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ENERGY
COMMISSION

RESIDENTIAL CFD STUDY

TECHNICAL REPORT

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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, "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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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.

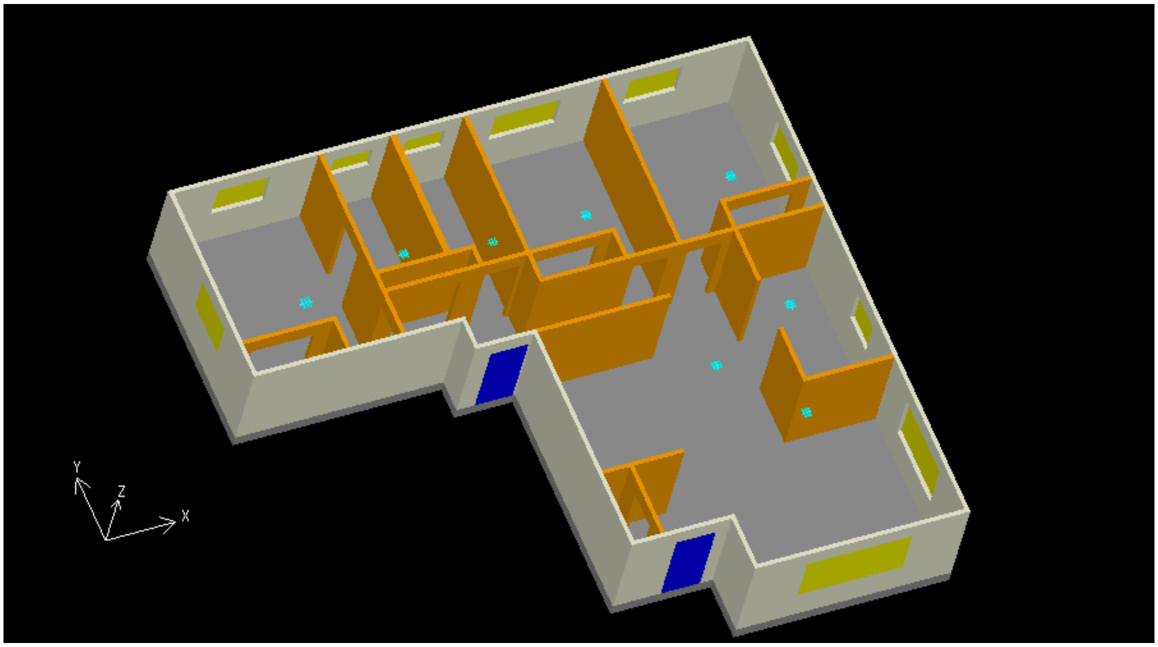


Figure 1: Solid model view of study house

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.

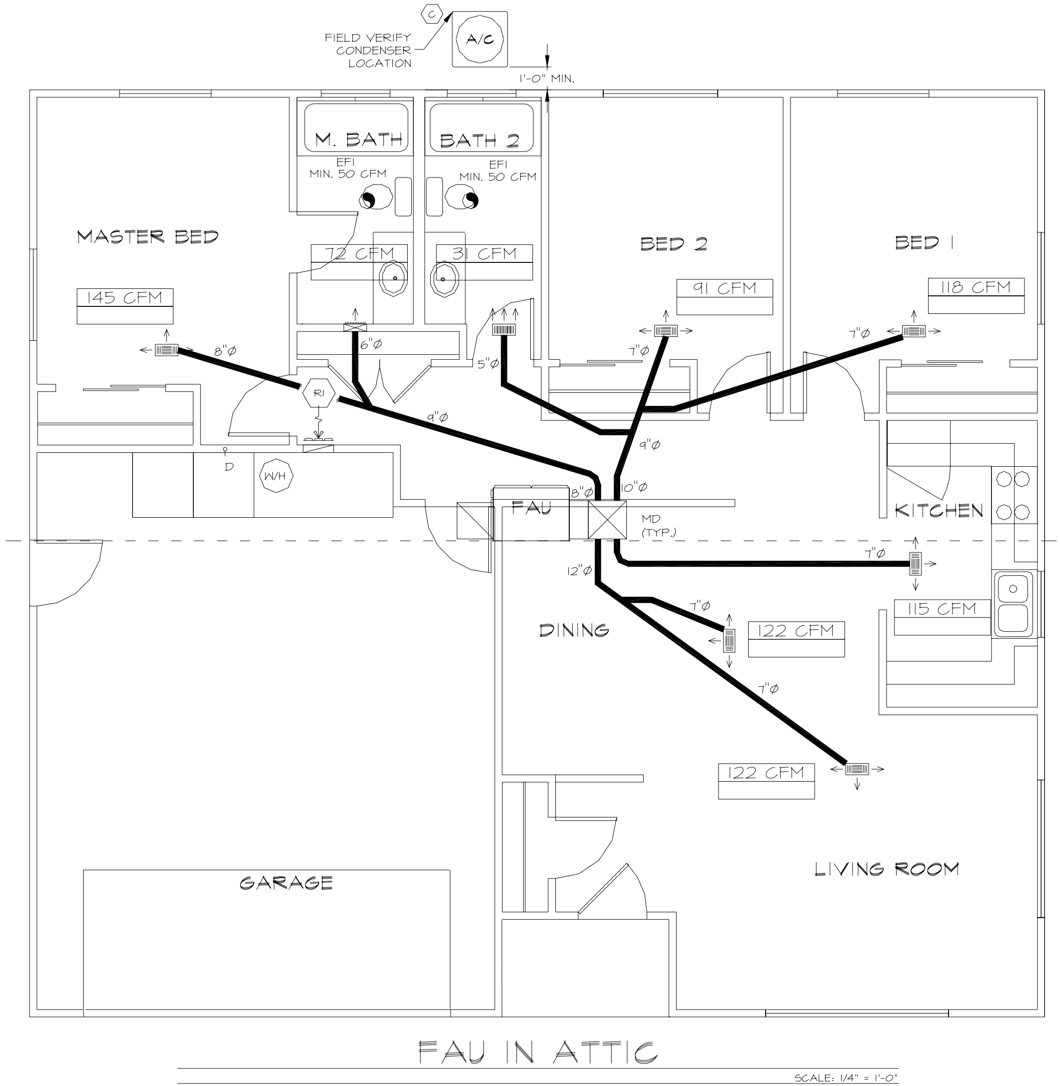


Figure 2: FAU in Attic, Ceiling Registers with Short Duct Runs

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).

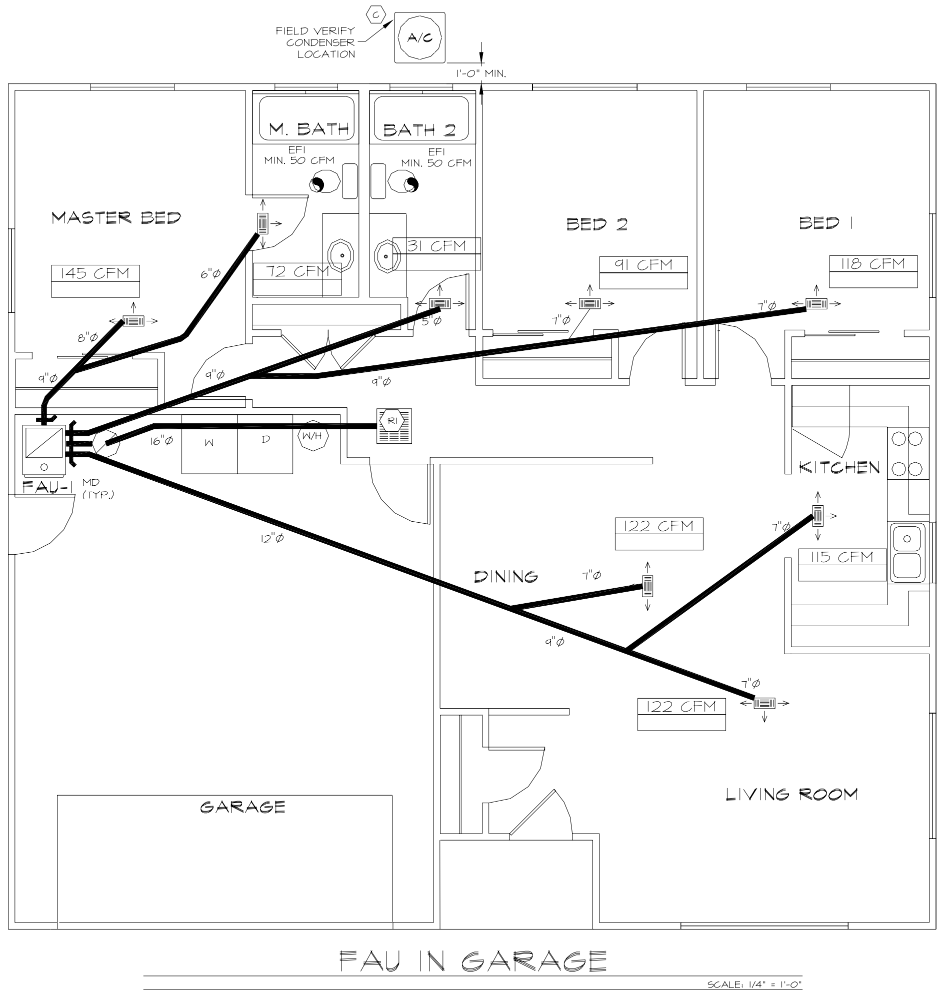


Figure 3: FAU in Garage, Ceiling Registers with Long Duct Runs

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.

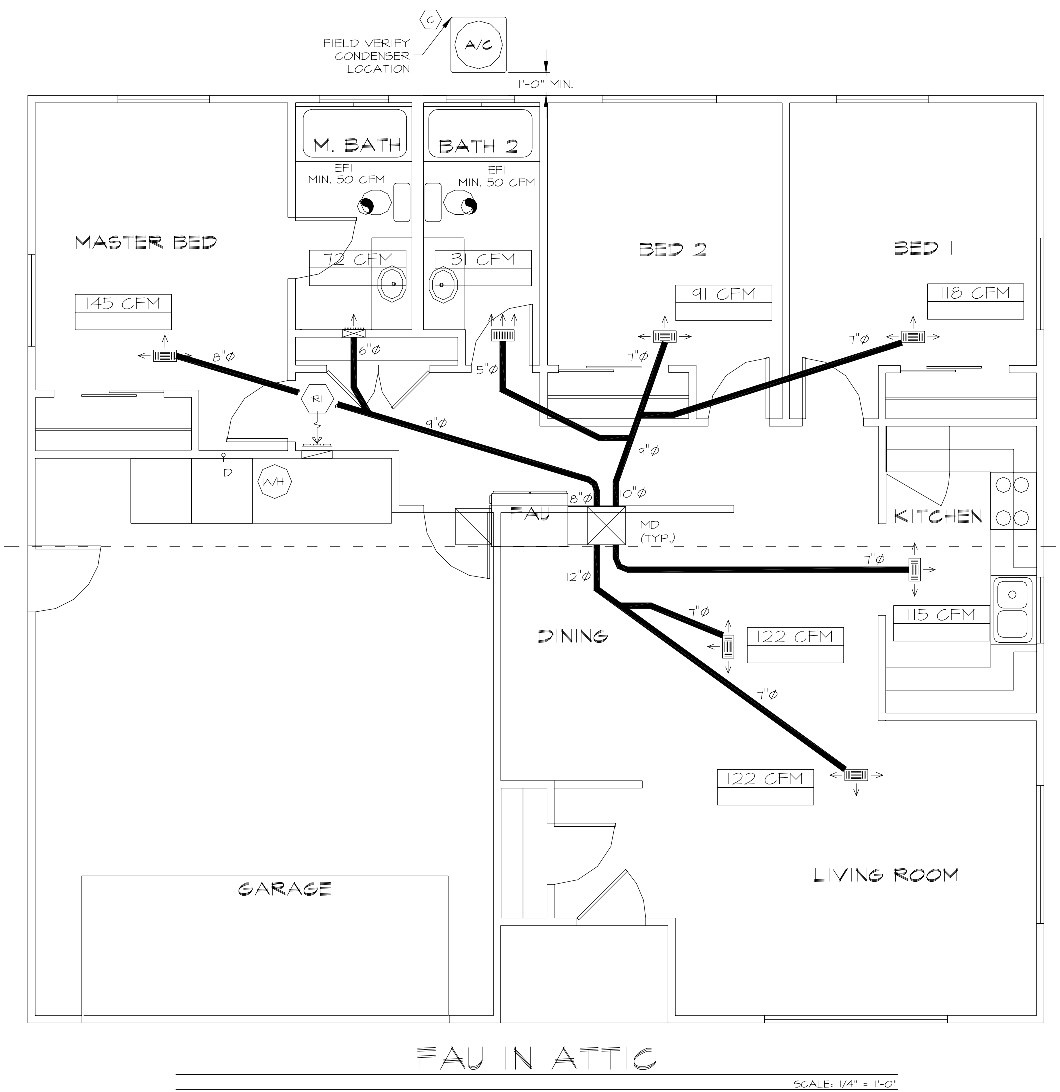


Figure 4: Case 1 – Ceiling Interior Registers

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

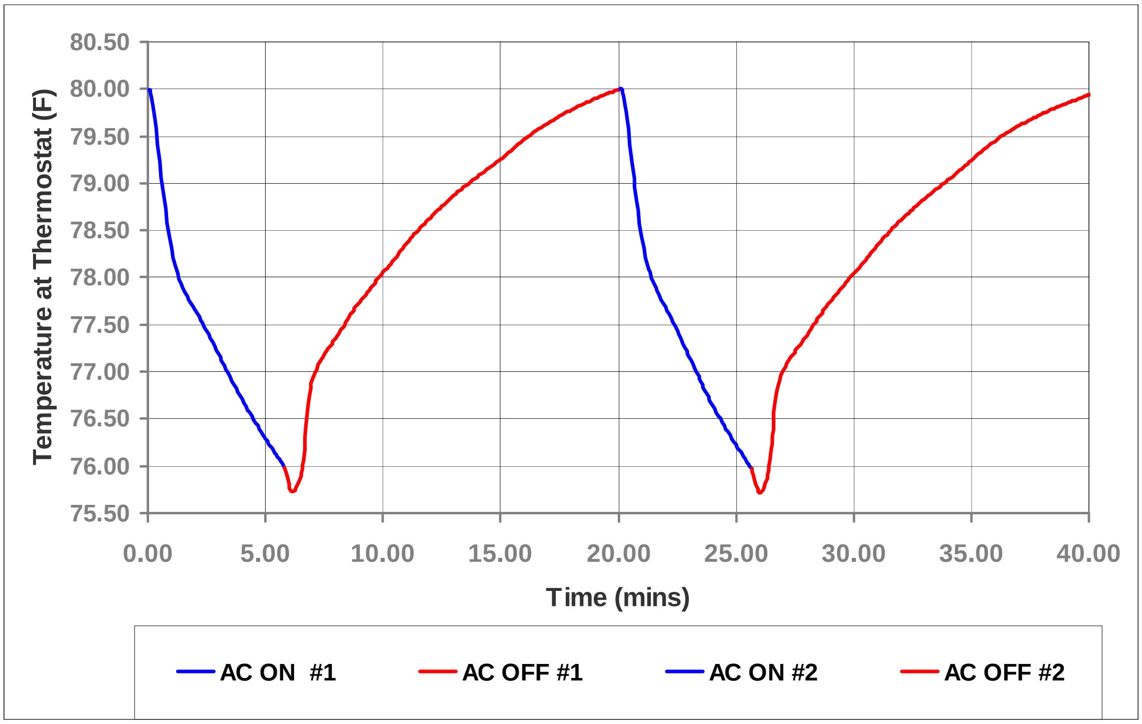


Figure 5: Case 1--Transient Temperature Variation at Thermostat

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.

