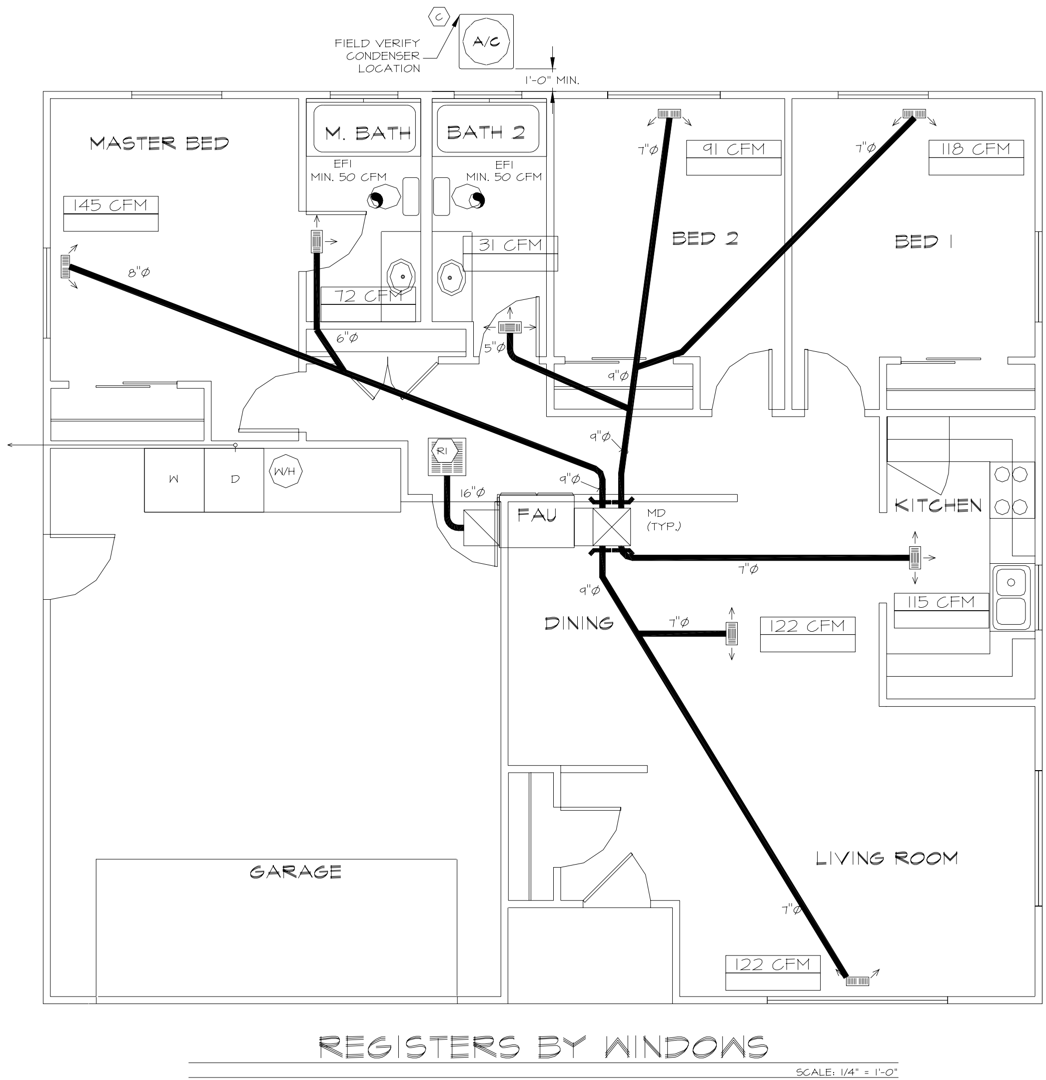


Figure 6: Case 2 -- Registers Over Windows

Inlet air temperatures through registers Ceiling Registers, Over Windows, Shoemaker Series 203 Registers			
Room	Duct Length (feet)	Duct flow rate (CFM)	Register Temp (ºF)
Living Room	23	129	60
Living Room	9	129	57
Kitchen	13	120	58
Bedroom 1	24	125	60
Bedroom 2	18	95	59
Bath 2	12	33	59
M Bath	21	33	63
Master Bed	28	152	61

Table 4: Case 2 Inlet air temperature and flowrates

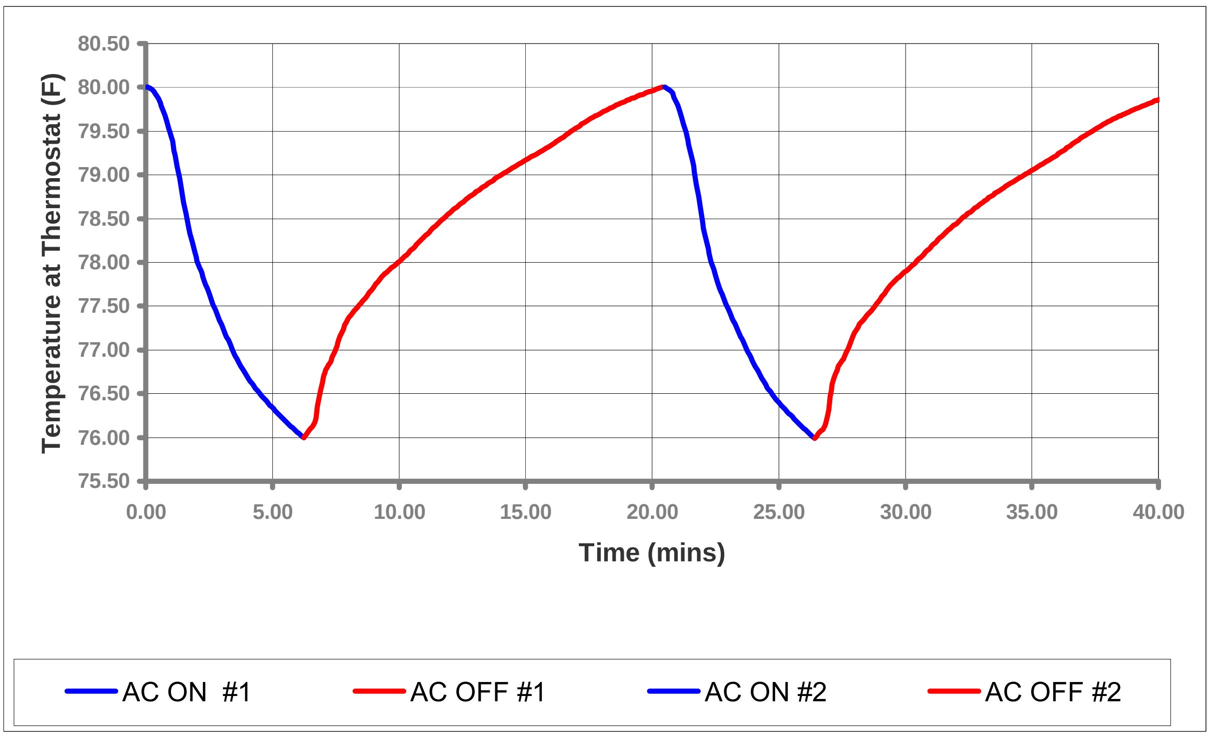


Figure 7: Case 2--Transient Temperature Variation at Thermostat

CASE 3: Cooling, Wall Mounted Registers, Ceiling Return

The register and duct configurations for Case 3 are shown below in **Figure 8.** The inlet air temperature and flow rates for this case are shown in **Table 5**. **Figure 9** shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. The total ON/OFF cycle time is approximately 25 minutes for this case. The HVAC ON cycle takes approximately 4 minutes.

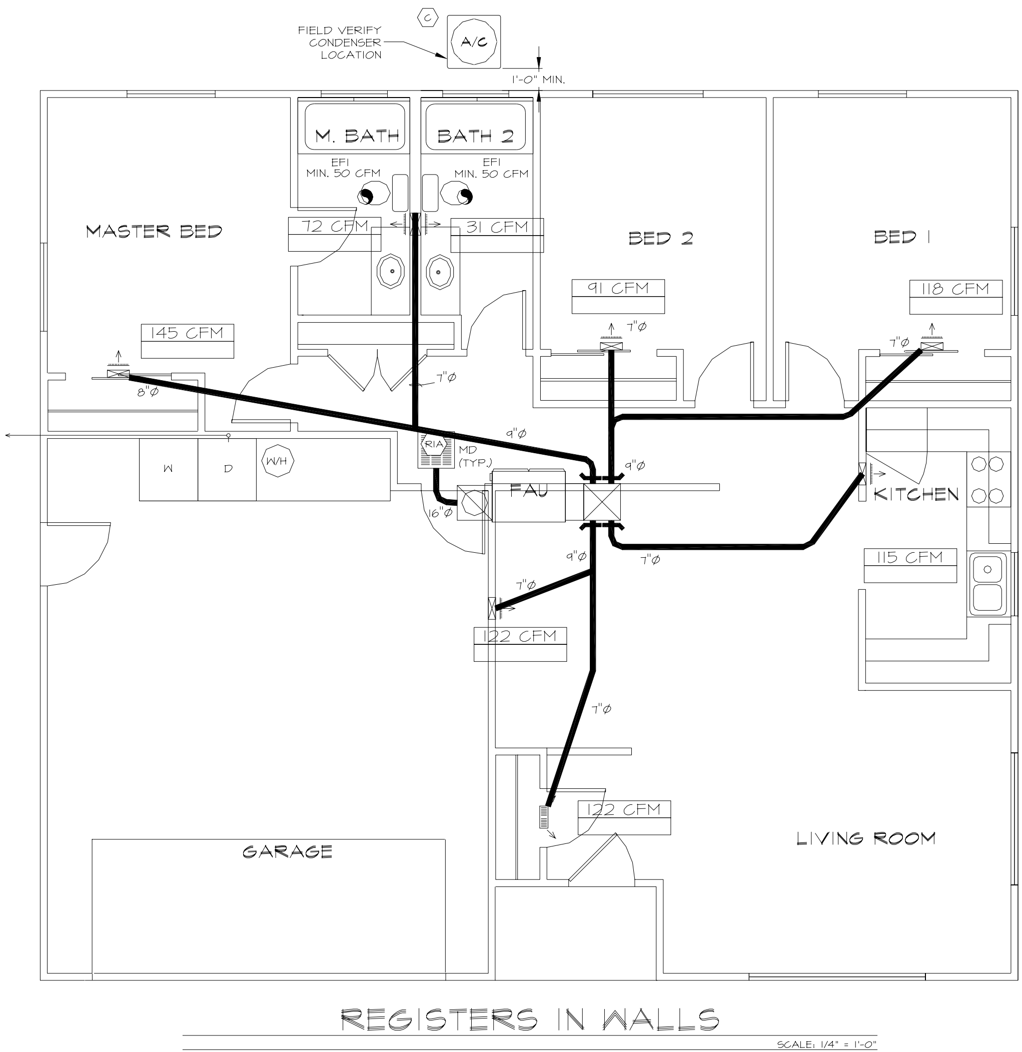


Figure 8: Case 3 -- Wall-Mounted Registers

Inlet air temperatures through registers Registers in Walls, Shoemaker Series 950 Registers			
Room	Duct Length (feet)	Duct flow rate (CFM)	Register Temp (ºF)
Living Room	14	129	58
Living Room	8	129	57
Kitchen	15	120	58
Bedroom 1	19	125	59
Bedroom 2	6	95	56
Bath 2	19	33	63
M Bath	19	33	63
Master Bed	23	152	59

Table 5: Case 3 Inlet air temperature and flow rates

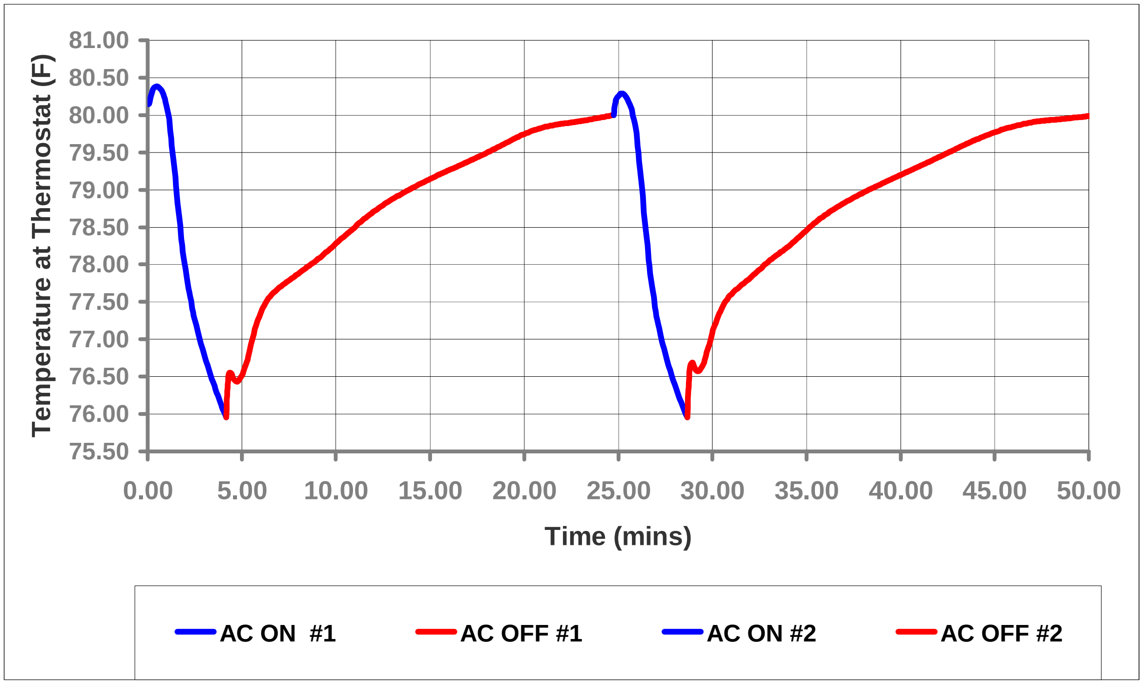


Figure 9: Case 3--Transient Temperature Variation at Thermostat

CASE 4: Heating, Ceiling Interior Registers, Ceiling Return

Case 4 uses the same register and duct configurations as Case 1 and is shown in **Figure 4**. **Figure 10** shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. Each ON/OFF cycle takes approximately 11 minutes for this case. The HVAC ON cycle takes approximately 6 minutes.

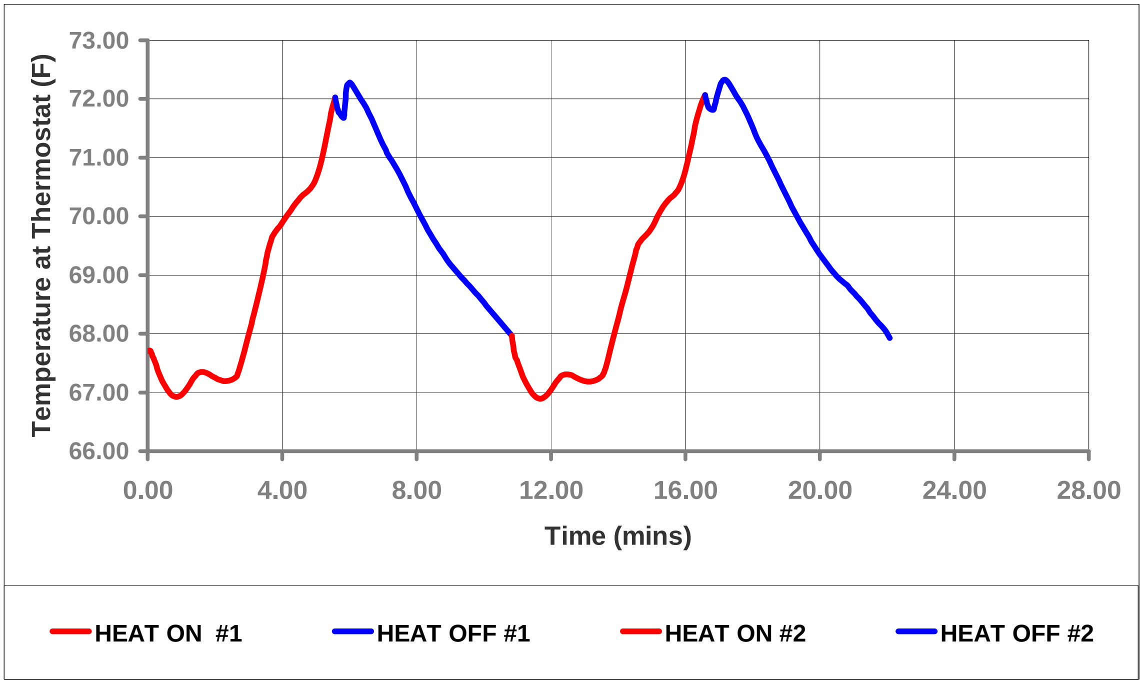


Figure 10: Case 4 --Transient Temperature Variation at Thermostat

CASE 5: Heating, Ceiling Over Window Registers, Ceiling Return

The register and duct configurations for Case 5 are the same as those for Case 2, shown in **Figure 6**. **Figure 11** shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. Each ON/OFF cycle takes approximately 11 minutes for this case. The HVAC ON cycle takes approximately 6 minutes. Note the difference in the HEAT ON curve shape from Case 4 with ceiling interior registers.

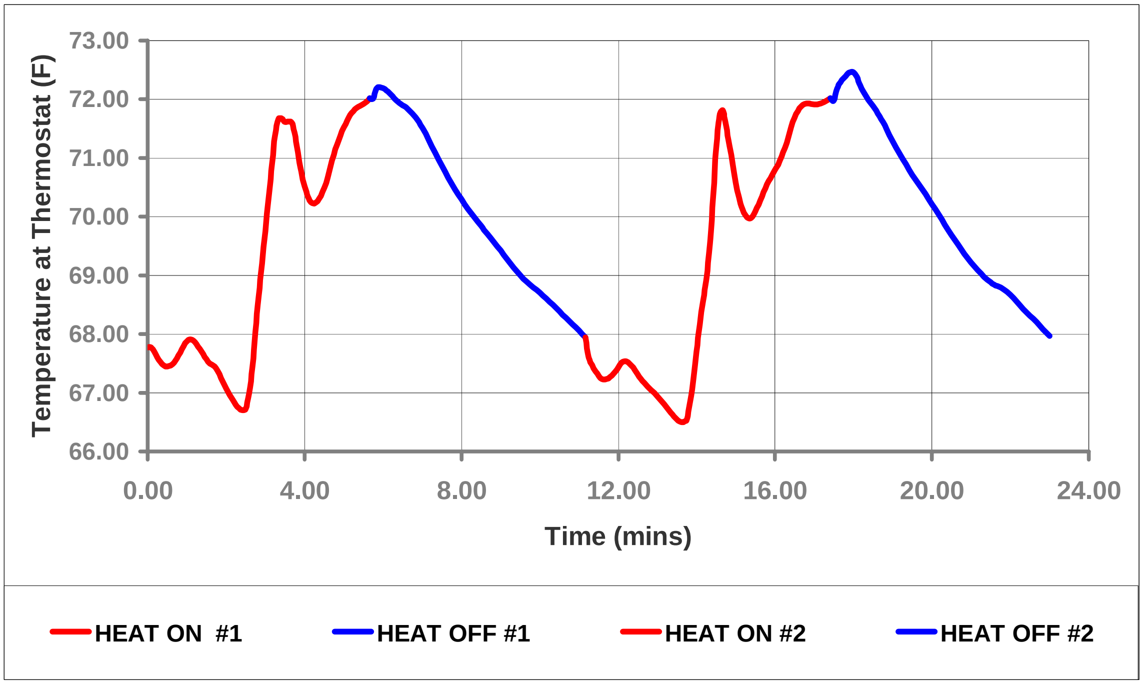


Figure 11: Case 5 --Transient Temperature Variation at Thermostat

CASE 6: Heating, Wall Mounted Registers, Ceiling Return

The register and duct configurations for Case 6 are the same as those for Case 3, shown in **Figure 8**. **Figure 12** shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. Each ON/OFF cycle takes approximately 8.5 minutes for this case. The HVAC ON cycle takes slightly over 4 minutes. Again, note the shape of HEAT ON curve from Case 4 and Case 5.

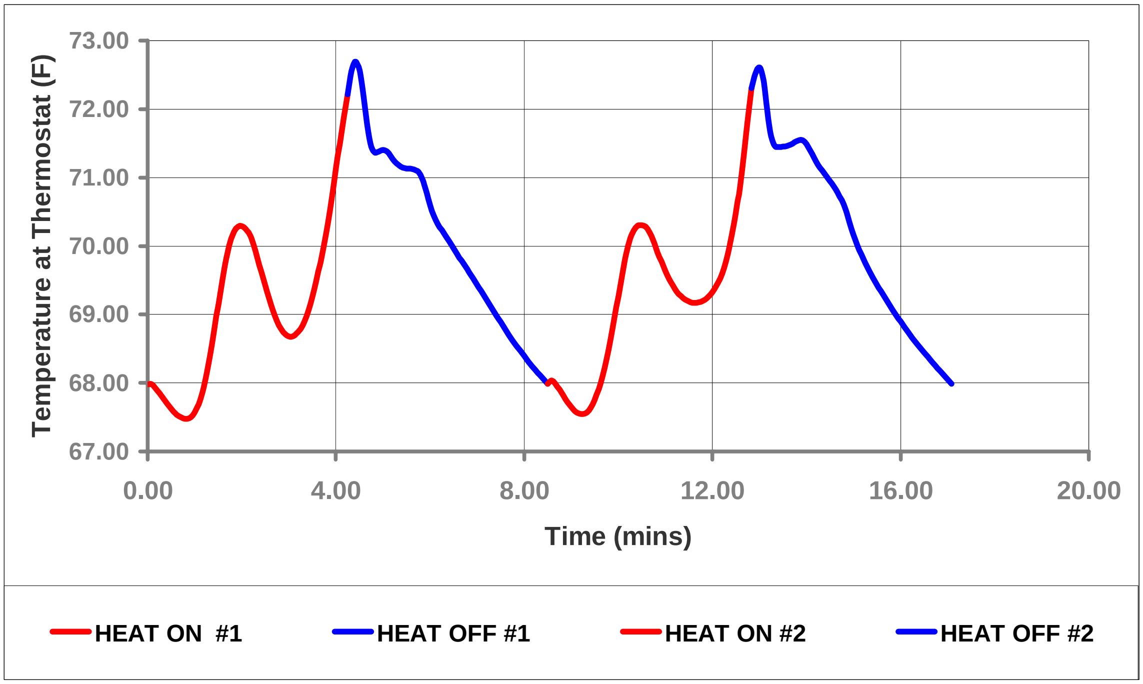


Figure 12: Case 6 --Transient Temperature Variation at Thermostat

CASE 7: Cooling, Ceiling Interior Registers, Low Wall Return

The register and duct configurations for Case 7 (same configuration as Case 1 and Case 4) are shown in **Figure 4**. **Figure 13** shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. The total ON/OFF cycle time is approximately 20 minutes for this case. The HVAC ON cycle is approximately 5 minutes.

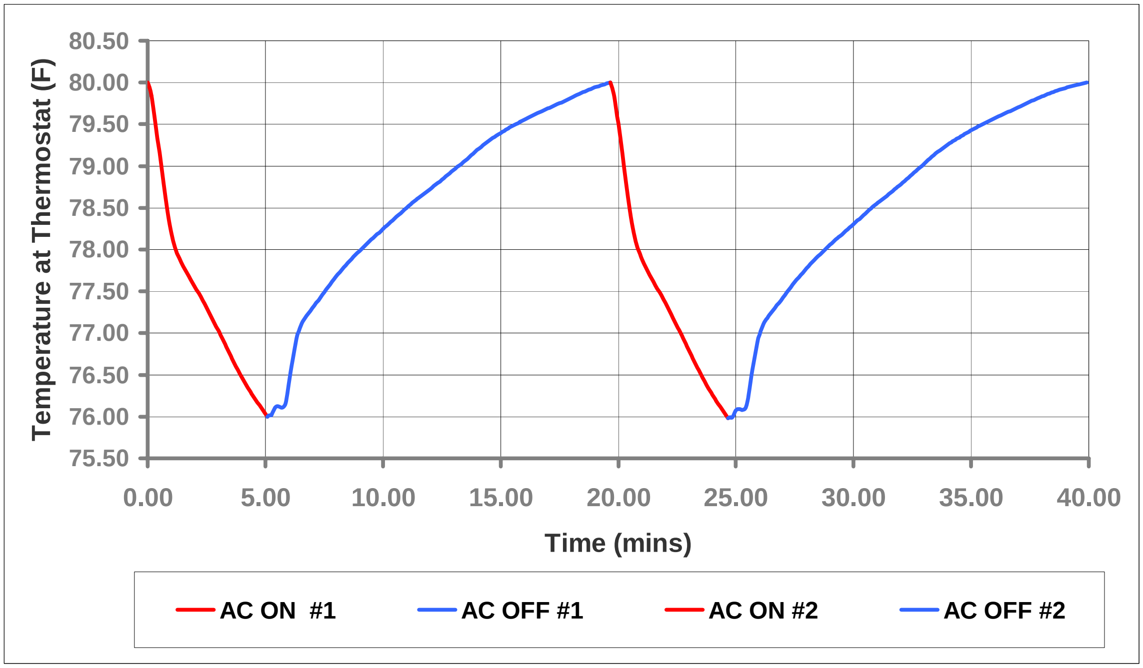


Figure 13: Case 7 --Transient Temperature Variation at Thermostat

CASE 8: Cooling, Ceiling Over Window Registers, Low Wall Return

The register and duct configurations for Case 8 (same configuration as Case 2 and Case 5) are shown in **Figure 6**. **Figure 14** shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. The total ON/OFF cycle time is slightly greater than 20 minutes for this case. The HVAC ON cycle is approximately 6 minutes. Note the duty cycle and curve shape results are very similar to Case 7.

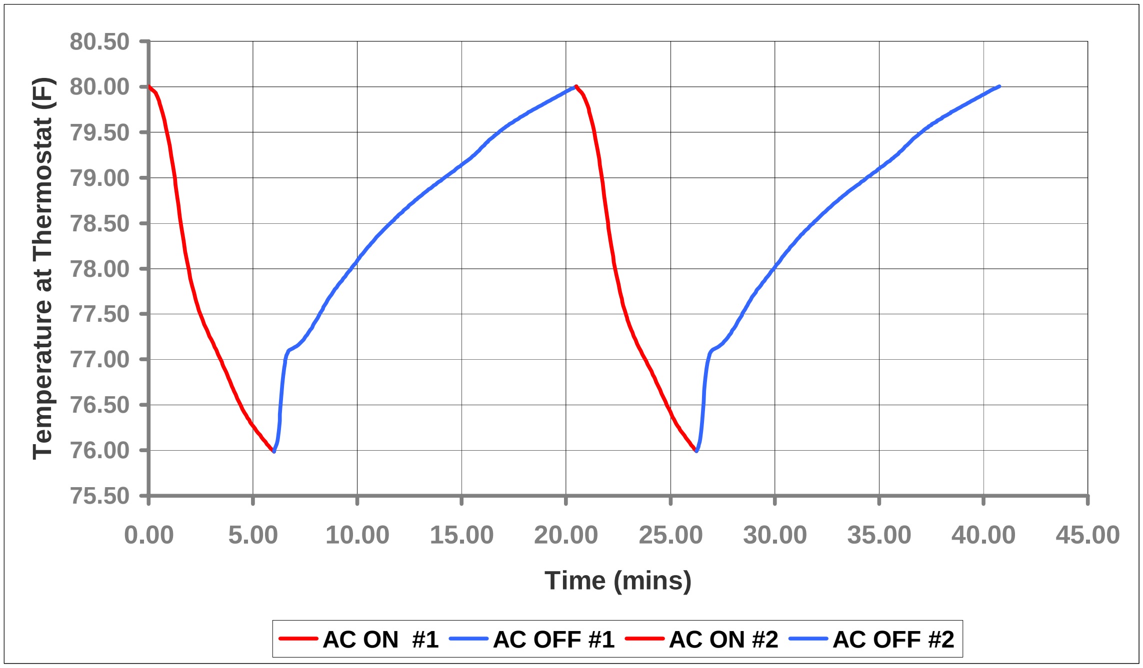


Figure 14: Case 8 --Transient Temperature Variation at Thermostat

CASE 9: Cooling, Wall Mounted Registers, Low Wall Return

The register and duct configurations for Case 9 (same configuration as Case 3 and Case 6) are shown in **Figure 8**. **Figure 15** shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. The total ON/OFF cycle time is slightly greater than 20 minutes for this case. The HVAC ON cycle is approximately 4 minutes. Note the total length of the duty cycle is very similar to Case 7 and Case 8; however, the HVAC ON cycle is noticeably shorter than in Case 7 and Case 8.

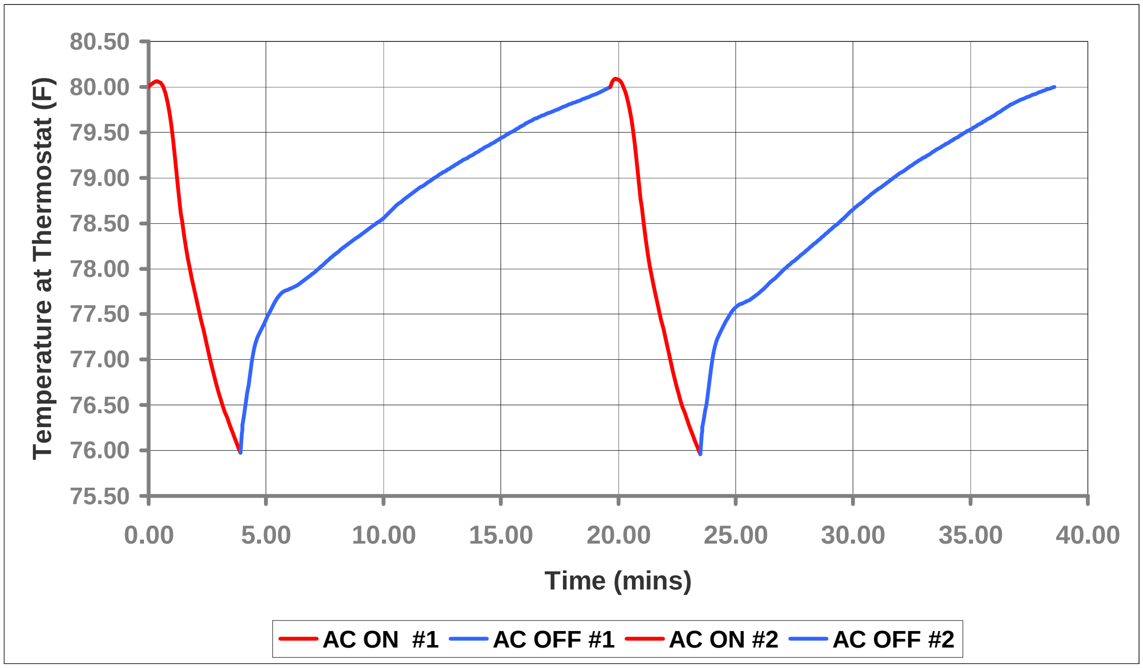


Figure 15: Case 9 --Transient Temperature Variation at Thermostat

CASE 10: Heating, Ceiling Interior Registers, Low Wall Return

The register and duct configurations for Case 10 (same as Case 1, Case 4, and Case 7) are shown in **Figure 4**. The inlet air temperature and flow rates for this case are shown in **Table 6**. **Figure 16** shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. The total ON/OFF cycle takes approximately 14 minutes for this case. The HVAC ON cycle takes approximately 4 minutes.

Inlet air temperatures through registers Ceiling Registers, Center of Ceiling			
Room	Duct Length (feet)	Register flow rate (CFM)	Register Temp (ºF)
Living Room	17	122	98º
Living Room	9	122	102º
Kitchen	15	115	103º
Bedroom 1	16	118	102º
Bedroom 2	8	91	102º
Bath 2	11	31	100º
Bath 1	21	72	101º
Master Bed	21	145	101º

Table 6: Case 10 -- Inlet air temperature and flow rates

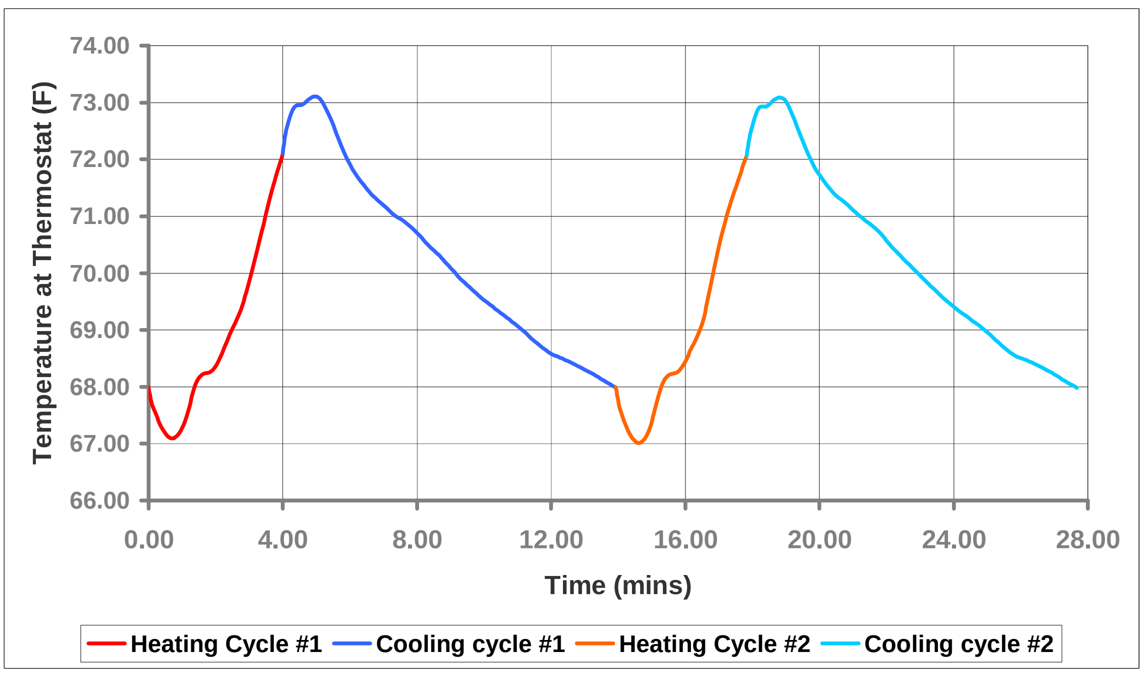


Figure 16: Case 10 --Transient Temperature Variation at Thermostat

CASE 11: Heating, Ceiling Over Window Registers, Low Wall Return

The register and duct configurations for Case 11 (same as Case 2, Case 5, and Case 8) are shown in **Figure 6**. **Figure 17** shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. The total ON/OFF cycle takes approximately 8 minutes for this case. The HVAC ON cycle takes approximately 3 minutes.