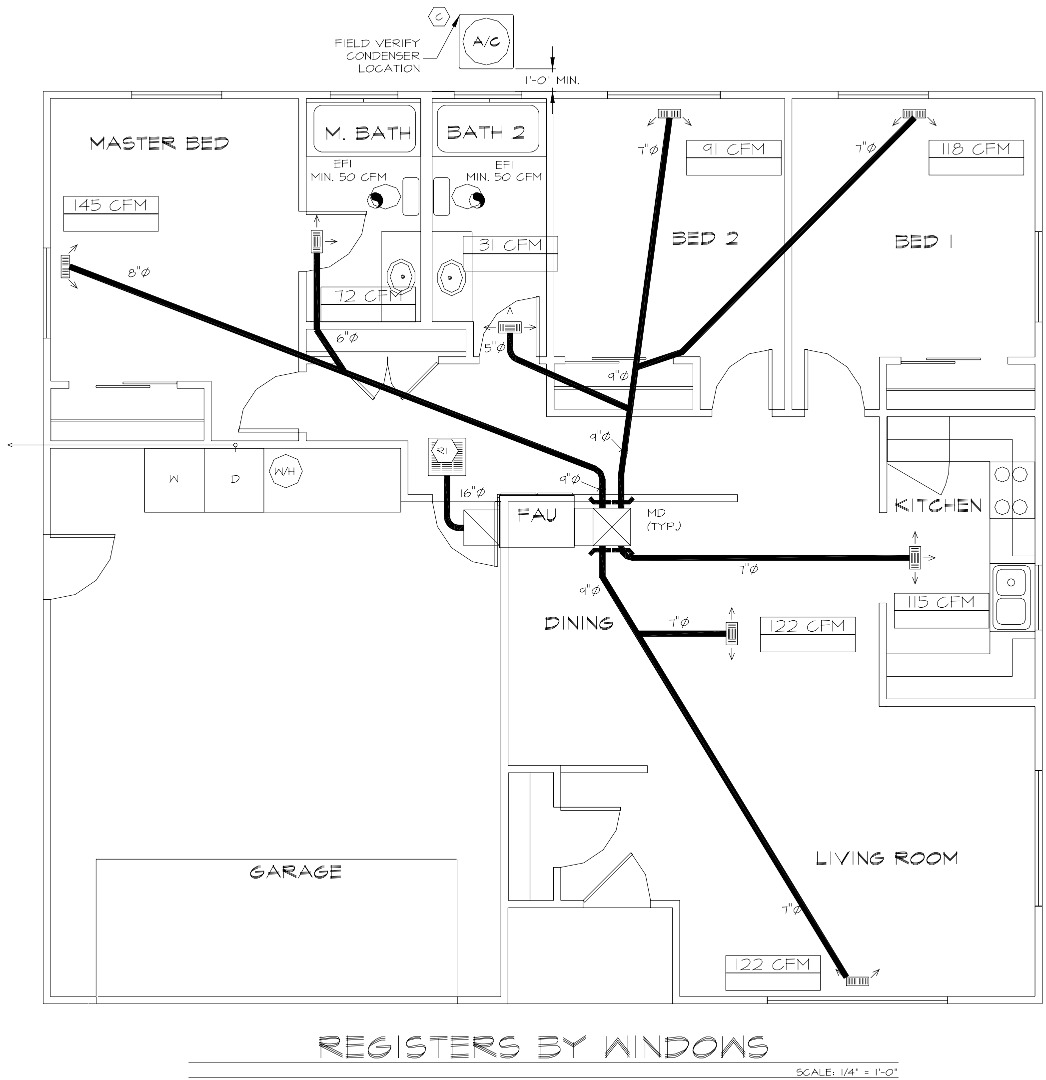


Figure 6: Case 2 -- Registers Over Windows

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

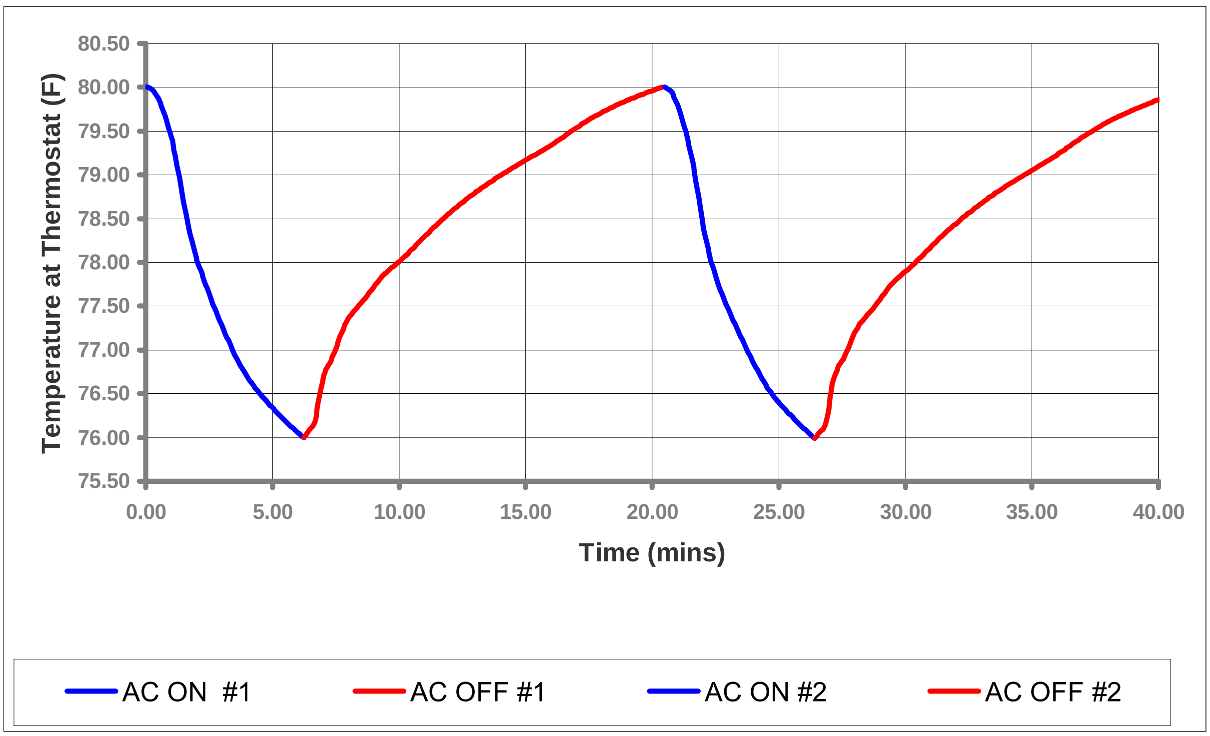


Figure 7: Case 2--Transient Temperature Variation at Thermostat

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.

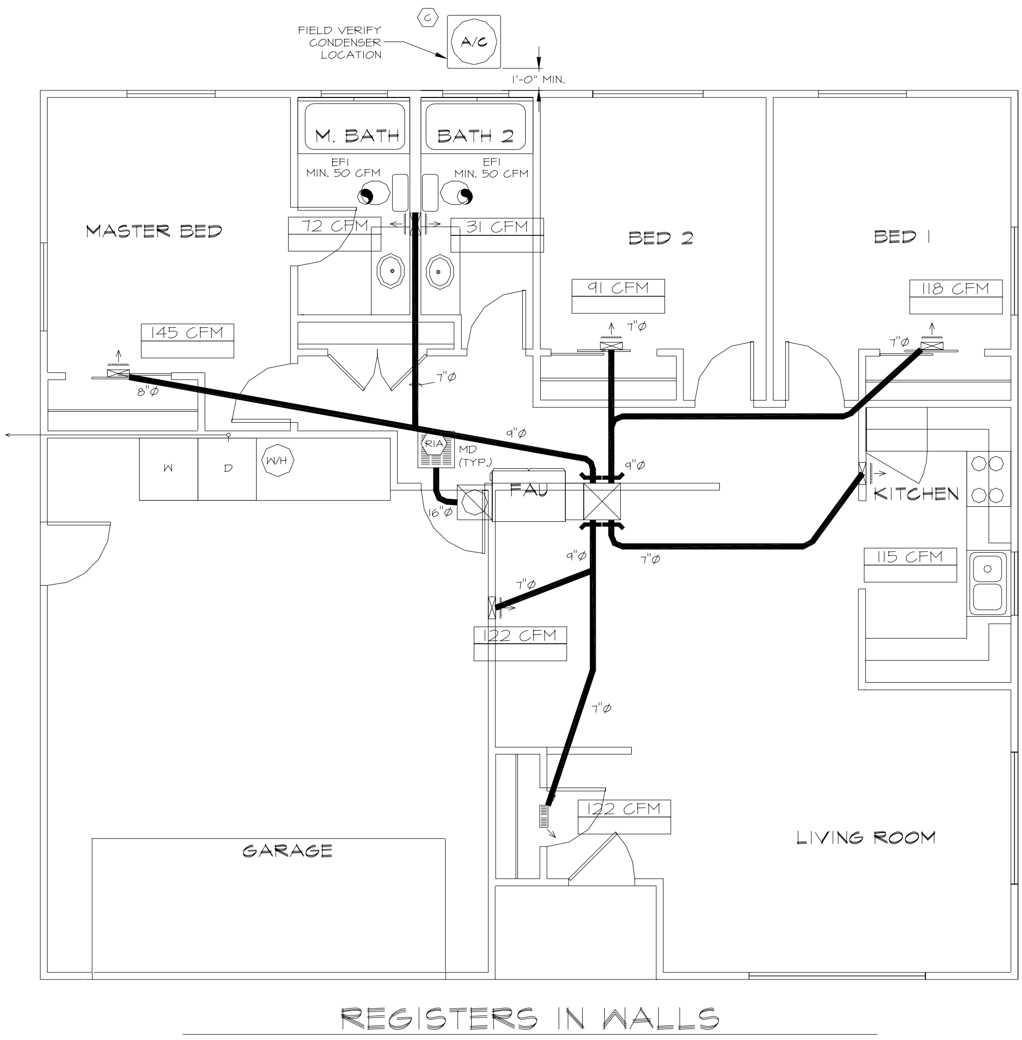


Figure 8: Case 3 -- Wall-Mounted Registers

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

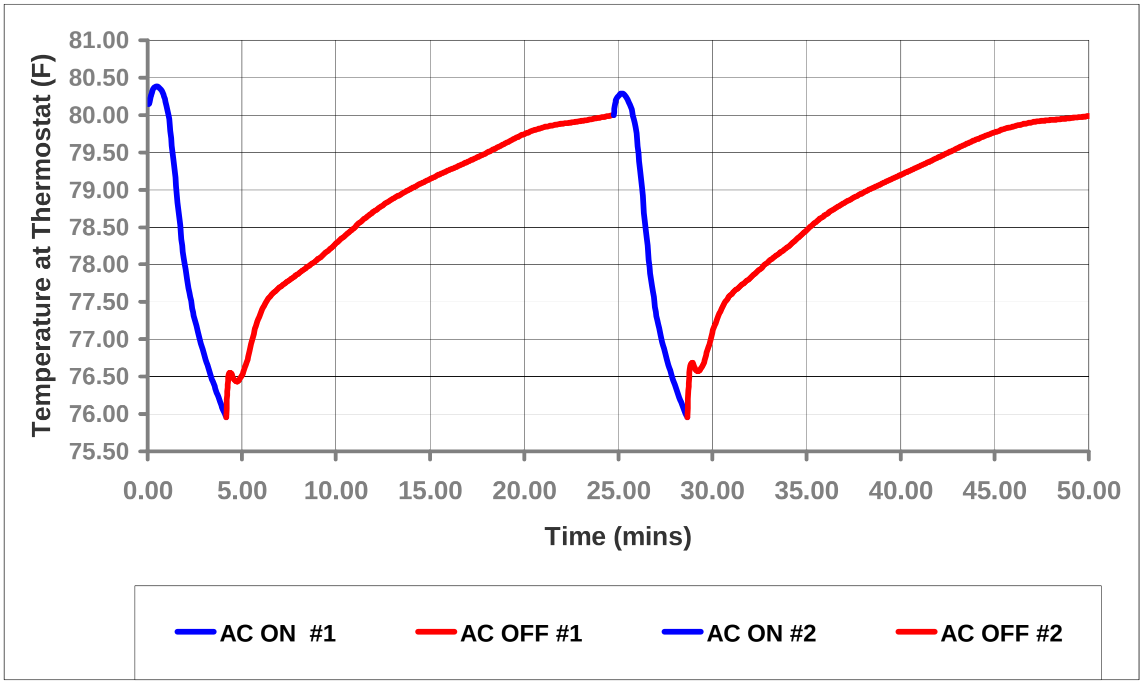


Figure 9: Case 3--Transient Temperature Variation at Thermostat

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.

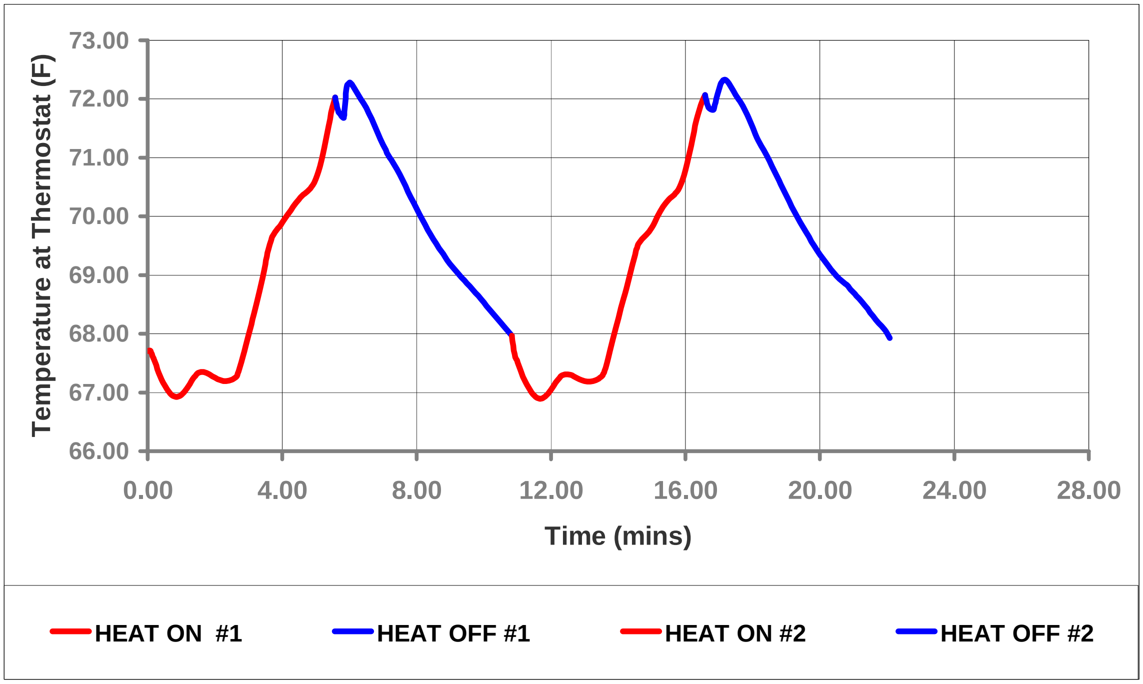


Figure 10: Case 4 --Transient Temperature Variation at Thermostat

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.

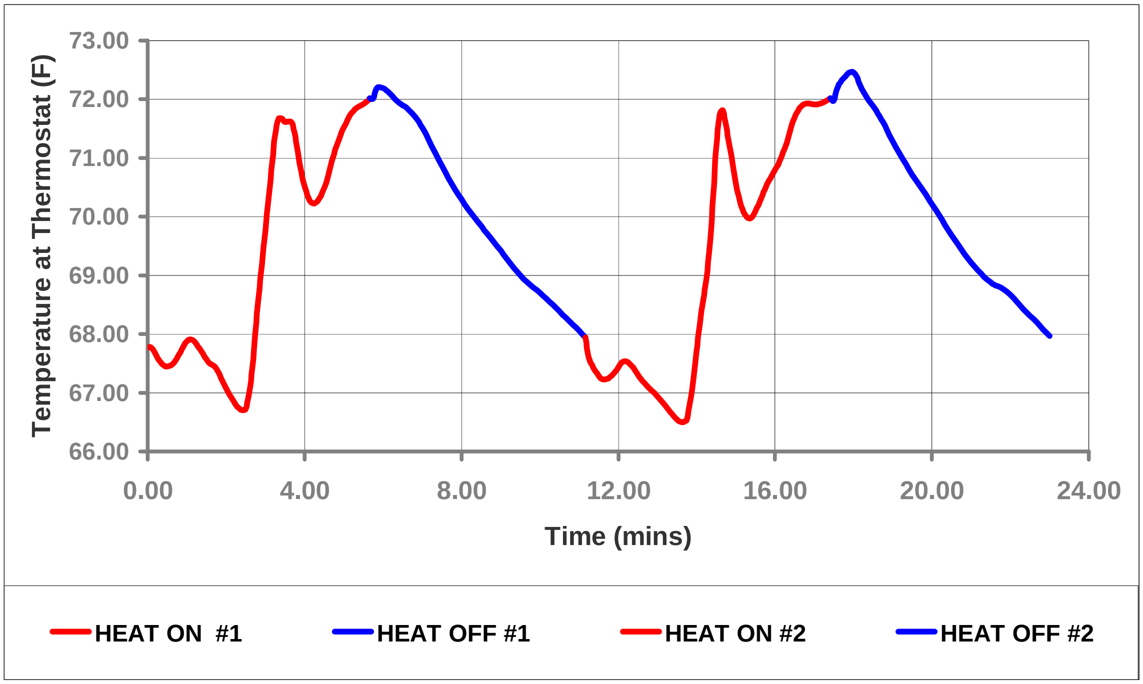


Figure 11: Case 5 --Transient Temperature Variation at Thermostat

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.

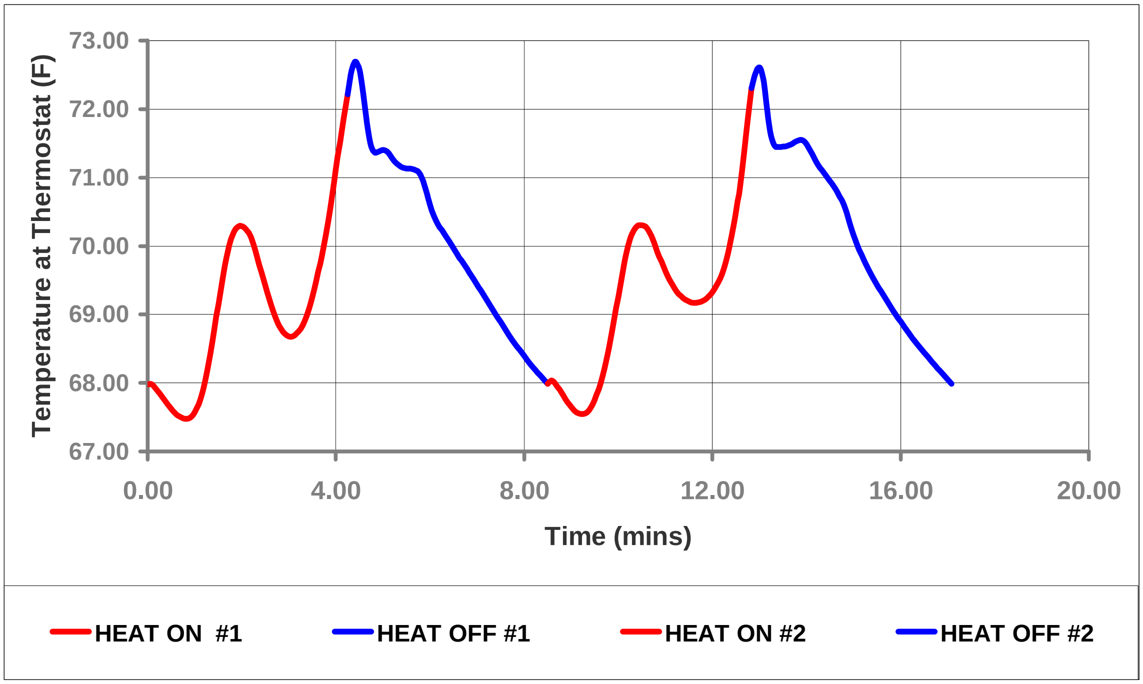


Figure 12: Case 6 --Transient Temperature Variation at Thermostat

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.

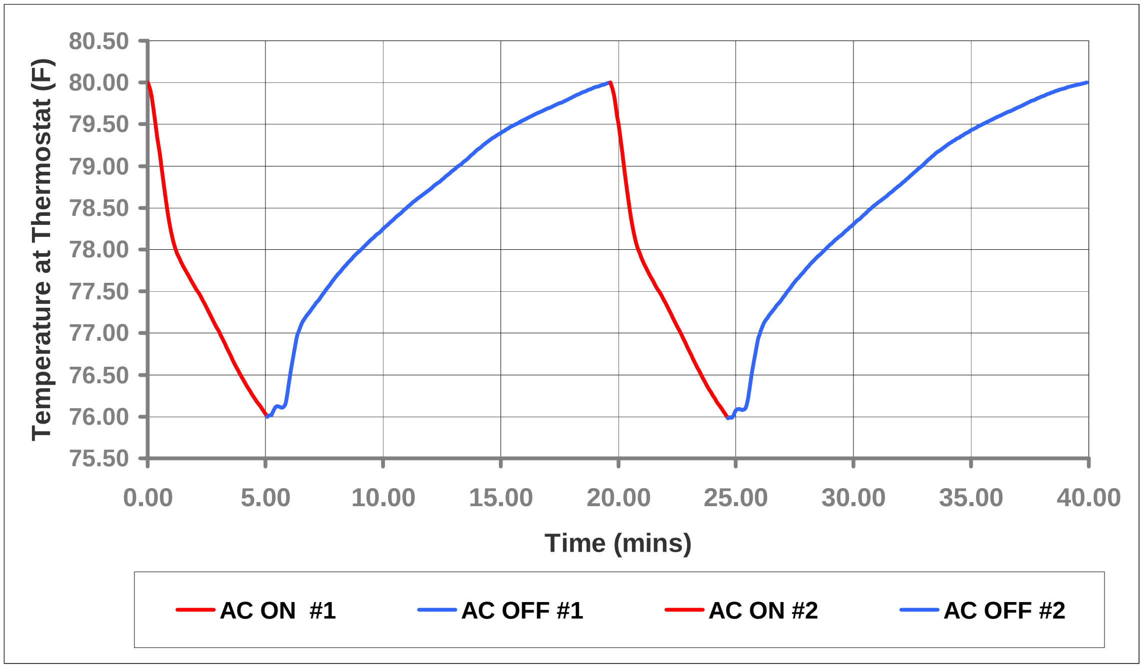


Figure 13: Case 7 --Transient Temperature Variation at Thermostat

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.

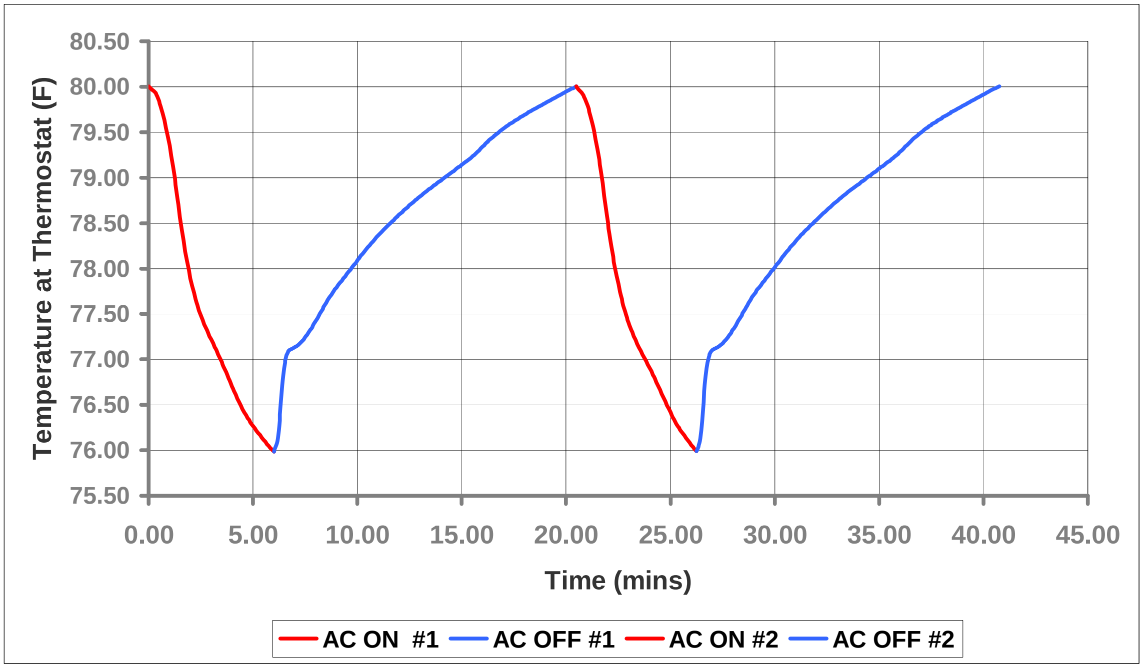


Figure 14: Case 8 --Transient Temperature Variation at Thermostat

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.

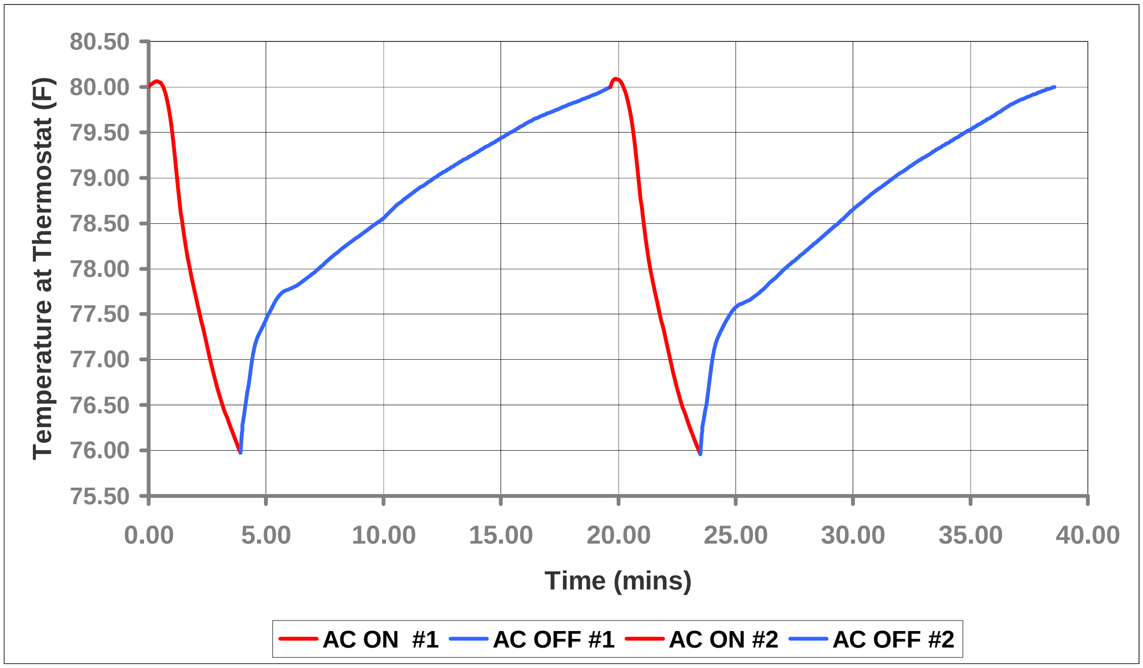


Figure 15: Case 9 --Transient Temperature Variation at Thermostat

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

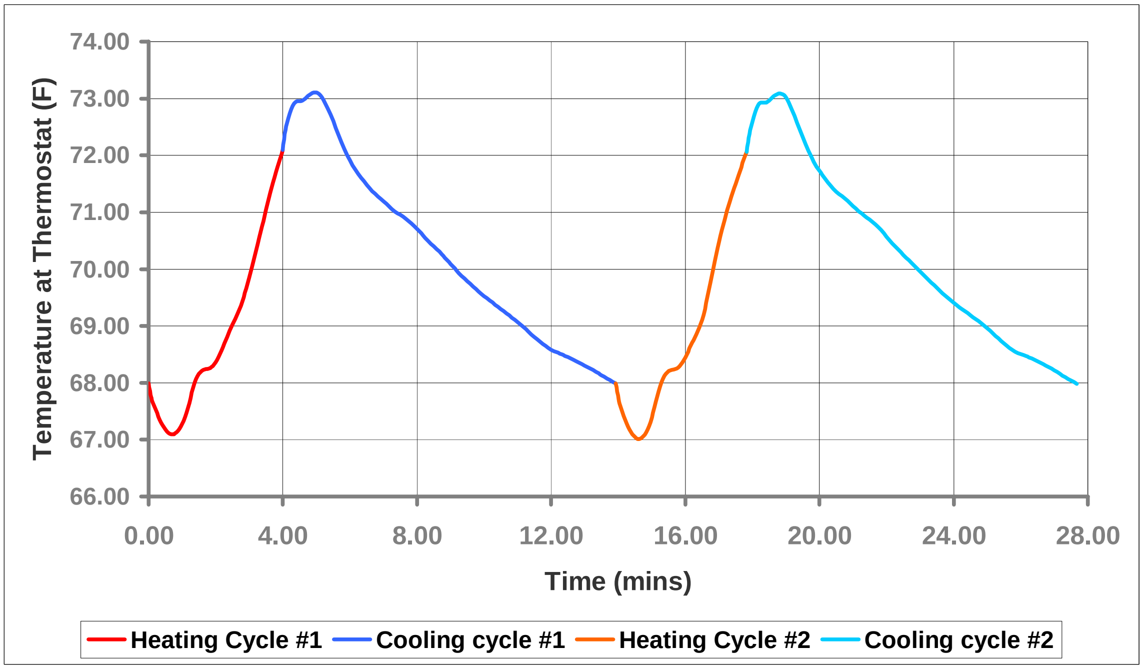


Figure 16: Case 10 --Transient Temperature Variation at Thermostat

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.

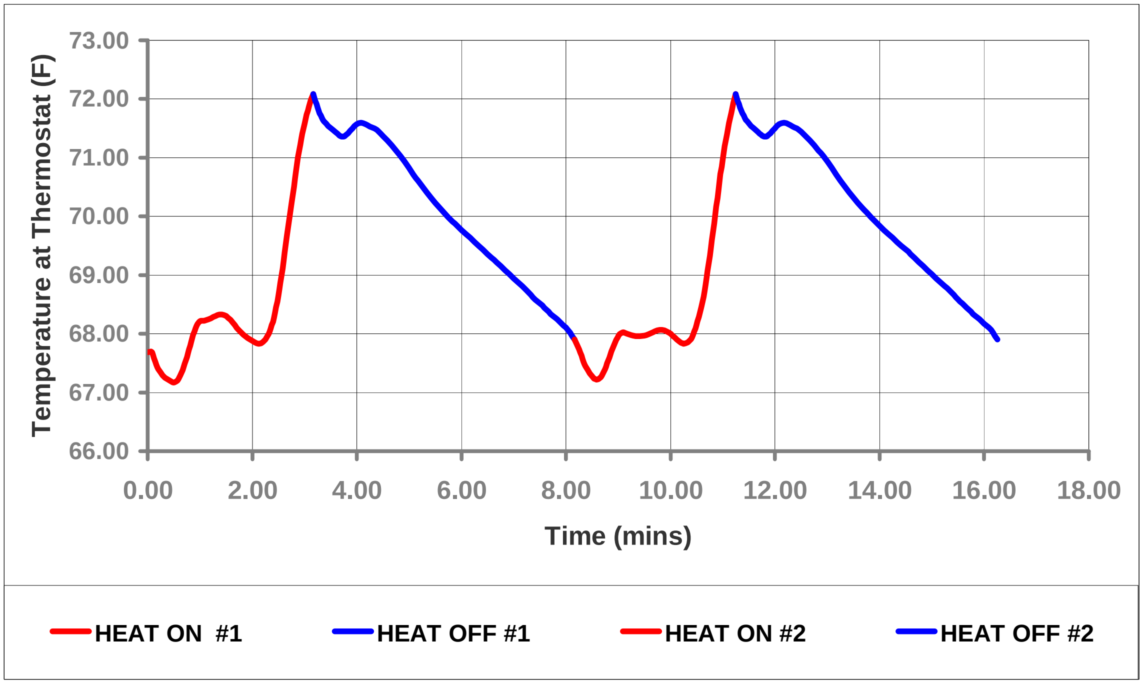


Figure 17: Case 11 --Transient Temperature Variation at Thermostat

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.