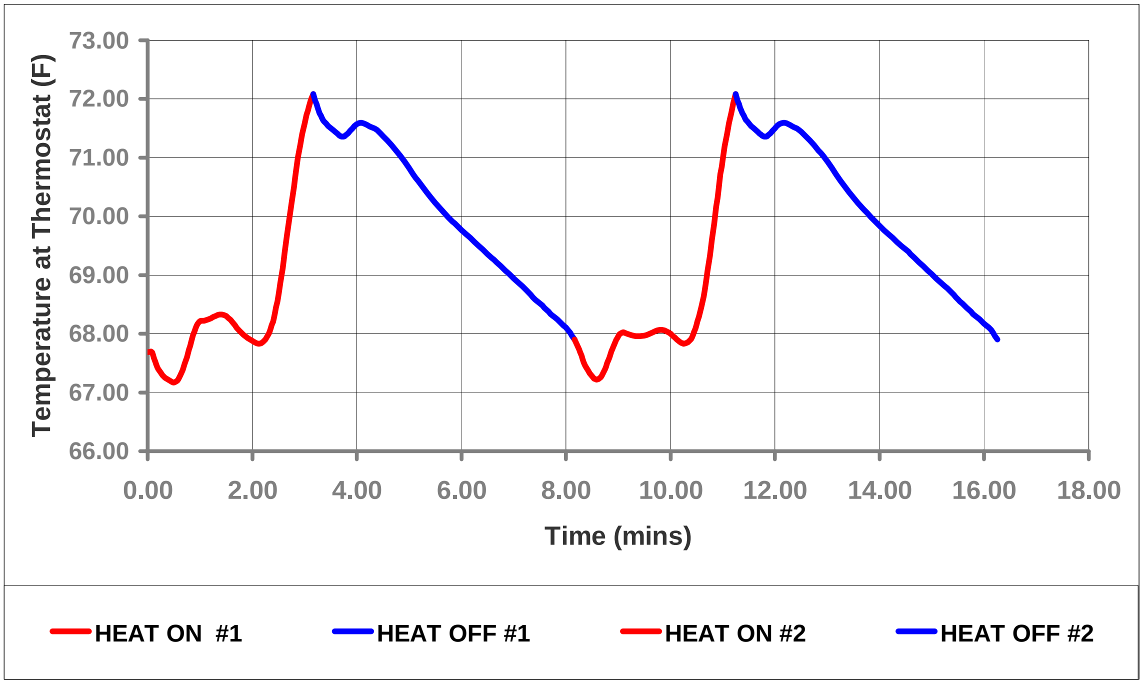


Figure 17: Case 11 --Transient Temperature Variation at Thermostat

CASE 12: Heating, Wall Mounted Registers, Low Wall Return

The register and duct configurations for Case 12 (same as Case 3, Case 6, and Case 9) are shown in **Figure 8**. **Figure 18** shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. The total ON/OFF cycle takes approximately 8 minutes for this case. The HVAC ON cycle takes approximately 3 minutes. Note the curve shape compared to Case 10 and Case 11.

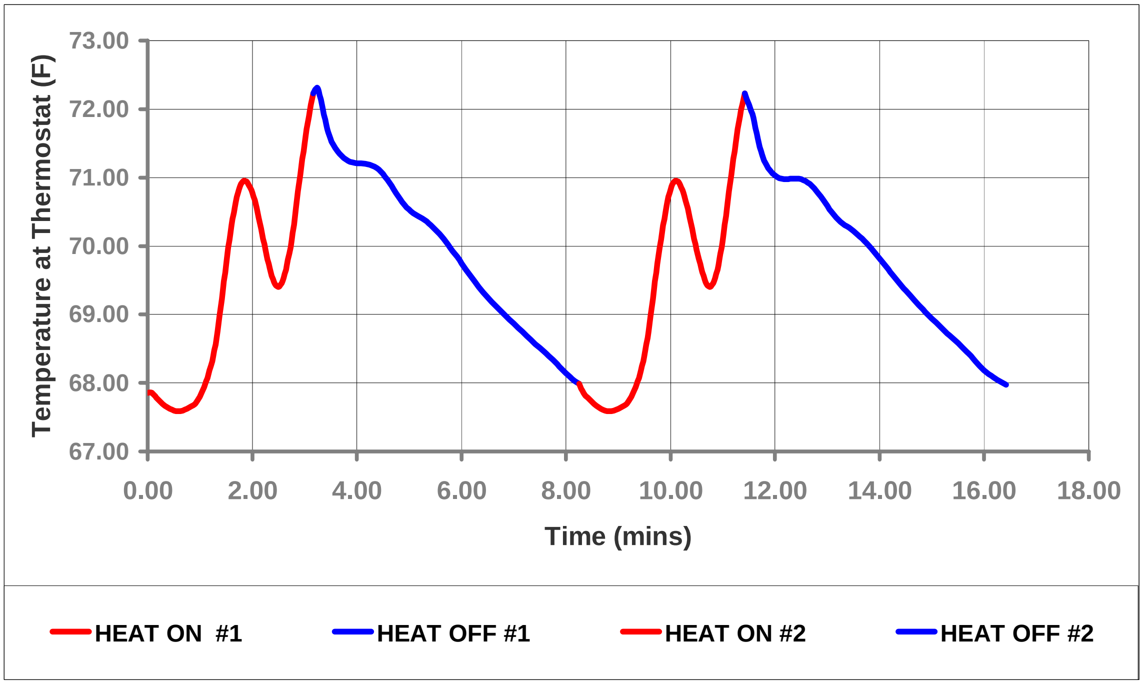


Figure 18: Case 12 --Transient Temperature Variation at Thermostat

One-Story Computed Results

The key results from these analyses were the predictions for transient airflows and temperature distributions within the home. The FAU run-time for each condition was based on reaching a set-point temperature around a thermostat located on the hallway in the house. The FAU was then “turned off” and air temperatures were allowed to drift based on naturally occurring static pressures. Three temperature cycles of the FAU system were performed for each case. Simple system efficiency can be evaluated by observing the FAU run time to achieve set point for the different cases. Differences in run time can argue for selecting a design that minimizes run time to achieve the most comfort.

The CFD results are provided in annotated PowerPoint presentations and include color contour plots and vector plots showing airflow and temperature distribution for all rooms in the house. Three-dimensional animations of human comfort levels over time are provided. The static example in Figure 19 shows a snapshot of the predicted mean vote (PPV), a seven point scale of occupant comfort ranging from +3 (very hot) to –3 (very cold) . Three-dimensional air movement animation “movies” are available as part of the presentations. A static example of airflow is shown in the Figure 20 below. Appendix B contains a description of the various results available for each case. These detail results are available for each case in Appendix B.

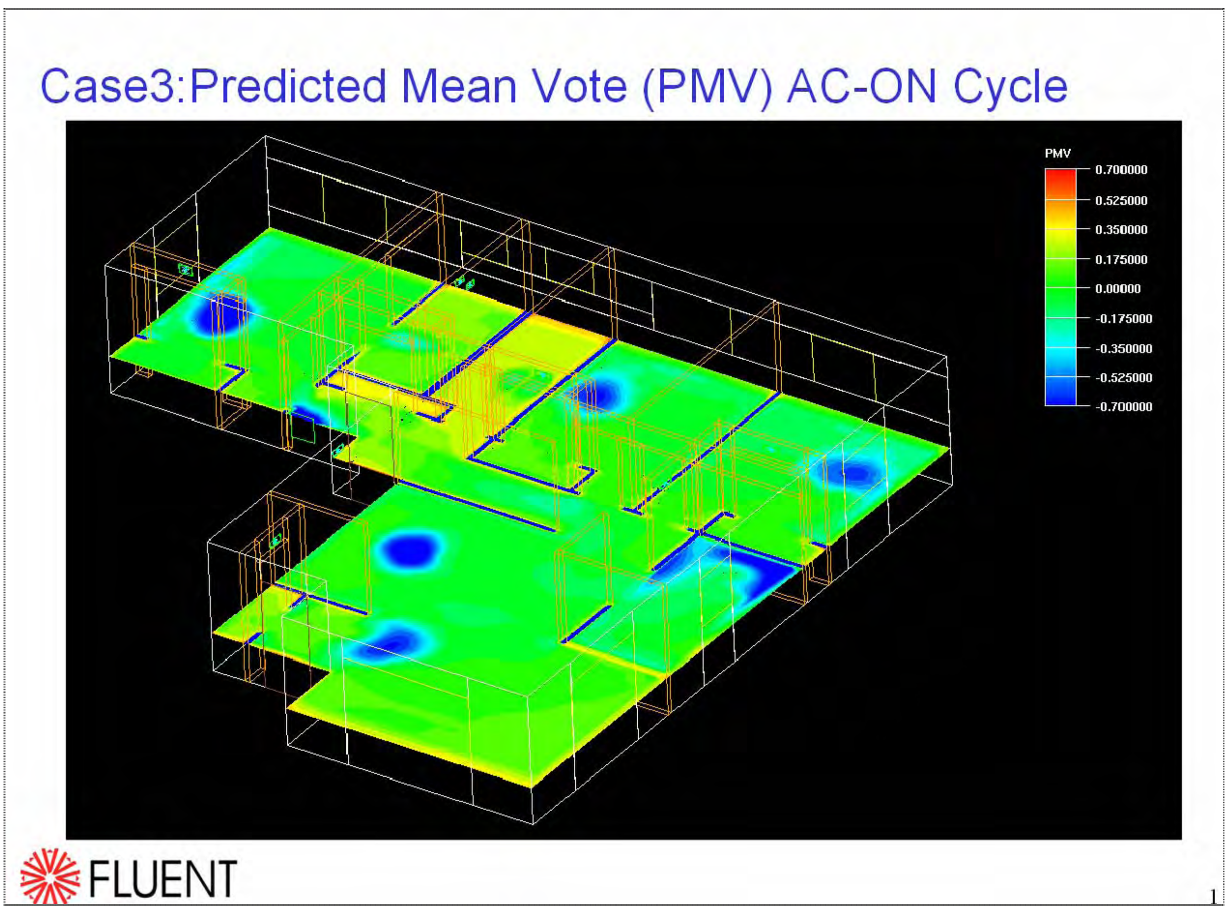


Figure 19: Example of Predicted Mean Vote during the AC ON cycle

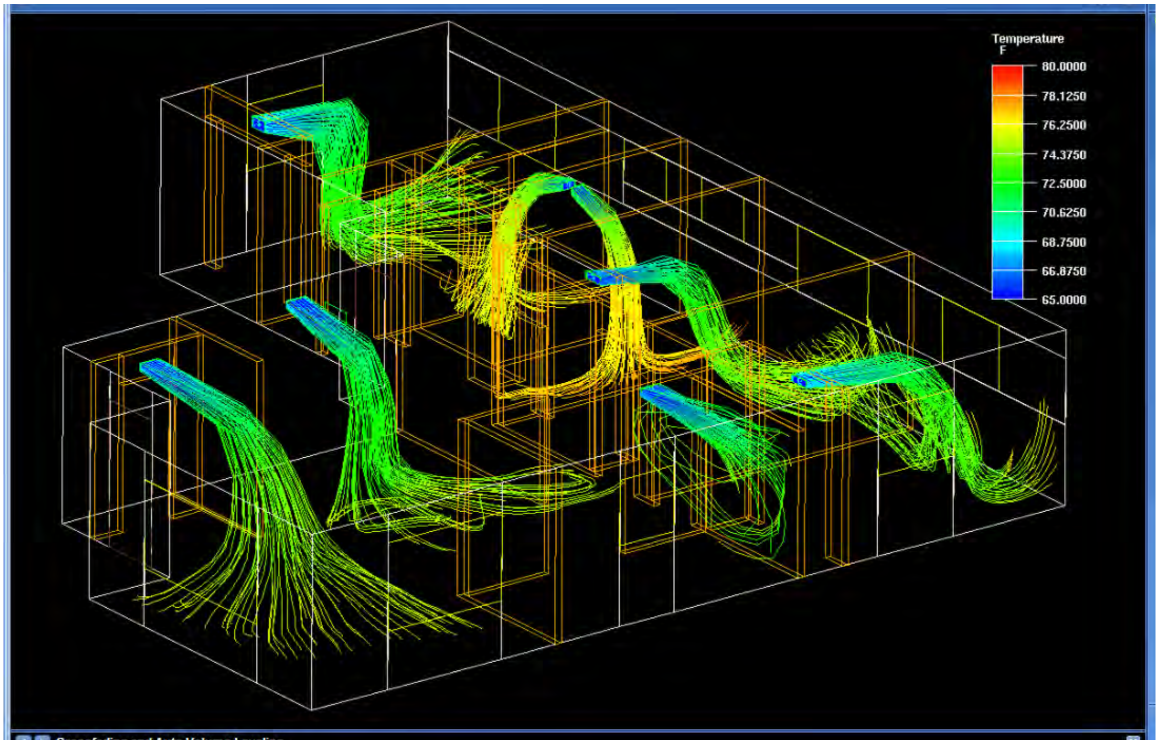


Figure 20: Example airflow animation for Cooling Case in-wall supply register, low-wall return

Improvements in comfort can be predicted by the examining the airflow in the house. The graphic data presented shows calculated flow patterns. Areas of dead or stagnant air are easily visible. The graphics showing temperature gradients in the rooms can also be used to predict comfort. Designs that result in minimal temperature gradients and velocity will be more comfortable. Comparison of the graphics for the different cases can help in the selection of a design that is both comfortable and efficient.

General Observations

The CFD method provided results that appear reasonable and consistent with anecdotal observations. Run times are consistent with real data collected from data loggers in actual homes.

Comfort and quality results, as reported by the model, show no significant benefit from any particular design choice.

Observations

- Airflow patterns indicate that the air temperature and adjacent obstructions such as walls can affect the extent of throws from the registers.
- In the case of registers over the windows, due to the square shape of the registers, the side air streams are wider than the central streams.

- In the case of wall registers, the resulting air jets directly impinge on the most utilized areas of the rooms affecting the thermal comfort of the occupants.

- The predicted temperature distribution during the AC-ON cycle indicates that the most areas of the house are adequately and reasonably uniformly cooled. In all three cases, the bathroom 2 shows consistently higher temperature indicating inadequate cooling.

- The transient animation of 75 F iso-surface indicates, among all three cases, the wall registers are the most appropriate for uniform cooling of the house.

- The prediction of Mean Age of Air indicates that kitchen, bedroom 1, master bedroom and the master bath are adequately ventilated whereas the bathroom2 followed by the living/dining areas are poorly ventilated

- The prediction of Predicted Mean Vote (PMV) indicate that in all the cases, occupants feel slightly “cold” in the kitchen and surrounding area whereas they feel slightly “hot” in the bathroom 2 and surrounding area.

- In the case of wall registers, occupants feel consistently cold directly in the path of the air jets in all the rooms.

- The results of Predicted Percent Dissatisfied (PPD) are consistent with the PMV values.

Assessment

As a first step in assessing the performance of the supply register configurations, the duty cycle (total on/off time for a heating or cooling cycle) were evaluated. The run times for the three supply registers configurations were plotted for cooling with the ceiling return separately from the low-wall return. The same plots were generated for six heating cases. These results are shown in **Figures 21 - 24**.

As these studies progressed, the impact of return location became apparent. So, a second assessment step was performed. The duty cycles for cooling with the in-wall register with the low wall return were plotted against the results for a ceiling return. The same data was plotted for the heating cycle. This provided a simplified comparison of the two return configurations. These results are shown in **Figures 25 -26**.

Cooling

The ceiling return is the most commonly used design in California production home building. In **Figure 21**, the HVAC cycle time and duty cycle are compared for the three cooling cases with a ceiling return. The simulation shows that the in-wall supply registers provided the longest cycle times with the shortest HVAC ON duty cycle. The airflow animations for these cases indicate that the in-wall supply configuration provides the best mixing, which results in good occupant comfort and reduced overall run times.

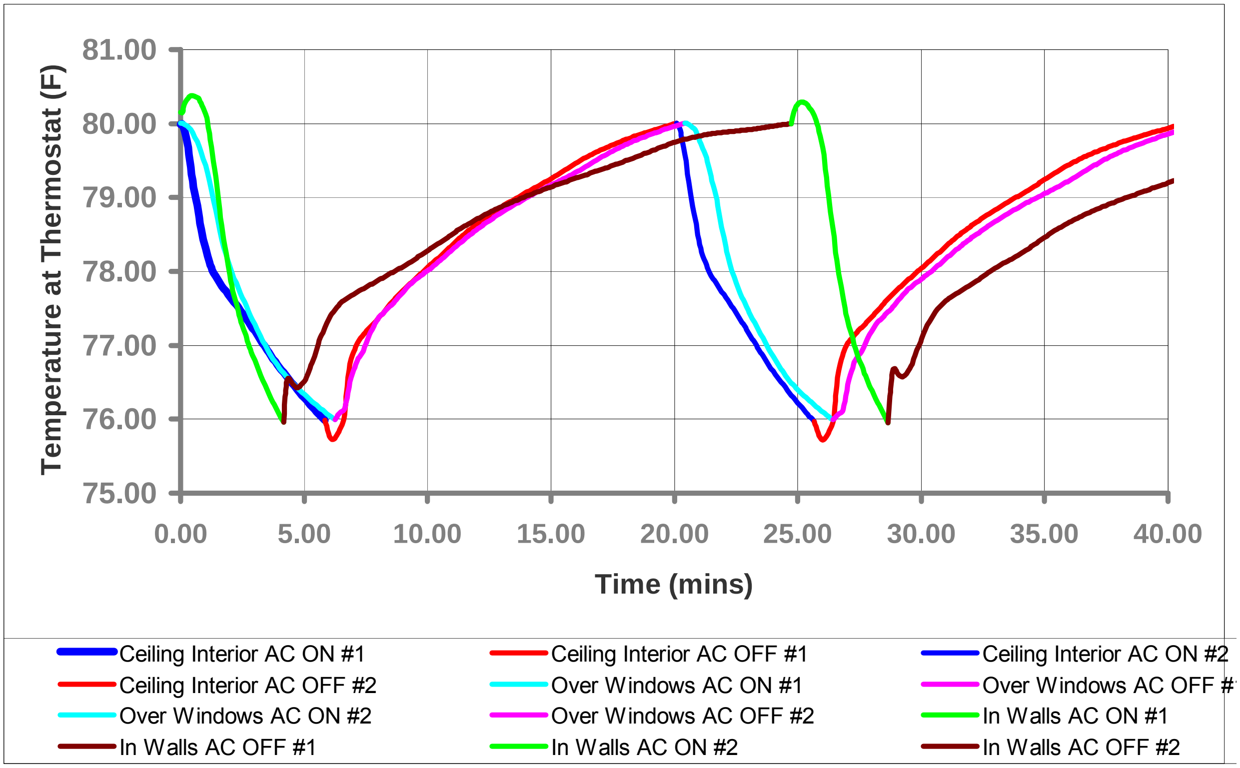


Figure 21: ON/OFF run times for three cooling configurations (Case 1, 2 and 3) Ceiling return, supply register interior ceiling, ceiling over windows, and in-wall

The cooling duty cycles for the three supply register configuration with the low-wall return are compared in **Figure 22**. These simulation results show that the in-wall supply registers provided improved performance, although less dramatic than with the ceiling return. The airflow animations for these cases indicate that the in-wall supply configuration provides good occupant comfort and slightly reduced overall run times.

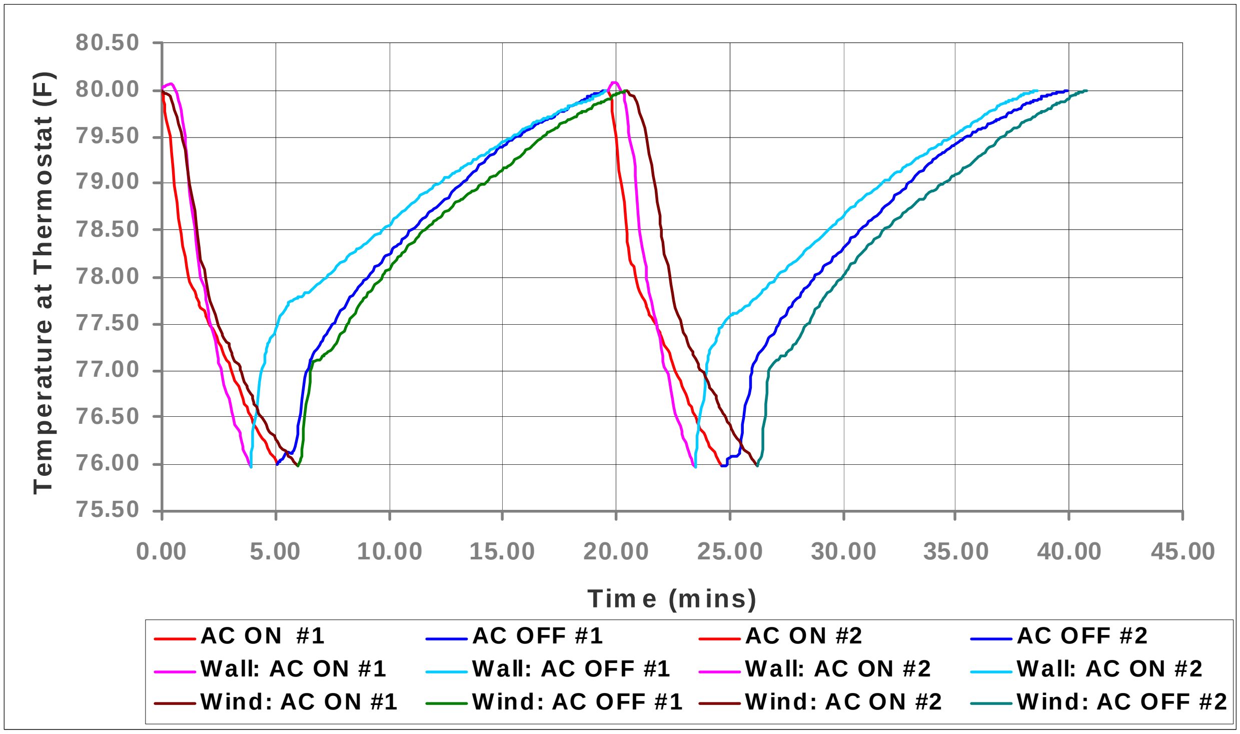


Figure 22: ON/OFF run times for three cooling configurations (Case 7, 8, and 9) Low-wall return, supply register interior ceiling, ceiling over windows, and in-wall

Heating

The heating duty cycles for the three supply register configuration with the ceiling return are compared in **Figure 23**. These simulation results show that both ceiling register applications have similar duty cycles. However, the temperature variations in over-window applications are more erratic. The in-wall application also shows erratic temperature variation and a shorter duty cycle. The air-flow animations for these cases indicate that the ceiling return has a significant impact on the mixing. The warm supply air is drawn quickly to the high return configuration. Based on this comparison, the in-wall supply register application would need to run more frequently. However, the total ON time for all three supply configurations is very close.

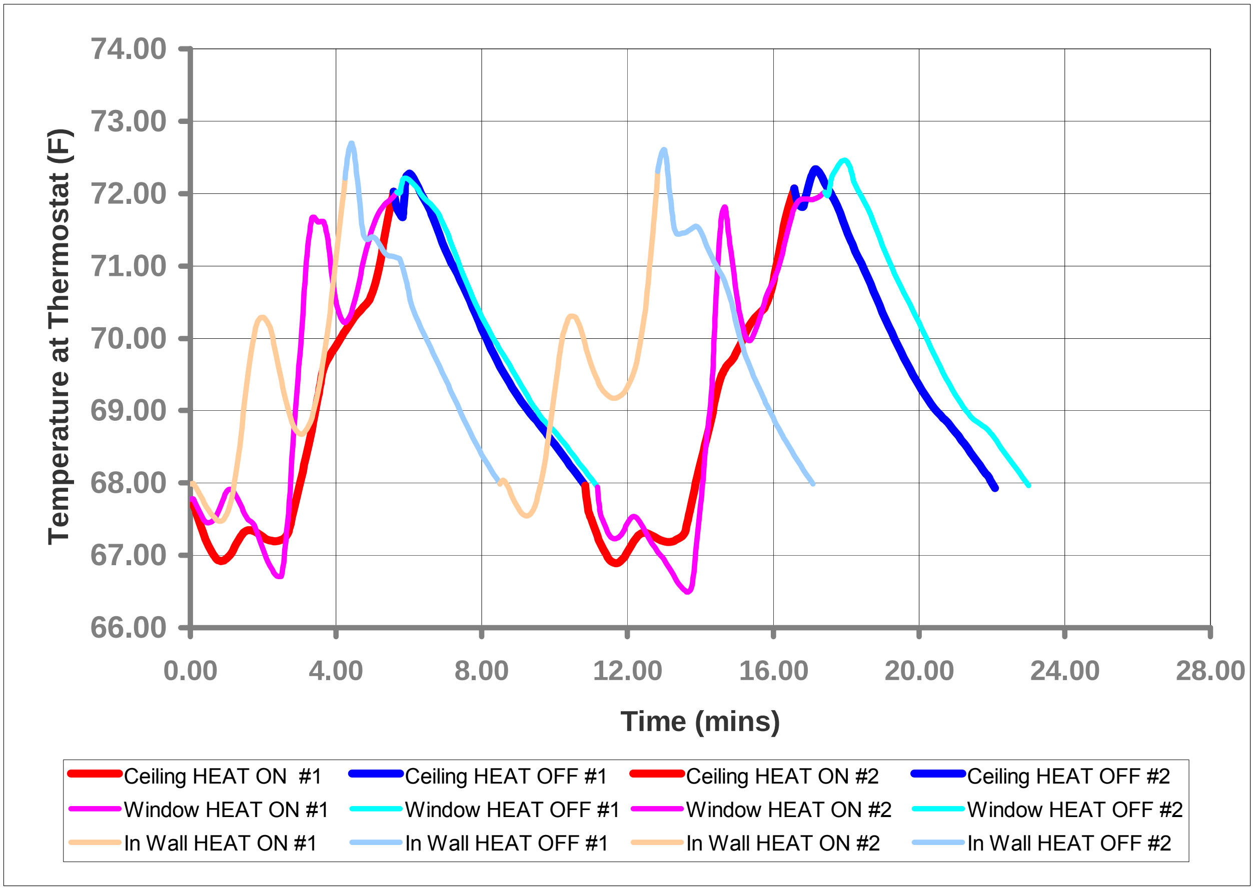


Figure 23: ON/OFF run times for three heating configurations (Case 4, 5, and 6) Ceiling return, supply register interior ceiling, ceiling over windows, and in-wall

The heating duty cycles for the three supply register configuration with the low-wall return are compared in **Figure 24**. These results show the ceiling register application has the longest duty cycle. The over-window and in-wall applications have similar duty cycles and more erratic thermal variations. In these cases, the low-wall return appears to have a very positive impact on the mixing. The warm supply air is allowed to mix before being drawn to the low wall return. Based on this comparison, the in-wall and over-window supply register applications would need to run more frequently. The total ON time for the ceiling supply configuration would run is less than the other two applications.

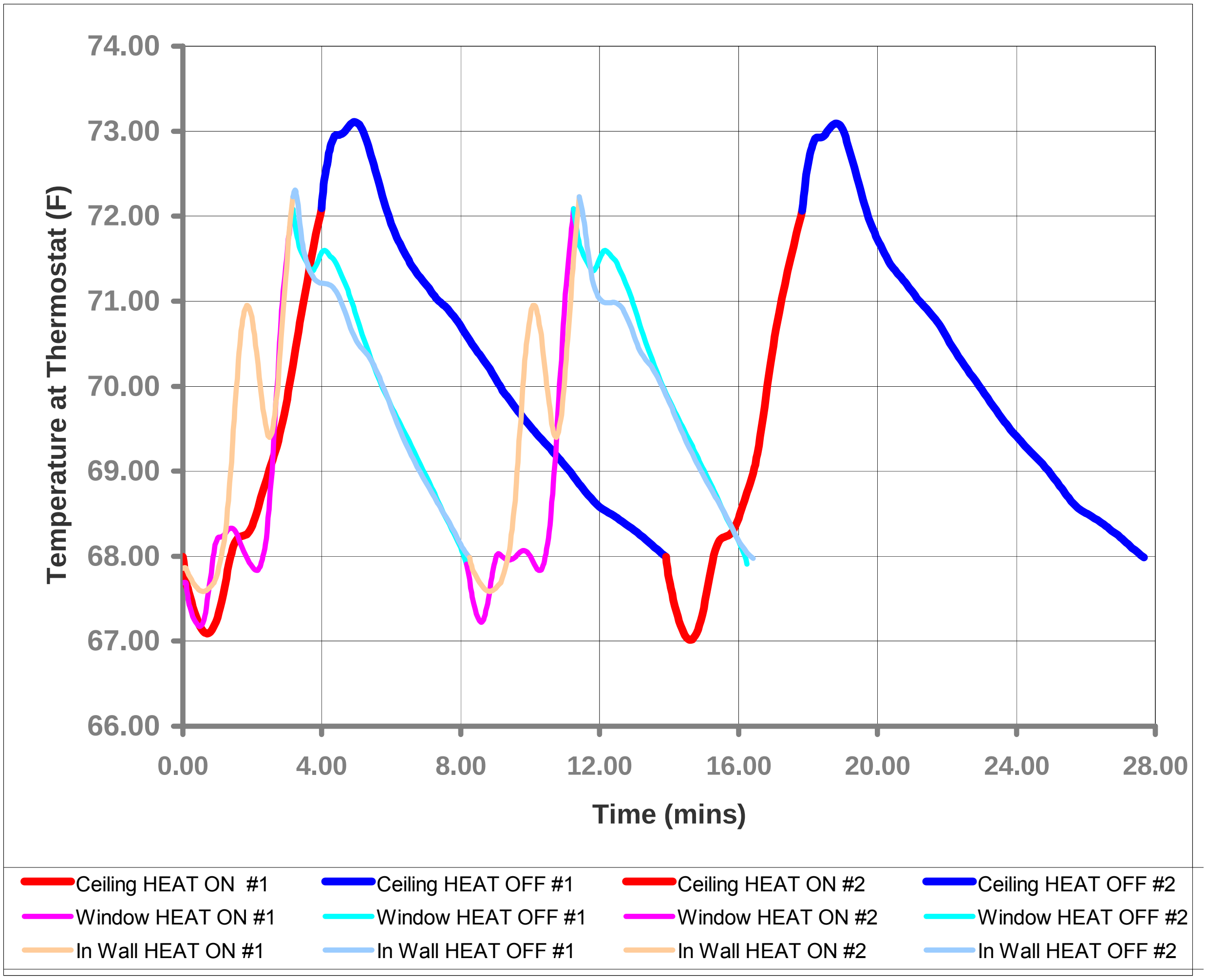


Figure 24: ON/OFF run times for three heating configurations (Case 10, 11, and 12) Low-wall return, supply register interior ceiling, ceiling over windows, and in-wall

Returns

To simplify the assessment of the ceiling vs. low-wall return, only the in-wall supply registers are compared in the **Figures 25** (cooling) and **26** (heating).

Figure 25 shows the impact of the return locations for the in-wall supply in the cooling case. The duty cycle is noticeable longer for the ceiling return. Also note that the transient temperatures seen at the thermostat are relatively smooth. For cooling, the combination of the wall supply and ceiling return provides good mixing as cold air falls and is drawn up to the return.

Figure 26 shows the impact of the ceiling return for the in-wall supply in the heating case. The duty cycle is slightly longer for the ceiling return but the actual HVAC ON time is shorter for the low-wall return. Also note that the transient temperatures seen at the thermostat are erratic for either return, probably due to buoyancy. For heating, the combination of the wall supply and low-wall return provides a slightly more energy efficient design in terms on total on-time. The length of low-wall return duty cycle is very close to the ceiling return duty cycle. However, the percent of ON-time for the low-wall return is smaller, likely due to a better mixing. The HVAC unit would cycle slightly more often with the low-wall design and this study does not consider that impact on the lifetime of the HVAC unit.

Since HVAC system in production homes are not built with both a high and low positioned return system, the designer will need to decide whether heating or cooling takes precedence and design accordingly.

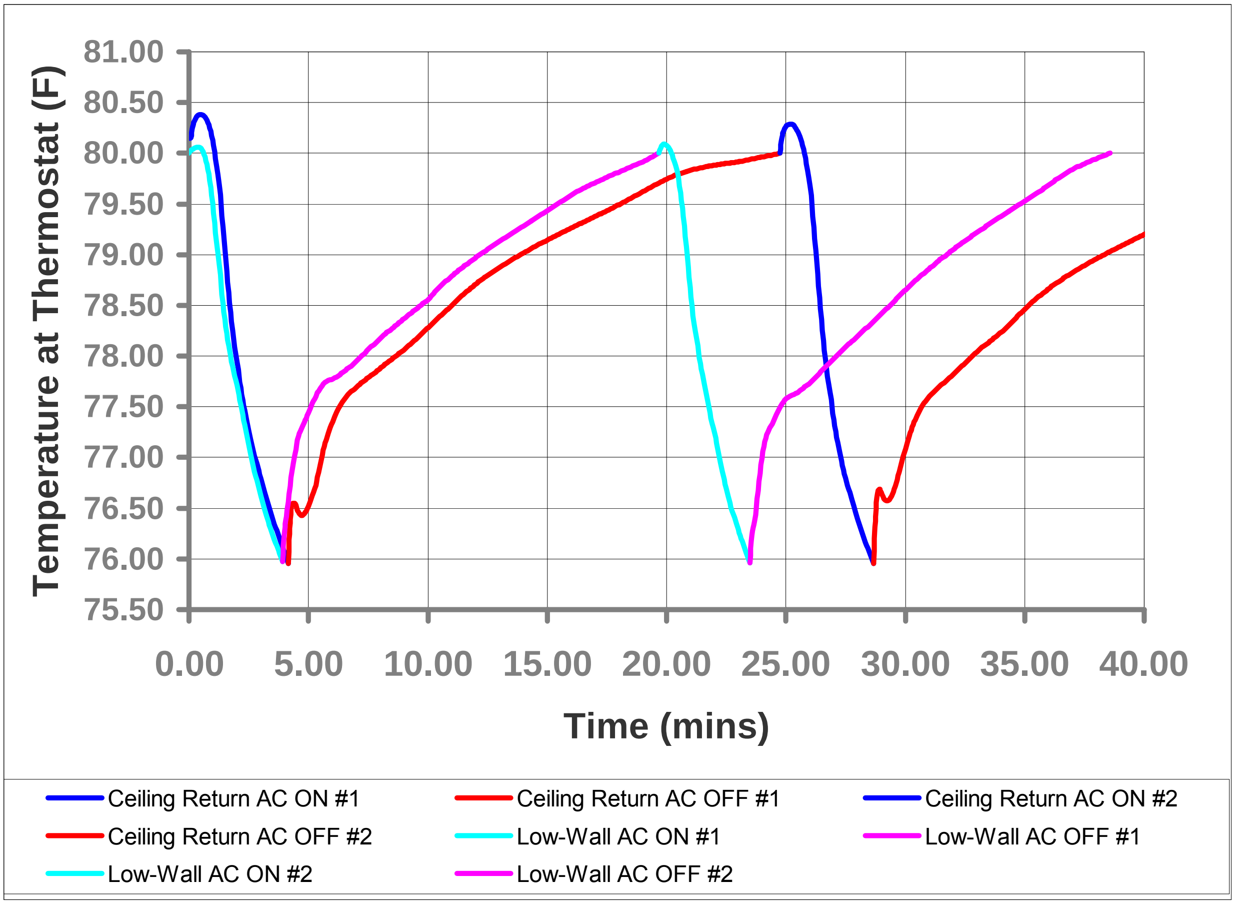


Figure 25: Ceiling Return vs. Low Wall Return for Cooling (in-wall supply registers – Case 3 vs. Case 9)

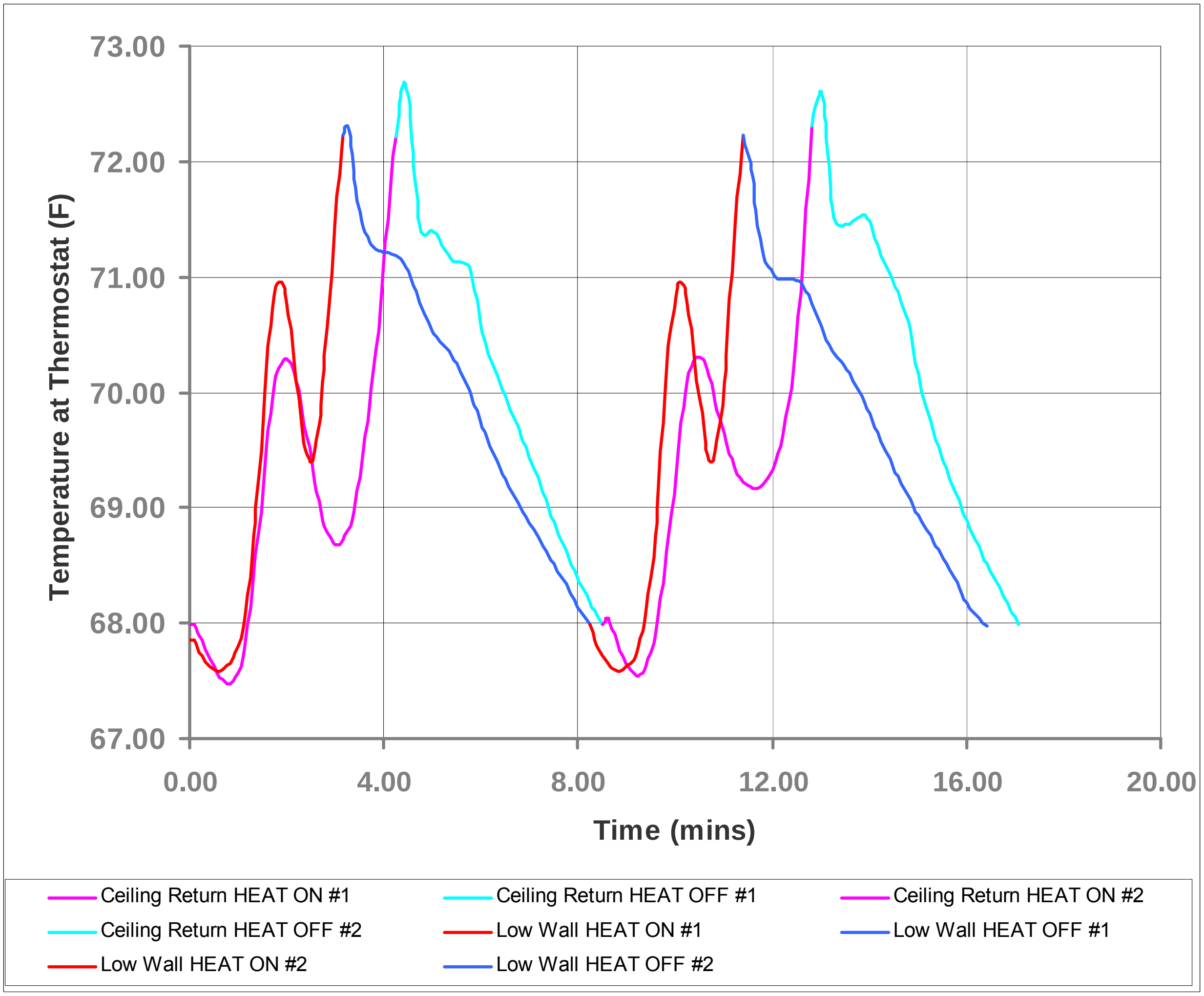


Figure 26: Ceiling Return vs. Low-Wall Return for Heating (in-wall supply registers – Case 6 vs. Case 12)

The table below summarizes the estimated duty cycle parameters based on these simulations. While these are approximate numbers, they provide an additional way of looking at the energy impacts. The "total on-time per hour" provides an estimate of the total number of minutes of ON-time for each case.

		On Time	Off Time	Total Cycle	Cycles/hr	total on-time/hr
Heating Ceiling Return						
	ceiling reg	5.5	5.3	10.8	5.5	30.5
	over window	5.6	5.6	11.2	5.4	30.0
	wall reg	4.3	4.3	8.6	7.0	29.7
Heating Hallway Return						

		On Time	Off Time	Total Cycle	Cycles/hr	total on-time/hr
	ceiling reg	4.1	9.8	13.9	4.3	17.6
	over window	3.2	5.0	8.2	7.3	23.3
	wall reg	3.2	5.1	8.3	7.3	23.1
Cooling Ceiling Return						
	ceiling reg	5.9	14.2	20.1	3.0	17.7
	over window	5.9	14.6	20.5	2.9	17.3
	wall reg	3.9	20.8	24.8	2.4	9.5
Cooling Hallway Return						
	ceiling reg	5.3	14.4	19.7	3.1	16.0
	over window	6.1	14.5	20.6	2.9	17.7
	wall reg	3.9	15.9	19.8	3.0	11.9

Table 7: Summary of HVAC Duty Cycle Data

Conclusion

One of the most common practices in California production home building is to place the supply registers in the ceiling and to locate the return in a hallway ceiling. While cost-effective for the builder, the CFD results show this to be the least energy efficient design, particularly in a cooling dominated climate zone. This practice should be discouraged and one of the alternative methods below should be followed.

In deciding supply register placement, heating versus cooling dominance needs to be considered:

- In a cooling dominant case, the in-wall supply registers with the ceiling return provide the best energy performance, whether the return is in the ceiling or the low-wall. If the ceiling return is used, there is a small positive impact when heating is considered. The low-wall return also provides improved energy performance.

- In a heating dominant situation, the ceiling register with low-wall return provided the best energy performance. Depending on the amount of required cooling, this design can have a negative impact on energy use.

- The ceiling register/wall return is a cost-effective compromise in a situation where heating and cooling needs are balanced.

Cost-benefit of CFD results

The different costs for materials and installations for the different cases with different register locations and/or different FAU locations were estimated. These estimates are based on cost information provided by two HVAC suppliers. These differential costs can be compared to the predicted differences in airflows and comfort for each design to further evaluate the cost-benefits of a particular design.

The design and installation costs for 4 cases along with calculated AC ON time/hr are provided below for comparisons. (Note: Framing cost information is not included and would depend on the application.)

The short-duct run times are from the ceiling return cases. The long-duct run times are from the low-wall return cases. The primary cost differences between short-ducts and long-ducts is the material cost for the length of the duct run and would depend on the application.

In discussion with the HVAC contractors, the most significant cost difference between the wall-mounted register and other applications is for the wall register boot.

Current installation practice in California production homes is to place the registers in the ceiling, centered in the room or over the windows, depending on the shortest duct length, to minimize costs. The “Incremental Cost” shown in the table below is the increased cost over registers in the ceiling, centered in the room.

FAU Location	Register Location	Incremental Cost	Calculated AC ON Time/Hr (seconds)
Attic (Short duct run)	Ceiling-Mounted Registers	Baseline cost	17.7
Attic (Short duct run)	Registers over windows	$3000	17.3
Attic (Short duct run)	Wall-Mounted register	$3400	9.5
Garage (Long duct run)	Ceiling-Mounted Registers	Not costed	16.0
Garage (Long duct run)	Registers over windows	$3400	17.7
Garage (Long duct run)	Wall-Mounted register	$3800	11.9

Table 8: Design and Installation Costs

Summary

Based on this CFD study, the registers-in-walls application provides the most energy efficient installation method with no cost in occupant comfort or air quality. This application provides the most efficient air mixing, reducing the actual time the HVAC unit is turned on.

However, current practice in production homes typically uses the ceiling mounted register to reduce initial duct/register costs. Although the framing costs differences are not included in this analysis, we believe the difference in installation costs can be recaptured in energy savings based on the difference in per cycle HVAC ON time. Better air mixing and longer duty cycles can also extend the equipment life. Most importantly, there is a significant long-term energy savings. If planning for the framing needs is done early in the design cycle and included in the Value Engineering meetings, any cost impacts can be minimized.

Good design practices and proper installation procedures are always encouraged as they can also recapture costs by downsizing the HVAC system.

How the builders can use the results of CFD.

The output products of the CFD can be presented to builders and the implications of the results can be discussed. Builders and their HVAC subcontractors would be able to see register placements that allow shorter duct runs can also provide as good air distribution as typical installations with ducts over the windows. The output products include air velocity vector diagrams, air temperature vector diagrams, and air movement animation. The comfort assessment for the various register placements can also be presented. The graphic nature of the results – especially the three dimensional airflows – may be more useful in presenting the relative merits of the different designs. The results may be easier to relate to actual experience.

HVAC System Design Manual

The information from these analyses has been incorporated into the *California New Construction HVAC Design Guide,* available from the California Energy Commission as Attachment 1 to the Final Report for the Profitability, Quality, and Risk Reduction through Energy Efficiency program. The Guide is also available through the Building Industry Institute (BII) or ConSol. This manual can help in applying an engineered approach to HVAC system design since the design approaches will have an analytical basis.

Further Study

Other program research has indicated consumer and builder interest in dual-zone HVAC systems and their impact on comfort and energy efficiency. Dual zone analyses would provide additional insights for HVAC designers and builders.

Analyses should be performed on common error conditions. This would provide a visual display of the impacts of common errors and practices. For example, what happens when the wrong register type is used, a common field error?

Any methods that help to thermally stabilize the building envelope can have an energy savings impact and this includes air mixing. Further study would be need to understand if better air mixing can lead to system downsizing.

Appendix A

A summary of the analytical model and engineering assumptions used to calculate, compare and contrast FAU locations and register types are available in this appendix.

Heating Case Specifications for AirPak

Modified: KOB, 2002-09-15

Specifications for the Computational Fluid Dynamics Model

Climate Zone 14

Operating Conditions:

Ambient temperature Heating Case): 13 ºF
Initial temperature in the room (Heating): 70 ºF

Inlet air temperatures through registers			
Room	Duct Length (feet)	Register flow rate (CFM)	Register Temp (ºF)
Living Room	17	122	98º
Living Room	9	122	102º
Kitchen	15	115	103º
Bedroom 1	16	118	102º
Bedroom 2	8	91	102º
Bath 2	11	31	100º
Bath 1	21	72	101º
Master Bed	21	145	101º

Thermostat cycle:

When Tstat <= 68 F -> Fan Turns ON -> Remains ON until Tsat reaches 72 F.
When Tsat >= 72 F turns OFF until Tsat <= 68 F

Tsat height above the floor is 5 feet at the locations is as shown in the drawing.

Boundary Conditions

Walls	Thickness (inches)	U value Btu/h.Sq.ft.ºF	Exterior Temperature ºF
Exterior walls with insulation	5.5	0.088	13
Windows Double pane glass	0.75	0.34	13
Entry Doors	1.75	0.33	13
Internal partition walls	as shown in the dwg	0.59	N/A: Temperatures on the either side of the wall will be predicted
Ceiling	12	0.031	13
Floor	4	0.54	60

Properties

Material	Specific Heat (BTU / lb.ºF)	Density (lb/ft)
concrete	0.2	140
gypsum	0.26	50
stucco	0.2	105
solid wood (fir)	0.33	32

Cooling Case Specifications for AirPak

Modified: KOB, 2003-04-18

Specifications for the Computational Fluid Dynamics Model

Climate Zone 14

Operating Conditions:

Ambient Outside temperature: 105 ºF
Initial temperature in the room: 80 ºF

Inlet air temperatures through registers Ceiling Registers, Center of Ceiling, Shoemaker series 203 registers				
Room -	Duct Length (feet)	Duct flow rate (CFM)	Register Temp (ºF)	Register Size (in)
Living Room	17	129	59	10X10
Living Room	9	129	57	10X10
Kitchen	15	120	58	10X10
Bedroom 1	16	125	58	10X10
Bedroom 2	7	95	57	10X10
Bath 2	10	33	59	6X6
M Bath	21	33	63	6X6
Master Bed	21	152	59	12X12

Inlet air temperatures through registers Ceiling Registers, Over Windows, shoemaker Series 203 registers				
Room	Duct Length (feet)	Duct flow rate (CFM)	Register Temp (ºF)	Register Size (in)
Living Room	23	129	60	10X10
Living Room	9	129	57	10X10
Kitchen	13	120	58	10X10
Bedroom 1	24	125	60	10X10
Bedroom 2	18	95	59	10X10
Bath 2	12	33	59	6X6
M Bath	21	33	63	6X6
Master Bed	28	152	61	12X12

Room	Duct Length (feet)	Duct flow rate (CFM)	Register Temp (ºF)	Register Size (in)
Living Room	14	129	58	12X4
Living Room	8	129	57	12X4
Kitchen	15	120	58	12X4
Bedroom 1	19	125	59	12X4
Bedroom 2	6	95	56	12X4
Bath 2	19	33	63	8X4
M Bath	19	33	63	8X4
Master Bed	23	152	59	10X6

Thermostat cycle :

When Tstat >= 80 F -> Fan Turns ON -> Remains ON until Tsat reaches 76 F.
When Tsat <= 76 F turns OFF until Tsat >= 80 F

Tsat height above the floor is 5 feet at the location as shown in the drawing

Boundary Conditions

Walls	Thickness in inches	U value Btu/h.Sq.ft.ºF	Exterior Temperature ºF
Exterior walls with insulation	5.5	0.088	105
Windows Double pane glass	0.75	0.34	105
Entry Doors	1.75	0.33	105
Internal partition walls	as shown in the dwg	0.59	N/A : Temperatures on the either side of the wall will be predicted
Ceiling	12	0.031	105
Floor	4	0.54	78

Properties

Material	Specific Heat (BTU / lb.ºF)	Density (lb/ft)
concrete	0.2	140
gypsum	0.26	50
stucco	0.2	105
solid wood (fir)	0.33	32

Summary of CFD Data Set

Project:	Habitat for Humanity
Location:	Palmdale CA
Climate Zone:	14
Heating db °F	13
Cooling db °F	101

Opaque Surfaces

Surface	Area Sq. Ft.	Orientation	Thickness	Solar Gains	Insulation R-value	U-Value	Location
wall	143	Vert	5.5"	Yes	13	0.088	Front Wall
wall	145	Vert	5.5"	Yes	13	0.088	Left Wall
wall	297	Vert	5.5"	Yes	13	0.088	Back Wall
wall	277	Vert	5.5"	Yes	13	0.088	Right Wall
wall	304	Vert	5.5"	No	13	0.088	Garage wall
Entry Door	20	Vert	1.75"	Yes	0	0.330	Entry Door
Garage Door	20	Vert	1.75"	No	0	0.330	Garage Door
Ceiling	1275	Horiz	12"	Yes	30	0.031	Flat w/attic

Floor

Surface	U-Value
Concrete slab on grade	0.980
Temperature.	60 degrees F

Interior Walls

	Thickness (in)	U-Value
2X4 stud walls, gypsum board	4.5	0.594

Glazing Surfaces

Type	Area Sq. Ft.	Orientation	Thickness	U-Value	Location
Casement	32.0	Vert	0.75"	0.340	Front Wall
Double Hung	14.4	Vert	0.75"	0.340	Left Wall
Double Hung	14.4	Vert	0.75"	0.340	Back Wall
Awning	6.0	Vert	0.75"	0.340	Back Wall
Awning	6.0	Vert	0.75"	0.340	Back Wall
Casement	16.8	Vert	0.75"	0.340	Back Wall
Double Hung	14.4	Vert	0.75"	0.340	Back Wall
Double Hung	14.4	Vert	0.75"	0.340	Right Wall
Double Hung	9.0	Vert	0.75"	0.340	Right Wall
Double Hung	24.0	Vert	0.75"	0.340	Right Wall

Cooling Cases

(This data is also contained in file ConSol_Specifications_for_Fluent_V2')

- Air Velocity = Air Flow Rate/Effective Area
- Duct Air Flow Rate from the Right J report
- Register Effective Area from the Shoemaker Residential Catalog, Engineering Data for 200 series registers.
- Register Output Velocity from Right Suite Duct System Summary. We assume the velocity is approximate constant from the duct to the register. The CFM out of the register is dependent on the design of the register.
- Register Temp from the spreadsheet Duct Loses

Velocities/Temperatures out of Registers---Ceiling Registers, center of ceiling

Room	Duct Length (ft)	Duct Air Flow Rate (CFM)	Register Size (in)	Register Effective Area(ft^2)	Register Output Velocity (approx.)	Register Type & Throw (3 way)	Register Temp (ºF)
Living Room	17	129	10X10	0.241	482	203	59
Living Room	9	129	10X10	0.241	482	203	57
Kitchen	15	120	10X10	0.241	447	203	58
Bedroom 1	16	125	10X10	0.241	467	203	58
Bedroom 2	7	95	10X10	0.241	357	203	57
Bath 2	10	33	6X6	0.084	373	203	59
Master Bath	21	33	6X6	0.084	373	203	63
Master Bed	21	152	12X12	0.349	437	203	59

Velocities/Temperatures out of Registers---Ceiling Registers, over the windows

Room	Duct Length (ft)	Duct Air Flow Rate (CFM)	Register Size (in)	Register Effective Area (ft^2)	Register Output Velocity (approx.)	Register Type & Throw (3 way)	Register Temp (ºF)
Living Room	23	129	10X10	0.241	482	203	60
Living Room	9	129	10X10	0.241	482	203	57
Kitchen	13	120	10X10	0.241	447	203	58
Bedroom 1	24	125	10X10	0.241	467	203	60
Bedroom 2	18	95	10X10	0.241	357	203	59
Bath 2	12	33	6X6	0.084	373	203	59
Master Bath	21	33	6X6	0.084	373	203	63
Master Bed	28	152	12X12	0.349	437	203	61

Velocities/Temperatures out of Registers---Registers in the walls

Room	Duct Length (ft)	Duct Air Flow Rate (CFM)	Register Size (in)	Register Effective Area (ft^2)	Register Output Velocity (approx.)	Register Type & Throw (3 way)	Register Temp (ºF)
Living Room	14	129	12X4	0.241	482	950	58
Living Room	8	129	12X4	0.241	482	950	57
Kitchen	15	120	12X4	0.241	447	950	58
Bedroom 1	19	125	12X4	0.241	467	950	59
Bedroom 2	6	95	12X4	0.241	357	950	56
Bath 2	19	33	8X4	0.155	373	950	63
Master Bath	19	33	8X4	0.155	373	950	63
Master Bed	23	152	10X6	0.313	437	950	59

Interior Walls

From ACCA Manual J rev 8, "Residential Load Calculation", Appendix 5, figure A5-1

Frame Wall construction, Construction Number 12. For interior 2X4 partition walls with gypsum board and no insulation.

For 2X4 wood studs	
$U_{effective}$	0.594463
$U_{parallel}$	0.893046
ACR	1.119763
$U_{isotherm}$	0.295879
Cavity_R_value	0.91
_2X4_Stud_R_Value	3.63
Gypsum_Board_R_Value	0.45
Air_film_R_Value	0.68

ACR = Average Cavity R-Value

Cavity_R_value = From Cavity Insulation column. No insulation in cavity

Shoemaker Registers

200 Series

Size	Velocity	300	400	500	600	700	800	900	1000
Effective Area	**Duct Pt**	**0.006**	**0.01**	**0.015**	**0.021**	**0.029**	**0.038**	**0.048**	**0.065**
10X4	**CFM**	29	38	0	57	67	76	86	95
0.093 ft^2	**Throw 203**	2.5/3/3.5	3.5/4/4.5	4.5/5/5.5	5.5/6/6.5	6/7/8.0	7/8/9.0	6.5/8/9.5	7/9/11.0
	NC	<20	20	25	25	30	35	35	40
10X6	**CFM**	43	58	72	81	100	114	129	144
0.143 ft^2	**Throw 203**	2.5/3/3.5	3.5/4/4.5	3.5/4/4.5	4.5/5/6	6/7/8.0	6/7/8.0	7/9/11.0	7/9/11.0
	NC	<20	20	25	25	30	35	40	40
12X6	**CFM**	54	68	87	101	119	140	154	172
0.17 ft^2	**Throw 203**	3.5/4/4.5	4.5/5/5.5	6.5/7/7.5	6/7/8.0	7/8/9.0	7.5/9/10.5	8/10/12.0	9.5/12/14.5
	NC	<20	20	25	30	30	35	40	45
14X6	**CFM**	62	82	101	119	139	163	182	200
0.2 ft^2	**Throw 203**	3.5/4/4.5	4.5/5/5.5	5.5/6/6.5	6/7/8.0	7/8/9.0	7.5/9/10.5	8/10/12.0	9.5/12/14.5
	NC	<20	20	25	30	35	40	45	45

Size: Nominal size or the duct opening

Effective Area: The space between the vanes actually utilized by the air

Velocity: The actual velocity of the air though the vanes measured with a velometer or similar device

Duct Pt: The total pressure behind the register in the duct forcing that air through the register.

Throw: The throws noted in the tables are the distance from the register to where the air stream velocity has dropped to not under 100/75/50 FPM.

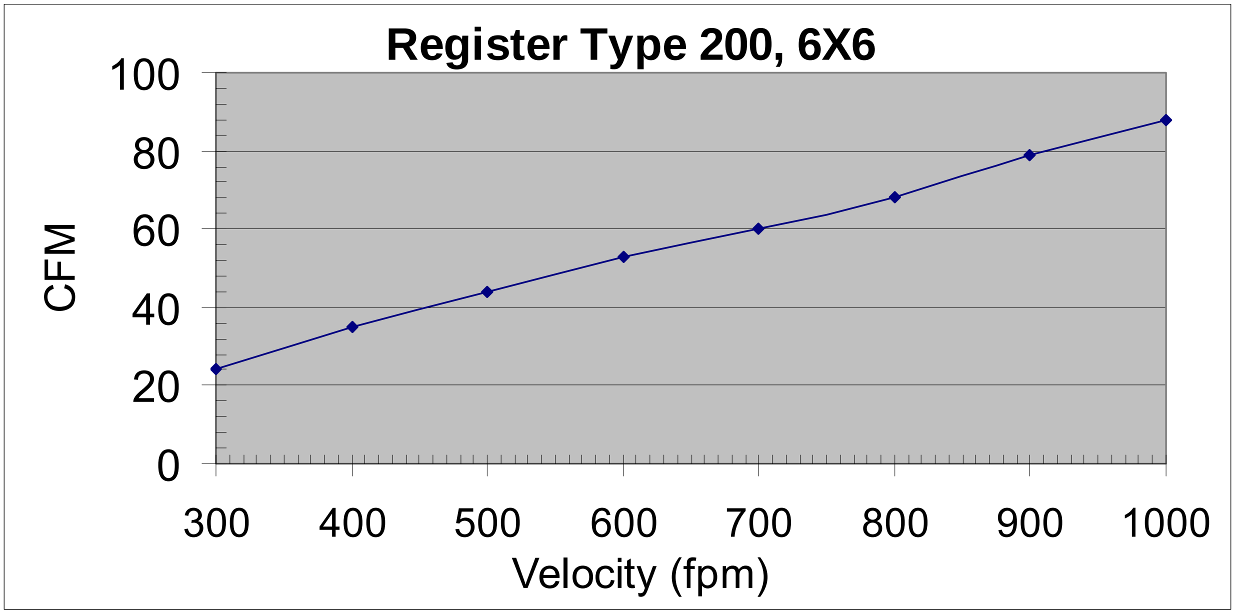
203: A register that directs the air in three directions

Noise Criteria (NC): 25 = broadcast studios, face velocity = 500 FPM

25-30 = residences, face velocity = 500 to 750 FPM

Note: all data taken from Shoemaker Engineering Data

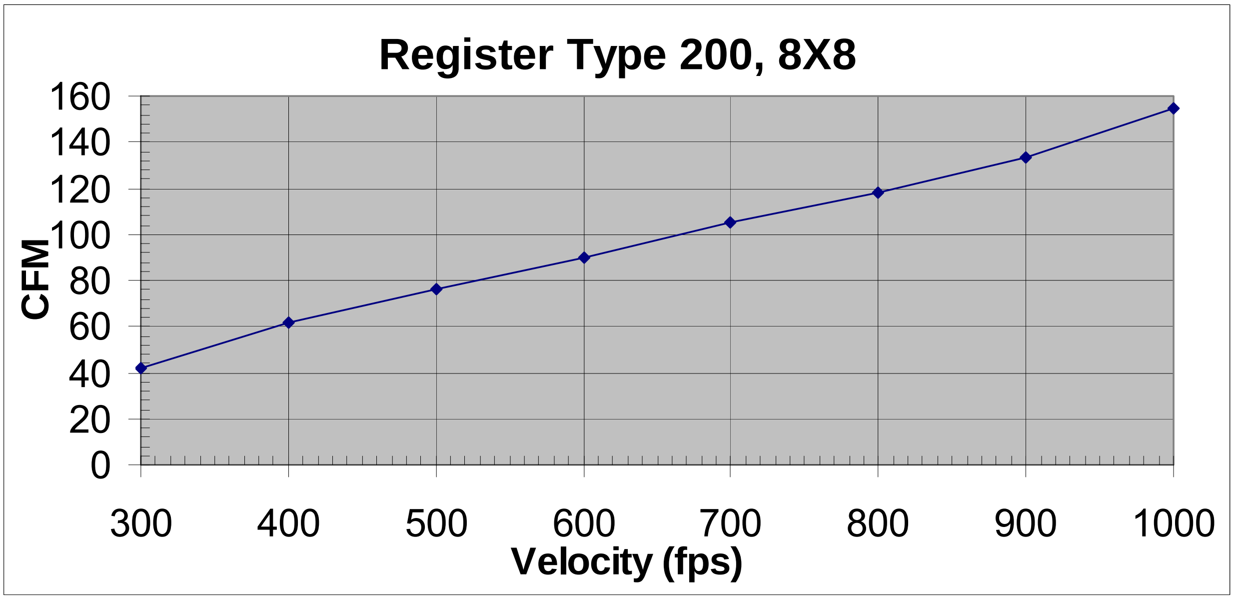
Type: 200 **Size: 6X6** **Effective Area: .084**								
Register Velocity	300	400	500	600	700	800	900	1000
Register CFM	24	35	44	53	60	68	79	88



Type: 200
Size: 8X8

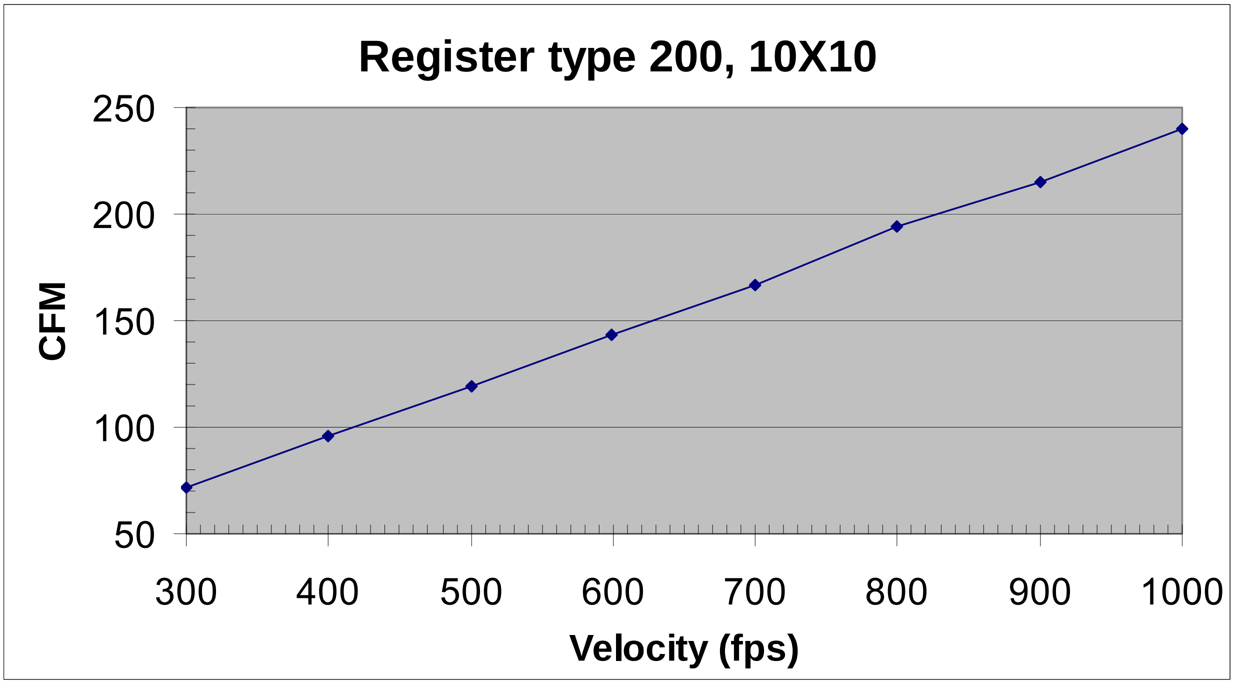
Effective Area: 0.151

Register Velocity	300	400	500	600	700	800	900	1000
Register CFM	42	62	76	90	105	118	133	155

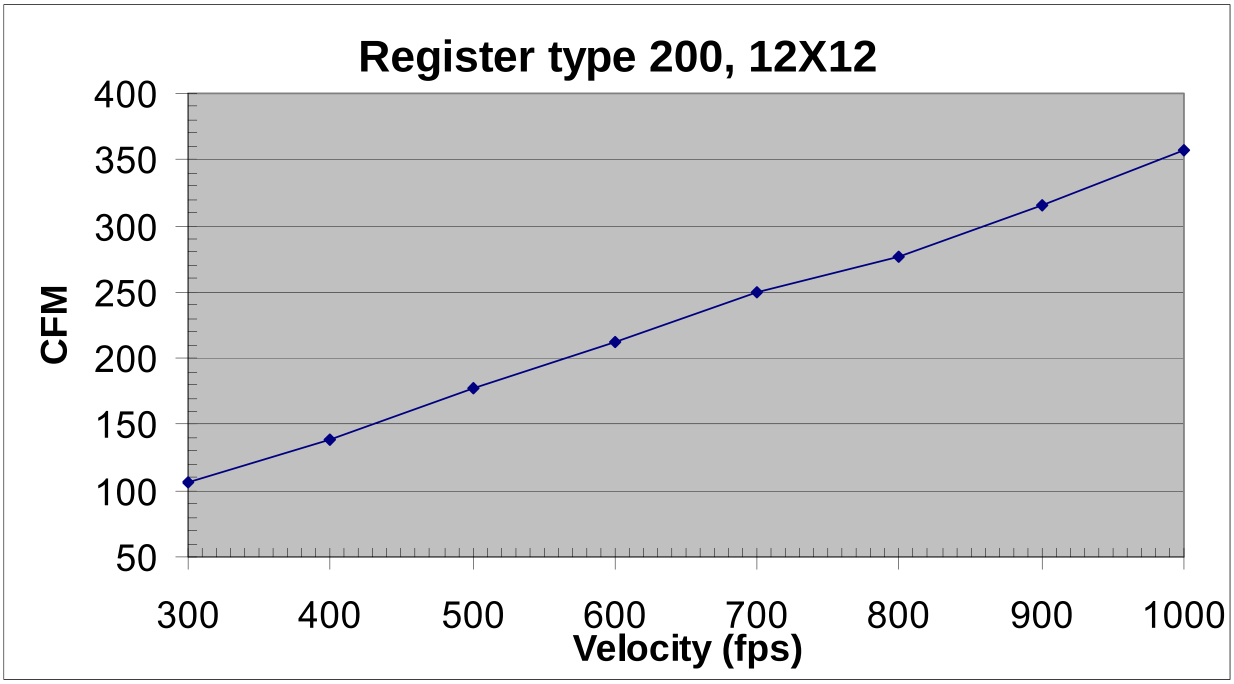


Type: 200
Size: 10X10
Effective Area: 0.241

Register Velocity	300	400	500	599	700	800	900	1000
Register CFM	72	96	119	143	167	194	215	240



Type: 200 Size: 12X12 Effective Area: 0.349								
Register Velocity	300	400	500	600	700	800	900	1000
Register CFM	106	139	177	212	250	276	316	357



950 Series

Size	Velocity	400	500	600	700	800	1000
Effective Area	**Duct Pt**	**0.011**	**0.017**	**0.024**	**0.034**	**0.044**	**0.055**
8X4	**CFM**	67	90	106	123	140	168
0.155 ft^2	**Throw**	5.5/6/6.5	7/8/9.0	8.5/10/11.5	10/12/14	11/13/15	13.5/17/20
	NC	20	25	30	30	30	35
10X4	**CFM**	90	112	134	157	179	224
0.198 ft^2	**Throw**	7/8/9.0	9/10/11	10/12/14	11/13/15	13.5/16/18	15/19/23
	NC	20	25	30	30	30	35
10X6	**CFM**	140	174	213	246	280	353
0.313 ft^2	**Throw**	8/9/10.0	11/12/13.0	13/15/17	14.5/17/20	17/20/23	20/25/30
	NC	20	25	30	30	30	35
12X6	**CFM**	168	213	213	297	342	426
0.380 ft^2	**Throw**	9/10/11	11.5/13/14.5	13.5/16/18	15.5/18/21	17/21/24	22/27/32
	NC	20	25	30	30	30	35
14X6	**CFM**	202	252	302	347	398	498
0.446 ft^2	**Throw**	10/11/12.0	13.5/15/17	15.5/18/21	17/20/23	20/24/28	24/30/36
	NC	20	25	30	30	30	35

Where,

Duct Pt is the total pressure behind the register in the duct forcing that air through the register

Throw is the distance from the register to where the air stream velocity has dropped to not under 75FPM.