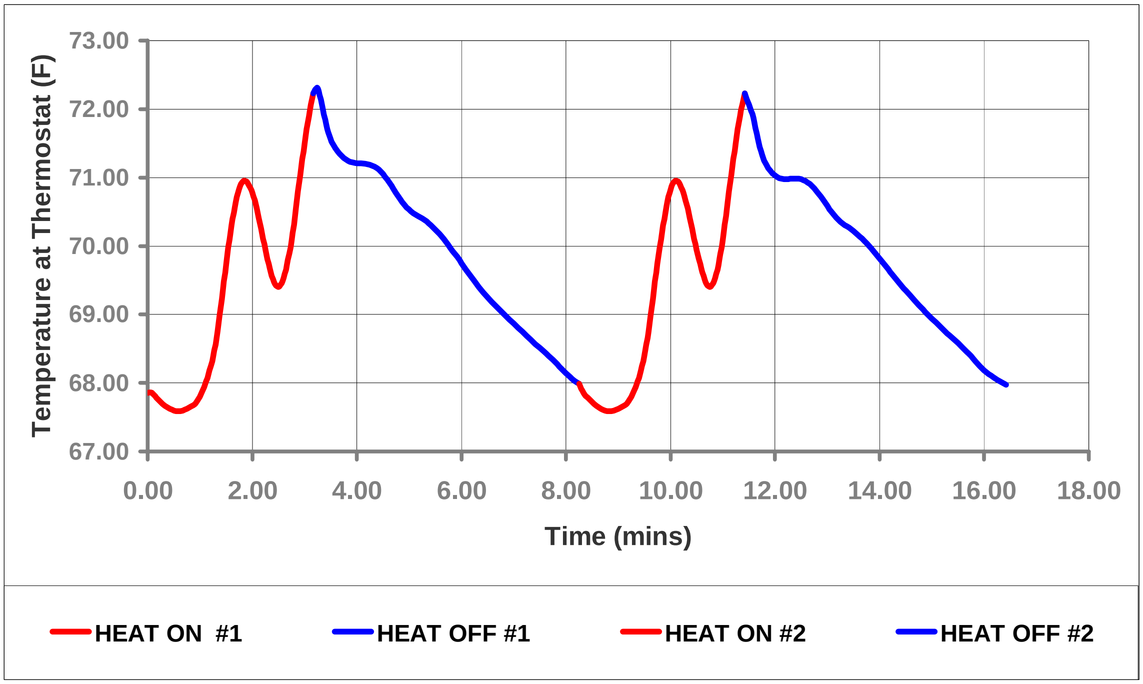


Figure 18: Case 12 --Transient Temperature Variation at Thermostat

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.

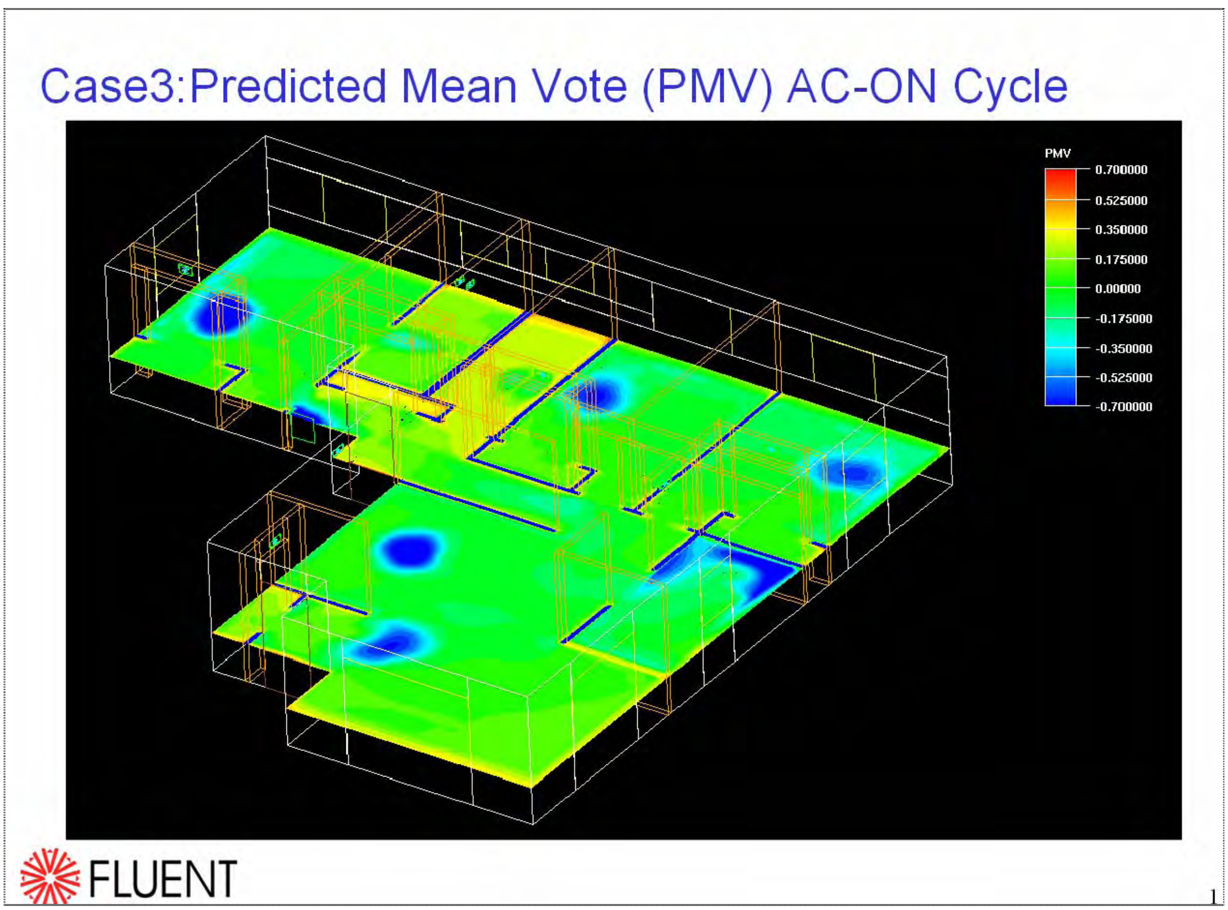


Figure 19: Example of Predicted Mean Vote during the AC ON cycle

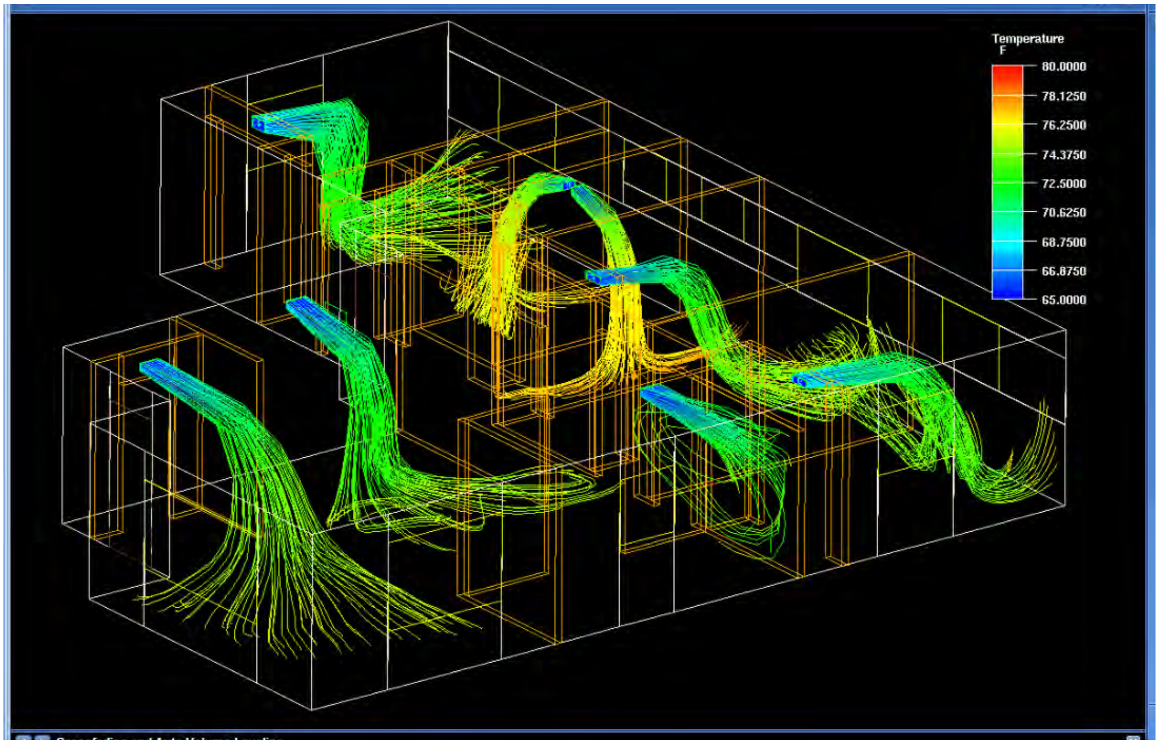


Figure 20: Example airflow animation for Cooling Case in-wall supply register, low-wall return

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.

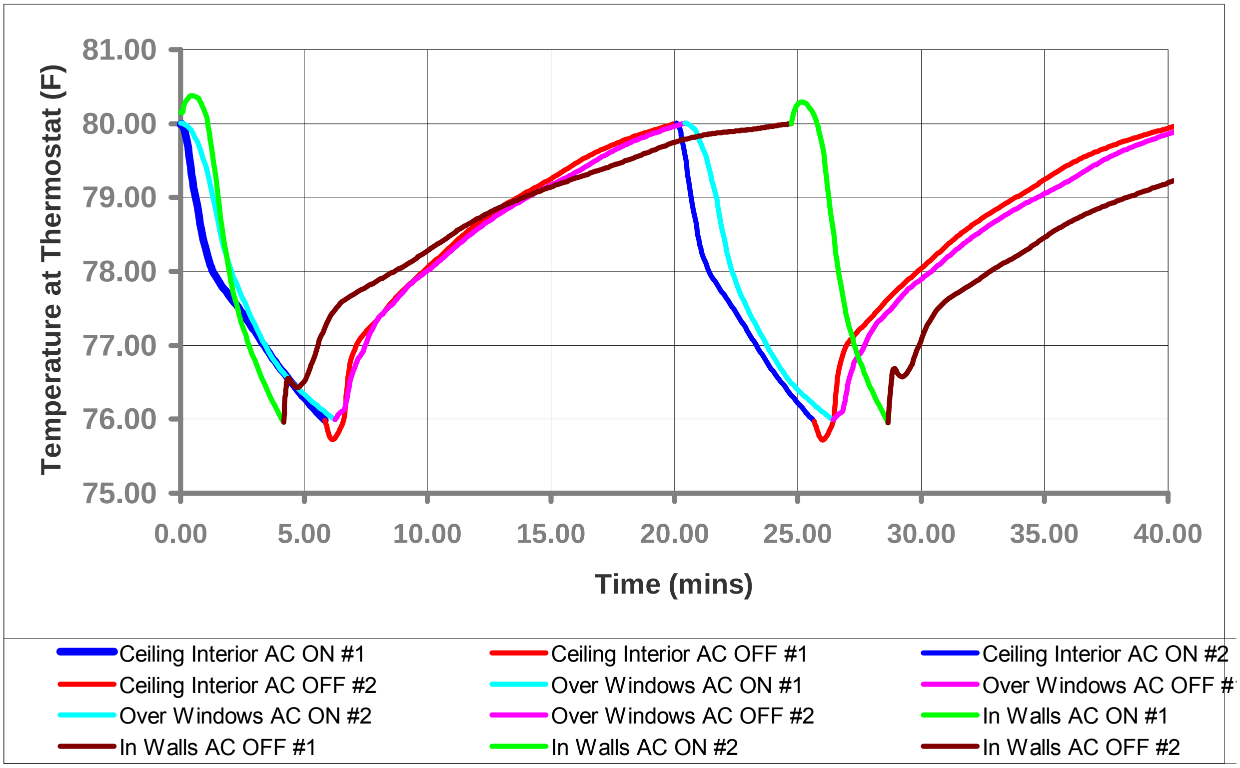


Figure 21: ON/OFF run times for three cooling configurations (Case 1, 2 and 3) Ceiling return, supply register interior ceiling, ceiling over windows, and in-wall

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.

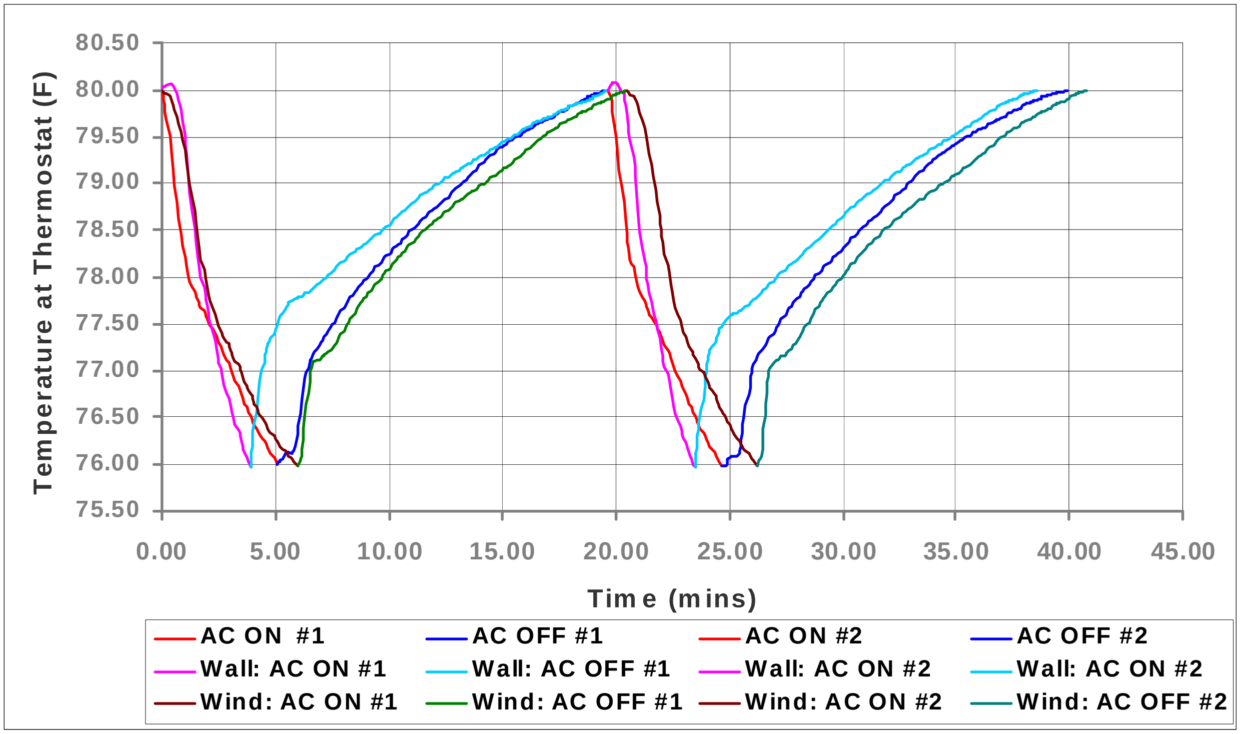


Figure 22: ON/OFF run times for three cooling configurations (Case 7, 8, and 9) Low-wall return, supply register interior ceiling, ceiling over windows, and in-wall

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.