NC is the noise criteria

Size: Nominal size or the duct opening

Effective Area: The space between the vanes actually utilized by the air

Velocity: The actual velocity of the air though the vanes measured with a velometer or similar device

Duct Pt: The total pressure behind the register in the duct forcing that air through the register.

Throw: The throws noted in the tables are the distance from the register to where the air stream velocity has dropped to not under 100/75/50 FPM.

Noise Criteria (NC): 25 = broadcast studios, face velocity = 500 FPM

25-30 = residences, face velocity = 500 to 750 FPM

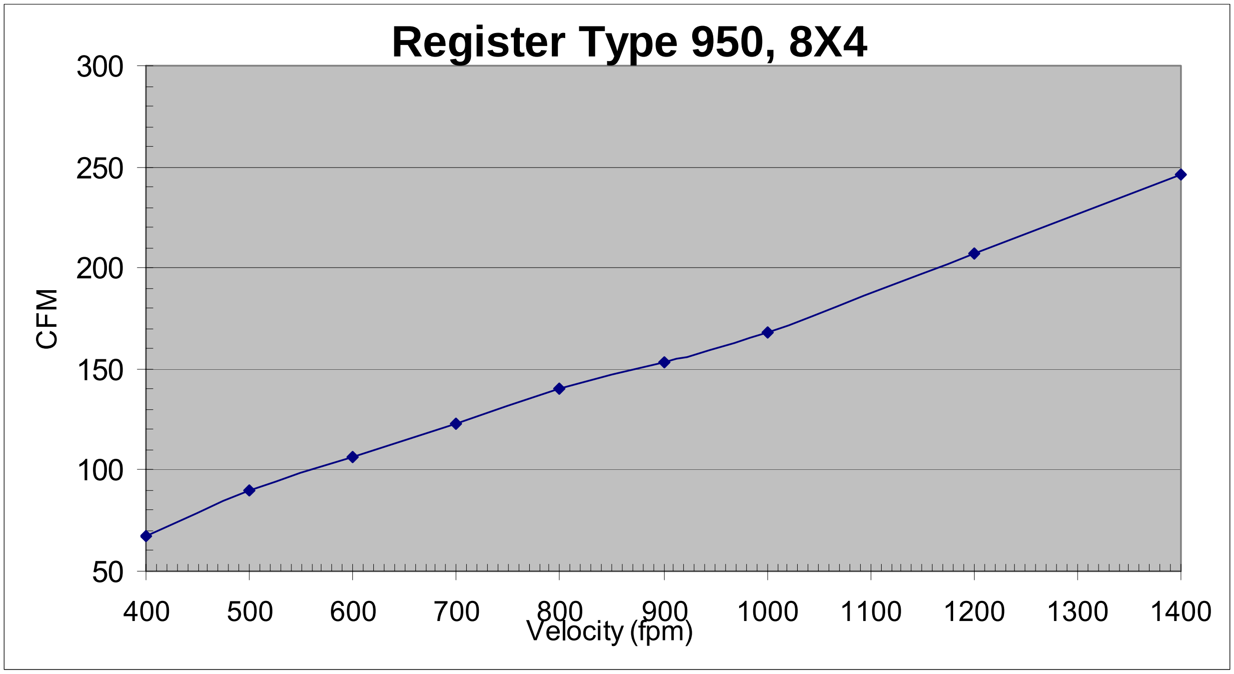
Note: all data taken from Shoemaker Engineering Data

Type: 950

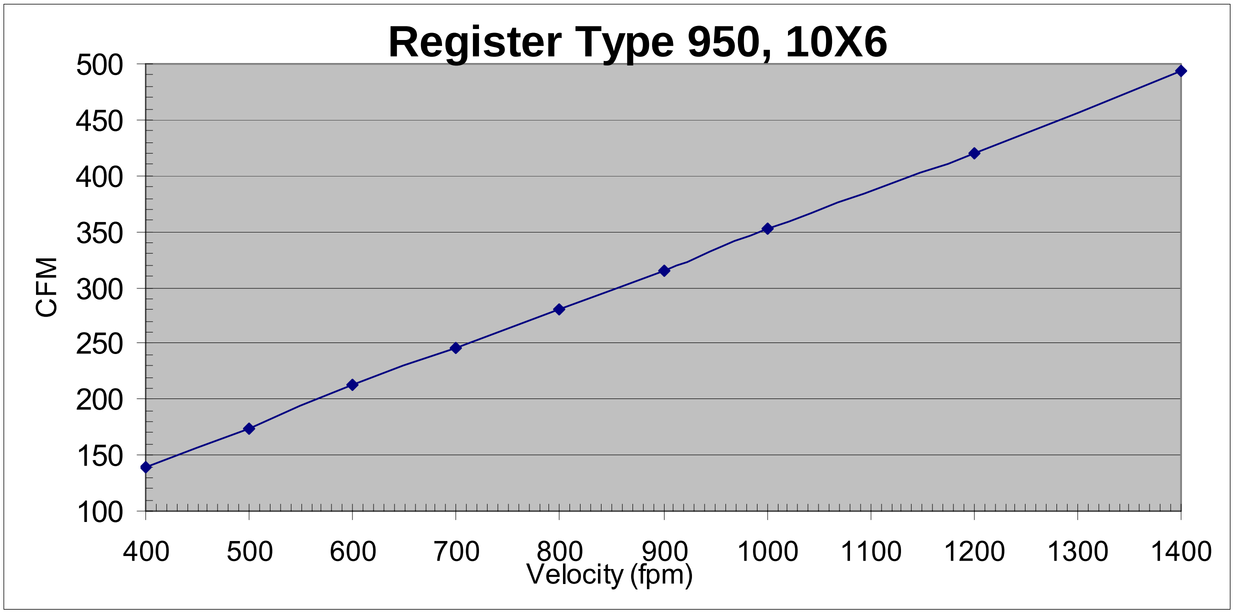
Size: 8X4

Effective Area: 0.155

Register Velocity	400	500	600	700	800	900	1000	1200	1400
Register CFM	67	90	106	123	140	153	168	207	246

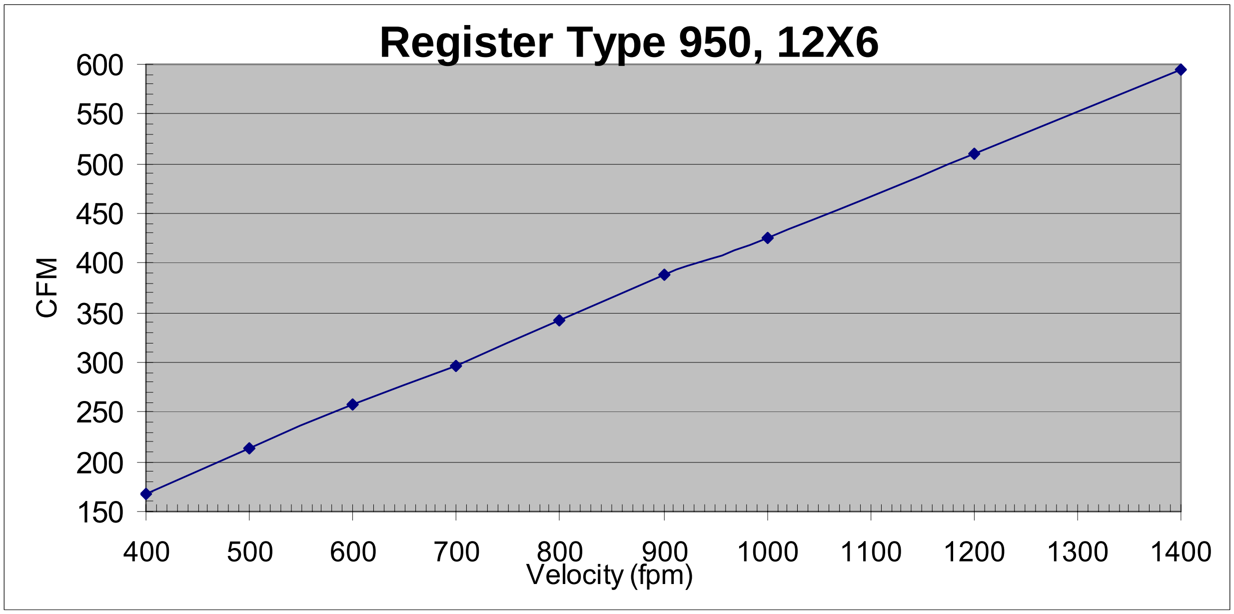


Type: 950 Size: 10X6 Effective Area: 0.313									
Register Velocity	400	500	600	700	800	900	1000	1200	1400
Register CFM	140	174	213	246	280	315	353	420	493



Type: 950
Size: 12X6
Effective Area: 0.38

Register Velocity	400	500	600	700	800	900	1000	1200	1400
Register CFM	168	213	258	297	342	388	426	510	594



Duct Loss Calculations

Heating Case

The exit temperature of the heated air leaving the registers was calculated using Equation 41 from 2001 ASHRAE Fundamentals Handbook, Chapter 34.14, Duct System Design. The resulting family of curves was used to provide the register exit temperature for each room as input to the CFD calculations.

Equation 41: $t_l = t_e(y-1) + 2\ t_a/(y+1)$

Where:

$y = 2.5\ DV\rho c_p/UL$ for round ducts

t_l = temperature of air leaving duct

t_e = temperature of air entering duct (design temperature = 105° F)

t_a = temperature of air surrounding duct (attic temperature)

D = diameter of duct

V = average velocity

ρ = density of air

c_p = specific heat of air

U = overall heat transfer coefficient of duct wall (Fig 13 B. Insulated Flexible Ducts)

L = duct length

V, the average velocity was calculated using Equation 11 from 2001 ASHRAE Fundamentals Handbook. Page 34.2, Duct System Design.

Equation 11: $V=Q/A$

Where:

V = the Average Air Velocity out of the duct, fpm

Q = the airflow rate out of the duct, CFM

A = cross-sectional area of the duct, ft

ROOM	CFM	AvgVel_h
Living	129	483
Dining	129	483
Kitchen	120	449
M.Bed	152	435
M.Bath	33	378
Bed_1	125	468
Bath_2	33	378
Bed_2	95	355

Parameters for H (heating)

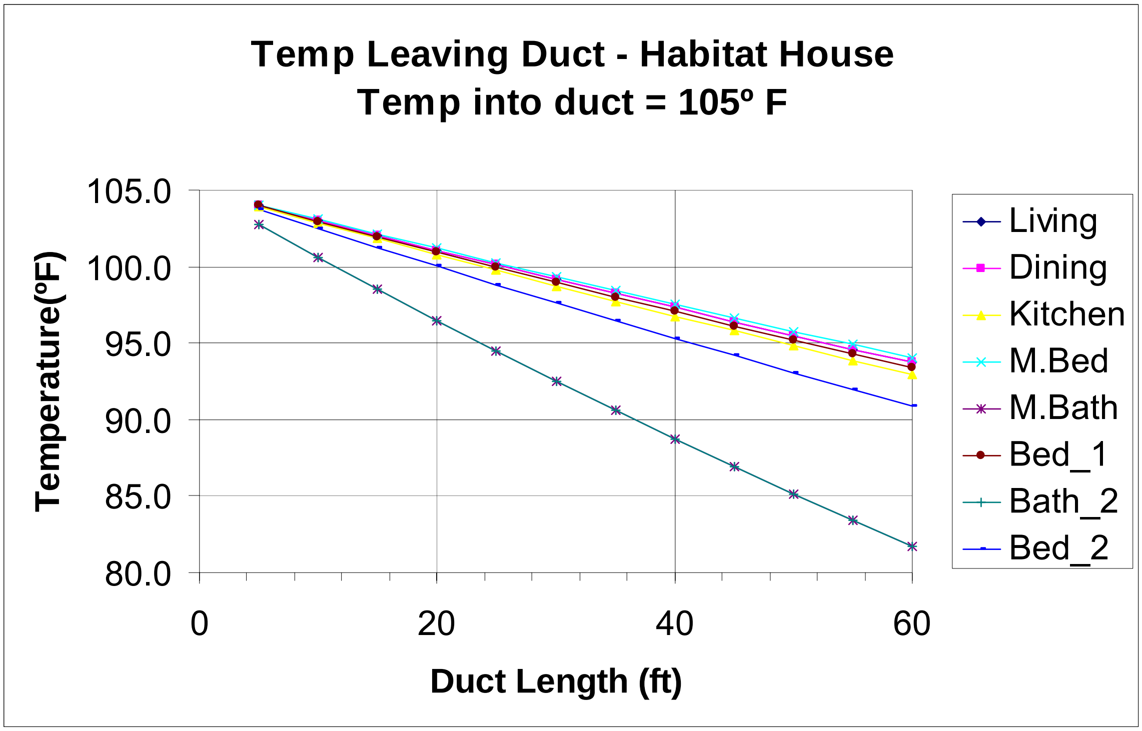
U_h (Overall heat transfer coefficient of duct wall)	0.18
TempEnter_h (Design temperature for air entering the ducts)	105.0
TempOutside_h (Design temperature for the air surrounding the ducts in the attic when outside air is at 20°F	20.0
AirDensity_h	0.075
SpHeatAir_h	0.24

Duct Exit Temperature as a function of Duct Diameter and Duct Length.

DuctDiam_h	7	7	7	8	4	7	4	7
Length_duct_h	Living	Dining	Kitchen	M.Bed	M.Bath	Bed_1	Bath_2	Bed_2
5	104.0	104.0	103.9	104.0	102.8	104.0	102.8	103.7
10	103.0	103.0	102.9	103.1	100.6	102.9	100.6	102.5
15	102.0	102.0	101.8	102.1	98.5	101.9	98.5	101.2
20	101.1	101.1	100.8	101.2	96.5	100.9	96.5	100.0
25	100.1	100.1	99.8	100.3	94.5	100.0	94.5	98.8
30	99.2	99.2	98.7	99.3	92.5	99.0	92.5	97.6
35	98.2	98.2	97.8	98.4	90.6	98.0	90.6	96.5
40	97.3	97.3	96.8	97.5	88.7	97.1	88.7	95.3
45	96.4	96.4	95.8	96.6	86.9	96.1	86.9	94.2
50	95.5	95.5	94.8	95.8	85.1	95.2	85.1	93.1
55	94.6	94.6	93.9	94.9	83.4	94.3	83.4	92.0
60	93.7	93.7	92.9	94.0	81.7	93.4	81.7	90.9

AirFlowRate (CFM)= 555 for the heating fan of the HVAC system

Reference: 2001 ASHRAE Fundamentals Handbook. Page 34.2, Duct System Design



Cooling Case

The exit temperature of the cooled air leaving the registers was calculated using Equation 41 from 2001 ASHRAE Fundamentals Handbook, Chapter 34.14, Duct System Design. The resulting family of curves was used to provide the register exit temperature for each room as input to the CFD calculations.

Equation 41: $t_l = t_e(y-1) + 2\ t_a/(y+1)$

Where:

$y = 2.5\ DV\rho c_p/UL$ for round duct

t_l = temperature of air leaving duct

t_e = temperature of air entering duct (design temperature = 55° F)

t_a = temperature of air surrounding duct (attic temperature)

D = diameter of duct

V = average velocity

ρ = density of air

c_p = specific heat of air

U = overall heat transfer coefficient of duct wall (Fig 13 B. Insulated Flexible Ducts)

L = duct length

V, the average velocity was calculated using Equation 11 from 2001 ASHRAE Fundamentals Handbook. Page 34.2, Duct System Design.

Equation 11: V=Q/A

Where

V = the Average Air Velocity out of the duct, fpm

Q = the airflow rate out of the duct, CFM

A = cross-sectional area of the duct, ft

ROOM NAME	CFM	AvgVel_C
Living	129	483
Dining	129	483
Kitchen	120	449
M.Bed	152	435
M.Bath	33	378
Bed_1	125	468
Bath_2	33	378
Bed_2	95	355
Total =	**816**	

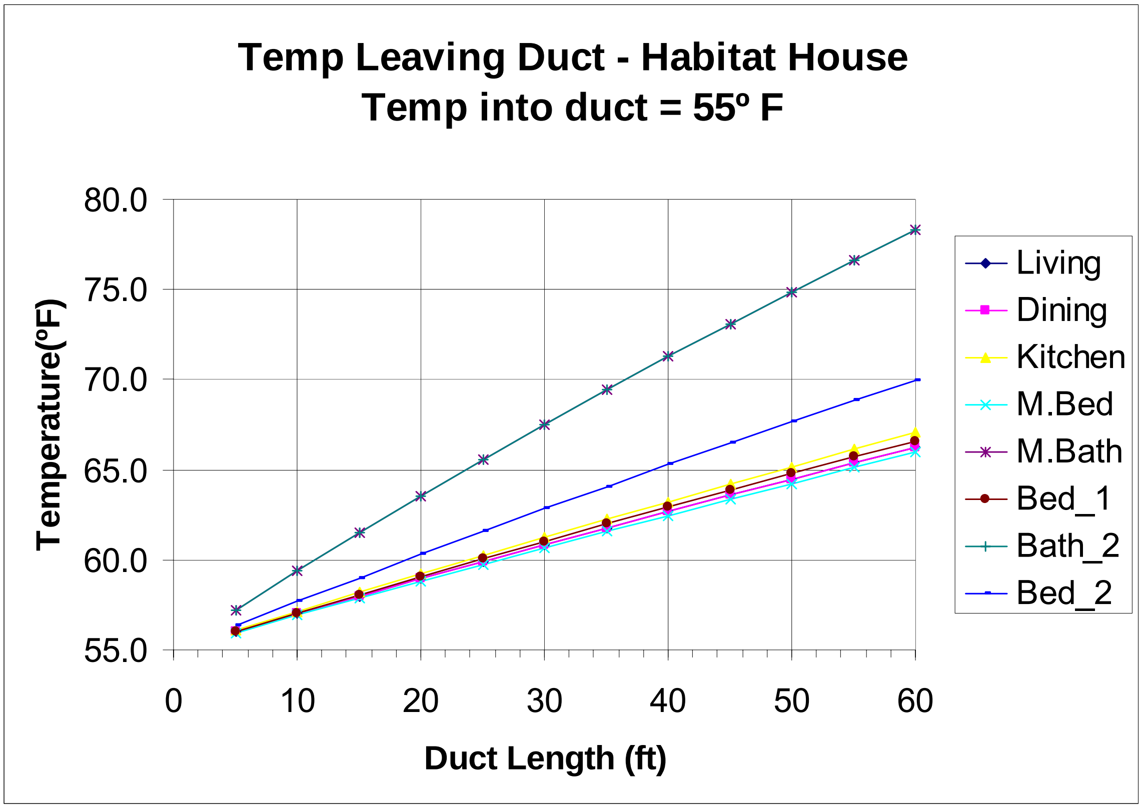
Note: As a cross-check on these calculated values, the design Air Flow Rate of the HVAC cooling fan for this house was 815 CFM. The room-by-room CFM shown above are from Right-J Short Form. The computed values for Average Velocity listed above are also very close to the values from the Right Suite reports.

Parameters for C (cooling)

U_C Overall heat transfer coefficient of duct wall	0.18
TempEnter_C Design temperature for air entering the ducts	55.0
TempOutside_C Design temperature for the air surrounding the ducts in the attic when outside air is at 105F	140.0
AirDensity_C	0.075
SpHeatAir_C	0.24

DuctDiam_C	7	7	7	8	4	7	4	7
Length_duct_C	Living	Dining	Kitchen	M.Bed	M.Bath	Bed_1	Bath_2	Bed_2
5	56.0	56.0	56.1	56.0	57.2	56.0	57.2	56.4
10	57.0	57.0	57.1	56.9	59.4	57.1	59.4	57.7
15	58.0	58.0	58.2	57.9	61.5	58.1	61.5	59.0
20	58.9	58.9	59.2	58.8	63.5	59.1	63.5	60.3
25	59.9	59.9	60.2	59.7	65.5	60.0	65.5	61.6
30	60.8	60.8	61.3	60.7	67.5	61.0	67.5	62.8
35	61.8	61.8	62.2	61.6	69.4	62.0	69.4	64.1
40	62.7	62.7	63.2	62.5	71.3	62.9	71.3	65.3
45	63.6	63.6	64.2	63.4	73.1	63.9	73.1	66.5
50	64.5	64.5	65.2	64.2	74.9	64.8	74.9	67.6
55	65.4	65.4	66.1	65.1	76.6	65.7	76.6	68.8
60	66.3	66.3	67.1	66.0	78.3	66.6	78.3	70.0

The resulting temperature loss vs. duct length is plotted below. For each cooling case, these curves are used to provide the register exit temperature for each room.



Appendix B – Two Story Study

Background

As homes become more and more efficient, their heating and cooling loads decrease. The result of this is that larger and larger homes are being served by single HVAC systems. In a typical California subdivision that offers four floor plans, three will be two-story homes. Many of those are served by a single system. This is a very common situation in California new construction and one that tends to have many customer service complaints related to temperature variations (stratification) in the home. The RAND builder survey of callbacks supports the importance of addressing complaints due to HVAC performance and its impact on comfort.

The ConSol Mechanical Design Department has been working for more than twenty years with HVAC subcontractors throughout the state and finds that many believe that a two-story home with a single system must have a substantial amount of the return air taken from the first floor. While there is no evidence to support this, HVAC subcontractors will insist that architects and builders go to great effort and expense to accommodate a relatively large return duct and grill to the first floor. At least one HVAC subcontractor lost a defect litigation lawsuit primarily because they did not put a return on the first floor. Some designers believe that a return in the ceiling of the second floor is adequate as long as the downstairs supply ducts are properly sized. One unanticipated result of our initial single story CFD study showed the return location (ceiling vs. low-wall) was a significant influence on system performance. Further CFD studies can address these conflicting perspectives and provide a broader application for the HVAC design guide.

There is also much debate and disagreement over the proper location of a thermostat in a two story home served by a single system. One school of thought is to put it upstairs because heat rises and that is where the most cooling is needed (cooling emphasized). The other school of thought is to put it downstairs because in the winter the first floor tends to be colder and that is where the most heating is needed (heating emphasized). These are overly simplistic points of view, but extremely common among HVAC subcontractors. The question to be answered is: Of the two options, which is most effective for both heating and cooling?

Overview

This study used Computational Fluid Dynamics (CFD) modeling to determine the performance of a typical two-story house served by a single system to answer these questions. These were run for (S) summer conditions, only.

The following return scenarios were modeled: (1) Return air grill upstairs only, (2) return air grills upstairs and downstairs. Since locating the return grill upstairs is the most common practice, it was analyzed with the thermostat located both upstairs and downstairs. As shown in **Table 11**, a total of three runs were analyzed: 2-U-S, 1-U-S, 1-D-S. The results were evaluated for temperature distribution, run times, and comfort/air quality.

Case	Run ID	Return Location	Thermostat location	Mode
Case 1	2-U-S	Split, upstairs and downstairs	Upstairs	Summer
Case 2	1-U-S	Upstairs only	Upstairs	Summer
Case 3	1-D-S	Upstairs only	Downstairs	Summer

Table 9: Summary of Two-Story Cases

Data Provided

The house used for the analysis was a 3-bedroom, two story design with a single Forced Air Unit (FAU). The thermal properties of walls, ceilings, floor, doors, and windows were determined for the home to meet 2001 Title 24 requirements, and are documented on the ACCA Manual J form for this house.

The design was provided as a 3-D AutoCAD drawing with walls, doors, and windows placed as in the actual design. **Figure 27** shows the basic plan view of the house. (The optional fourth bedroom was not used in these analyses.) This view shows the HVAC duct design and supply registers placements for each room. The return is located in the upstairs hallway and/or downstairs kitchen area.

The following sections describe the key results of the three cases.

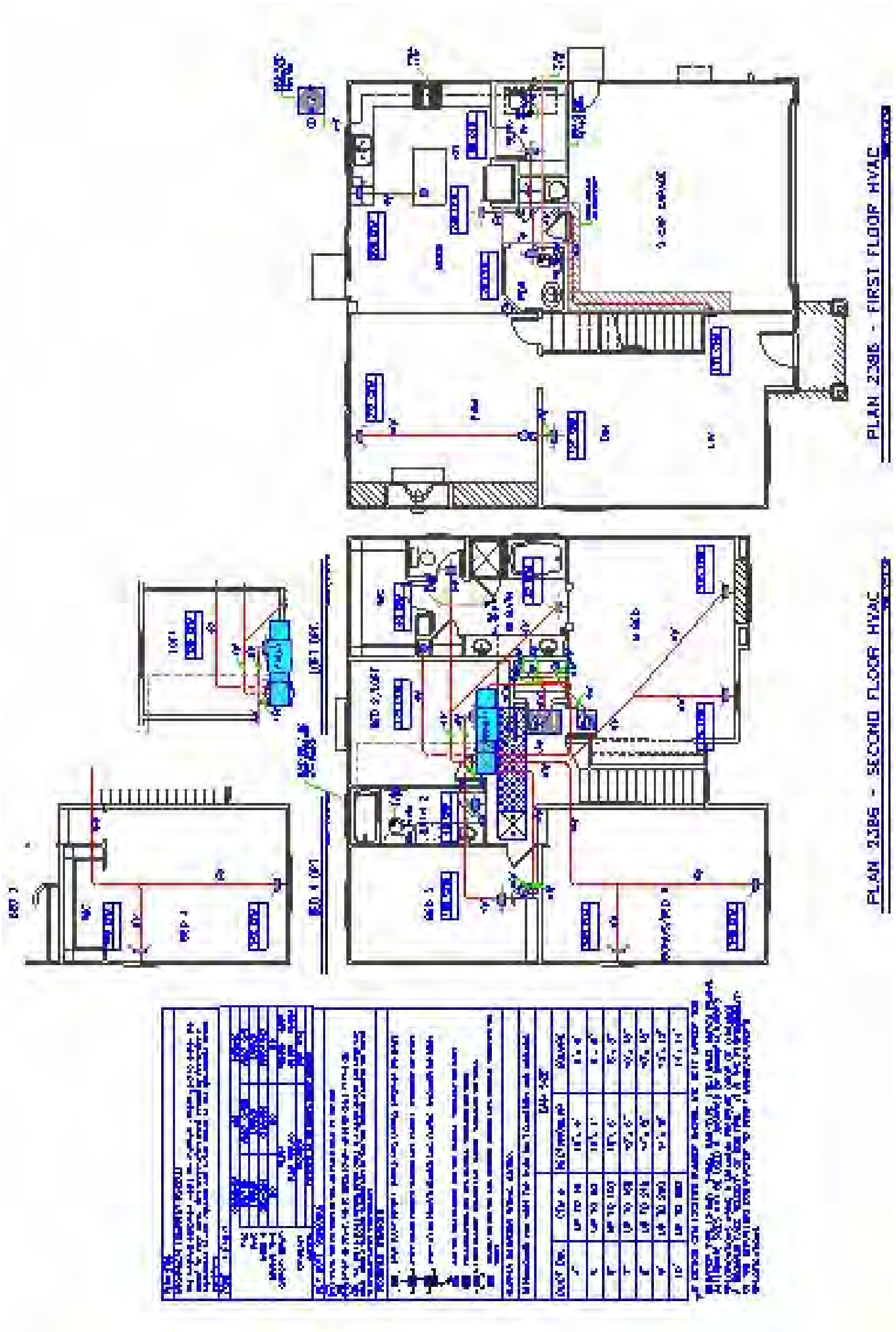


Figure 27: Two-Story Study House – Base Plan

Figure 28 shows a solid model of the house. The supply registers are located in the ceiling for all cases. The upstairs return (shown in green) is shown at the top of the stairway in the second floor hallway. The thermostat is also located in the hallway, just outside of the center bedroom. This configuration is representative of the typical two-story production home being built in California.

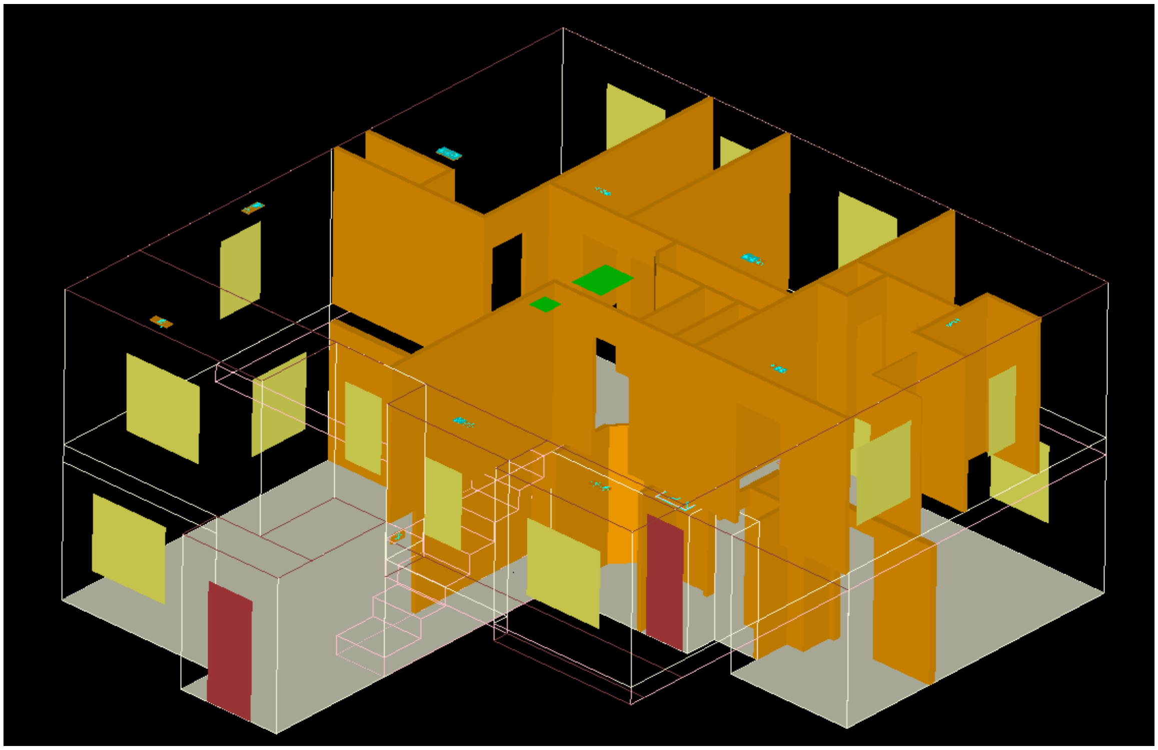


Figure 28: Study House Solid Model

Evaluation of Two-Story Cases

For the summer cooling mode, the ambient temperature was set to 105^{o}F. The HVAC system fan was set to turn on when the thermostat reached 76^o F and remain ON until the thermostat reached 75^o F.

The effects of convection and radiation transfer are included in the model through effective U values on different surfaces of the model. Computational runs were conducted in a transient (time varying) mode using Fluent's AIRPAK software.

The inlet air temperature and flow rates for these cases are shown in **Table 12**.

Room	**CFM**	**Temp (^{o}F)**
Living	114	58.0
Living/High	123	57.6
Dining	114	57.5
Kitchen	173	57.1
Nook	173	56.9.
Powder	24	58.1
Service	30	58.7
M. Bed A	146	60.9
M. Bed B	146	59.9
M. Bath	72	61.9
M. Bath/WC	33	66.3
Bed 2	149	57.0
Bath 2	41	58.2
Bed 3	158	59.1
Bed 4/Loft	123	61.8
Family	230	56.8

Table 10: Cooling Supply Flow Rates and Air Temperatures

Case 1: Cooling, Ceiling Registers, Return Upstairs and Downstairs, Thermostat Upstairs

Case 1 models the summer cooling conditions. Heat fluxes are specified for walls and windows. **Figure 29** shows a wire frame model of the Case 1 configuration. Supply registers are located in the ceiling. The return is split between the upstairs (green) hallway and downstairs (blue), off the kitchen. The thermostat is located in the upstairs hallway. The supply register flow rates and air temperatures for this case are shown in **Table 12**.

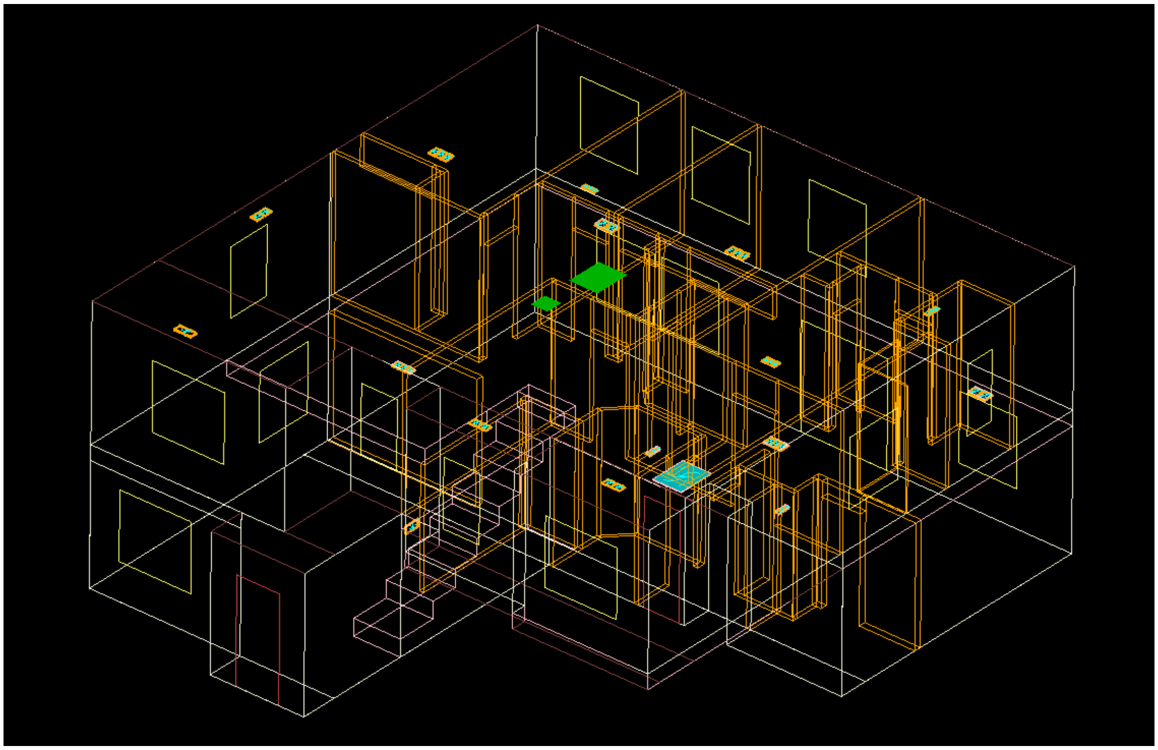


Figure 29: Case 1 – Register and Return Locations

Figure 30 shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. The total ON/OFF cycle is approximately 5.4 minutes for this case. The HVAC ON cycle takes approximately 2.3 minutes. The results of this case indicate that the combination of returns both upstairs and downstairs provides good mixing of air.

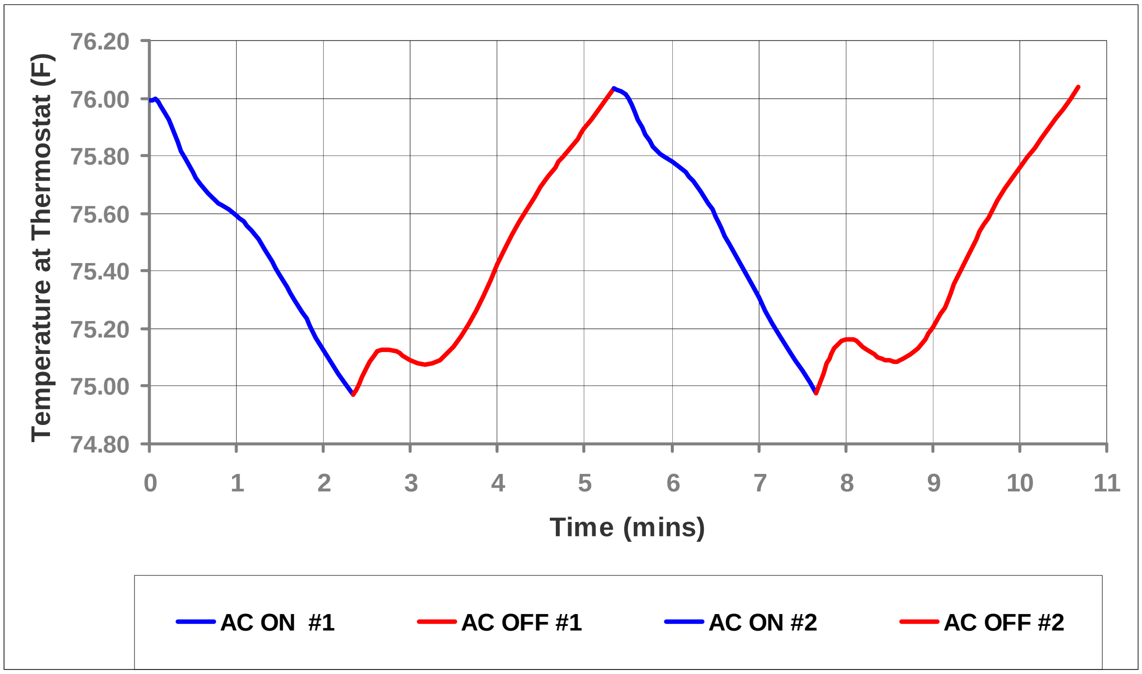


Figure 30: Case 1 -- Transient Temperature Variation at Thermostat

Case 2: Cooling, Ceiling Registers, Return Upstairs, Thermostat Upstairs

Case 2 models the summer cooling conditions. Heat fluxes are specified for walls and windows. **Figure 31** shows a wire frame model of the Case 2 configuration. Supply registers are located in the ceiling. The return is located in the upstairs (green) hallway only. The thermostat is located in the upstairs hallway. The supply register flow rates and air temperatures for this case are shown in **Table 12**.

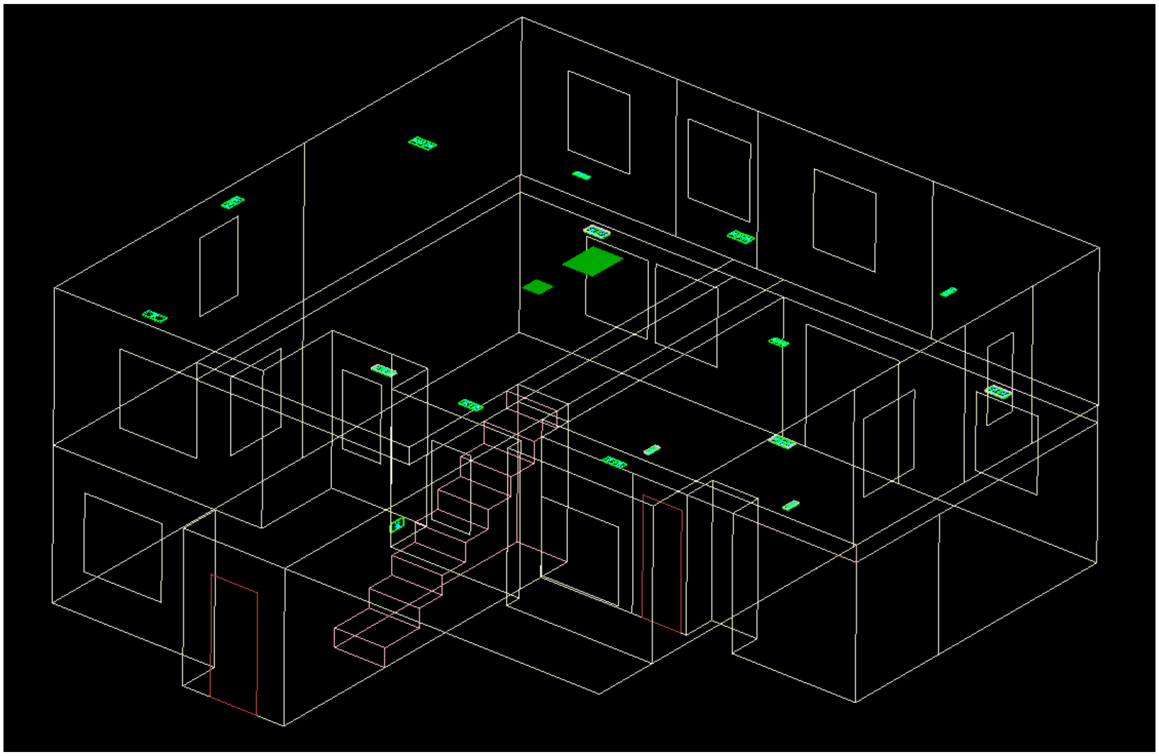


Figure 31: Case 2 – Register and Return Locations

Figure 32 shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. The total ON/OFF cycle is approximately 4 minutes for this case. The HVAC ON cycle takes approximately 1.6 minutes. The results of this case indicate that the single returns does not provide adequate mixing and the HVAC system cycles frequently as the air quickly returns to ambient.

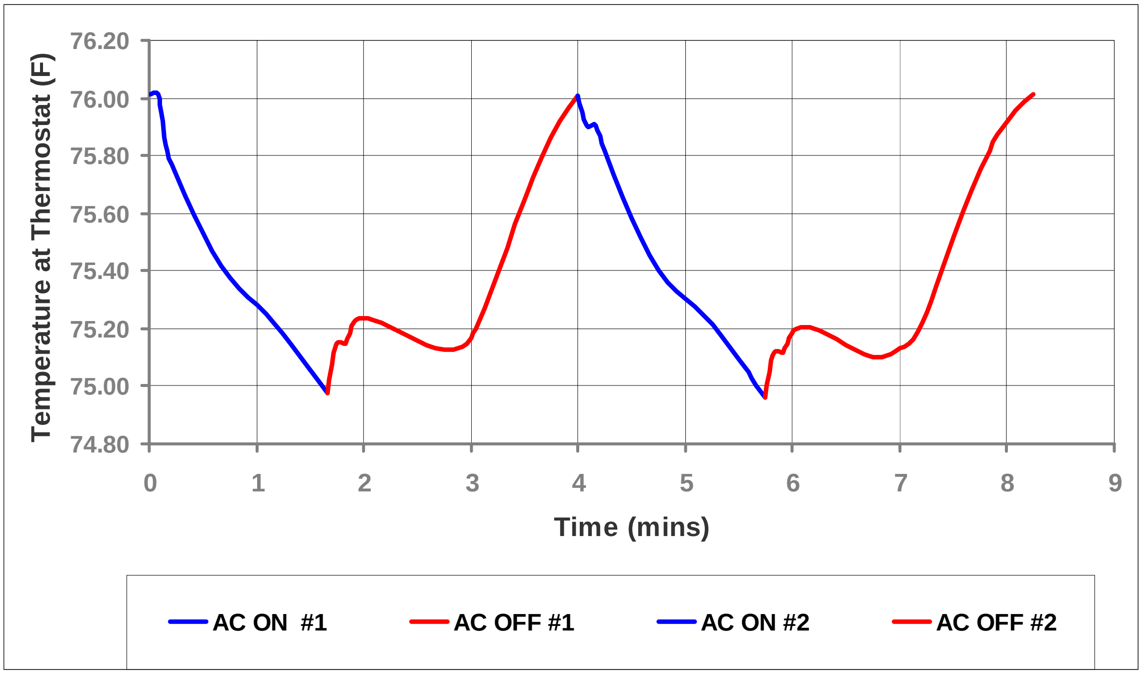


Figure 32: Case 2 -- Transient Temperature Variation at Thermostat

Case 3: Cooling, Ceiling Registers, Return Upstairs, Thermostat Downstairs

Case 3 models the summer cooling conditions. Heat fluxes are specified for walls and windows. **Figure 33** shows a wire frame model of the Case 6 configuration. Supply registers are located in the ceiling. The return is located in the upstairs (green) hallway only. The thermostat is located downstairs. The supply register flow rates and air temperatures for this case are shown in **Table 12**.

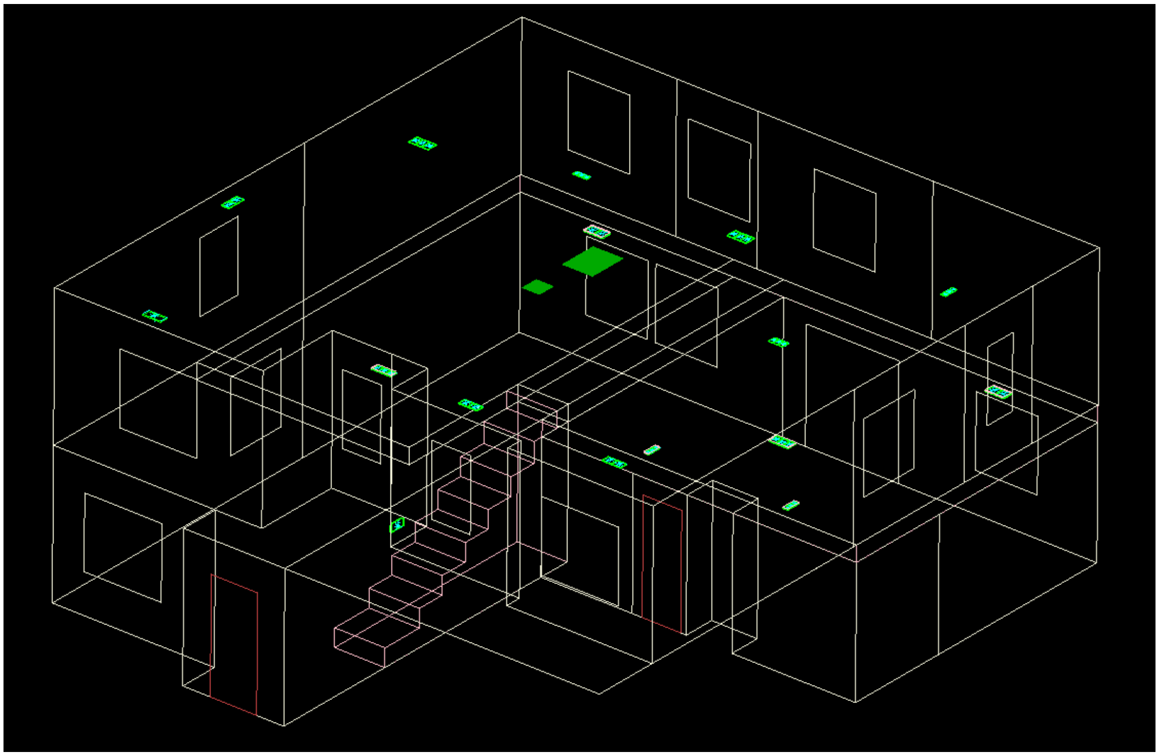


Figure 33: Case 3 – Register and Return Locations

Figure 34 shows the temperature variation at the thermostat during the HVAC ON/OFF cycle. The total ON/OFF cycle is approximately 2.6 minutes for this case. The HVAC ON cycle takes approximately 1.1 minutes. The results of this case indicate that the single returns does not provide adequate mixing and the HVAC system cycles frequently as the air quickly returns to ambient. Having the thermostat and return separated by floors causes an extremely short duty cycle time.

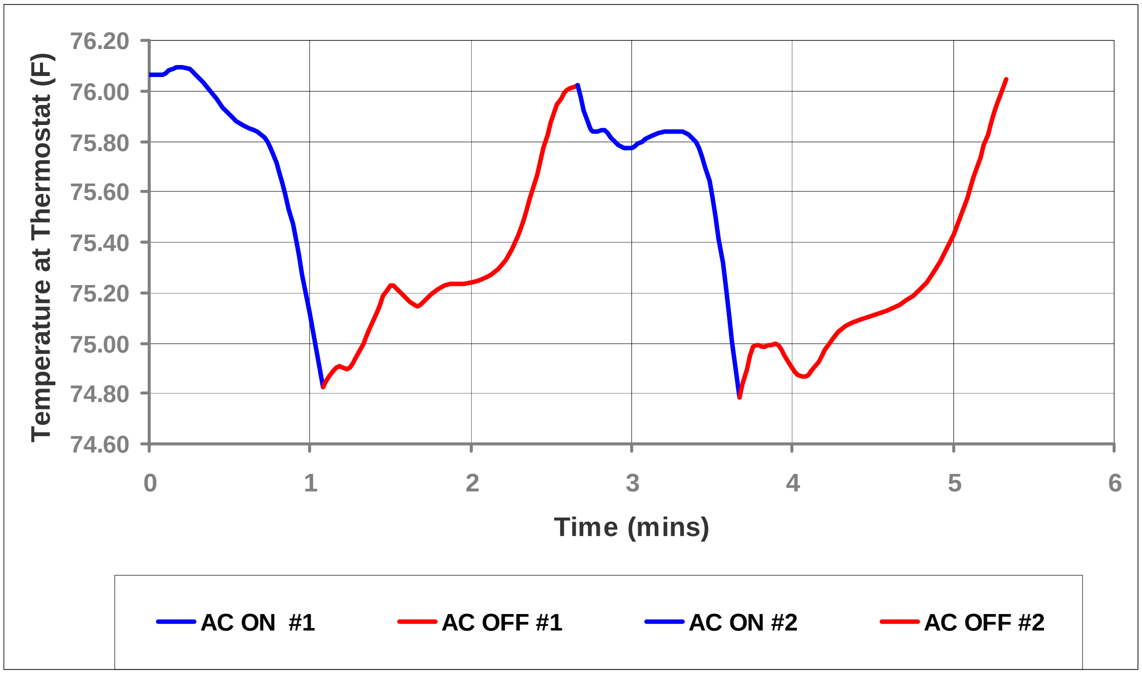


Figure 34: Case 3 -- Transient Temperature Variation at Thermostat

Assessment

Occupant comfort and air quality are acceptable with all configurations. There is no design driver based on comfort.

Figure 35 shows a comparison of the temperature variations at the thermostat for all three cases. The duration of the total cycle times is apparent, with both Case 2 (return upstairs/thermostat upstairs) and Case 3 (return upstairs/thermostat downstairs) cycling twice as often as Case 1(returns upstairs and downstairs/thermostat upstairs). The second return in Case 1 provides a better mixing of air, delaying the return to ambient temperature.

Locating the both thermostat and return on the upstairs floor (case 2) has the most significant effect on the duty cycle. This is most likely due to the lack of mixing with the thermal control near the return. This configuration runs the HVAC system twice as often, although the total On-Time is slightly less overall. This frequent cycling would have a negative impact on the equipment lifetime.

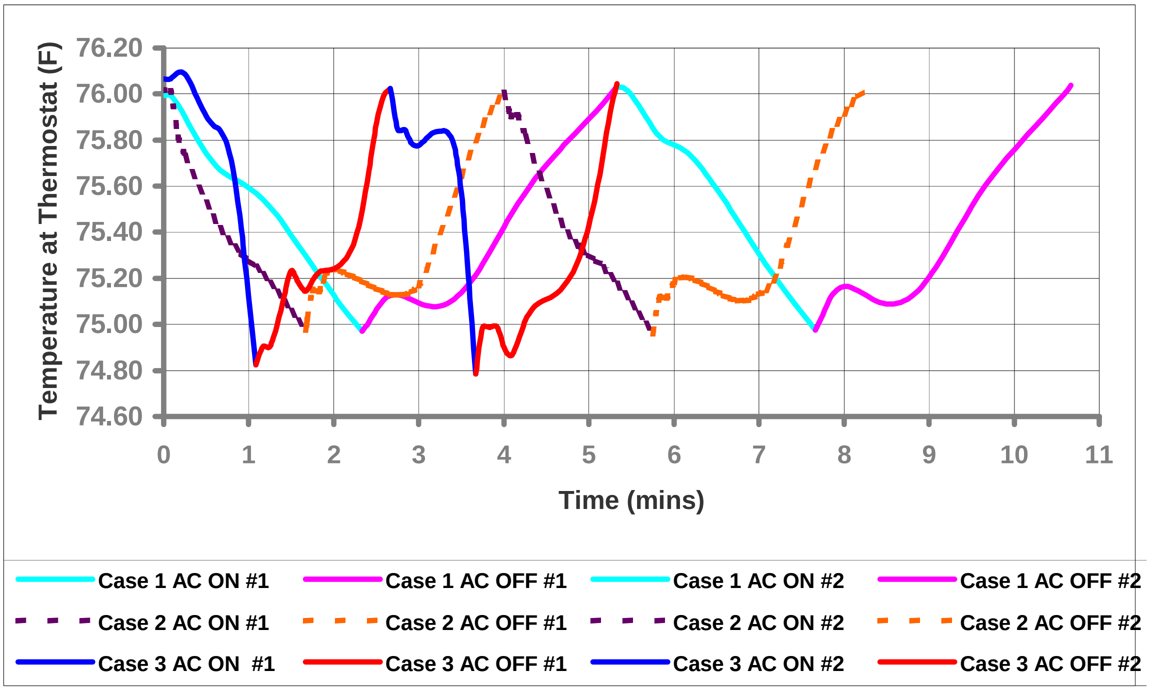


Figure 35: Comparison of HVAC Cycle Time for Case 1, 2 and 3
(Return Upstairs and Downstairs, Return Upstairs Only, Thermostat Downstairs)

Table 13, below, shows a comparison of cycle times for the three cooling cases. The total On-time/hour for all three cases is very similar. However, Case 3 clearly cycles frequently to achieve cooling; Case 2 also cycles more frequently. This frequent cycling will cause additional wear on the HVAC system components.

	On-time	Total Cycle Time	Cycles/hr	Total ON-time/hr
Case 1	2.33	5.33	11.26	26.24
Case 2	1.67	4.0	15	25.05
Case 3	1.08	2.67	22.47	26.21

Table 11: Comparison of Cycle Times for Case 1, 2, and 3

Recommendations

For the two-story application, installing returns both upstairs and downstairs provides longest duty cycles with good comfort and air quality. While the total On-Times are nearly equal for all cases, the two-return design causes the least cycling and wear on the HVAC equipment.

The thermostat located downstairs, farthest from the return, has the most negative effect on duty cycle. This configuration would require frequent cycling of the system and should be avoided.

CALIFORNIA
ENERGY
COMMISSION

CALIFORNIA RESIDENTIAL NEW CONSTRUCTION

HVAC DESIGN GUIDE

DESIGN GUIDELINE

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Arnold Schwarzenegger, *Governor*

Prepared By:
Dr. Robert Hammon
Building Industry Institute
Sacramento, CA
Contract No. 400-00-037

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

Martha Brook,
Contract Manager

Ann Peterson,
PIER Buildings Program Manager

Nancy Jenkins
Office Manager
ENERGY EFFICIENCY RESEARCH OFFICE

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

B. B. Blevins,
Executive Director

DISCLAIMER

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 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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

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

What follows is an attachment to the final report for the Profitability, Quality, and Risk Reduction through Energy Efficiency program, contract number 400-00-037, conducted by the Buildings Industry Institute. This project contributes to the PIER Building End-Use Energy Efficiency program. This attachment, “California Residential New Construction HVAC Design Guide" (Attachment 2), provides supplemental information to the program final report.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

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Abstract

Adequate tools and methods now exist to design energy-efficient HVAC systems. Failure to correctly apply them in production homes costs California homeowners. This major missed opportunity is a function of both a faulty design process and inaccessibility of the design methods. The cost-centric design-build process commonly employed by production builders rarely includes a skilled HVAC designer early in the development phase where they can most effectively integrate HVAC requirements with the house design. Currently available HVAC design tools and methods require time and high levels of skill, which negatively affects the cost/profit agenda. A more integrated design process and simplified design methods are essential to improve usage, increase HVAC design quality, and reduce HVAC energy consumption.

This design guide is not intended to be a step-by-step instruction book on how to design an HVAC system because adequate methodologies already exist for that. Rather, it is intended to be a step-by-step guide for clarifying those methodologies and integrating them into the overall design process for an entire house. It also addresses important topics particularly important to California, and specific to new-construction production homes.

1.0 Introduction

1.1 Purpose

The purpose of this Design Guide is:

1. To be a useful tool for the planning and implementation of a good residential HVAC design *process* and to assist during that process.
2. To encourage coordination between key players such as the architect, builder, structural engineer, framer, HVAC designer, HVAC installer, energy consultant, electrical designer, and plumber to minimize conflicts during the installation of a properly designed system.
3. To help identify how all of the designers, consultants, and trades people are impacted by the process and how they need to communicate in order to further minimize conflicts.
4. To explain and simplify current HVAC design methodologies so that they are more applicable to California production homes, more useful, and more widely used.
5. To address topics not well covered by existing HVAC design methodologies and provide guidance on issues that have been of particular concern in production homes.

1.2 Target Audience

The target audience for this design guide is:

1. HVAC designers, whether they work for the design-build contractor who will eventually be installing an HVAC system or a consulting engineering firm hired to provide a detailed design for others to follow.
2. Architects desiring to better incorporate the HVAC system into their house designs.
3. Builders desiring to better coordinate the installation of the HVAC system into their houses.
4. Related trades or consultants interested in better coordinating their work with that of the HVAC designer and installer.

1.3 Limitations

This design guide is not intended to walk you through all of the steps necessary to design an HVAC system. There are some very sophisticated design methodologies currently available which are well-supported by trade and professional organizations (e.g., ACCA's Manuals J, S, and D). Unfortunately, they tend to be complex and overly precise. Also, the time necessary to properly use them (not to mention the time needed to learn them) does not fit well within the current design process. They tend to be slanted toward issues related to custom houses and retrofitting older houses. They also devote much time and text to building practices atypical of California residential new construction, such as basements and sheet metal ducting. This Design guide is intended to supplement those methodologies and encourage wider use by making them more consistent with current practices in the construction of California production homes.

2.0 The Design Process

2.1 Designing houses around the HVAC system

Wouldn't it be nice houses were designed around the HVAC system? If special consideration was given to the architectural design for making the HVAC system easy to design and install? If adequate space was provided for the furnace and all of the duct work? If the house was designed with thermodynamics in mind, to minimize stratification, cross-zone interference and other problems that are difficult and/or expensive to remedy with standard HVAC practices?

This is unlikely to happen without the input of a qualified HVAC designer, and the designer's involvement needs to happen early in the design process. More typically, a house is almost completely designed before an HVAC designer ever sees it, and the HVAC system designed with an emphasis on fitting into the house rather than efficiently conditioning the house. Unfortunately, HVAC installers have become quite proficient at getting systems to fit into houses (whether they will work or not!). The result has been undersized and inefficient ducts that are difficult to balance and create unnecessary operating pressure on the fan motor. To compensate for the shortcomings of such duct systems, many installers have increased the size of the furnace, coil and condenser. This is the same logic as putting a larger engine in your car because the tires are too small. The car might go faster, but it sure wouldn't perform well or get very good gas mileage.

Often the reason given for a particular size duct being installed is, "that's the largest that would fit." If adequate space is a critical impediment to the installation of a properly designed system, then adequate space and clearance must be designed into the home by the architect and built into the home by the framer. No matter how well an HVAC system is designed on paper, the design efforts are wasted if the system cannot be installed in the field.

Typically a house goes through the following design process:

- Conceptual Development: Determines price range, square footage, number of stories, lot sizes, general features and styles.
- Preliminary Design: Develops floor plan sketches, number of bedrooms, major options, basic circulation and function locations, as well as some elevation concepts. Some early Value Engineering (VE) meetings.
- Design Development: Preliminary structural, mechanical, electrical, plumbing and Title 24 energy compliance. Some VE meetings.

- Construction Documents: final working drawings ready for bidding, submittal. Back checking and coordination by consultants. Some late VE meetings.

The HVAC designers need to provide input as early as possible. They need to tell the architect which architectural features cause comfort issues and are difficult or impossible to overcome with typical HVAC practices. They also need to make sure the architect allows adequate space to run ducts. Many architects have had to re-design plans enough times due to HVAC issues that they know fairly well how to accommodate HVAC items. Still, many problems commonly arise that could be avoided through earlier input and better coordination.

2.2 Coordination with other trades

The following matrix shows the main trades and consultants who are affected by the HVAC system. The first column lists the item or issue and each subsequent column how each trade is affected by it.

Matrix of Trades

Item	Architect	Builder/Framer /Structural Engineer	HVAC Installer	Energy Consultant	Electrical	Plumber	Drywall or insulation
FAU location	Roof pitch, furnace closets, clearance in garage	Truss design, platform, clearance, closets, bollards, attic access framing	Type of FAU (upflow, horizontal), clearance, timing of installation	Modeling correct location of ducts for computer model	Power, service light, control wiring, etc.	Condensate lines, gas piping	Insulation under platform may be different
Equipment size, load calculations	Clearances, # of systems, building features	Structural impacts (weight)	Materials, labor, costs	Energy features impact sizing	Electrical loads		
Supply register locations	Aesthetics, clearances	Register boot support	Materials, labor				Sealing around registers
Return grille locations	Aesthetics, noise issues	Framed openings	Materials, labor				Sealing around grilles
Condenser locations and line set	Aesthetics, noise issues	Clearance, accessibility to yard (set-back issues), 2x6 walls, chases	Materials, labor, serviceability		Power, service disconnect		
Attic access	Aesthetics	Framed opening, truss issues	Access, serviceability				
Routing B-vent	Chases, clearances, aesthetics (on roof)	Framed chases, roof cap	Materials, labor, installation			No conflicts with vent	
Chases, soffits, and drops	Aesthetics, feasibility	Framing, clearances for ducts, conflicts	Materials, labor, installation			No conflicts with ducts	
Thermostat location	Aesthetics		Materials, labor, installation		Wiring		Seal hole for wires
Equipment efficiency			Materials	Efficiency determined by energy consultant			
Combustion air	Attic vent calcs, routing for CA ducts	Adequate attic vents (roofer)	Ducting, if any				

Table 1: Matrix of Trades

3.0 Design Methodology

3.1 Code issues related to HVAC design

3.1.1 ACCA Manual D required by 2000 UMC

It is not widely known that the 2000 Uniform Mechanical Code (2001 California Mechanical Code) requires that all residential duct systems be sized according to ACCA's Manual D, which itself requires Manual J as a prerequisite design step. The exact language is:

Chapter 6, Duct Systems, Section 601.1 Sizing Requirements. Duct system used with blower-type equipment which are portions of a heating, cooling, absorption, evaporative cooling or outdoor air ventilation system shall be sized in accordance with Chapter 16, Part II Referenced Standards or by other approved methods.

Chapter 16, Part II Referenced Standards. Residential duct systems, ACCA Manual D.

Very few jurisdictions are enforcing this, most of them because they are not aware of it. This of course doesn't mean that it isn't required. It is unclear what exactly needs to be submitted in order to verify that a home has been designed to the ACCA method. One would assume that a clearly drawn mechanical plan along with supporting calculations and/or worksheets would be required.

The ACCA manuals were not written with the intent of being used as specific code language, therefore it will be up to the local jurisdiction to decide exactly how to enforce adherence to them. The Uniform Mechanical Code states that ducts must be "sized" according to Manual D. There are many suggestions and requirements in Manual D that do not relate duct sizing, some of which are impractical or simply inappropriate to California new construction. Flexibility in design is important and since little of Manual D is related to health and safety, much of Manual D outside of the sizing methodology should be considered discretionary.

Note: The next revision of the CMC may alter the Manual D requirement to be only for homes that require outdoor air. It has been suggested that this was the original intent and why it is in the UMC.

3.1.2 Title 24 load calculations

Chapter 2.5.2 of the 2001 Residential Manual expands on Section 150(h) of the Energy Efficiency Standards, which establishes the criteria for sizing residential HVAC systems in California. It provides for three different methods for calculating the building's design heat loss and heat gain rates (loads). It also establishes the design temperatures to be used for sizing equipment.

> *For the purpose of sizing the space conditioning (HVAC) system, the indoor design temperatures shall be 70 degrees Fahrenheit for heating and 78 degrees for cooling.[note: effective 10/1/05, the indoor design temperature will change to 75 degrees Fahrenheit for cooling] The outdoor design temperatures for heating shall be no lower than the Winter Median of Extremes column. The outdoor design temperatures for cooling shall be from the 0.5 percent Summer Design Dry Bulb and the 0.5percent Wet Bulb columns for cooling, based on percent-of-year in ASHRAE publication SPCDX: Climate Data for Region X, Arizona, California, Hawaii, and Nevada, 1982.[note: effective 10/1/05, the outdoor design temperatures for cooling changes to 1.0 percent Summer Design Dry Bulb and the 1.0 percent Wet Bulb columns for cooling]*

The three approved load calculation methods are written and supported by three different trade organizations ASHRAE, SMACNA, and ACCA. Micropas and Energy Pro, the two most common Title 24 compliance software programs, both use the ASHRAE method. They generate whole house heat loss and gain calculations in order to meet the requirement of submitting approved load calculations as part of the energy compliance package. Whole house loads are useful for sizing the equipment but are of little use for designing a duct system, which requires room-by-room loads. However, it is very useful to have a whole-house load calculation to compare to the total of the room-by-room loads. This ensures consistent and accurate calculations and helps catch errors.

The Residential Manual also reminds us that the Uniform Building Code addresses the sizing of the heating system, though not the cooling system. It states:

> *The sizing of residential heating systems is regulated by the Uniform Building Code (UBC) and the Standards. The UBC requires that the heating system be capable of maintaining a temperature of 70 ºF at a distance three feet above the floor throughout the conditioned space of the building.*

None of the calculations approved by Title 24 address the temperature at any distance above the floor. They all assume that the temperature is the same everywhere in the house, that temperature being whatever the inside design temperature is. The specification of 3 feet above the ground simply provides a reference for testing an actual system. It is generally assumed that if the heater has a capacity equal to or greater than the heating load calculations and a reasonable distribution system, it will meet this requirement.

The residential manual reiterates that the load calculations are only part of the information used to size and select the equipment and who can prepare those calculations (presumably based on the Business and Professions Code), but does not go into much more detail about what else goes into the sizing and selection process.

*The calculated heat gain and heat loss rates (load calculations) are just two of the criteria for sizing and selecting equipment. The load calculations may be prepared by: (1) the [*Title 24*] documentation author and submitted to the mechanical contractor for signature, (2) a mechanical engineer, or (3) the mechanical contractor who is installing the equipment.*

Title 24 does not specifically state how cooling loads should be considered when sizing an air conditioner. It doesn't even state that an air conditioner has to be installed at all. Most jurisdictions treat the Title 24 cooling loads as a minimum sizing criteria. In other words, a system must be installed that has a cooling capacity that at least meets the Title 24 cooling load. In some climate zones, it is common practice to offer air conditioning as an option. So, apparently the sizing criteria only apply *if* air conditioning is to be installed. [note: 2005 amendments to Title-24 will offer an alternate sizing method.]

The following link will direct you to an on-line copy of the Title 24 Residential Energy Manual, Appendix C – California Design Location Data. A map of the California climate zones can be found in this appendix along with information on California climate zone requirements. http://www.energy.ca.gov/title24/residential_manual/res_manual_appendix_c.PDF. Or, if you are connected to the internet, you can click on the link below:

Title 24 Residential Manual, Appendix C -- California Design Location Data

3.2 ACCA Manuals J/S/D

3.2.1 The Overall Design Method

The overall design steps for the ACCA J/S/D methodology, as it should be used in typical California new construction production homes, is described in the following list. Throughout the execution of this list, certain decisions are made that may affect other trades. It is important that this coordination be made in a continuous and consistent manner. The Matrix of Trades (page 10) is provided to help guide you in this coordination.

Step 1. Determine Zones

Step 2. Calculate Room by Room Loads

Step 3. Select/size Equipment

Step 4. Layout duct system
- Locate FAU(s)
- Locate grilles and registers
- Route ducts
- Sub zones (trunks)

Step 5. Determine operating conditions
- Static pressure
- Total CFM
- Equivalent lengths
- Friction rates

Step 6. Size ducts
- Room air flow is proportional to room load
- Friction rate and room air flow determine duct size

Step 7. Final touches
- Locate thermostat
- Locate condenser

Step 1. Determine Zones

Zones, as discussed here, are defined as areas of the house that are to be independently controlled, typically by their own thermostat. Smaller houses typically only have one zone. If the main criterion for zoning a house is whether it can be served by a single system or not, the designer may want to wait until after doing the load calculations. The new load calculation software products allow you to easily assign and reassign rooms to different zones and this step can be integrated into the next step of performing the actual room-by-room load calculations. However, evaluating a house for possible zone considerations is still a useful first step.

There are a variety of ways to zone a house and there are several factors to take into account. These include use patterns such as "living" areas and "sleeping" areas. Thermodynamic zones play an important role as well. These are areas of a house that will behave substantially different because of their relative position or isolation from each other such as upstairs and downstairs, east wing and west wing, etc. Sometimes use patterns and thermodynamic zones do not coincide and you may have to prioritize one over the other. Usually thermodynamic considerations take precedence.