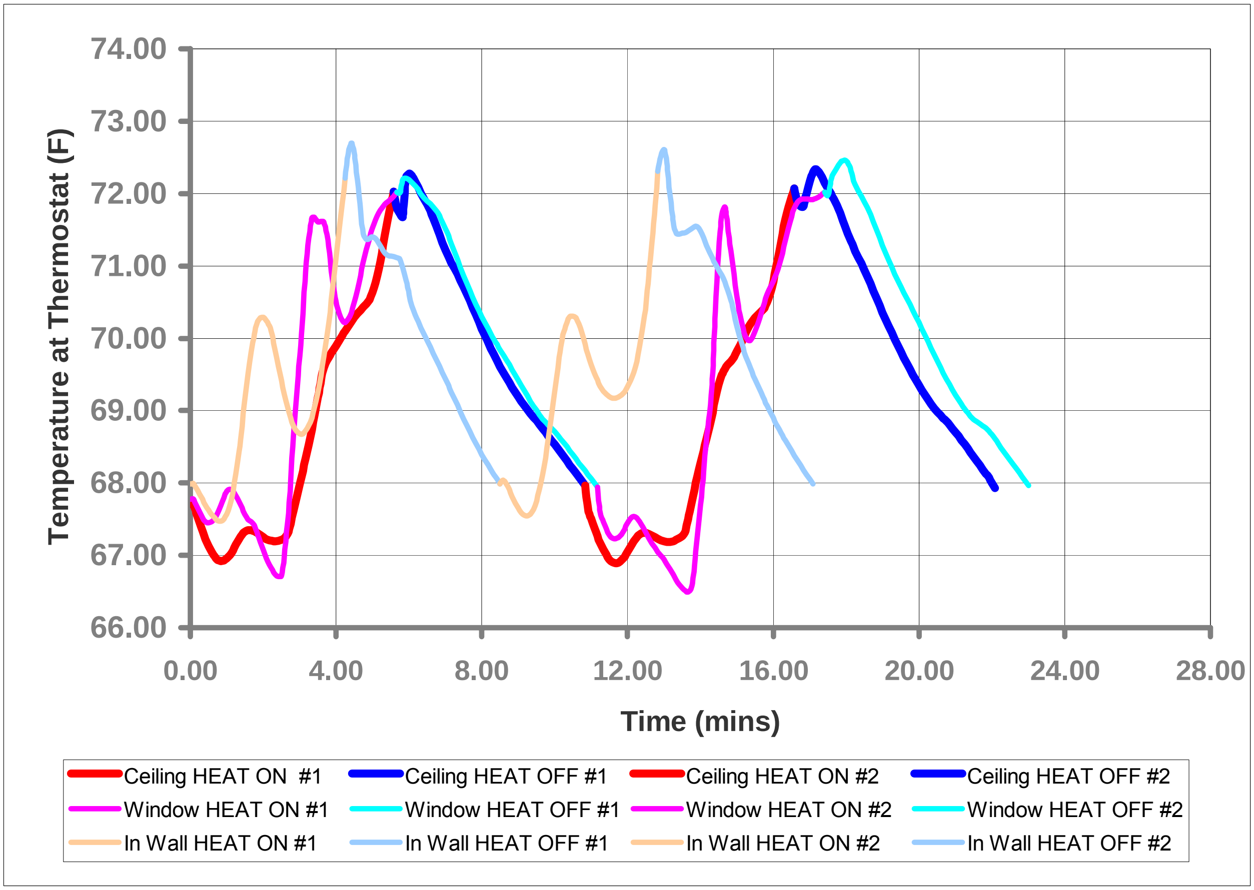


Figure 23: ON/OFF run times for three heating configurations (Case 4, 5, and 6) Ceiling return, supply register interior ceiling, ceiling over windows, and in-wall

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.

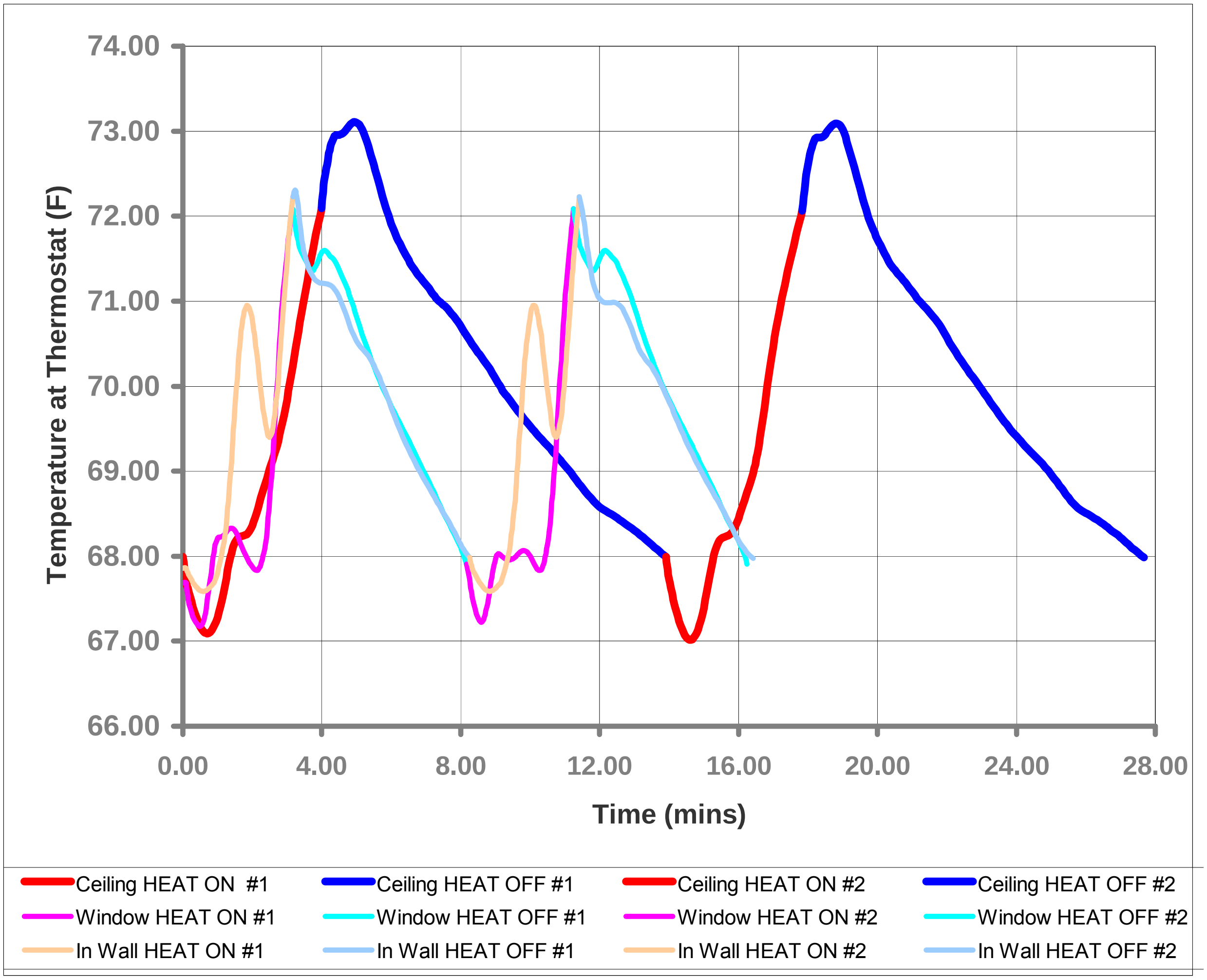


Figure 24: ON/OFF run times for three heating configurations (Case 10, 11, and 12) Low-wall return, supply register interior ceiling, ceiling over windows, and in-wall

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.

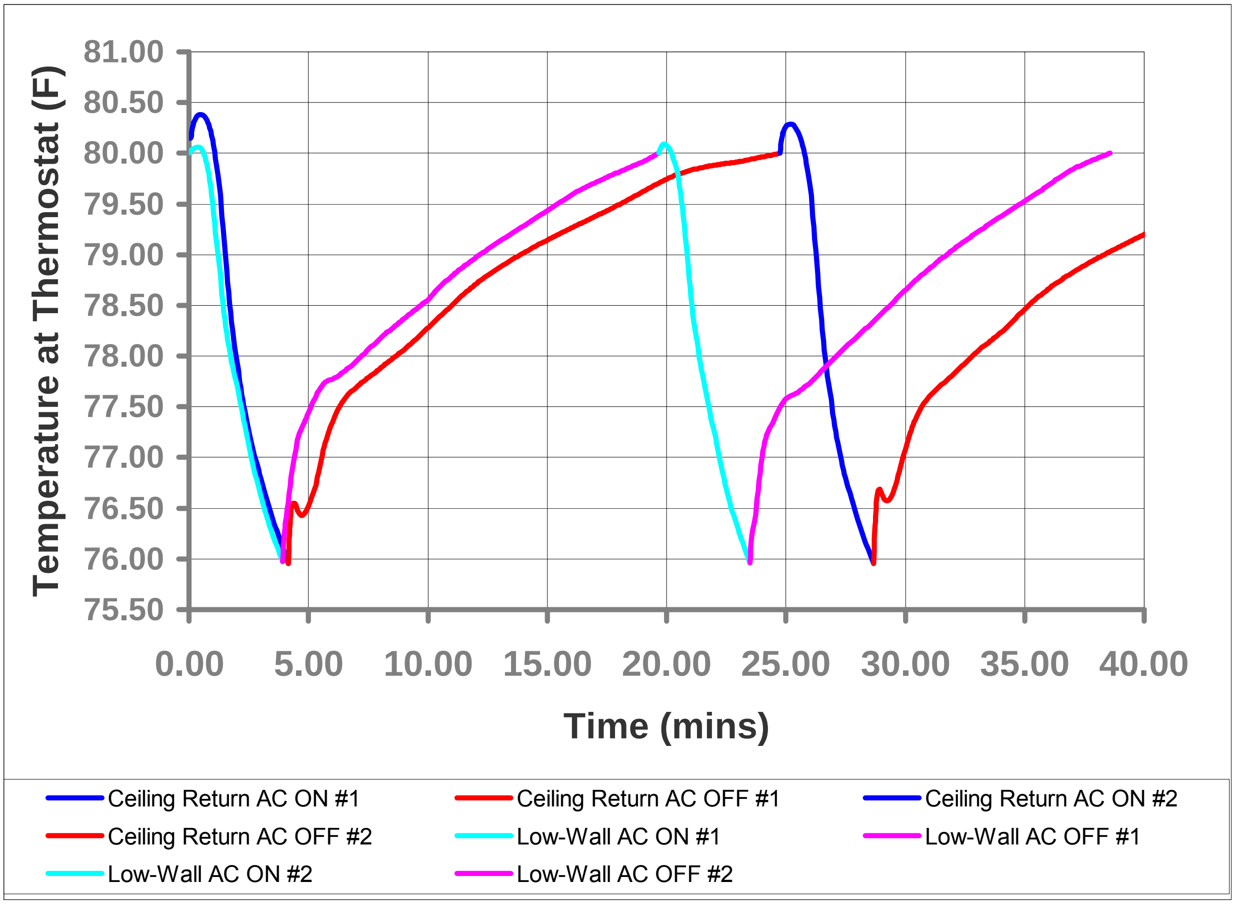


Figure 25: Ceiling Return vs. Low Wall Return for Cooling (in-wall supply registers – Case 3 vs. Case 9)

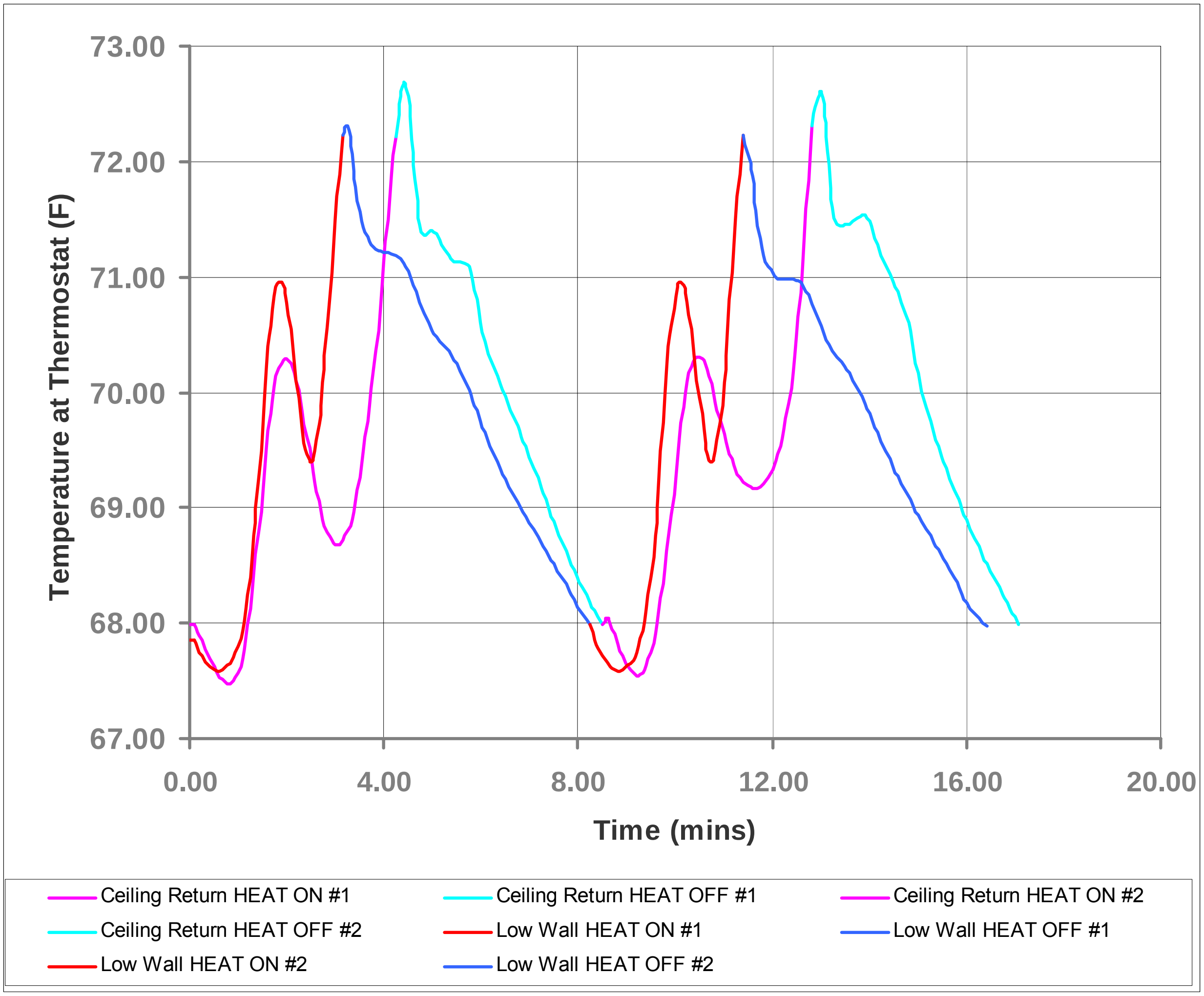


Figure 26: Ceiling Return vs. Low-Wall Return for Heating (in-wall supply registers – Case 6 vs. Case 12)

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

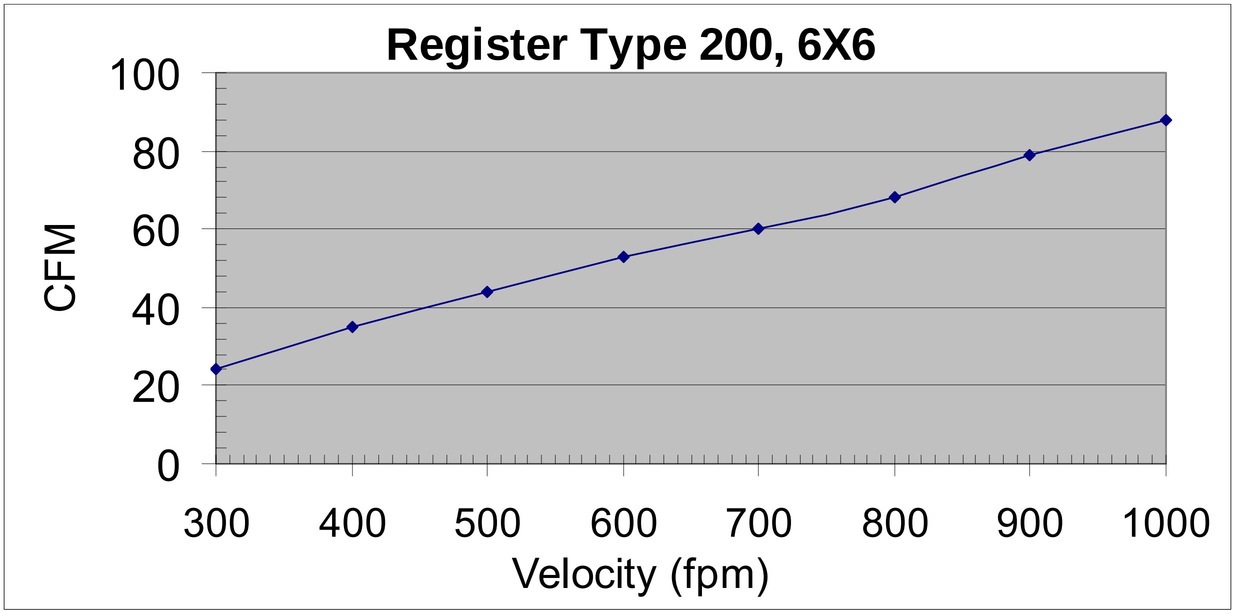
Noise Criteria (NC): 25 = broadcast studios, face velocity = 500 FPM