Zoning a house for living/sleeping can generate an energy efficiency credit toward Title 24[1] compliance. This energy efficiency credit is based on the ability to program the thermostat schedule differently for these two zones thereby saving energy. The real energy savings of this strategy is highly dependent on the occupant's proper programming and operation of the thermostats. It can either be accomplished by a single system with zonal control (single system with dual zone components) or by separate systems. See Section 4.4. Zonal Control for more discussion on zonal control. If the dual zone strategy is used for Title 24 compliance, the HVAC design must ensure that it does not have an adverse affect on comfort.

If all of the spaces defined as either living areas or sleeping areas are not located in thermodynamically similar zones, special steps may be required to ensure consistent comfort throughout each zone. For example, if a two-story house large enough to require two systems has all of the bedrooms upstairs except the master bedroom, it may be difficult to zone the house for living/sleeping. Because it is a two-story house, it wants to be zoned up/down for thermodynamic reasons. The sleeping zone is split between two floors and may require further zonal control to achieve satisfactory comfort, resulting in a total of 3 thermostats.

Usually the first question asked from a cost perspective is "Can the entire house be served by a single HVAC system?" In other words, can the total cooling loads, regardless of other considerations, be met by a single 5-ton air conditioner (the largest system typically used in residential construction)? This is not known until the loads are calculated. A preliminary estimate can be made based on square footage and window area and then later revised if the results of the load calculations change the assumptions.

[1] Energy Efficiency Standards for Residential and Nonresidential Buildings Publication Number: 400-01-024, August 2001

As homes get more and more efficient, especially in regard to window technologies, larger and larger homes can be served by a single 5-ton system. At some point, other considerations need to be taken into consideration. Things such as adequate airflow (air changes) need to be considered. Does a single 5-ton system at approximately 2000 cfm have enough air moving capability to adequately distribute air throughout a very large house, even if it can meet the steady state cooling load? Also, how susceptible is the house to non-steady state conditions? In other words, what happens if in cooling mode the temperature is inadvertently allowed to substantially exceed the comfort temperature? Will the system be able to catch up in a reasonable amount of time? This can be a critical customer service issue in production homes and is a topic that needs further research.

If the house can be served by a large single system (i.e., 5-tons) but has distinct zones (e.g., upstairs downstairs) it is recommended that those zones be controlled independently (separate thermostats). This can be accomplished by multiple systems or by a single system with zonal controls. See Section 4.4 for more on zonal control

Step 2. Calculate room by room loads

For room-by-room loads, ACCA's Manual J is the most widely used and most widely supported standardized methodology. There are at least two software versions of it (See Appendix A for resource information). Even though it was originally intended to use hand written forms and worksheets, it is now virtually mandatory to use a computer method (unless your are extremely accurate and patient – the type of person who can fill out complicated tax forms by hand.). Because ACCA Manual J is all based on published tables and worksheets, some people have written their own load calculation spreadsheets based on Manual J.

The two available software packages (Right-Suite[2] and Elite[3]) have very sophisticated features allowing Computer Aided Design (CAD)-based take-offs for window and wall areas. This makes very easy and quick work of entering physical building data if you have access to an architect's CAD files. The software packages allow you to import a CAD floor plan of the home and essentially trace over it to create the rooms and zones. Windows and doors are drag-and-drop components. If you do not have access to the architect's CAD files, you can use the software to do a pretty reasonable job of recreating the floor plan of a house. These software packages also have useful duct layout drawing features.

The underlying concept of room-by-room loads is that each room, or area served by a supply register, is treated as an individual load. This provides for a very accurate determination of how to distribute the air. If air is distributed proportionally to each room's load, then each room will be conditioned appropriately; resulting is even temperature distribution across a home. This is the basis for ACCA Manual D. It's not perfect in reality. However, it is the best method we have right now and works quite well for most production homes. The more complex and "broken up" the house layout is architecturally, the less this assumption is applicable.

[2] Wrightsoft Software,
[3] Elite Software

Step 3. Select and Size Equipment

Use total of room-by-room loads for each zone

1. Once the house has been zoned and the loads for each of the zones are finalized, the system can be sized and selected. ACCA's Manual S provides detailed information for determining heating and cooling capacities of various types of equipment. In California residential new construction, the most common HVAC system type is split-system Direct-Expansion (DX) cooling with a gas furnace. The heating capacity is easy to determine based on the rated heating output of the furnace, which changes very little based on actual conditions. Some adjustment may need to be made for high altitudes. Determining the cooling capacity at actual conditions is more complex. It depends on several conditions: a) the outdoor temperature, b) the indoor entering wet bulb[4] and dry bulb[5] temperatures, and c) the airflow (cfm) across the coil. In order to properly account for these conditions it is necessary to use detailed capacity tables provided by the manufacturer. Again, ACCA's Manual S goes into good detail on this process.

In California residential new construction the following conditions are typical:

1. Outdoor temperature: This is the temperature of the air that is blowing through the condenser to cool the refrigerant and is usually the same outdoor temperature that is used for the cooling load calculations unless it is known that the condenser will be located in a hotter location such as on a roof.
2. Indoor entering wet bulb and dry bulb: These describe the condition of the air blowing across the coil and are usually assumed to be the same as the indoor conditions used in the load calculations. Title 24 cooling loads are calculated using an indoor temperature (dry bulb) of 78 deg F. Some designers use a lower temperature, such as 75 degrees to be safe. (Note: lower indoor temperatures drive up the cooling load and decrease the calculated capacity, potentially requiring a larger system.) Except for some coastal areas, California is considered a dry climate. A safe indoor wet bulb temperature is 65 degrees F. This corresponds to 78 degrees F and 50% relative humidity on the psychometric table. (Note: The higher the humidity, the higher the wet bulb temperature, and the lower the cooling capacity will be.)

[4] The wet bulb temperature (WBT) relates relative humidity to the ambient air or dry bulb temperature. When moisture evaporates, it absorbs heat energy from its environment in order to change phase (via latent heat of vaporization), thus reducing the temperature slightly. The WBT will vary with relative humidity. If the relative humidity is low and the temperature is high, moisture will evaporate very quickly so its cooling effect will be more significant than if the relative humidity were already high, in which case the evaporation rate would be much lower. The difference between the wet bulb and dry bulb temperature therefore gives a measure of atmospheric humidity.

[5] Dry bulb temperature refers basically to the ambient air temperature. It is called dry bulb because it is measured with a standard thermometer whose bulb is not wet - if it were wet, the evaporation of moisture from its surface would affect the reading and give something closer to the wet bulb temperature. In weather data terms, dry bulb temperature refers to the outdoor air temperature.

3. Airflow across the coil: This is typically the same as the design airflow for the system. It comes from the furnace airflow tables at the design static pressure (usually between 0.5 and 0.7 inches water column, 0.6 is a reasonable number to use but it depends on the specific design criteria) and ranges from 350-425 cfm per “ton” of the furnace.

The following basic concepts are good things to keep in mind when designing (or evaluating the performance of) a system:

1. As the outdoor design temperature goes ***up***, the cooling capacity of the AC unit goes ***down*** (and the load on the house goes up). This is because the outdoor air is the heat sink used by the air conditioner to dump the heat into that is extracted from the indoor air. As the outside air gets warmer, it is harder for the air conditioner to dump heat into it.
2. As the indoor dry bulb temperature goes ***down***, the cooling capacity goes ***down***. This is because it is harder to extract heat from colder air.
3. As the indoor wet bulb temperature goes ***down***, the cooling capacity goes ***down***. This is because the air has more moisture in it and cooling capacity is used up when this moisture is condensed out of the air.
4. As the airflow across the coil goes ***down***, the cooling capacity goes ***down***. This is because with less air passing across the coil, there is less opportunity for the coil to extract heat from the air stream.

Step 4. Lay Out Duct System

- Locate Forced Air Unit(s) (FAU) – The location of the FAU (furnace) depends on a variety of factors. These include such things as clearance, accessibility, duct routing, and venting. Personal preference even comes into play. An analysis was done on the impacts of energy consumption and furnace location (See Section 4.1 for details of this study) as part of the research project that included the writing of this design guide. It found that furnace location had little impact on energy consumption and effectiveness of the system. The only notable difference between a furnace in the attic and a furnace in a garage, for example, was that the furnace in the garage tended to have somewhat longer ducts, which resulted in more conductive losses/gains and more resistance to air flows. It also showed a bit more fan power consumption due to the longer duct runs, but this can be compensated for by using larger ducts, if they can be accommodated.

  First cost (due to labor) tends to be the biggest consideration in deciding where to put the furnace. The general trend today is to put furnaces in attics even though they are less accessible. Floor area, even in a garage, is at a premium. Also, since an attic location is more centrally located, it tends to have duct runs of more equal length. In other words, there are less likely to be very long duct runs. Also, venting a furnace is more straightforward from an attic than from a garage, especially in a two-story building. Furnace location (see Section 5.2) is a good discussion topic for value engineering meetings.

- Selecting and locating grilles and registers - ACCA also publishes a Manual T “Terminal Selection”, which contains some good information on the selection criteria for supply registers and return grilles. It covers such topics as register type (2-way, 3-way, etc.), pressure drop, face velocity, noise criteria, and throw distance. In residential new construction grilles are often sized based on the size of the duct serving them, which is altogether inadequate. Similarly, grille types are often selected based on personal preference and sometimes faulty reasoning. Much more thought should go into this process.

In a typical, "square-ish" room such as a secondary bedroom, there are four basic locations for a supply registers, five if you count floor registers, which are almost always located under a window. The four main locations are shown **Figure1**.

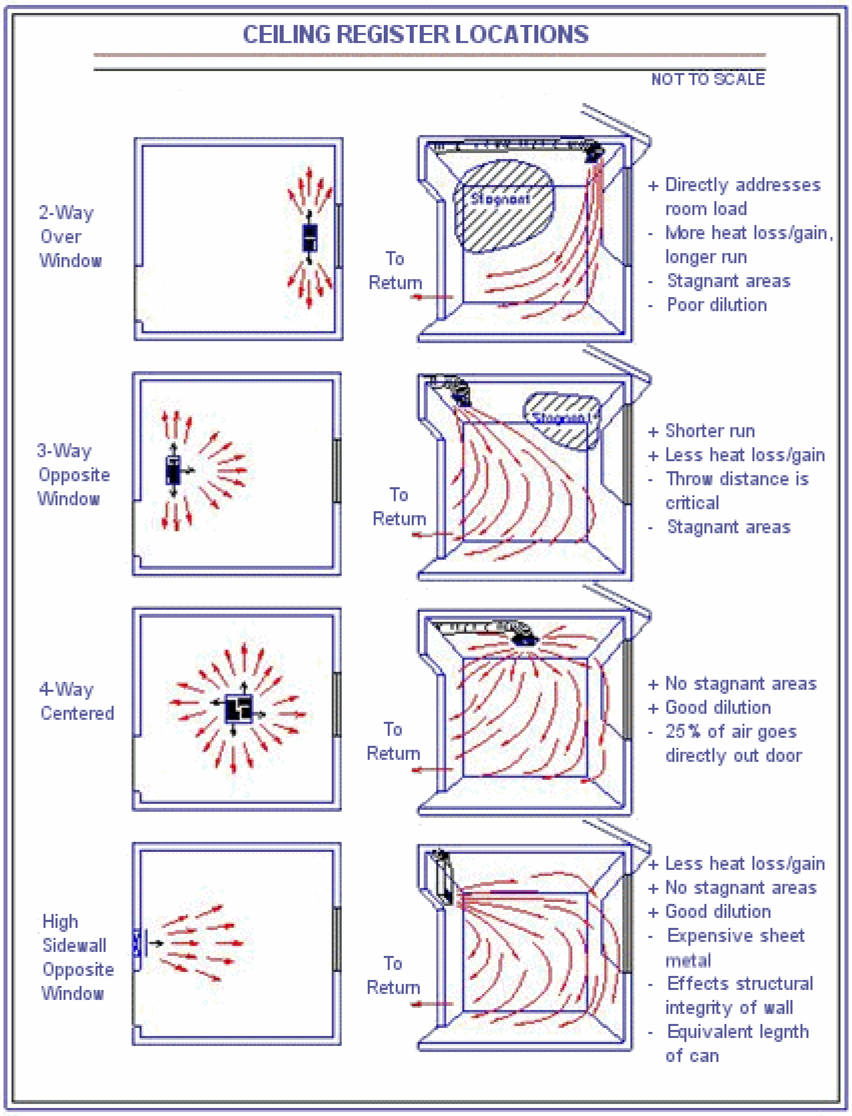

Figure 1: Ceiling Register Locations

A study on the impacts of energy consumption, comfort and supply register location was performed as part of the research project that included the writing of this design guide. This study evaluated and compared the most common of these locations: 2-way over a window, 3-way near an interior wall, and high sidewall opposite a window. See Section 4.2 for details on this study.

Given a choice, the results of this study provide important considerations. Sometimes, however, the geometry of the room dictates where you must place registers. For example, in a long narrow room where the exterior wall is on the narrow dimension, you may be forced to put a register over the window because the interior wall is too far away. Also, structural and architectural constraints such as locations of chases, floor joist directions and beams may dictate register locations. Any of the locations mentioned above can be made to work adequately well if certain considerations are made. Whatever the register location, the following considerations should be emphasized:

1. **Register over window or on exterior wall**. Use a 2-way register oriented parallel to the window/exterior wall. This will create a curtain or sheet of supply air parallel to the exterior wall and the air will naturally move away from the wall and mix with the air in the room. Using a 3-way register pointed away from the window/exterior wall will throw the back into the room too quickly and may not adequately condition the area directly in from of the window. It may also “short circuit” the airflow by throwing it back into the natural return path before it has a chance to mix with the return air. A 3-way register located near a window but pointed directly at it will blow air directly on the window. This will heat and cool the window, which serves little benefit when the purpose is to heat and cool the air inside the room. In fact, this most likely wastes substantial energy.
2. **Register near an interior wall.** Use a 1-way or 3-way register with the primary direction toward the window/exterior wall. It is important to ensure that the register’s throw distance is adequate to reach near the window/exterior wall.
3. **Register centered in a room.** Use a 4-way register. 4-way registers deliver the air equally in all four directions. Consideration must be given for interference with light fixtures or ceiling fans. If this is the case, then locate the register an aesthetically appropriate distance away from the fixture, but toward the exterior wall.
4. **High sidewall registers.** Use a bar-type register that throws air perpendicular to the face of the register. Point the register toward the window/exterior wall. As with a register near an interior wall, it is important to ensure that the register’s throw distance is adequate to reach near the window/exterior wall. Bar-type registers located in a vertical wall typically have much, much greater horizontal throw distances than 3-way or 1-way ceiling registers, and better overall air flow characteristics in general (more cfm per square inch, quieter, etc.).

The basic things to keep in mind when selecting and locating a register are:

1. Good air mixing: you want the supply air to mix in with the room air as much as possible. This is aided by directing the air in the opposite direction of the natural path back to the return (e.g., out the door).
2. Good air distribution and no stagnant areas: you want the supply air to reach all of the occupied areas of a room, especially areas close to a load (e.g., window). Throw distance is an important consideration for this.

- Determining sub-zones (trunks) and the use of balancing dampers – In production building, a designer is typically designing the system for a home that may be built in several different orientations. (See Section 4.3 for discussion on designing for multiple orientations.) The system is typically designed for the worst-case orientation with consideration for airflows needed in other orientations. The system must at least be able to be easily balanced to work in all orientations. A strategy that helps accomplish this is to divide the main zones of the house into sub-zones. These sub-zones are areas in the main zone that will be affected similarly when the house is in an orientation other than worst case. For example, **Figure 2** shows a basic single-story, single-zone house in its worst-case orientation.

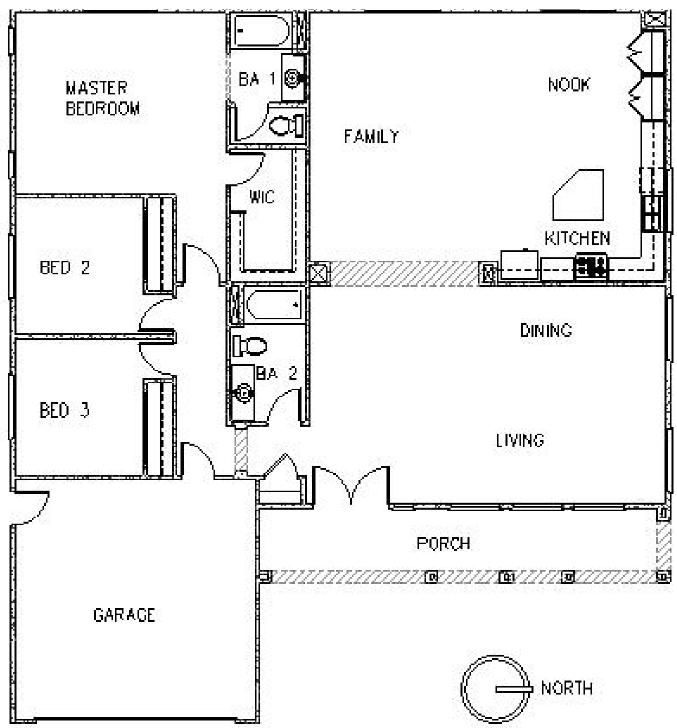

Figure 2: Example House Plan

If the house is rotated 180 degrees, bedrooms 2 and 3 will go from the south side of the house to the north side of the house and probably need much less air. If these two rooms are on the same trunk, this can be accomplished easily by using a manual balancing damper located right at the supply plenum. The family/kitchen area, living/dining area master bedroom may be treated similarly.

Figure 3 shows a reasonable layout and approach to accomplish orientation-dependent balancing using manual balancing dampers that are easily accessible.

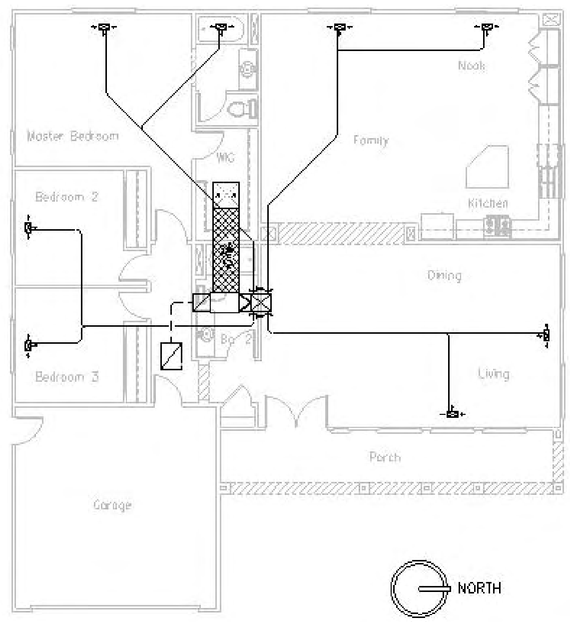

Figure 3: Example HVAC Design

- Routing ducts – The actual routing of ducts is a function of the number and location of supply registers (and to a lesser extent return grilles), architectural and structural constraints, duct size, duct length, and other practical issues such as preferred types of fittings (t-wyes vs. duct-board transition boxes). In a single-story house with ample attic space this is pretty straightforward. You can locate the registers first and then simply sketch the ducts in. In a multiple-story house, this is a much greater challenge, at least for all but the top floor. Assuming the system serving the first floor is located in the attic (a typical scenario), the ducts serving the first floor must pass vertically through the upper floor(s), and then horizontally (unless you are lucky) to the ceiling registers on the first floor. There is usually a great deal of framing (such as trusses, blocks, joists, beams, headers, and top/bottom plates) between the furnace and the register. In fact, very often the framing is the deciding factor in determining where registers are ultimately placed.

The following are some ideas for getting ducts from one point to another.

Vertical Duct Runs

Chases and voids – These are shafts between walls, either created intentionally (chases) or incidentally (voids) that can be used to run ducts from the attic, through the upper floor(s), to the lower floor(s).

Samples of Incidental Voids

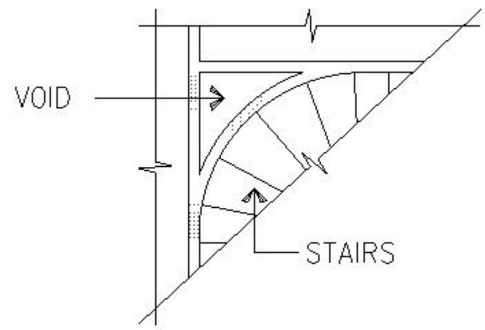

Figure 4: Example Void in Interior Stair Chase which often occurs adjacent to round room or stairways

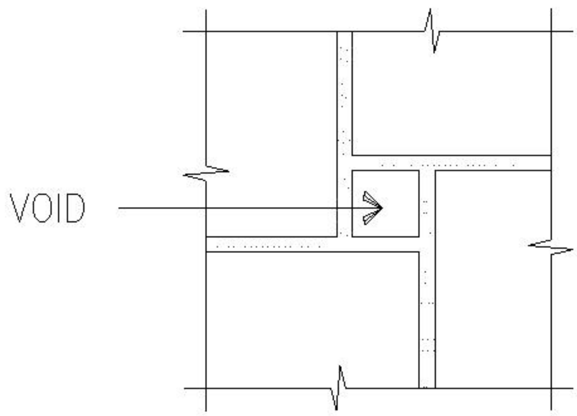

Figure 5: Example Void in Dead Space (where spaces of unequal size or shape are adjacent to each other)

Samples of Chases

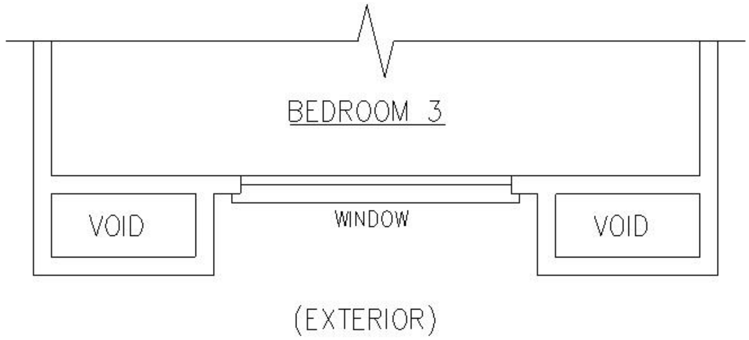

Figure 6: Example Exterior Chase
Voids can be found in the "bump outs" of exterior architectural details, but care must be taken to ensure that that particular architectural detail occurs in all elevation styles

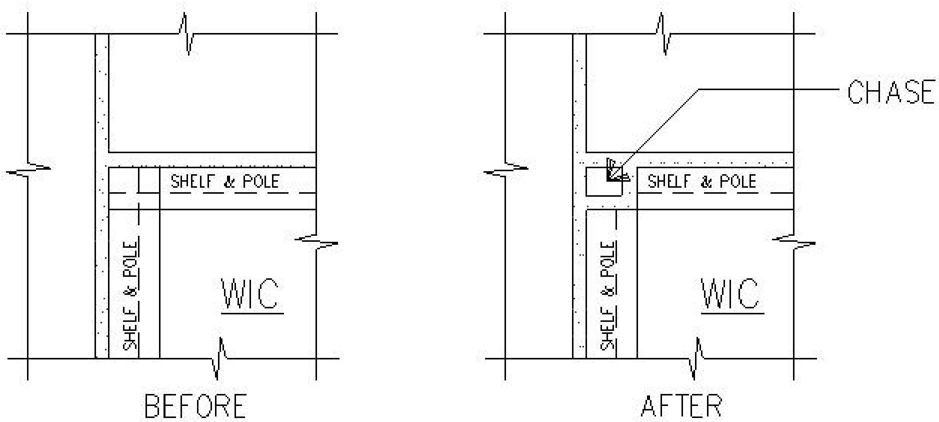

Figure 7: Walk-In Closet with Interior Chase
Chases can be created in corners of closets. The "dead corner" of a walk-in closet is an ideal place because it has minimal impact or hanging space and it provides a convenient way for the shelf and pole to be supported.

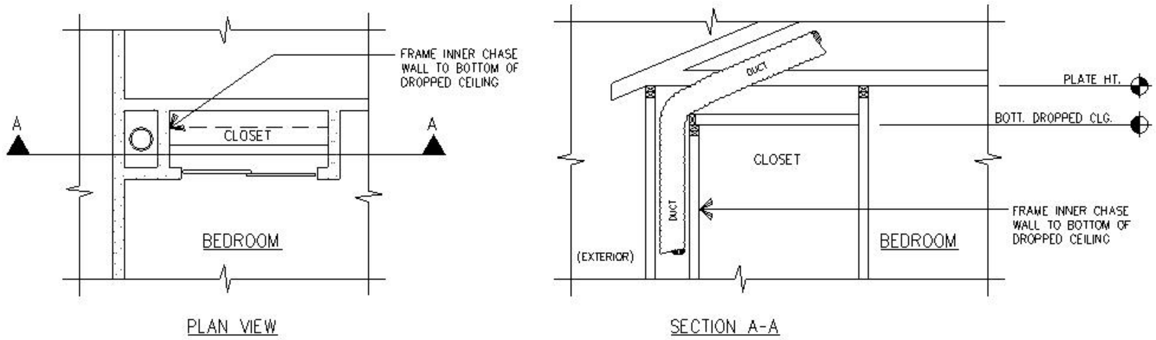

Figure 8: Closet Chase Example
Chases may also be added to either end of a "flat" closet. If given the choice, it is preferable not to have a chase adjacent to an exterior wall when the roof slopes down to that wall (i.e., hip roof), because the roof can interfere with the duct getting down through the top of the chase. If this cannot be avoided there are various ways to drop the ceiling in the closet to better accommodate the duct.

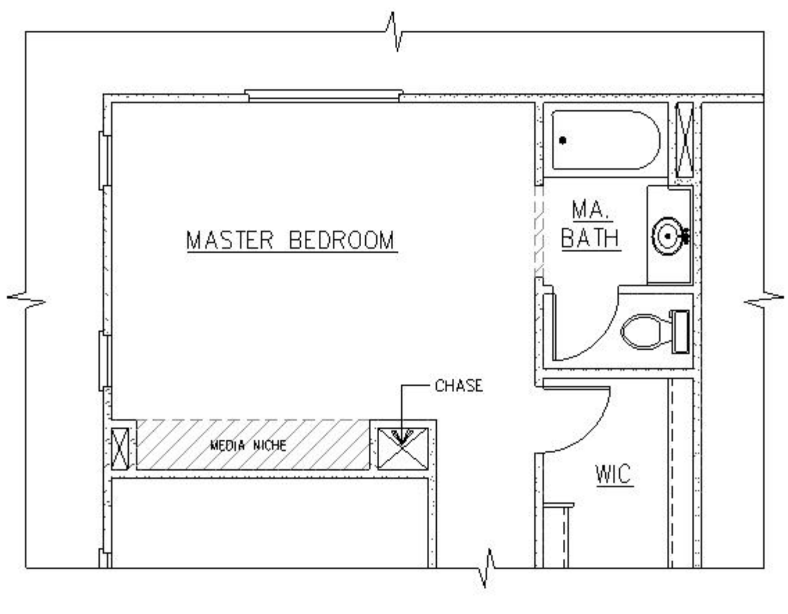

Figure 9: Media Chase
A good location for creating chases is in a media niche

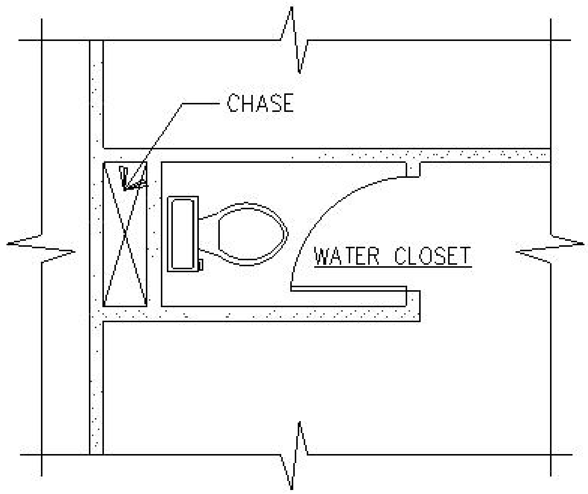

Figure 10: Water Closet Chase
Another good location for creating chases is in a water closet

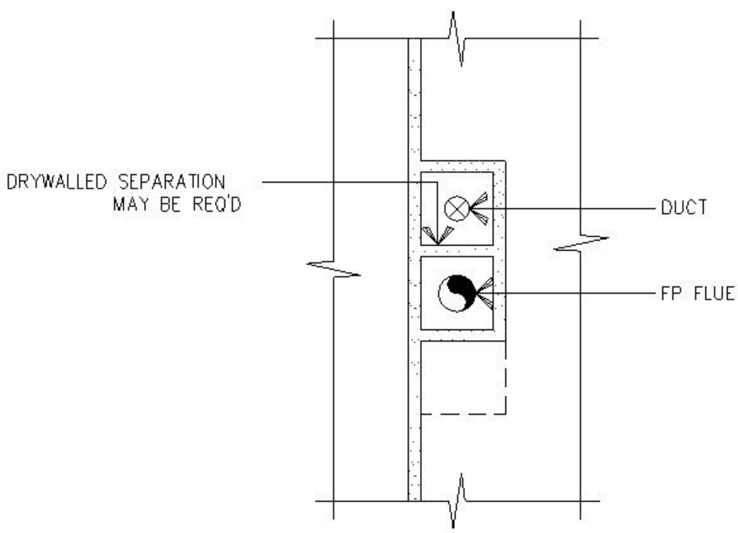

Figure 11: Chimney Chase
Chases can also be in chimneys, even as false chimneys

Riser cans – These are rectangular ducts, usually sheet metal, which fit in a wall cavity between the studs. They are relatively common, but due to potential noise problems, high resistance to airflow (high equivalent length), structural constraints, and installation costs, they are typically used only as a last resort. If care is taken in their design and construction, they can however be a viable solution to many routing problems. You should keep the following things in mind if considering riser cans:

1. Noise – Thermal expansion and contraction can cause sheet metal riser cans to make substantial amounts of noise. This is called “oil canning” and can manifest itself in clicking, popping, clanking, squeaking and other annoying noises. Many contractors have had to tear out riser cans due to customer service complaints. This is a very expensive and messy retrofit. Some contractors will flat-out refuse to install them. Avoid putting riser cans in bedroom walls if at all possible. Some precautions to preventing noise are using heavier gauge metal, caulking *between* all metal-to-metal seams, and using lead tape as a sound dampener. You might also consider using duct board rather than sheet metal. It requires a larger cross sectional area than sheet metal but is virtually silent and has much better insulation properties.
2. *High Resistance to air flow* – The available space in a typical (16” on center) 2x4 and 2x6 stud wall is 3½”x14” and 5½”x14”. The typical size riser cans used in these walls are 3”x14” and 5”x14”, which correlate to round flex duct equivalent sizes of 8” and 9”, respectively The high resistance to air flow comes not so much from the riser can itself, but from the round-to-rectangular and rectangular-to-round transitions. It is highly recommended that smooth, rounded transitions be used where possible. It is highly discouraged to simply cut a round hole in the side face of the riser can.

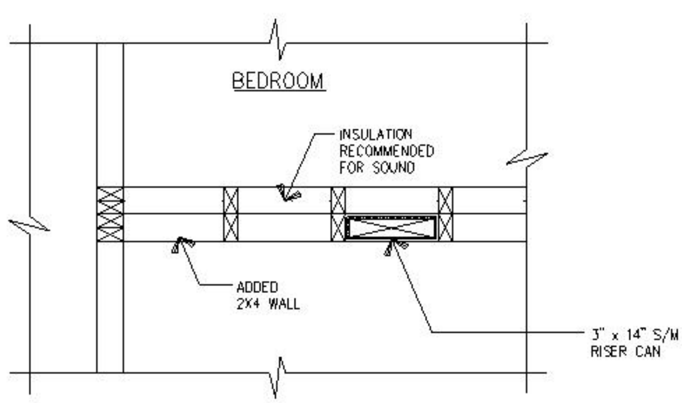

Figure 12: Riser Can Installation

Design Methodology 3.2 – ACCA Manuals J/S/D (Step 4)

3. *Structural Constraints* – Because the riser can takes up the entire stud bay in a wall it is necessary to cut out a 3½”x14” and 5½”x14” piece of the top and bottom plates. This is never allowed in a structural shear wall and rarely allowed on an exterior wall (not to mention the requirement for at least R-13 insulation in the wall and R-4.2 insulation on the riser can itself, if not located within the conditioned shell). One solution is to double the wall, install the riser can in one side, and leave the other intact.

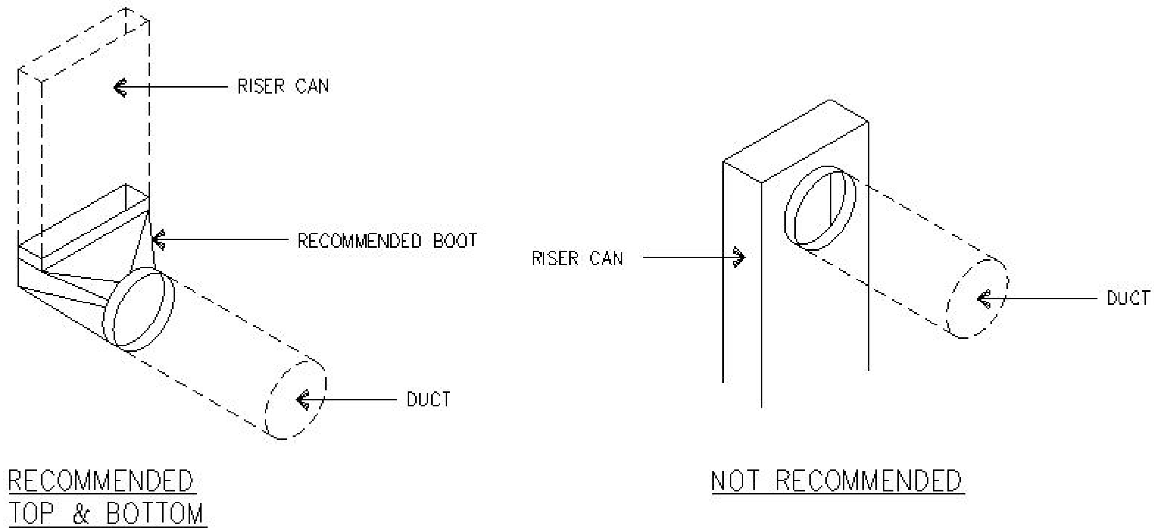

Figure 13: Riser Can Detail

Care must be taken to ensure that no truss sits on top of the stud bay that you intend to use and the stud bay must line up with the floor joists below. The use of riser cans requires careful coordination between the HVAC subcontractor, the architect, the structural engineer, and the framer.

Horizontal Duct Runs

Floor Joist Bays – These are the spaces between the parallel floor joists. California builders often use wooden “I-beam” type floor joists.

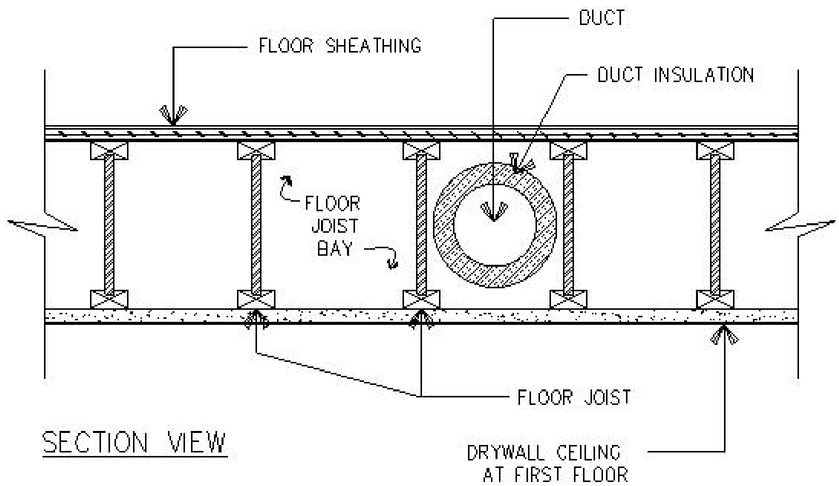

Figure 14: Floor Joist Detail

Common sizes (heights) are 12”, 14”, and sometimes 16”. While it is possible to cut holes in floor joists as big as the height of the web, there are strict limitations on this and joist penetrations must always be approved by the structural engineer. Even if you do cut the I-joists it can be difficult to pull flex duct through these holes. The other coordination that must take place is with the trades that will be sharing this space, especially plumbers. Gas piping, sanitary drains and water piping can all be run either perpendicular to or parallel with the I-joists, and can interfere with ducts.

Some builders use floor trusses rather than I-joists. These consist of diagonal framing members similar to a roof truss rather than solid webbing.

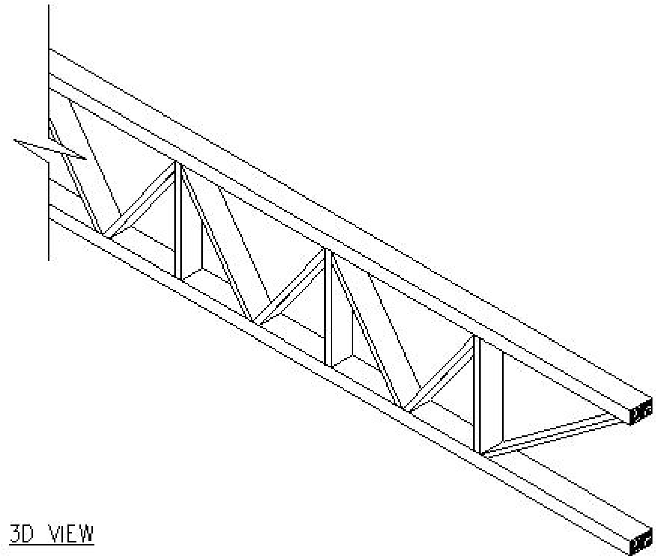

Figure 15: Floor Truss

These are much more accommodating of ducts without cutting holes but similar coordination must be made with the plumbers.

One important thing to keep in mind when running ducts in floor joist bays is that the best practice for connecting to a ceiling register may require a special transition fitting rather than simply making a 90-degree bend in the duct.

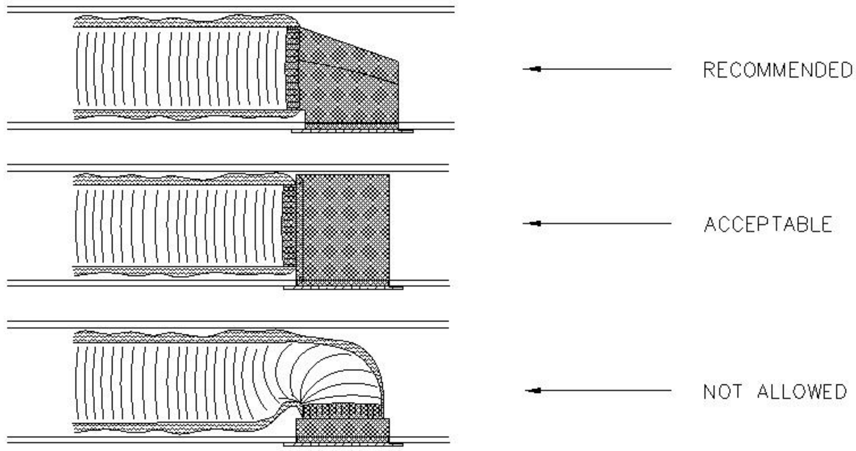

Figure 16: Duct-to-Register Connections

Dropped ceilings and Soffits – Sometimes the only way to get past a beam, wall or floor joists is to create a dropped or "false" ceiling below the obstruction that provides room to run a duct. When considering these as an option one must realize that they can be relatively expensive to build and often have aesthetic disadvantages because they lower the ceiling height. Usually lowering the ceiling in a small room such as a bathroom, laundry room, or hallway is not a big problem. The total drop required to run ducts is the outer diameter of the duct plus 3 ½" for the framing. In smaller rooms the dropped ceiling can be "flat studded" (with the 2x4's turned sideways) and then you only need to add 1 ½" to the outer diameter of the duct. Most builders and architects do not like to go with less than an 8" ceiling height, but may sometimes allow a 7' 6" ceiling height if absolutely necessary.

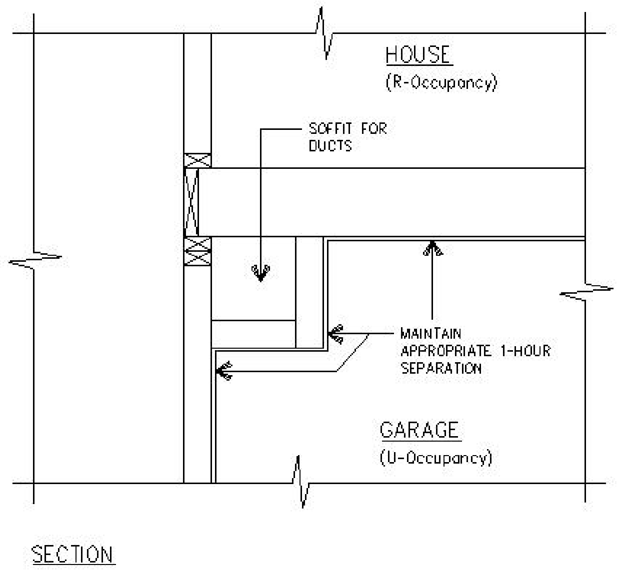

Figure 17: Soffit Chase

Soffits are similar to dropped ceilings except that they are localized and resemble a horizontal chase. Soffits provide a boxed-in area where a wall meets a ceiling as an alternative to dropping the entire ceiling. They are common in garages. When building a soffit in a garage care must be taken to maintain the integrity of the 1-hour fire separation between the garage (Group U occupancy) and the house (Group R occupancy).

Step 5. Determine Operating Conditions

- Static pressure

Static pressure is the pressure at which the fan (in the furnace, FAU, or fan coil) must operate. It is the absolute sum of the supply pressure (positive) and the return pressure (negative). The higher this pressure, the lower the airflow will be. The ACCA method allows you to size your ducts around a specified static pressure, ensuring that the fan will operate at conditions suitable to proper air flow and fan performance.

Most furnaces are rated at a nominal 400 cfm per ton. This usually corresponds to a static pressure of 0.5 inches of water columns (iwc). Because of this, many subcontractors assume that they are operating at 0.5 iwc and 400 cfm/ton just because they install a certain size piece of equipment. Many don't realize just how dependent static pressure and airflow are on how they size the ducts. If the duct sizing methodology does not properly account for pressure losses in the distribution system (e.g., coils, fittings, filters, bends, and registers), the static pressure will be too high and possibly outside the furnace manufacturer's recommended range, resulting in poor performance and premature equipment failure. In addition, the airflow will be too low, decreasing the performance of the system and possibly reducing cooling capacity to below the cooling load (in effect making the air conditioner too small).

A design static pressure that gives good airflow and results in reasonably sized ducts is 0.6 iwc. ACCA utilizes a value called "Available Static Pressure" in its important equations. It is the operating static pressure across the furnace less the static pressure drops of various items such as, the coil, filters, heat exchangers (external to furnace), registers, grilles, etc. The values for all of these pressure losses are given in Manual D.

- Total CFM

  Total Cubic Feet per Minute (CFM) can be determined by picking the design static pressure and referring to the furnace manufacturer's airflow table for the airflow at that static pressure. Use high speed for cooling. The total CFM is used to determine actual design cooling capacity. This number is distributed to each room proportional that each rooms load. As long as the ducts are sized properly, this total airflow will be met or exceeded in the field.

- Equivalent lengths

  The pressure drop of duct and duct fittings are accounted for using equivalent lengths. They are expressed in units of feet, which make sense for a length of duct but is a bit unusual for a fitting such as a t-wye or elbow. It is simply a way of accounting for pressure drop of a fitting by equating it to an equivalent length of duct. Equivalent lengths are used in the calculation for friction rate.

- Friction rates

  The friction rate is the critical factor for determining what size duct is needed to provide a certain amount of CFM. The units are inches of water per 100 feet. It describes the pressure loss for every 100 feet of duct. The equation for friction rate is fairly simple:

$$FrictionRate = (AvailableStatic\,\mathrm{Pr}\,esssure * 100)/(TotalEquivalentLength)$$

  It is used in the friction charts in Appendix A of Manual D. It is also used in duct slide rules, which are essentially the friction charts put into a slide rule or wheel format. Note that there is a different friction chart for different duct types. Chart 7 is for "Flexible, Spiral Wire Helix Core Ducts", a.k.a. "flex duct" or "vinyl flex". For a common friction rate of 0.1 and 200 cfm, the chart shows that you would need between and 8" and a 9" duct, so a 9" duct must be installed to ensure that at least 200 cfm is delivered.

  In typical California residential new construction, friction rates between 0.9 and 1.2 are most common. Looking on chart 7, this is a very small area on the chart. Also, when you consider that the typical 5-ton system only goes up to about 2000 cfm, the area of chart 7 that is commonly used is very small and the accuracy is questionable. It is recommended that a designer not using the software use a good quality duct slide rule such as the wheel-type duct-sizing calculator published by ACCA.

Several duct slide rule manufacturers recommend that you use a friction rate of 0.1. This only works if you can design the system to ensure the correct available static pressure and total equivalent length. However, simply using a friction rate of 0.1 and the room-by-room air flows generated by Manual J for a residential new construction home would be better than most rules of thumbs currently being used.

Here are some examples using the friction rate equation and friction chart:

Example 1.The available static pressure (ASP) is calculated to be about 0.25 iwc. The total equivalent lengths (TEL) are estimated to be about 250 feet. The equation for friction rate (FR) yields a value of 0.1. If 130 cfm are required, the duct calculator shows that a 7” flex duct is not adequate so an 8” must be used. In the field, it is determined that the duct cannot be run as expected and a new route is determined, which adds 30 of extra length to the duct. Will this affect the duct sizing? In this case, no, it would not. Adding 30 feet changes the friction rate to 0.09. Using the duct calculator, an 8” duct is still adequate. In fact, an 8” duct would work as long as the friction rate was 0.065 or higher. This means that up to 130 feet of extra length (actual or equivalent) could be added and the duct would still supply at least 130 cfm.

This is not always the case, however. Each duct diameter can handle a range of airflows. It depends on how close you are to the upper limit of that range. Theoretically, adding just one foot of extra length could require increasing the duct size.

Example 2: Using the same starting point as Example 1 (ASP=0.25, TEL = 250 and FR = 0.1), the builder wants to offer electronic filters and needs to know if they would affect the duct sizing. The filter manufacturer lists a static pressure drop of 0.10 iwc.

This changes the friction rate from 0.1 to $(0.25 - 0.10) * 100/250 = 0.06$, which would require that a 9” duct be used to deliver 130 cfm and because the filter affects the entire system, many other ducts may be affected as well.

This scenario assumes that the designer intends to maintain the operating static pressure of 0.6 iwc in order to maintain a certain total airflow. A different approach would be to keep the ducts the same size and let the static pressure change. For the ducts to stay the same size, the friction rate must not change. For this to be true the available static pressure needs to stay the same (assuming that the equivalent lengths are not going to change, in other words the basic duct layout does not change), which means that the starting static pressure across the fan has to go up by the same amount that the electronic filter will "use up". If we assume an operating static pressure across the fan of 0.7 iwc (0.6 originally + 0.10 for the filter), the most obvious impact will be that the airflow will go down. This can be quantified using the furnace fan flow table. What needs to be confirmed is that the airflow is still adequate to meet the sensible cooling capacity (remember that as air flow goes down, so does cooling capacity). Also, maximum air velocities must be confirmed as does the furnace manufacturer's recommended operating range for static pressure.

Step 6. Size Ducts

Room airflow should be proportional to room load. Once the room-by-room loads have been completed and the equipment has been selected, it is a simple matter to determine how much air each room or space needs. The airflow required in each room is proportional to each room's load. In other words, if the room accounts for 10% of the load it must get 10% of the airflow.

Friction rate and room airflow determine duct size. Once airflow is determined, a duct calculator (duct slide rule) can be used to determine duct size using the friction rate.

Step 7. Final Touches

Locate thermostat (refer to Section 5.8 Thermostat Location.)

Locate condenser (refer to Section 5.1 Condenser Locations and Refrigerant Lines.)

4.0 Special Design Topics

4.1 Furnace Location

As part of the task of developing this design guide, a case study was conducted to evaluate the impact of furnace and register placement on energy, comfort, and quality. The results of that study, as related to furnace location are:

- Furnace location has little impact on energy consumption and effectiveness of the HVAC system;
- One difference between an attic and a garage location is that the furnace in the garage tends to have somewhat longer ducts, resulting in more conductive losses/gains and more resistance to air flow; and
- More fan power consumption is required due to the longer duct runs, but this can be compensated for by using larger ducts, if they can be accommodated.

Detailed information on this study is available from the California Energy Commission as Attachment 2 to the Final Report for the Profitability, Quality, and Risk Reduction through Energy Efficiency program. The report is also available through the Building Industry Institute (BII) or ConSol.

4.2 Register Location

As part of the task of developing this design guide, a study was conducted to evaluate the impact of furnace and register placement on energy, comfort, and quality.

Three supply register configurations were evaluated using a computational fluid dynamics model (CFD) for both heating and cooling. These three configurations represent the most common practice in California production homebuilding: register centered in the ceiling, register over window, and high sidewall. Two return locations, ceiling and low-wall, were also evaluated.

This study used a computer simulation and is not a perfect model of reality. For example, interior furnishings were not included in the model. However, the results do provide a reasonable picture that matches well with real-world experience. Detailed information on this study is available from the California Energy Commission as Attachment 2 to the Final Report for the Profitability, Quality, and Risk Reduction through Energy Efficiency program. The report is also available through the Building Industry Institute (BII) or ConSol.

The studies indicate that the most energy efficient location, with no negative impact on comfort, is to place the supply register on a high sidewall. The study results show that this location provides the best mixing and is the preferred location. In general, high wall registers are a good idea since they allow the air stream to mix with room air above the heads of the occupants and minimize air velocity and temperature non-uniformities in the occupied part of the room. There are other considerations in selecting the supply register location and these are covered in Step 4 of the Overall Design Method.

The figure below is an example of the information generated by this study. This example shows the duty cycle for the three supply configurations with a ceiling return under cooling conditions. The duration of the HVAC ON time is notably shorter for the in-wall supply. Also note that the total duty cycle time for the in-wall configuration is nearly 25% longer than the other cases.

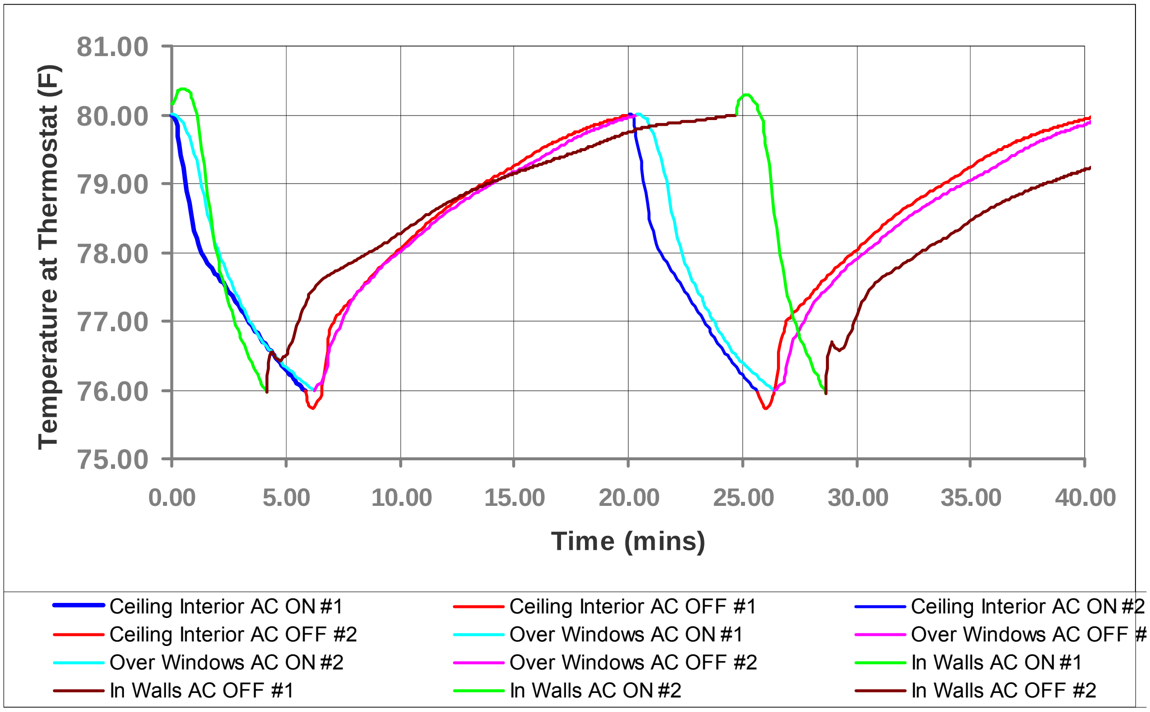

Figure 18: ON/OFF run times for three cooling configurations with ceiling returns: supply register interior ceiling; ceiling over windows; and in-wall

4.3 Multiple Orientation Designs

In a cooling dominated climate, which includes most of California, orientation has a dramatic impact on equipment sizing because most homes, especially new production homes, have the largest concentration of glazing on the back of the home. The required cooling equipment of a typical 2300 square foot home can change from 3.5-ton to 5-tons, a 30% increase in capacity, just by rotating the house from south-facing to east-facing. The orientation of a home, or more precisely its windows, is what determines the majority of its heat gain. East- and west-facing windows have the greatest heat gain because the sun is lower in the sky and shines through the window at an angle more perpendicular to the windows, increasing the amount of radiation entering the home.

Sun angle and window orientation are accounted for in the heat transfer multipliers used in the load calculation methods. Heat transfer multipliers (HTM) are values that when multiplied by the area of the window produces the heat gain of that window including conductive as well as radiative heat gains. The units are Btuh/sf. The following HTMs for a dual-pane, low-e, aluminum-framed window illustrate the impact of orientation on heat gain.

North	East/West	South	SE/SW	NE/NW
21.4	61.0	32.8	53.1	44.3

Table 2: Orientation Effect on Heat Transfer Multiplier

As this shows, each square foot of east- or west-facing glass has nearly twice the heat gain of south facing glass and nearly triples that of north facing glass. Most typical homes tend to have the majority of the glass on the back of the house. This is where most of the sliding glass doors and large family room/great room windows are typically located. When so much of the glass is loaded on one side of the house, the variation in total cooling load is much greater between orientations. Conversely, if the glazing area of a house were exactly evenly distributed on all four sides of the home, the total cooling load would be equal in all orientations. This is rarely, if ever, the case in typical production home design.

Because the majority of homes built in California are production homes using the master plan concept (several plan types used over and over, and built multiple times in various orientations), the variation between best and worst case orientation must be considered. Standard practice is to design for worst-case orientation. This is an acceptable practice for the vast majority of plans. The risk of this approach is that the equipment in the best-case orientation is oversized to a degree that can negatively impact effectiveness and efficiency.

Not only does orientation impact the total cooling load of a home, it has an even greater impact on an individual room's load. The key to a good duct design is even distribution of air in amounts proportional to the load from each room. If a house is built in multiple orientations, then each of its rooms can and will face any orientation. This means that an individual room's calculated cooling load can change by a factor of nearly three times (recall the difference between the North HTM and East/West HTM.) This, in turn means that a room's air flow requirement can nearly triple. The net result is that duct sizing requirements for a given room can change as the orientation changes, but it is extremely impractical to require different duct layouts for a single master plan depending on what orientation it is to be built in. Thus, the worst-case orientation is used even though it may not provide the best layout for all orientations.

Best Practices

The best practice for evaluating and implementing orientation dependent features in a residential HVAC design is to assess the potential equipment and duct-sizing impacts for all of the eight cardinal and semi-cardinal orientations that may be built for a given plan. To do this the designer should obtain a site/plot map of the subdivision and create a list of all possible orientations (to the nearest 45 degrees) for the project. It is possible that even in a large project the worst-case orientation may not even be plotted for one or more plan types.

Once this information has been determined, the loads can be calculated for just the orientations to be built. If the loads result a very high variation in equipment sizing (1 ton or more per system) then the designer should confer with the builder developer to see if it would be cost-effective to vary the equipment size by orientation. It is recommended that only the condenser tonnage be varied and not the furnace or coil. Leaving the furnace and coil the same for all orientations will allow the system air flow to remain essentially the same and reduces the potential need for varying duct sizes

Most manufacturers allow a 1-ton or more variation between condenser and furnace/coil. In other words, it is not uncommon to match a 4-ton condenser with a 5-ton furnace and coil, or a 3-ton condenser with a 4-ton furnace and coil. This allows the designer to have up to three levels of cooling capacity for a given duct layout. For example a single plan could utilize a 3/4/4, a 3.5/4/4 or a 4/4/4 system (condenser/coil/furnace) with sensible cooling capacities of around 26,000 Btuh, 30,000 Btuh and 34,000 Btuh. All of these systems would deliver approximately 1600 cfm.

Once the system airflow is determined the duct sizes can be determined and evaluated for all orientations. Currently it is a very tedious exercise to do this because it must be done manually. Eight duct tables must be printed out and each trunk and branch evaluated for the maximum size.

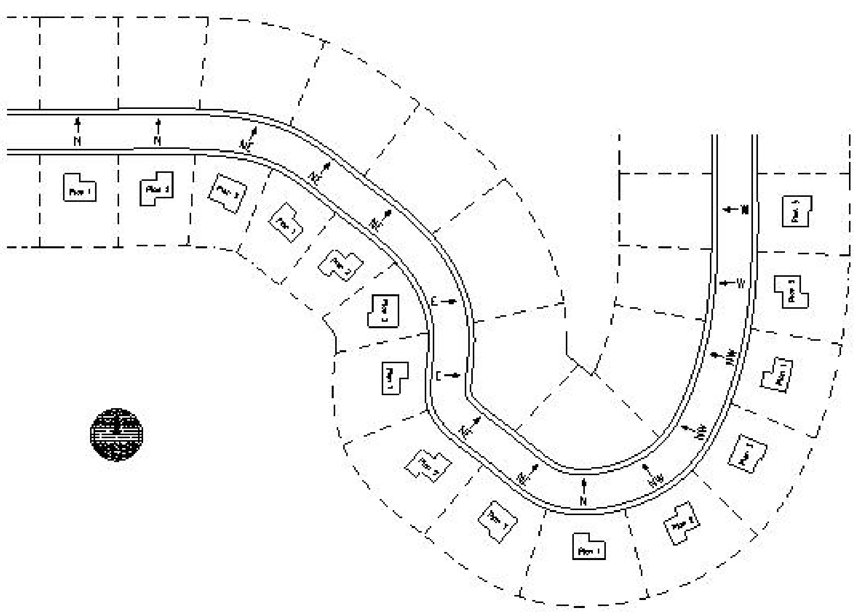

Figure 19: Sample Site Plan with Varying Orientation

Example:

The following example is for a 30-lot subdivision with three plan types. Plan 1 is a 2000 square foot single-story home. Plan 2 is a 2400 square foot two-story home. Plan 3 is a 2850 square foot two-story home. Each plan is to be built 10 times as shown below.

Table 3: Subdivision Site Plan Orientation

Lot	Plan	Front Orientation	Lot	Plan	Front Orientation
1	1	N	16	1	SW
2	2	N	17	2	SW
3	3	NE	18	3	SW
4	1	NE	19	1	S
5	2	NE	20	2	S
6	3	E	21	3	S
7	1	E	22	1	SE
8	2	NE	23	2	SE
9	3	NE	24	3	SE
10	1	N	25	1	E
11	2	NW	26	2	NE
12	3	NW	27	3	NE
13	1	NW	28	1	N
14	2	W	29	2	N
15	3	W	30	3	E

The loads and equipment sizing can be tabulated as shown below.

Table 4: Plan 1 Loads and Equipment Sizing

Plan1			
Orientation	**Lots**	**Sensible Load (Btuh)**	**Cond/coil/furnace (tons)**
N	1, 10, 28	29067	3.5/4/4
NE	4	33201	4/4/4
E	7, 25	33071	4/4/4
SE	22	26871	3.5/4/4
S	19	25067	3/4/4
SW	16	26721	3.54/4
W	-	33972	4/4/4
NW	13	32871	4/4/4

Table 5: Plan 2 Loads and Equipment Sizing

Plan 3			
Orientation	**Lots**	**Sensible Load (Btuh)**	**Cond/coil/furnace (tons)**
N	2, 29	34999	5/5/5
NE	5, 8, 26	38071	5/5/5
E	-	37088	5/5/5
SE	23	33281	4/5/5
S	20	33018	4/5/5
SW	17	33697	4/5/5
W	14	40021	5/5/5
NW	11	35881	5/5/5

Table 6: Plan 3 Loads and Equipment Sizing

Plan 3					
		Downstairs System		**Upstairs System**	
Orientation	**Lots**	**Sensible Load (Btuh)**	**Cond/coil/furnace (tons)**	**Sensible Load (Btuh)**	**Cond/coil/furnace (tons)**
N	-	22555	3/3/3	28900	3.5/4/4
NE	3, 9, 27	24082	3/3/3	30721	2.5/4/4
E	6, 30	23621	3/3/3	30020	3.5/4/4
SE	24	21921	3/3/3	27222	3.5/4/4
S	21	21002	2.5/3/3	26199	3.5/4/4
SW	18	20822	2.5/3/3	26789	3.5/4/4
W	15	25017	3/3/3	31110	3.5/4/4
NW	12	23221	3/3/3	29181	3.5/4/4

Plan 1: Since only lot 19 had a load low enough to make it a 3/4/4, it would be recommended that a 3.5/4/4 be used here and on the other lots where appropriate. The other lots would get 4/4/4 systems.

Plan 2: The sizing shown is a reasonable breakdown. Note that there is no such thing as 4.5-ton system. If there were, there would be three sizes of systems.
Plan 3: The sizing shown is a reasonable breakdown. Note that all of the lots had the same equipment sizing upstairs. This is because the second floor typically has a more even window distribution.

Note that this approach would result in the opportunity to downsize 10 out of 40 condensers by at least one-half ton at a substantial cost savings.

An example of how the front orientation of the house affects the duct layout for an example house is tabulated below. The numbers are the diameter of the branch duct serving the rooms shown. The numbers vary because as the house turns the orientation of each room changes, which changes each room's load and subsequently, its air flow.

Trunk ducts are not shown but are affected similarly.

Table 7: Branch duct diameters under multiple orientations

Room	N	NE	E	SE	S	SW	W	NW	Max
Living	7	6	6	7	7	7	6	7	7
Dining	7	6	6	7	7	7	6	7	7
Living	7	6	6	7	7	7	6	7	7
Family	7	7	7	7	7	7	7	7	7
Family	7	7	7	7	7	7	7	7	7
Kitchen	7	7	7	7	7	7	7	7	7
Nook	7	7	7	7	7	7	7	7	7
Den	6	6	6	6	5	6	6	6	6
Bath3	4	4	4	4	4	4	4	4	4
Laundry	5	5	5	5	5	5	5	5	5
Mbed	8	8	8	8	7	8	8	8	8
Mbath	6	6	6	6	6	6	6	6	6
Mwic	4	4	4	4	4	4	4	4	4
Bed2	6	6	6	6	6	6	5	6	6
Bath2	4	4	4	4	4	4	4	4	4
Bed3	6	6	6	6	6	6	6	6	6
Bed4	6	6	6	6	6	6	6	6	6

As one can see, the required duct sizes never vary more than one size for any particular room. Also, many rooms are unaffected by orientation. This particular house had a fairly good fenestration distribution. As glazing gets more loaded on any single side, the variation in duct sizes gets greater.

Designing to the maximum size for each room does not result in a large amount of change for most homes but it does insure that all rooms will have ducting large enough to provide its fair share in all orientations.

Balancing

Once the home is built according to the mechanical plans, the next challenge is to properly balance the system. Because the system is designed to accommodate any and all orientations, there will be some adjustment necessary for each and every home by means of in-line manual balancing dampers. In most cases, these adjustments will be very small.

The number of manual balancing dampers can be reduced and the locations can be more accessible if the duct system is laid out carefully. A simple four-trunk system can work adequately for most homes. The house is divided into four sub-zones. Sub-zones are one or more adjacent rooms whose loads are impacted in a similar fashion as the house rotates and are otherwise thermodynamically similar. Each sub-zone is served by a supply trunk that is controlled by a single balancing damper. The more complex that a home's floor plan is, the more sub-zones it will need.

It is common practice to leave the entire manual balancing dampers fully open until the homeowner has lived in the home for a while. If areas of excess air flow (over conditioning) occur the dampers controlling those areas can be closed down. It is usually not necessary to precisely balance a home to the exact design flows because individual homeowner preferences and use pattern sometimes outweigh the design assumptions.

4.4 Zonal Control

Zonal control typically refers to a single HVAC system with 2 or more independent zones. This independence is accomplished through a control panel and motorized dampers that send air to the zones that require it and limit or stop altogether the air going to zones that do not require it. Each zone has its own thermostat.

As homes get more and more efficient, the size of a home served by a single system gets larger and larger. The larger a house is, the more difficult it can be to adequately control the indoor temperature with a single thermostat. Zonal control is an effective way to add zones without the expense of multiple systems. Zonal control should be used for comfort only. It will not reduce the load of the envelope nor will it increase the total capacity of the system at peak conditions.

In deciding whether zonal control is needed or not, the designer must consider the diversity of the home. For example a 3000 square foot 1 story house that is sprawling and spread out with many wings and "appendages" would be more likely to need zonal control than a house with the exact same cooling load but that is larger but more compact.

The designer must also consider the relative airflow requirements between the two zones as they change between heating and cooling modes. For example a two-story house may require more air downstairs than upstairs in heating mode but that may reverse in cooling mode. Because the ducts are sized for cooling air flow (due to the higher fan speed) the home may need to be balanced seasonally by closing dampers and/or registers in order to get adequate comfort distribution between the upstairs and downstairs in heating mode. This is not an unreasonable expectation but a zonal control system would help alleviate this effort. If a zonal control is not installed in this situation, the occupants should be informed of the seasonal balancing requirement and educated on how to perform it.

For more discussion on zonal control, see Section 3.2.1 The Overall Design Method, Step 1.

4.5 Window Loads

Windows account for a very large fraction of cooling and heating loads in a building. The glazing type, the amount of glazing, insulation and shading devices used all contribute to a significant portion of the overall cooling loads (mainly solar gains) and heating loads (conductive heat losses) in a building.

As an example, a 1940 square foot home with an 18.6% window-to-wall ratio was analyzed in 4 climate zones (zones 7, 10, 12, and 14) and four orientations using Micropas[6]. Heating loads attributed to glazed surfaces remained approximately equal (16.5% - 18.0%, depending on climate zone). Cooling loads varied between 32.0 % and 41.3% depending on both orientation and climate zone. Because windows represent such a high percentage of heating and cooling loads, it is important that their impact be accurately quantified.

4.5.1 Heating loads from windows

In calculating heating load, only conductive heat loss is calculated because solar gains reduce the net heat loss and actually assist the heater. Heat loss calculations are therefore based on nighttime conditions when there are no solar gains. A simple UAΔT calculation is used:

$$q = UA\Delta T = \frac{A}{R}\Delta T$$

In this equation, “U” is the overall window u-value including glass and frame; “A” is the rough opening of the window; and “ΔT” is simply the difference between the indoor and outdoor winter design temperatures.

The ability of the UAΔT formula to predict actual heat losses is limited by the accuracy of the input parameters. Area is not a problem since it is a fixed value. U-value is limited by the accuracy of generic window descriptions to accurately reflect the actual U-values of all the different brands of windows that may meet the generic definition. If the make and model of the window to be installed is known and it is a window that has been tested to National Fenestration Rating Council (NFRC) standards there will be a reasonably accurate U-value that can be used for that window. Even tested values have their limitations. U-value within a particular make and model of window will vary by window size because the frame-to-glass ratio changes. As a reasonable simplification and to keep the cost of testing windows down, only a single “common” size window is tested and that tested U-value is used for all windows in that product line.

The actual ΔT (difference between the indoor and outdoor winter design temperatures) value can vary somewhat from the number used in the calculations. Of course, outdoor temperature varies with season and time of day, but the ΔT used in the calculation can be wrong even at the time when they are *supposed* to be correct. To understand this, it is important to understand how these temperatures are selected.

The indoor design temperature is the desired indoor temperature. It can be thought of as the thermostat set point. However, even when a thermostat reads a certain temperature, 70 degrees for example, it will not be 70 degrees everywhere in a house. There can be places in the house where the temperature is substantially higher or lower than 70 degrees. For example, supply air registers are commonly placed directly above or below windows. When the heater is operating, hot air of up to 150 degrees is blowing on or near the window. With an

[6] Enercomp, Inc

outdoor temperature of 30 degrees, this yields a real ∆T of 120 degrees. If the design temperatures were assumed to be 70 degrees indoors and 30 degrees outdoors, the real ∆T is three times the design ∆T of 40 degrees, tripling the heat loss.