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

Note: all data taken from Shoemaker Engineering Data

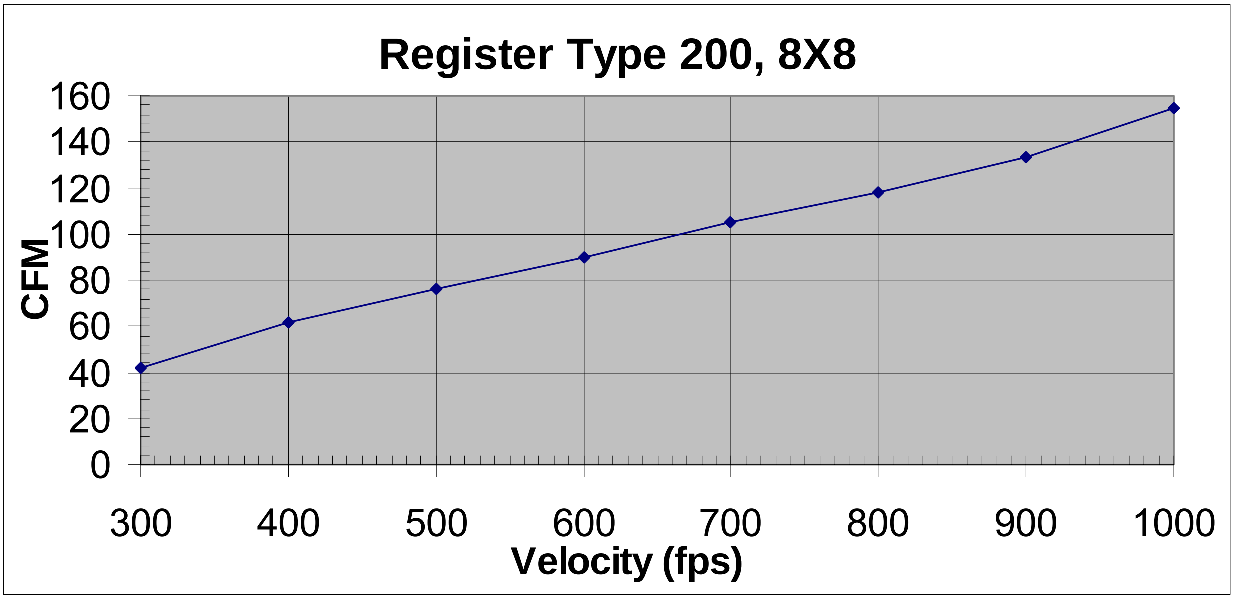
Type: 200
Size: 6X6
Effective Area: .084

Register Velocity	300	400	500	600	700	800	900	1000
Register CFM	24	35	44	53	60	68	79	88



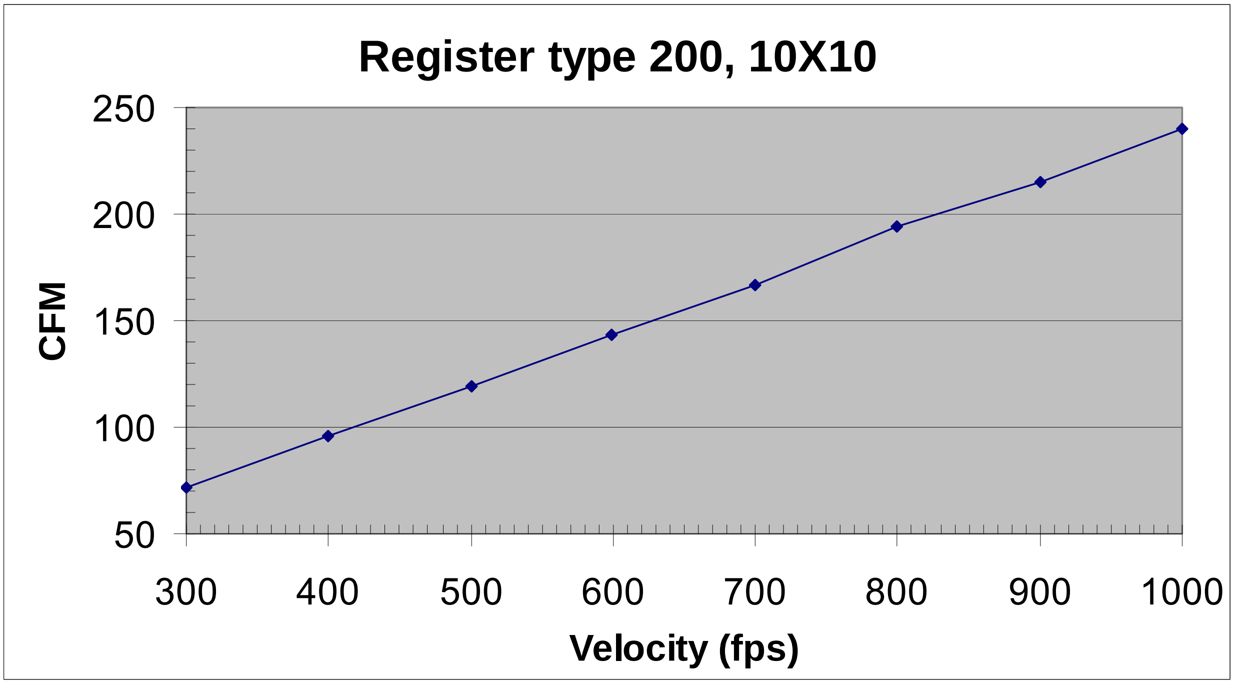
Type: 200
Size: 8X8
Effective Area: 0.151

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

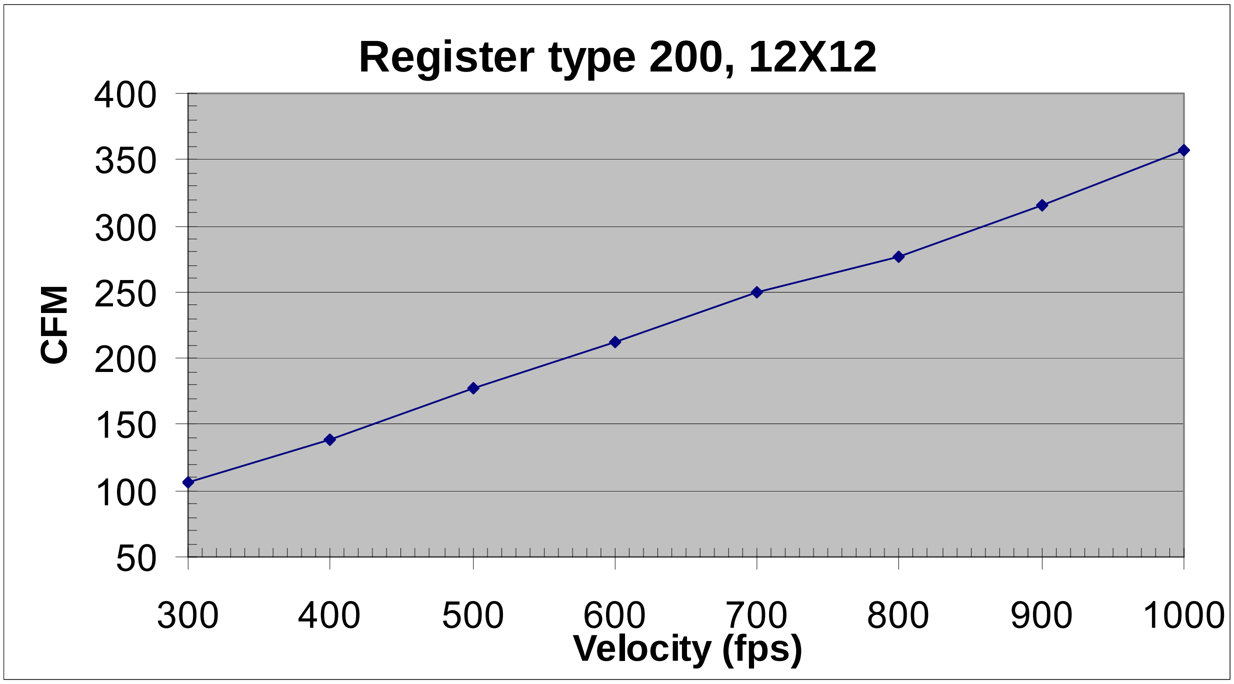


Type: 200
Size: 10X10
Effective Area: 0.241

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.

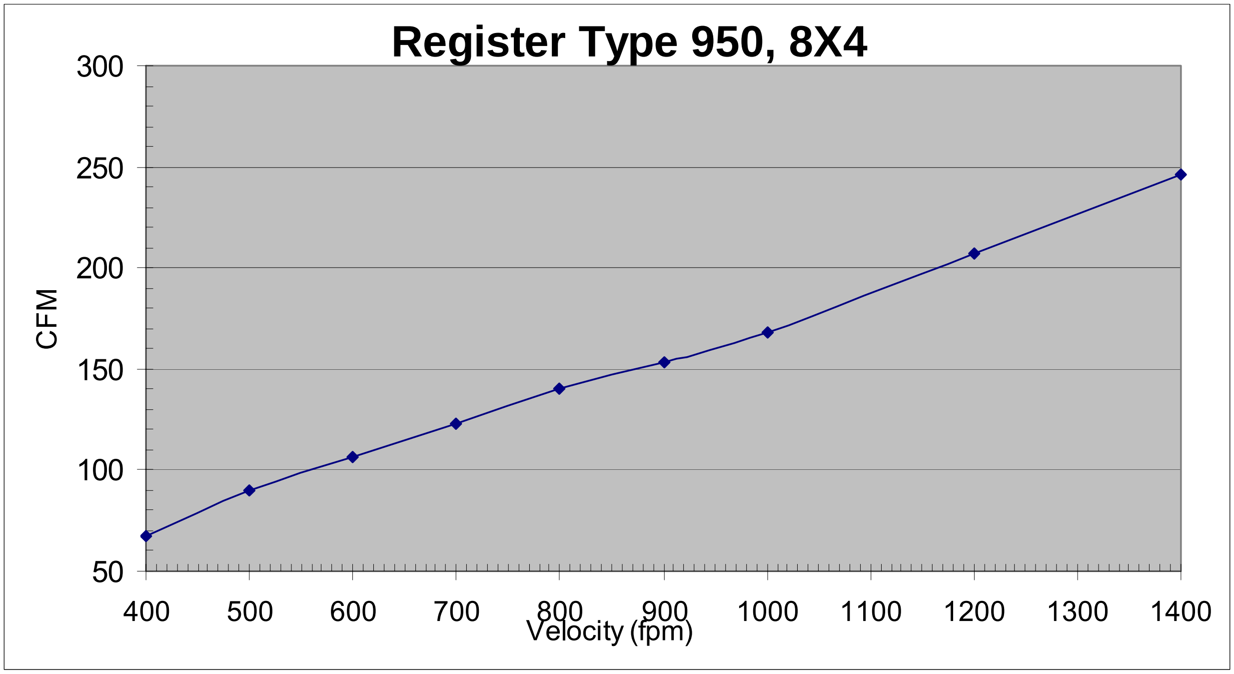
Noise Criteria (NC): 25 = broadcast studios, face velocity = 500 FPM

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

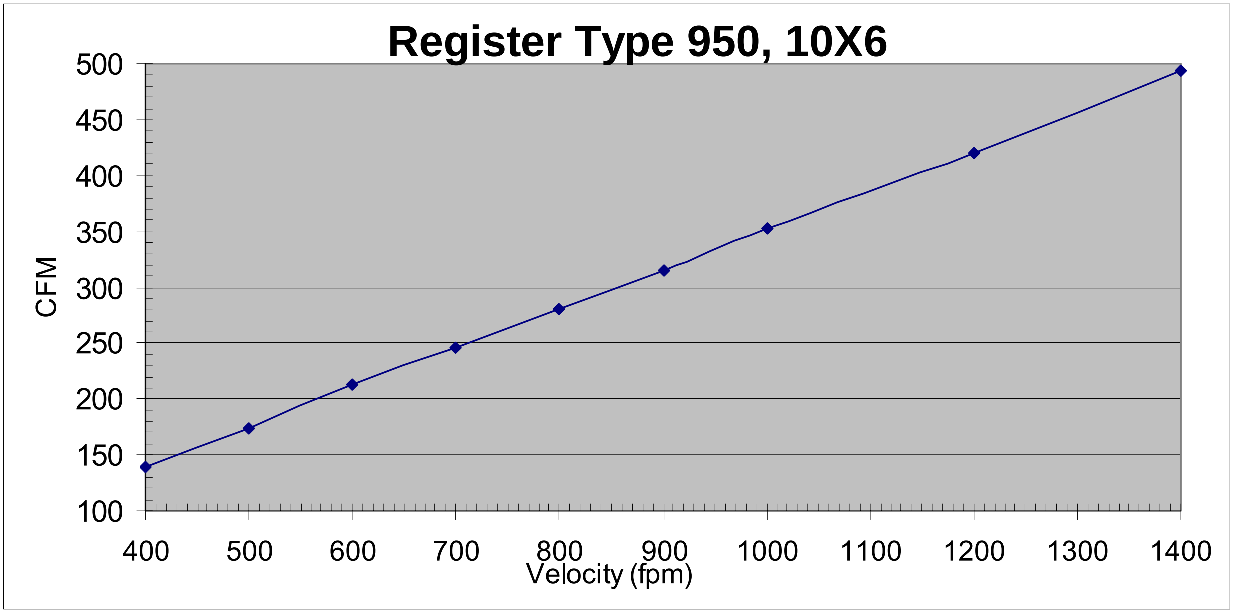
Note: all data taken from Shoemaker Engineering Data

Type: 950
Size: 8X4
Effective Area: 0.155

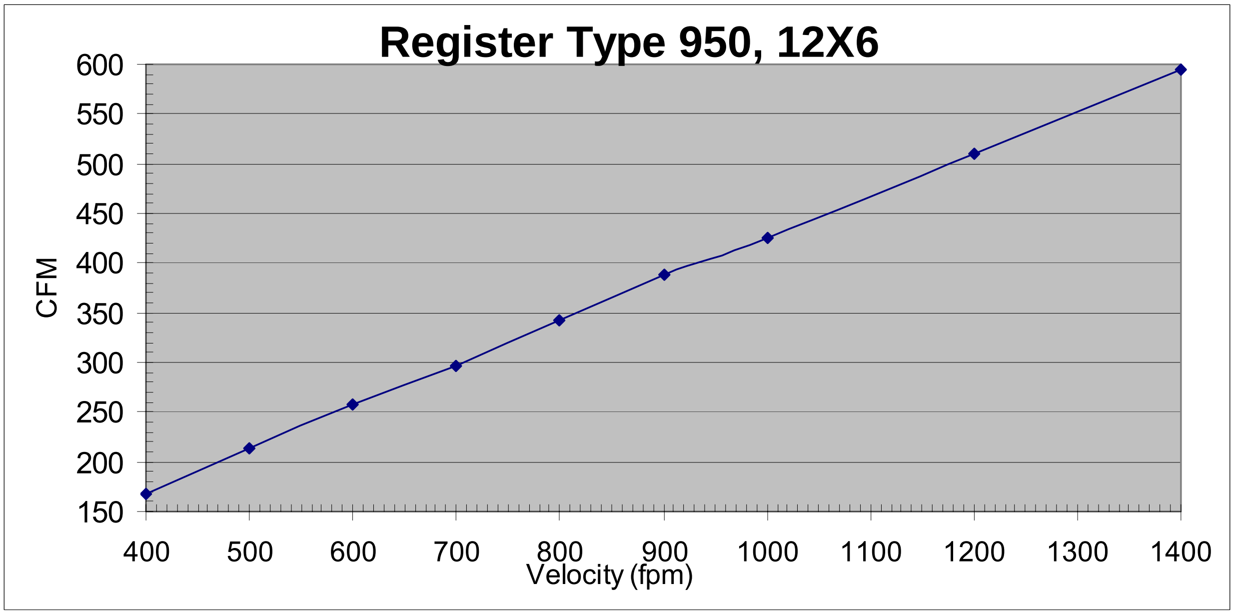
Register Velocity	400	500	600	700	800	900	1000	1200	1400
Register CFM	67	90	106	123	140	153	168	207	246



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)

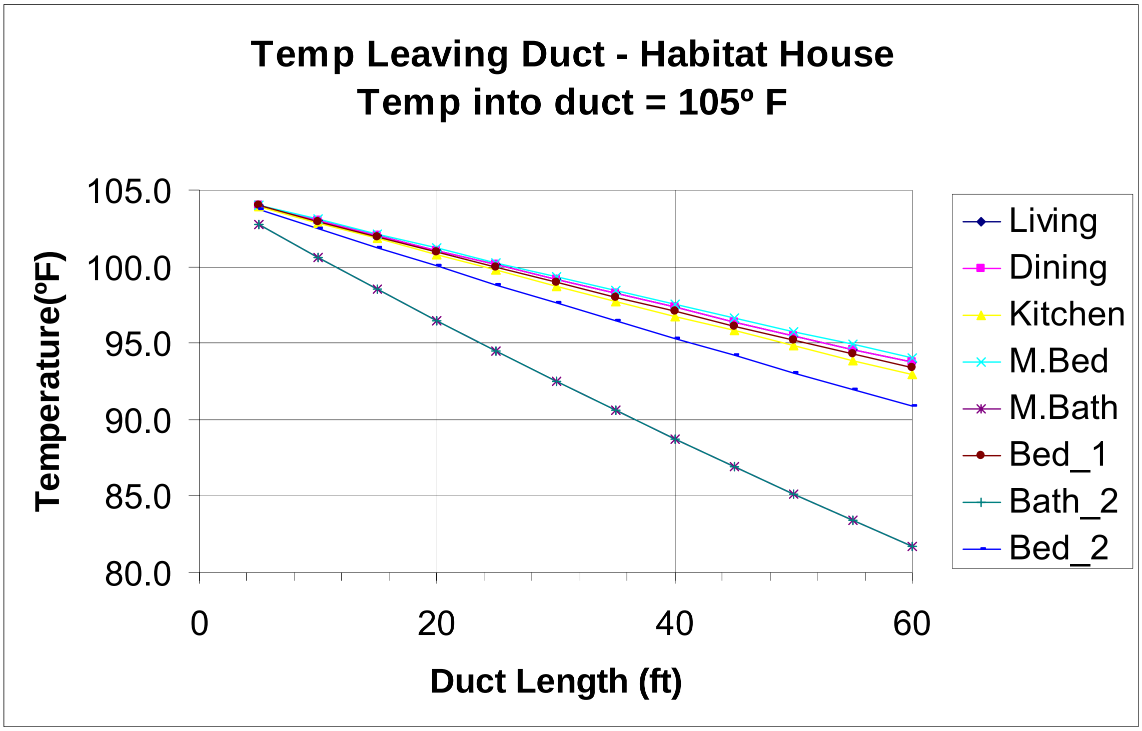
U_h (Overall heat transfer coefficient of duct wall)	0.18
TempEnter_h (Design temperature for air entering the ducts)	105.0
TempOutside_h (Design temperature for the air surrounding the ducts in the attic when outside air is at 20°F	20.0
AirDensity_h	0.075
SpHeatAir_h	0.24

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**	

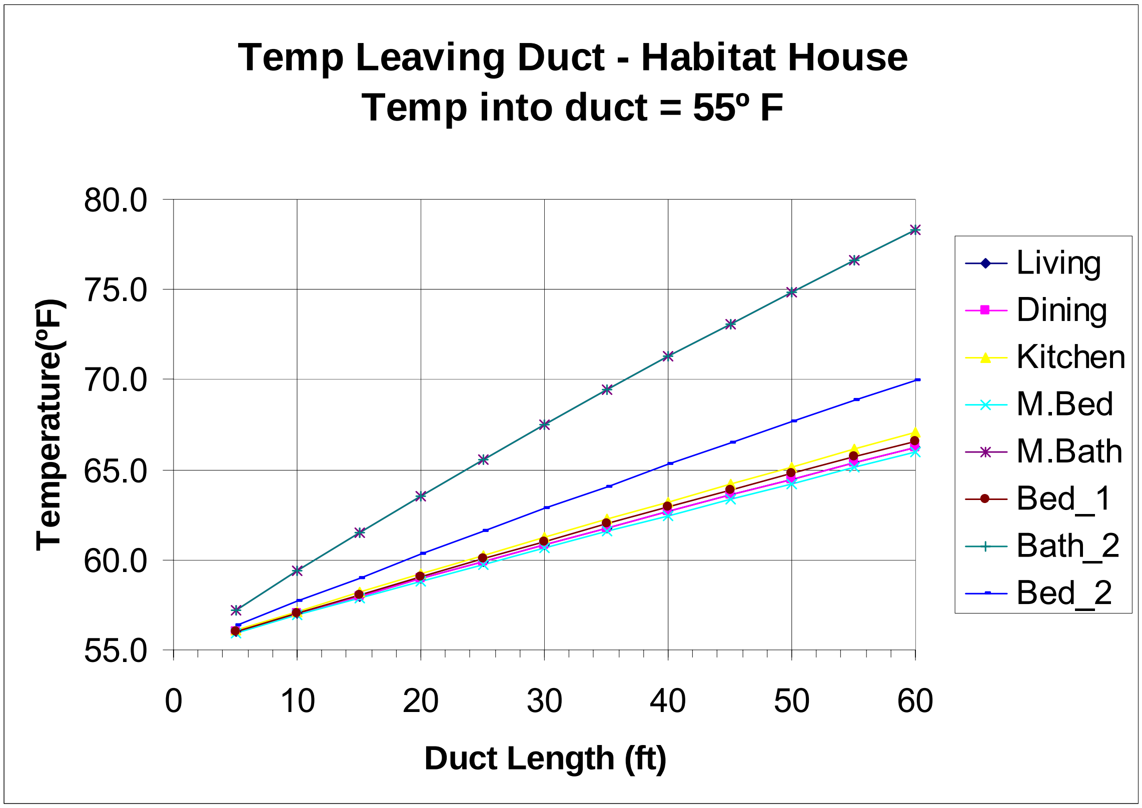
Note: As a cross-check on these calculated values, the design Air Flow Rate of the HVAC cooling fan for this house was 815 CFM. The room-by-room CFM shown above are from Right-J Short Form. The computed values for Average Velocity listed above are also very close to the values from the Right Suite reports.

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.

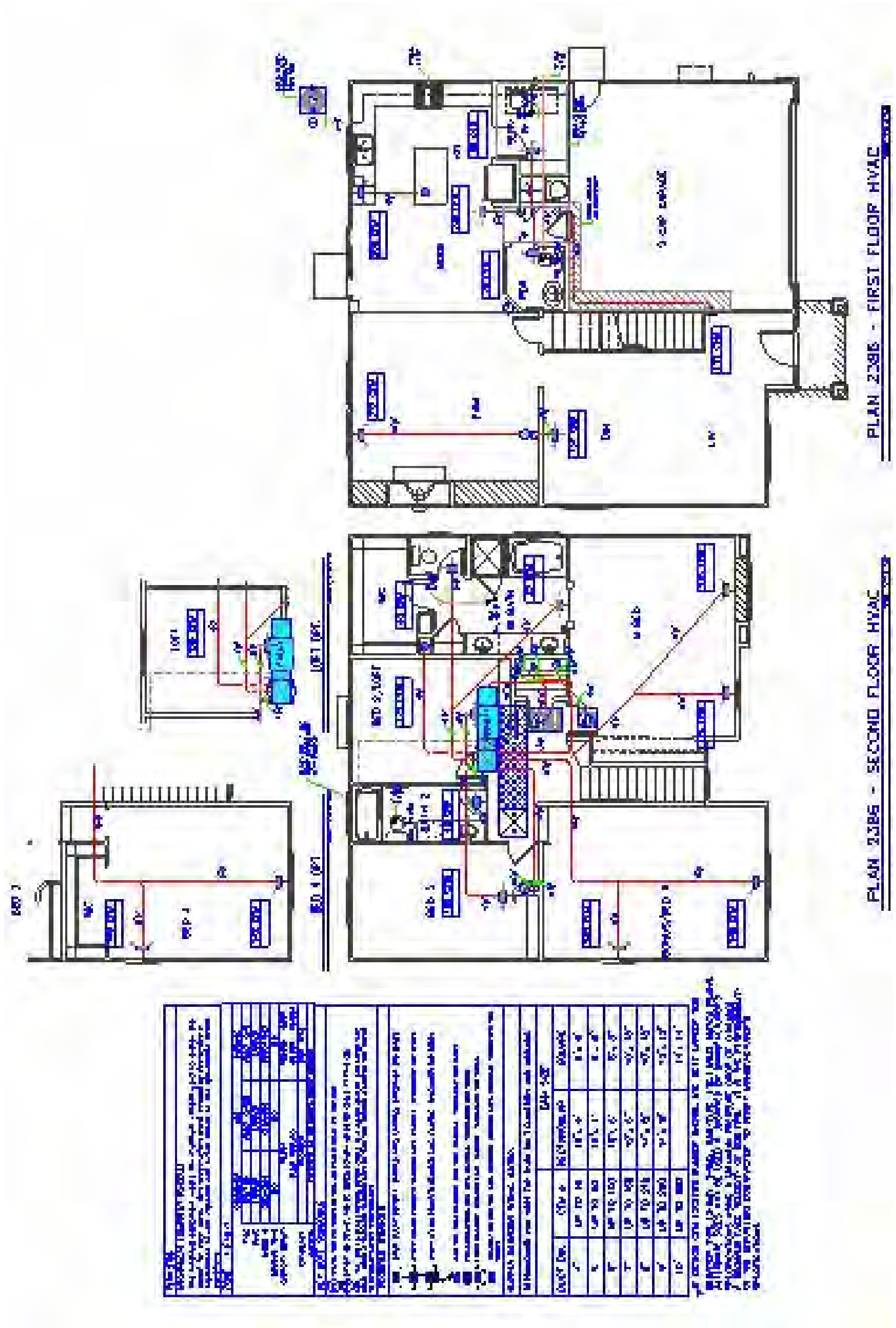


Figure 27: Two-Story Study House – Base Plan

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.

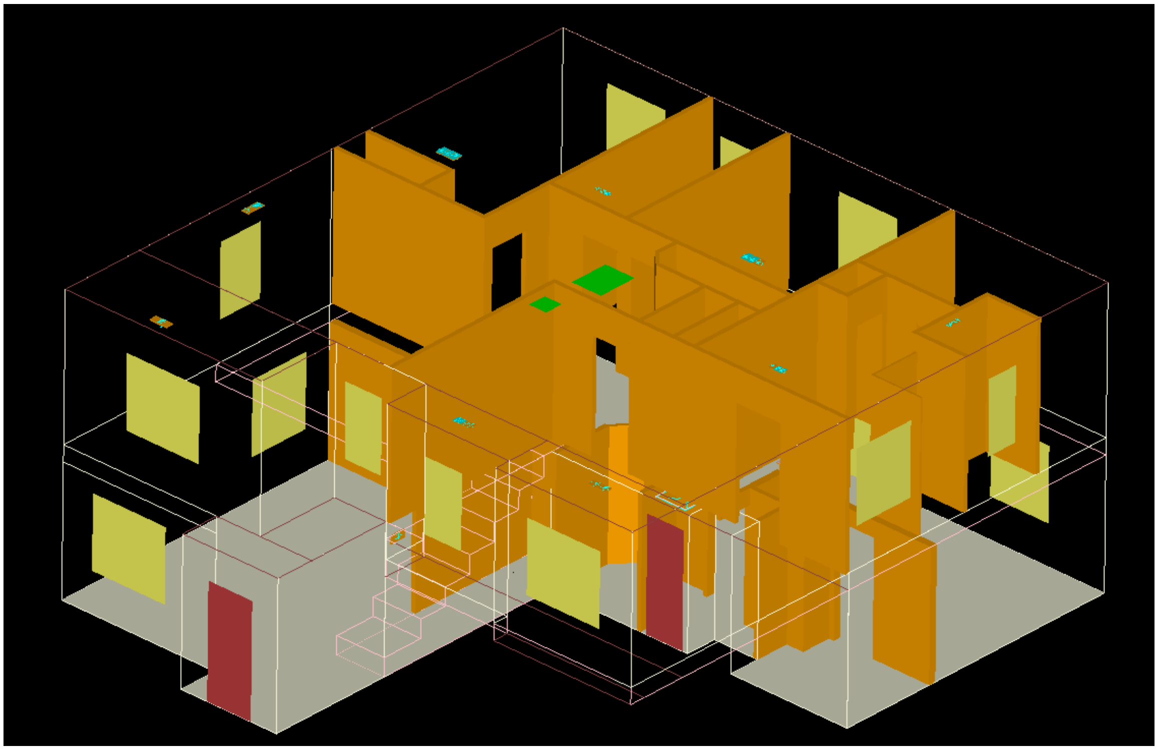


Figure 28: Study House Solid Model

Evaluation of Two-Story Cases

For the summer cooling mode, the ambient temperature was set to 105°F. The HVAC system fan was set to turn on when the thermostat reached 76° F and remain ON until the thermostat reached 75° 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 (°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**.

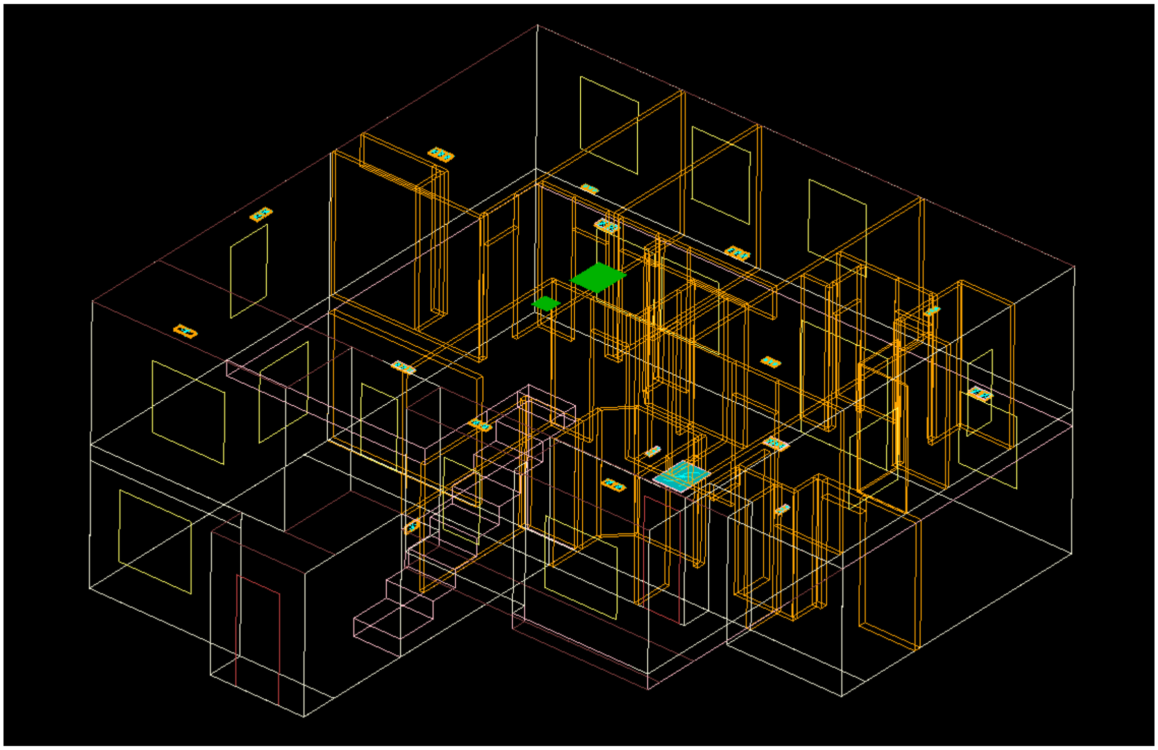


Figure 29: Case 1 – Register and Return Locations

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.