The outdoor design temperature is a statistically derived temperature based on historical temperature data collected at a nearby data collection point. There are hundreds of these throughout the state. Because it is a statistically derived value, rather than the coldest temperature on record, for example, it is understood that this temperature will, by definition, be exceeded a certain number of hours per year. The statistical number that is used is determined to be one that makes these excessive temperatures (i.e., temperatures colder than the assumed outdoor design temperature) an acceptable occurrence. Variations from this data can be caused by microclimates or normal (or abnormal) macro climatic changes and will throw off the *statistical* accuracy load calculations, but problems with the indoor temperature as described above will have an even greater impact in the statistical accuracy of the loads. In other words, the actual number of hours that the real heat load exceeds the calculated heat load may be dangerously high; the heater may be unable maintain a comfortable indoor temperature during long periods of extreme cold when reality exceeds the design margin.

4.5.2 Cooling loads from windows

Cooling loads largely consist of the incoming solar radiation through the windows and conductive heat gain. Heat gain calculations are made up of a conductive component, very similar to heat loss calculations, but the heat is traveling into the house rather than out of the house. Heat gain calculations are susceptible to the same factors that make heat loss calculations inaccurate. They are also made up of a much larger radiant component. This is the heat gain associated with sunlight passing through the windows and is effected by a very large number of factors, only a few of which are accounted for in the load calculations, for simplicity reasons. Also, for simplicity reasons, the load associated with sunlight is averaged throughout the day. This is called "diversity" and has to do with the fact that the sun travels across the sky and the actual load on rooms in a house will not match this averaged value. Some calculation methods allow a "peak load" to be calculated when appropriate. This is the highest cooling load that will occur at any time during a given day.

Factors that effect window heat gain and loss, calculated and actual, are summarized below:

- Window area – total and for each orientation. Because windows are a less efficient part of the building shell than walls, floors or ceilings, the more windows you have, the higher the heating and cooling loads will be. Some windows have a higher heat gain per square foot because of their orientation. See the orientation discussion in the next section.
- Location – The geographic location of the house can impact the cooling loads associated with windows other than simply affecting the outdoor design temperatures. The latitude of house determines the angle of sun and sun's path across the horizon. Local factors can affect the intensity of sun. These include cloud cover, pollution, and humidity.
- Window solar heat gain coefficient (SHGC). This is a property of the particular window and is defined as the ratio of the solar heat gain entering the space through the fenestration area to the incident solar radiation. Solar heat gain includes directly transmitted solar heat and absorbed solar radiation, which is then radiated, conducted, or convected into the space. The SHGC of a window is affected by the number of panes, thickness and clarity of the glass panes, any tinting or other special coatings,

thickness of the frame, mullions and other details. SHGC can be dramatically improved through the use of special coatings that block certain wavelengths of light, particularly those responsible for heat gain.

- U-value. The U-value describes a window assembly's ability to transmit heat conductively and is a function of the properties of both the frame and glass panes. Like the SHGC, it can either be a generic number based on the general description of the window or it can be a National Fenestration Rating Council (NFRC) tested value.
- Emissivity of window. This number describes the amount of heat that is emitted from a window due to its being warmer than the surroundings. The lower the level of emissivity, the more efficient the window. Emissivity levels generally range from 0 to 1 and can be dramatically improved through the use of special coatings. Emissivity is usually accounted for in load calculations by adjusting the window U-value.

◊ Shading. Shading devices are either interior or exterior. They can be further subdivided into removable (or otherwise controllable) and fixed. This controllability is important because they can assist in reducing heat gain in cooling mode but they can also reduce heat gain in heating mode when heat gain may be desired (i.e., on a cold but sunny day). An additional type of exterior shading includes those that are not necessarily integral to the building and are categorized as "adjacent structures".

◊ Interior shading devices. Curtains, blinds, roller shades and other such interior window treatments, though often aesthetic in purpose, can have a substantial impact on heat gains when used correctly. The more opaque and reflective the material, the more it will reduce solar heat gain. For example, a white, opaque roller shade will reduce solar gains better than a dark drape. One disadvantage of interior shading devices is that solar gains have already entered the space by the time they are intercepted by the interior shade device. This heat is trapped between the shading device and the window. Some of the heat is reflected or radiated back out of the window, but much of it remains inside.

◊ Exterior shading devices. These are devices that are part of the building or window assembly and include overhangs, bug screens, solar screens, and awnings. Overhangs are often overlooked as very efficient devices for reducing loads and energy consumption. Architectural fashion typically outweighs their practicality. Though a permanent component of the building they can be designed to maximize the benefit in the summer and minimize their impact in the winter. Bug screens are not considered an energy device but can have a noticeable impact on the SHGC of a window assembly. Sun-screens (a.k.a. solar screens) can be a very cost effective means of reducing heat gain. Also, because they are removable, their impact in the heating season can be minimized. Awnings behave as an overhang and are also seasonally removable.

◊ Adjacent structures. These can include buildings, trees, fences, and terrain such as hills. They may have a substantial impact on actual loads but are rarely accounted for in the calculations. They most commonly shade a window but can have the opposite impact of reflecting light into a window. In this regard, the ground adjacent to a building is considered an adjacent structure because it can reflect additional light into a window. Imagine the difference in solar gains between a house surrounded by lush lawn and a house surrounded by a bright white concrete surface.

Best Practices

Best practice for new construction loads would be to model no internal or external shades in the load calculations, but to model overhangs because they are fixed architectural features of the building that are unlikely to be removed. Internal and external shades are frequently left open, left off or otherwise removed. To assume that they are in place when calculating cooling loads is risky. Some designers believe that interior shades should be assumed closed. This results in dramatically lower solar gains and cooling loads. However, if the cooling equipment is sized under these assumptions, the home will not cool properly on hot days if the homeowner does not close the drapes. While closing drapes on a hot day is a praiseworthy behavior, this design philosophy is not consistent with the expectations of most homebuyers.

The approach used for modeling features in Title 24 compliance is usually appropriate for load calculations in new construction. In Manual J, Version 8, the designer should always assume NFRC rated windows will be used in new construction. If non-rated windows are used default performance values can be used that are consistent with Title 24 calculations but entered in the load calculations as though they are rated windows. Assume the same minimum features necessary for compliance, if slightly better features get installed, fine. If, however, better features get installed than were assumed in the load calculations, there is a small risk of over sizing the equipment to a point of reduced energy efficiency and conditioning performance. However, the potential expense to a builder of under sizing equipment is far greater than that of over sizing.

Performance values used in the load calculations (U-value, SHGC, and shading coefficient of screens and other shading devices) should be consistent with those used in the Title 24 calculations. The current computerized versions of Manual J, Version 8, for room-by-room loads and the current methodology used by Micropas for whole-house loads do a very adequate job accounting for loads associated with windows. It is a useful exercise to compare the Micropas load to the total of the room-by-room manual. This provides a trustworthy check to help ensure that no calculation errors have been made. This is another reason why it is important to use the same window performance values in both calculations.

For duct sizing it is appropriate to assume worst-case window conditions. For example a home may have a window that could be replaced by an optional sliding-glass door, which substantially increases the glazing area and the subsequent load on that room. Sizing the duct for the worst case (with the sliding-glass door) ensures that the duct serving the room will accommodate the amount of air required for the higher load. When the higher load does not occur, it is a simple matter to damper down the airflow if it is excessive. Again, the potential cost of underestimating the load is far greater than overestimating it.

4.6 Duct Loads

Duct leakage rates of up to 45% were not uncommon in *new* homes built and tested prior to the late 90's. This is a direct loss of concentrated energy; the heated or cooled air is dumped directly into unconditioned spaces (e.g., supply leaks into attics), or conditioned air is displaced by unconditioned air (return leaks in attics or garages).

Manual J does a reasonable job of accounting for duct leakage loads, given a known leakage. The problem lies not in quantifying a known leakage rate but in estimating the actual leakage amount. Prior to construction and/or without actually testing the system leakage, it is very difficult to predict. Field-testing has shown that using very similar installation protocols on two similar houses can still result in leakage rates that are vastly different. Even the brand of furnace can affect the leakage rate by one-third or more.

Title 24 software assumes that the system is "tight" if it is known that the home will be tested, and repaired if the leakage is greater than 6%. If the home is subsequently tested and the leakage is indeed less than 6% then the designer can rest assured that the load calculations are valid. However if the system is not tested and the leakage is significantly more than 6%, the equipment may be undersized. Commonly, if the system is not going to be tested, current practice is to assume that the system is "guilty until proven innocent" – i.e. it leaks more than 6%. The system is assumed to be "typical," with a leakage of 22%. If the designer assumes this higher leakage and the installer does an excellent job of installing the system, the system may potentially be oversized.

Even testing a system using common procedures such as a duct blaster test does not guarantee that the actual load of the duct leakage will be accurately estimated. Limitations of current duct leakage tests result in substantial variances between tested leakage and actual leakage. These limitations include the inability of the test, using common practices, to distinguish between supply and return leaks and the inability to identify the location of a leak, which may be located in a very high pressure part of the system (near the fan) or in a very low pressure part of the system (near a register or grille). Note: The duct blaster test pressurizes the entire system to the same pressure level and thereby treats all leaks equally.

Best Practices

The best way to minimize variances between estimated and actual leakage is to assume that the leakage is attainably low and then make the appropriate effort to ensure that it is installed that way. More sophisticated test methods may improve the accuracy of measuring leakage, but the tighter the systems become, the law of diminishing returns makes more testing expensive and unnecessary.

4.7 Two-story Considerations

As homes become more and more efficient, their heating and cooling loads decrease. The result of this is that larger and larger homes are being served by single HVAC systems. In a typical California subdivision that offers four floor plans, three will be two-story homes. Many of those are served by a single system, a very common design in California new construction and one that tends to have many customer service complaints related to temperature variations (stratification) in the home.

Many HVAC subcontractors believe that a two-story home with a single system must have a substantial amount of the return air taken from the first floor. While there is no evidence to support this, HVAC subcontractors will insist that architects and builders go to great effort and expense to accommodate a relatively large return duct and grill to the first floor. Some designers believe that a return in the ceiling of the second floor is adequate as long as the downstairs supply ducts are properly sized.

There is also much debate and disagreement over the proper location of a thermostat in a two-story home served by a single system. Some designers locate it upstairs because heat rises and that is where the most cooling is needed (cooling emphasized). Others locate it downstairs because in the winter the first floor tends to be colder and that is where the most heating is needed (heating emphasized).

As part of the task of developing this design guide, a study was conducted to evaluate the impact of the number and locations of returns and the placement of the thermostat in a two-story home served by a single HVAC system.

Three return configurations were evaluated for cooling using a computational fluid dynamics model (CFD). These three configurations were designed to address the common practices in California production homebuilding:

- Case 1: split returns upstairs and downstairs; thermostat upstairs
- Case 2: return upstairs; thermostat upstairs
- Case 3: return downstairs; thermostat downstairs

The figure below is an example of the information generated by this study showing the temperatures and duty cycles for the three configurations. Case 2 (return upstairs/thermostat upstairs) and Case 3 (return upstairs/thermostat downstairs) cycle twice as often as Case 1(returns upstairs and downstairs/thermostat upstairs). Case 1, with split return upstairs and downstairs, provides a better mixing of air, delaying the return to ambient temperature.

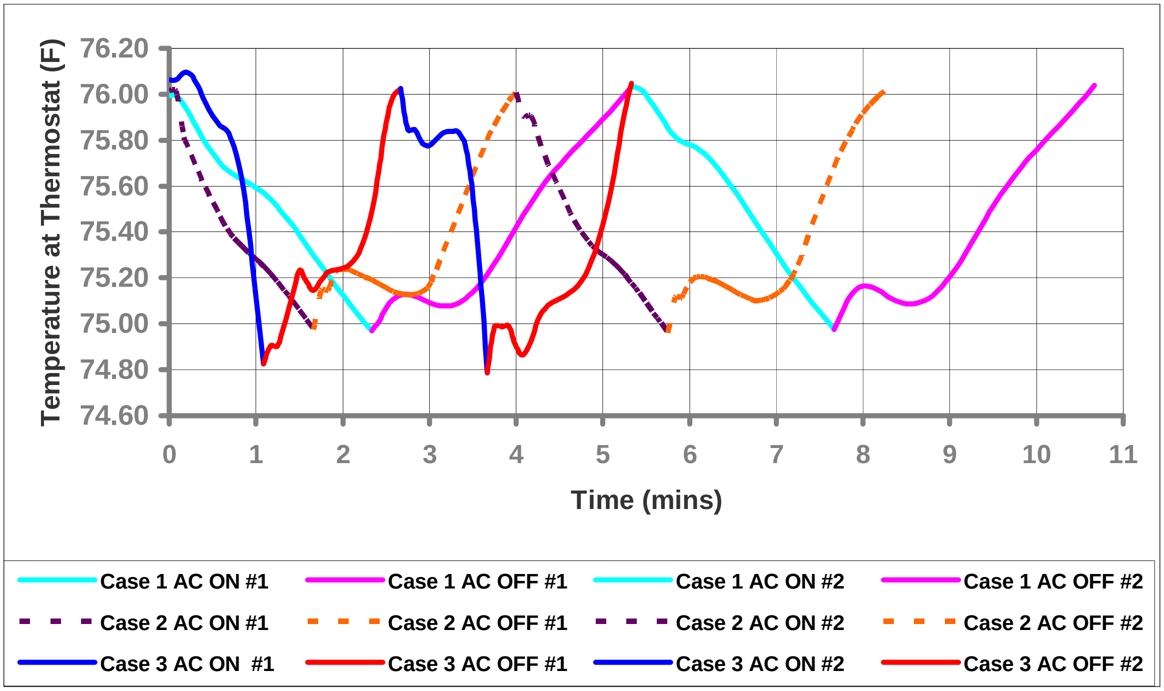

Figure 20: Comparison of HVAC Cycle Time for Case 1, 2 and 3

Recommendations

For the two-story application, installing returns both upstairs and downstairs provides longest duty cycles with good comfort and air quality. While the total On-Times are nearly equal for all cases, the two-return design causes the least system cycling, less startup demand, and less wear on the HVAC equipment.

The thermostat located downstairs, farthest from the return, has the most negative effect on duty cycle. Not only does it generate more startup demand for each cycle, this configuration requires frequent system cycling, causing additional equipment wear, and should be avoided.

5.0 Other Mechanical Design Related Issues

Many HVAC-related items should be coordinated in a meeting between stakeholders early in the design process, such as at a value-engineering meeting. The following checklist is provided for use at such a meeting. A detailed discussion of each item follows.

A value engineering meeting checklist

- Condenser locations and refrigerant lines
- Furnace location and clearance
- Attic access locations
- Flue (b-vent) locations and routing
- Duct sizes and locations (soffits, joist bays, chases and drops)
- Supply register locations
- Return air locations
- Dryer vent routing
- Combustion air supply
- Thermostat location

5.1 Condenser Locations and Refrigerant Lines

From a design/performance standpoint, condensers and refrigerant lines are a simple concept: obey the minimum clearances and the maximum line lengths and the design should work fine. From an installation/practical standpoint, they can be a real headache. The noise they generate can be real problem. Bedroom walls should be avoided when running lines and locating condensers. Some manufacturers make special noise reduction kits that can help avoid or resolve noise problems. Vibrations transferred from the compressor through the refrigerant lines can be transferred and magnified by walls. Care should be taken not to let the lines come in direct contact with framing. Always use some sort of gasket or cushion. With the higher insulation requirements for refrigerant lines (Title 24 requires R-3 minimum insulation on the suction line, see section 2.5.5 of the Residential Manual) it is recommended that a 2x6 wall or some sort of a chase be provided to run the lines. Some builders have been known to run a 6”x6” framed chase down the exterior of the house.

Minimum clearances for condensers may vary by manufacturer but they are typically 6” on one side, 30” on the service access side, 12” on the other two sides, and 48” above. (Consult specific manufacturer’s specifications.) They should also be 24” apart if more than one is used. These clearances can sometime cause problems in narrow side yards. Minimum access requirements must be verified with the builder and can sometimes vary by lot. A condenser works best in a cool, shady spot with good air circulation, but this is usually an impractical request in production homes.

Typically, most manufacturers do not recommend that you exceed refrigerant line lengths of 75’, some even say 50’. Some allow lengths up to 175’ using a special kit. The impact on capacity and efficiency must be taken into account. Always refer to specific manufacturer’s requirements.

The electrical contractor also needs to know exactly where the condensers are located so the power and disconnect can be properly located.

5.2 Furnace Locations (also see previous discussion)

Most single-family detached homes in California are designed with the furnace(s) located in the attic. This is because the attic provides a good central location with good clearance and good direct access to get ducts to most rooms, which reduces overall duct length. Furnaces in garages are the next most common location. Furnaces in closets are rare because of the restrictive clearances and service access to the unit, plus the valuable floor area it takes up. Even if a furnace has a minimum clearance of 0", code requires at least 3" for removal and service. Occasionally, homes with very low-pitched roofs or floors that are difficult to access will have furnaces in a closet. They are most common in attached and multi-family projects.

The popularity of low-pitched roofs in current architecture has made it more of a challenge to locate furnaces in attics. Clearance must be verified if it appears that it will be a tight fit. There are always unexpected items that will use up whatever clearance you thought you had. Careful coordination in the field is critical. <UBC/UMC access and clearance>

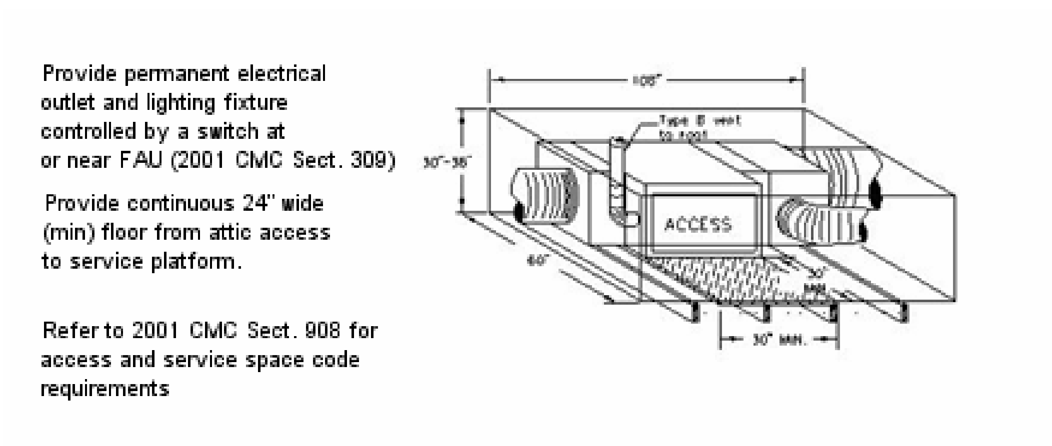

Figure 21: FAU Clearance

The truss designer and structural engineer need to know where the furnace platform will be located and how big it needs to be (how many units, up flow or horizontal, etc.) so the trusses can be properly designed and the weight of the furnaces can be accounted for. The electrical contractor will need to provide electricity, a disconnect, a light and a light switch per the Uniform Building Code.

5.3 Attic Access Locations

The location of the attic access is especially important if the furnace is located in the attic. Section 908.0 of the UMC requires a minimum 30”x30” opening and passageway but allows for an opening as small as 22”x30” as long as the largest piece of equipment can be removed through the opening. Sometimes this is not very easy to determine because more than just the dimension of the opening and dimension of the furnace needs to be considered. Notice that it does not say, “as long as the larger piece of equipment can *fit* through the opening”. Remember that just because a furnace has a dimension of 21”x29” does not mean that it can be *removed* through a 22”x30” opening. You have to consider the length of the furnace, the attic access’ proximity to trusses and the roof decking, and the angle that the furnace must take to be removed.

In case of a hip roof, the attic access must also be located far enough away from the exterior of the building so that there is a full 30” clearance above it. There should be a 30”x30” passageway all the way to the furnace and then there should be a 30”x30” work area in front of the furnace. The way it is sometimes described is that you need to be able to push a 30”x30”x30” cardboard box from directly above the access all the way to the furnace (but not more than 20 feet) and park it right in front of the furnace.

It is allowed to locate the furnace immediately next to the attic access as long as the 30” cube is provided and the unit can be served from the access (e.g., standing on a ladder).

<UBC attic access locations, UMC 908.0 and 304.1 (clearances)>

5.4 Flue (b-vent) locations and routing

Furnaces located in an attic can usually be easily vented straight up through the roof unless the aesthetics of the vent termination is an issue. B-vents can angle 60 degrees from vertical one time or 45 degrees from vertical more than one time, and must run in a generally vertical direction. Clearance from framing is very important. <UMC chapter 8>

The vent termination must also be at least 8 feet from any vertical wall, including a turret, tower, upper floor, etc. If not, it must extend above that wall.

A 90% or condensing furnace may provide a suitable alternative to a B-vent. Condensing furnaces and boilers are the most energy efficient units on the market today, potentially 10-15% more efficient than conventional units. The combustion process produces gas by-products that include water vapor and carbon dioxide. In a conventional heating system, these by-products are vented out of the house. Condensing systems cool the combustion gases to the point that water condenses and the process releases additional heat that is captured and distributed to the home. The extracted heat lowers the temperature of the combustion products to a point that any of the approved types of pipe can also be used for venting combustion products outside the structure. The combustion-air and vent pipes can terminate through a sidewall or through the roof when using one an approved vent termination kit, consistent with local codes.

5.5 Duct sizes and locations (soffits, joist bays, chases and drops)

Two-story homes with the furnaces in the attic pose a special challenge: how do you get ducts from the upper attic down past the second floor rooms to rooms on the first floor? Sometimes it is easy and sometimes it is impossible. Typically, in a two-story house the upstairs is predominantly bedrooms. Bedrooms have closets. Despites the protests from the architect, closets are a good place to locate a vertical chase that cuts through the second floor. The “dead” corners of walk-in-closets work very well because they don’t use up too much hanging space and they provide a nice wall for the shelves and poles to die into. Care must be taken when using vertical chases adjacent to an exterior wall. The slope of the room can severely restrict access to the top of the chase in the attic. It may be necessary to drop the ceiling adjacent to the chase and “low-frame” the interior wall(s) of the chase. See Section 4, Chases and voids, for more discussion on chases.

It is recommended that chase locations be conveyed to the architect so they can be put on the official floor plans and coordinated with the framer. Nothing ruins a good chase faster than dissecting it with a roof truss or floor joist. It may be useful to explain to the framer that two 6” ducts are not the same as one 12”duct!

Soffits and dropped ceilings are often necessary evils for getting ducts to a particular location if it cannot be accomplished using floor joist bays alone. The total depth of a drop (reduction in ceiling height) is typically the diameter of the duct to be run, plus 4-6 inches to allow for framing and duct insulation. Sometimes this can be reduced if “flat framing” is allowed and the insulation can be compressed, which is allowed if the drop is between conditioned spaces. Generally speaking, the amount of clear space required for a duct of a given diameter is the nominal diameter plus two inches. Less is feasible if the insulation can be compressed 5 but it can make it much harder to install.

5.6 Duct Installation, Insulation, and Location

Ducts carry air from the central heater or air conditioner to each part of the home and back again. Unfortunately, ducts can waste a significant amount of energy and money due to improper installation and poor materials. A number of factors can affect the functioning of ducts, including:

5.6.1 Duct Sealing

Typically, ducts are so leaky that more than 35% of the conditioned air is lost before it arrives at the target room the duct is trying to reach. This means that more than 20% of the energy used to condition the air is wasted. Improved duct performance depends on sealing the seams between the ducts. Duct tape, which is commonly used, does not adequately seal the joints nor does it last very long. UL listed tapes or duct mastic should be used to seal all joints and seams in the ductwork.

The following link, "Procedures for HVAC System Design and Installation" (http://www.thebii.org/hvac.pdf) lays out the criteria and procedure for designing and installing a quality HVAC system. It provides the "Details for an HVAC System: Material, Fabrication, Design, and Installation, and Performance Testing" that will help to insure a lasting, tight installation (aka "tight duct protocol").

5.6.2 Duct Location and Insulation

Builders often place ducts in spaces that homeowners do not heat or cool, such as attics, crawlspaces, garages, or unfinished basements. The extreme temperatures that can occur in these spaces (attic air in the summer can reach above 150^{o}F) will affect the temperature of the air moving through the ducts into the home.

As air moves through the ducts, the temperature of the duct location, either hot or cold, affects the air temperature. To reduce these temperature variations, ducts need to be insulated. The R-value of ducts in unconditioned space is R-4.2. There is a compliance credit for higher R-values.

If the ducts are located in the living area of the home, which tends to remain at a reasonable temperature, then the need for insulation is reduced. However, some insulation is still needed to ensure that the conditioned air is delivered at the desired temperature and to prevent condensation on the duct walls

Installing ducts within the conditioned area of a home will substantially reduce duct air losses "Ducts in Conditioned Space" minimizes conduction and radiation losses. In addition, air that leaks out of the ducts goes into conditioned spaces. There are a number of publications available on this topic. For example: Locating Ducts in Conditioned Space, from the EnergyStar Program.

5.7 Combustion air supply

Furnaces (and any gas burning appliances) need to be provided with combustion air. This is air that provides the oxygen for the combustion of the gas. If a typical furnace is located in a closet, that combustion air should be ducted. Chapter 7 provides some options for providing these ducts and openings. This can be quite a challenge if the furnace closet is deep within the building because two ducts are required and they can be 6 or even 8 inches in diameter and made of sheet metal. Some higher efficiency condensing furnaces can solve a lot of combustion air problems because they provide their own combustion air through PVC piping as small as 2" and as long as 70-80 feet. They also vent through a similar pipe and the termination of the vent and combustion air can be through the same concentric terminal.

Furnaces located in a garage may not need special combustion air vents if the volume of the garage is adequate to meet the definition of an unconfined space. Be sure to count all gas burning appliances when making this determination.

Furnaces located in attics are typically assumed to have adequate combustion air as long as the attic is adequately ventilated based on the attic ventilation requirements of section 1505.3 of the UBC. This is because the venting area required for attic venting is much greater than that for combustion air. However, despite the logic that if combustion air can be ducted from an attic to a closet (section 703.1.2 of the UMC) then you should be able to locate the furnace in that attic, some building departments require that the attic meet the high/low requirements for combustion air. Some building departments go even farther and require that combustion air venting be installed *in addition to* the normal attic venting. They do not understand that the air that serves to vent the attic can do double duty and also be combustion air.

5.8 Thermostat location

Properly locating a thermostat can be as much a Zen art as a science. There are 10,000 bad places to put a thermostat in a house. Your job is to choose the “least bad” of those places. Some places to definitely avoid are exterior walls, locations that get direct sun, locations that a supply register will blow on, locations near an exterior door or window, walls adjacent to or near a fire place, etc.

Remember that a thermostat does two basic things: It turns the system ON and it turns the system OFF. The best location for turning the system on may not be the best location for turning the system off. The best place for turning the system off is usually under or near the main return grill. This is because when the system is running, the return is pulling air from all over the house and it is a good sampling of the average temperature in the house. When the system shuts off this may not be a very good place to sense the average temperature in the house.

As part of the task of developing this design guide, a study was conducted that included evaluating the locations of the thermostat in a two-story home served by a single HVAC system. Reference Section 4.7 Two-story Considerations for recommendations on thermostat placement. Detailed information on this study is available from the California Energy Commission as Appendix C of Attachment 2 to the Final Report for the Profitability, Quality, and Risk Reduction through Energy Efficiency program. The report is also available through the Building Industry Institute (BII) or ConSol.

5.9 Ventilation and Indoor Air Quality

In the old days, the wind and other uncontrolled forms of air leakage ventilated buildings. Today, people no longer accept such cold, drafty houses. Houses are now expected to be cozy, draft free and energy efficient and a tight home is fine, as long as it comes with good ventilation and indoor air quality. Modern building materials tend to make newly constructed homes much tighter than old ones. Plywood, house wrap, better windows, caulk and expanding foam are a few examples of common products that tighten a house. Research has shown that some builders inadvertently build houses much tighter than intended.

If too little outdoor air enters a home, pollutants can accumulate to levels that can pose health and comfort problems. Unless they are built with special mechanical means of ventilation, homes that are designed and constructed to minimize the amount of outdoor air that can "leak" into and out of the home may have higher pollutant levels than other homes. However, because some weather conditions can drastically reduce the amount of outdoor air that enters a home, pollutants can build up even in homes that are normally considered "leaky."

In any home, uncontrolled air leakage is an unreliable ventilator. The best way to ensure adequate ventilation is to install some type of automatically controlled ventilation system and there are several choices for the builder to consider, depending on local codes and costs.

5.9.1 Indoor Air Quality

Indoor air quality (IAQ) refers to the physical, chemical, and biological characteristics of air in the indoor environment within a building or an institution or commercial facility. These characteristics can be influenced by many factors, even though these buildings or facilities do not have industrial processes and operations found in factories and plants.

Factors that influence indoor air quality include:

- Inadequate supply of outside air.
- Contamination arising from sources within the building (e.g., combustion products including carbon monoxide and environmental tobacco smoke; volatile organic compounds from building materials, fabric furnishings, carpet, adhesives, fresh paint, new paneling, and cleaning products; ozone from office equipment).
- Contamination from outside the building (e.g., ozone, carbon monoxide, and particulate matter) through air intakes, infiltration, open doors, and windows.
- Microbial contamination of ventilation systems or building interiors.

Here are a few important actions that can make a difference in indoor air quality:

- Provide proper drainage and seal foundations in new construction. Air that enters the home through the foundation can contain more moisture than is generated from all occupant activities.
- Become familiar with mechanical ventilation systems and consider installing one. Advanced designs of new homes are starting to feature mechanical systems that bring outdoor air into the home. Some of these designs include energy-efficient heat recovery ventilators (for example, air-to-air heat exchangers).

- Ensure that combustion appliances, including furnaces, fireplaces, woodstoves, and heaters, are properly vented and receive enough supply air. Combustion gases, including carbon monoxide, and particles can be back-drafted from the chimney or flue into the living space if the combustion appliance is not properly vented or does not receive enough supply air. Back-drafting can be a particular problem in weatherized or tightly constructed homes. Installing a dedicated outdoor air supply for the combustion appliance can help prevent backdrafting.

5.9.2 Ventilation Systems

Ventilation systems serve three important functions:

- Expelling stale air containing water vapor, carbon dioxide, airborne chemicals and other pollutants.
- Drawing in outside air, which presumably contains fewer pollutants and less water vapor.
- Distributing the outside air throughout the house.
- Controlling system operation automatically.

The basic ventilation system has two elements. First, there's a fan to pull stale air out. Pickup points for stale air are generally in high moisture areas, such as the kitchen, utility and bathrooms. Second, there should be a makeup air supply. Outside air is delivered around the house, with one supply point in each bedroom and at least one in the living area. The suction, also called negative pressure, created by the exhaust fan pulls air through the house from supply points to the pickup points. By properly locating the pickup and supply points, you make outside air travel through the entire house.

Mechanical ventilation systems are designed and operated not only to heat and cool the air, but also to draw in and circulate outdoor air. If they are poorly designed, operated, or maintained, however, ventilation systems can contribute to indoor air problems in several ways.

Advanced designs of new homes are starting to feature mechanical systems that bring outdoor air into the home. Some of these designs include energy-efficient heat recovery ventilators (also known as air-to-air heat exchangers).

5.9.3 Ventilation and Indoor Air Quality Standard

The ASHRAE Standard 62-1999 — Ventilation for Acceptable Indoor Air Quality, specifies the minimum ventilation rates and indoor air quality that will be acceptable to human occupants. It is intended to minimize the potential for adverse health effects and applies to all indoor or enclosed spaces that people may occupy except where other applicable standards and requirements dictate larger amounts of ventilation. Release of moisture in residential kitchens and bathrooms, locker rooms and swimming pools is included in the scope of this standard. The standard also includes Addenda A.

A copy of this standard can be found on-line using the following link:

ASHRAE Standard 62-1999 — Ventilation for Acceptable Indoor Air Quality:

ASHRAE recommends a ventilation rate of 0.35 ach (air changes per hour) for new homes, and some new homes are built to even tighter specifications. Particular care should be given in such homes to prevent the build-up of indoor air pollutants to high levels. An alternate measure of controlled ventilation rate is to use 15 cubic feet per minute (cfm) per person. A household of four would require 60 cfm. (You can quickly estimate the airflow in cfm needed to meet the 0.35-ach requirements by dividing the floor area in square feet by 20.)

Appendix A: References & Resources

ACCA Manual D ACCA Manual J ACCA Manual S	Residential Load Calculations See: http://www.acca.org/tech/manualj/ (this page contains links for Manual D and S)
Title 24	Energy Efficiency Standards for Residential and Nonresidential Buildings Publication Number: 400-01-024, August 2001, available online at: http://www.energy.ca.gov/title24/2001standards/index.html
Right-Suite	Wrightsoft, http://www.wrightsoft.com/
Elite	Elite Software, http://www.elitesoft.com/ 2700 Arrington Road, College Station, Texas 77845
Micropas	Enercomp, Inc http://www.micropas.com/

Appendix B: Glossary

ACCA Trade Association	Air Conditioning Contractors of America see <http://www.acca.org>
ASHRAE Trade Association	American Society of Heating, Refrigerating and Air-Conditioning Engineers see <http://www.ashrae.org>
ASP	Available Static Pressure
BII	Building Industry Institute
Btuh	British Thermal Units per Hour
CAD	Computer Aided Design
Cardinal Orientations	North - South - East - West
CEC	California Energy Commission
CFD	Computational Fluid Dynamics
CFM	Cubic Feet per Minute
CMC	California Mechanical Code
DBT	Dry Bulb Temperature – relates to ambient air temperature
DX	Direct Expansion
Elite	Elite Software - software package featuring CAD-based take-offs for windows and wall areas
Energy Pro	Common Title-24 compliance software using ASHRAE method
F	Fahrenheit
FAU	Forced Air Unit
FR	Friction Rate
HTM	Heat Transfer Multiplier
IAQ	Indoor Air Quality
iwc	Inches of Water Column
Load Calculations	Building's design calculated heat loss and heat gain
Manual D	ACCA Manual which includes duct sizing
Manual J	ACCA Manual with room-by-room loads
Manual S	ACCA Manual with detailed information for determining heating and cooling capacities of various types of equipment
Manual T	ACCA Manual with selection criteria for supply registers and grilles
Micropas	Common Title-24 compliance software using ASHRAE method
NFRC	National Fenestration Rating Council
Right-Suite	Wrightsoft - software package featuring CAD-based take-offs for windows and wall areas
SHGC	Solar Heat Gain Coefficient
SMACNA Trade Association	Sheet Metal and Air Conditioning Contractors' National Association see <http://www.smacna.org>
SPCDX	ASHRAE Publication
TEL	Total Equivalent Length
$UA\Delta T$	U = Window U value, A = Rough opening of window, ΔT = Difference between indoor & outdoor winter design temperature
UBC	Uniform Building Code
UMC	Uniform Mechanical Code
WBT	Wet Bulb Temperature – relates relative humidity to ambient air temperature