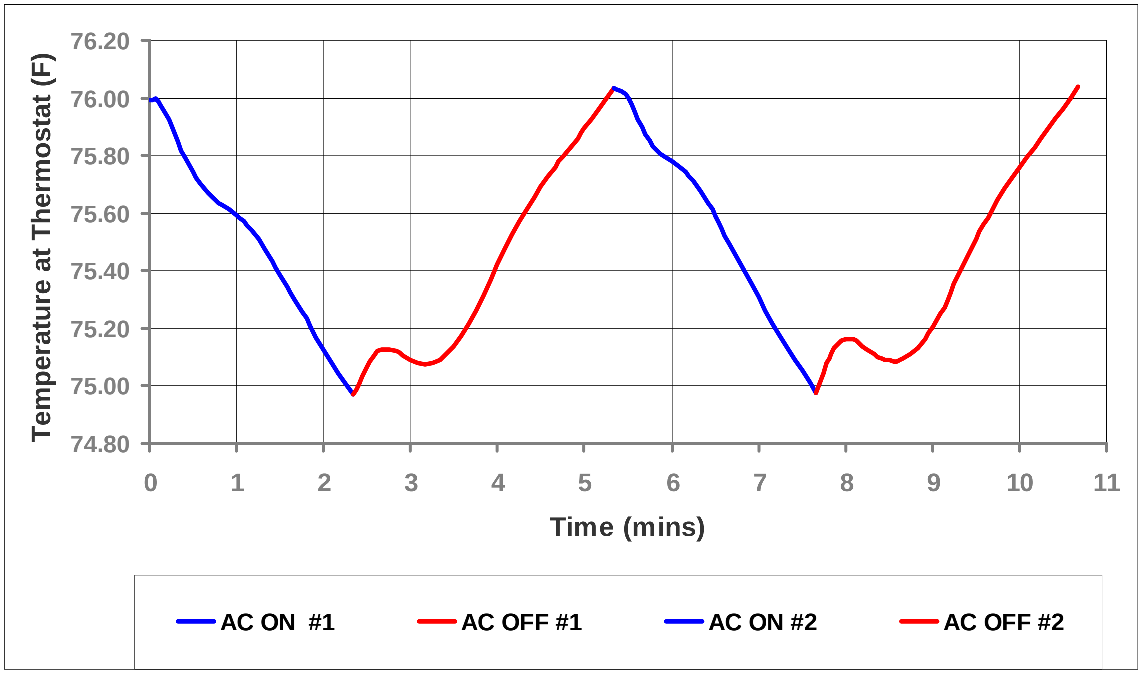


Figure 30: Case 1 -- Transient Temperature Variation at Thermostat

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**.

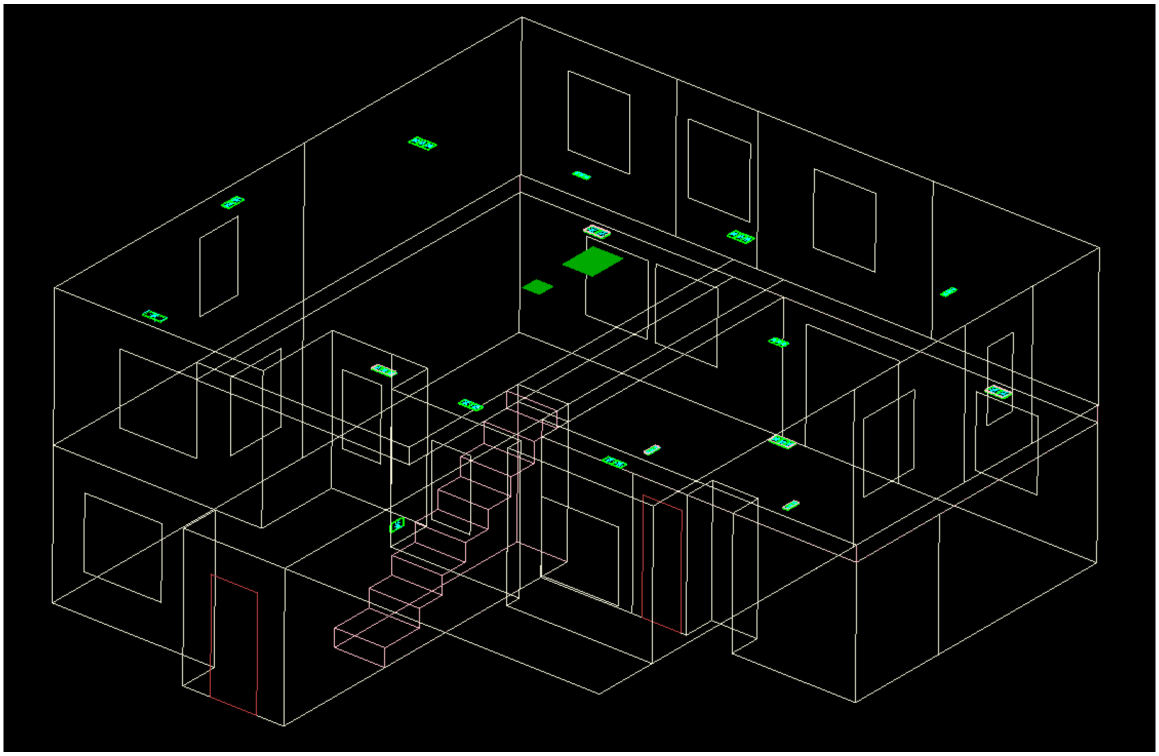


Figure 31: Case 2 – Register and Return Locations

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.

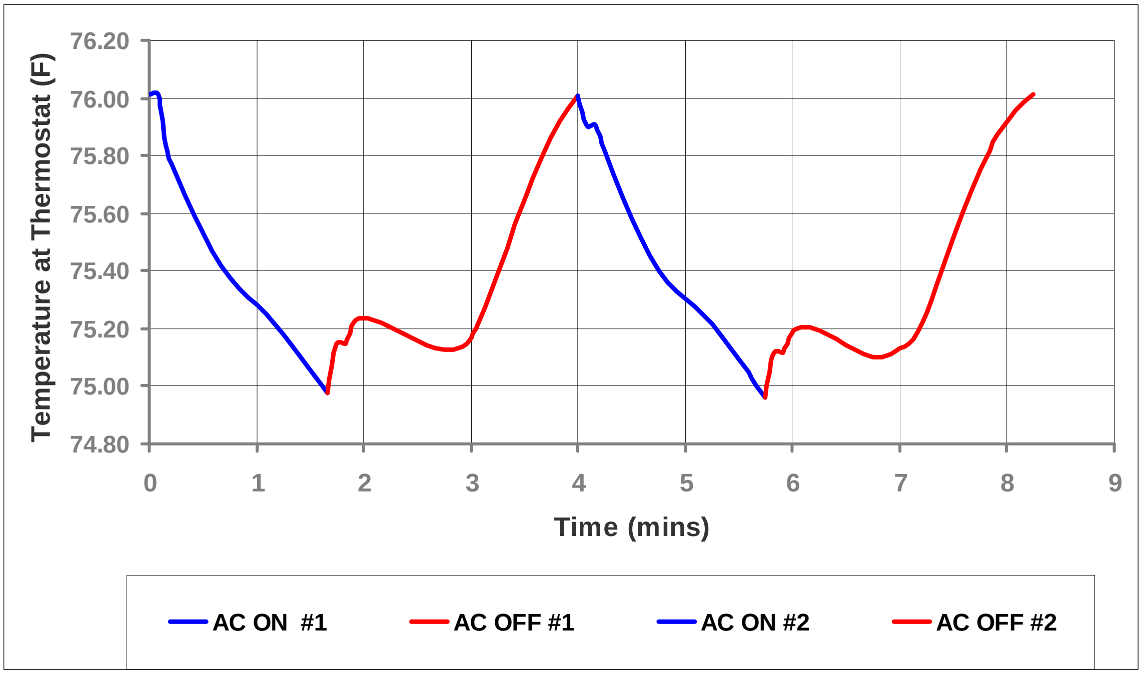


Figure 32: Case 2 -- Transient Temperature Variation at Thermostat

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**.

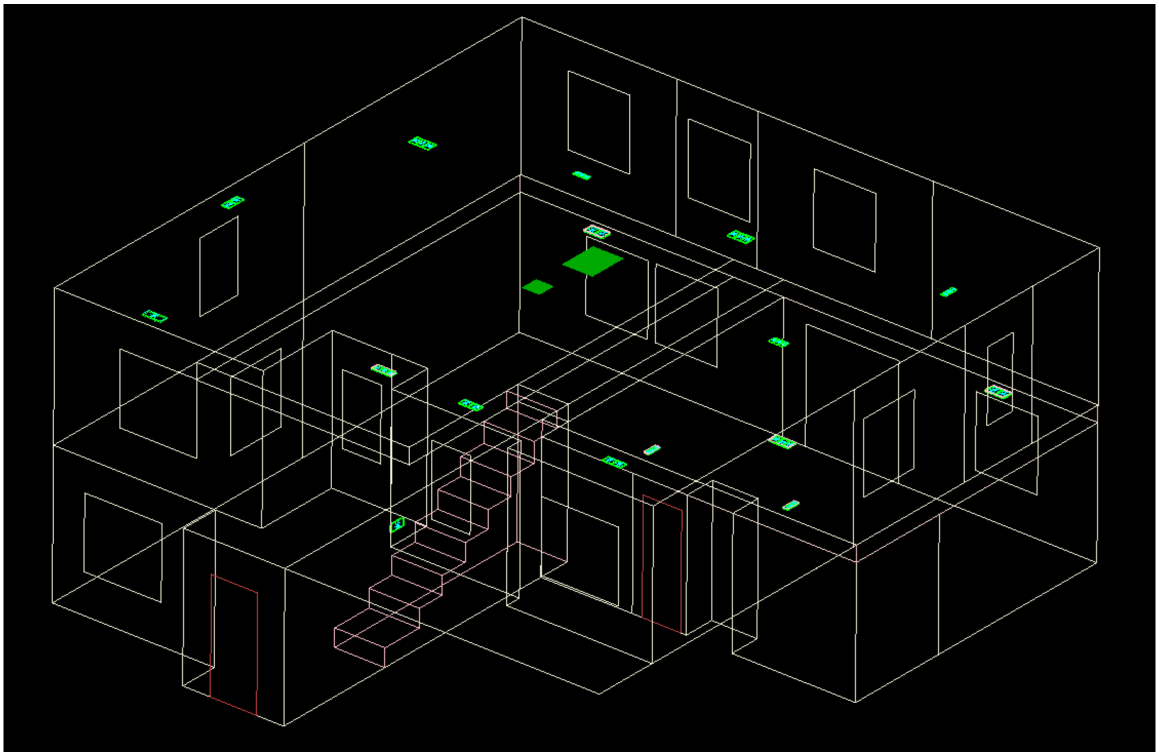


Figure 33: Case 3 – Register and Return Locations

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.

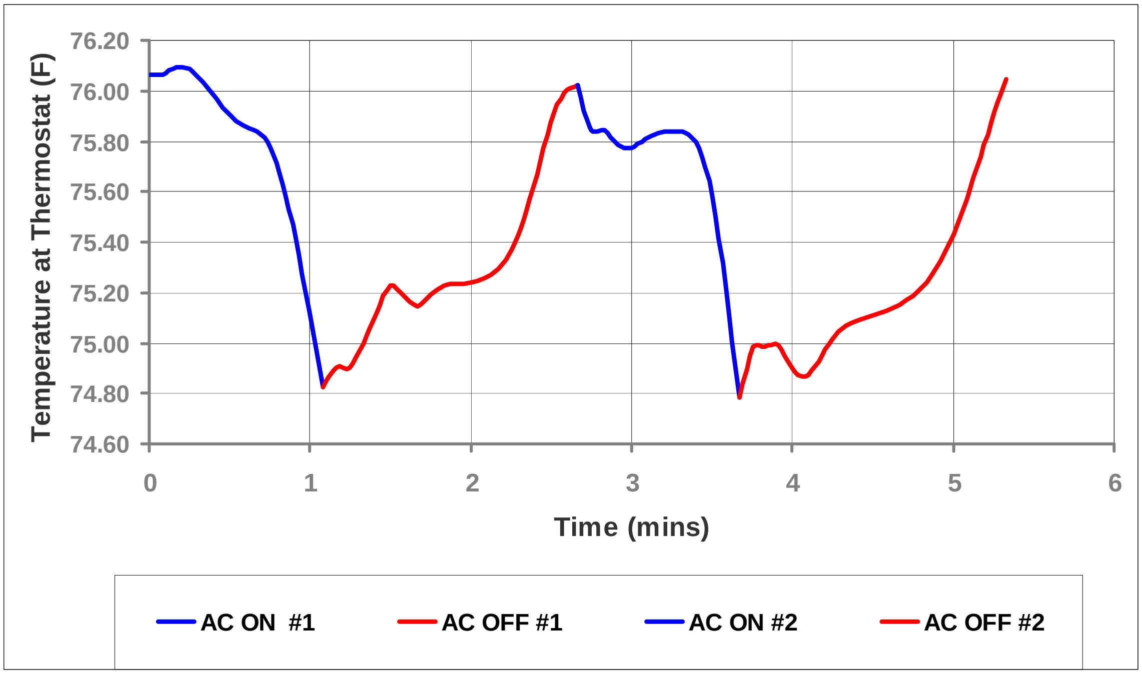


Figure 34: Case 3 -- Transient Temperature Variation at Thermostat

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.

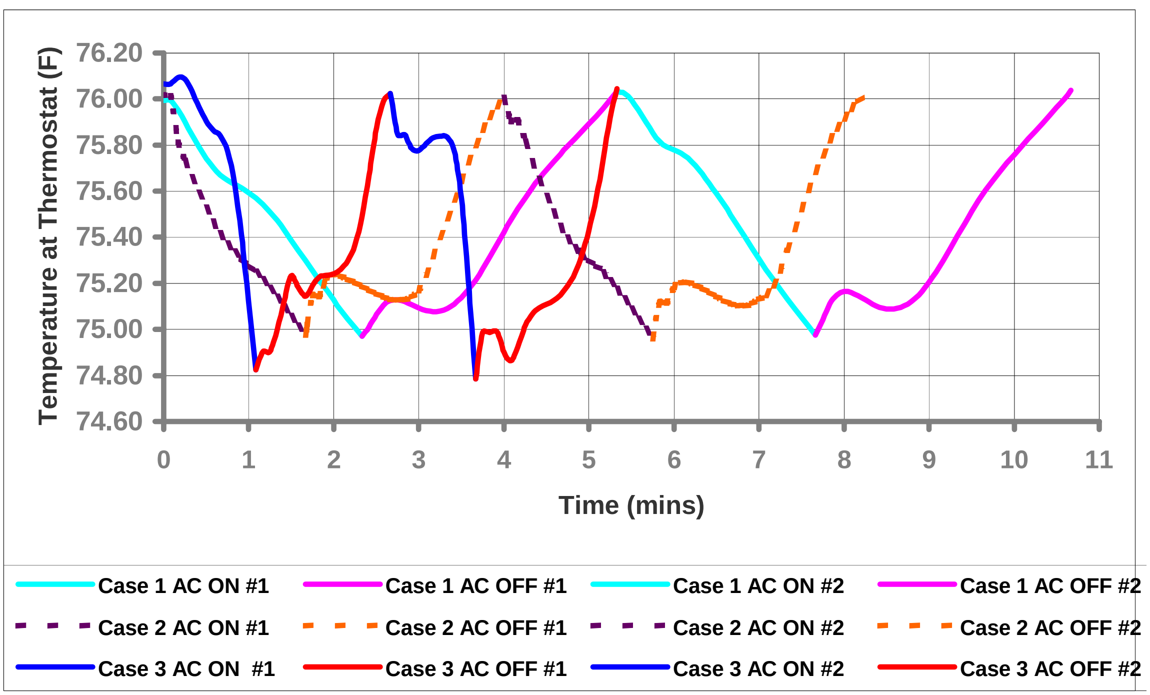


Figure 35: Comparison of HVAC Cycle Time for Case 1, 2 and 3 (Return Upstairs and Downstairs, Return Upstairs Only, Thermostat Downstairs)

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.