Public Interest Energy Research (PIER) Program
FINAL PROJECT REPORT

# MULTIFAMILY CENTRAL DOMESTIC HOT WATER DISTRIBUTION SYSTEMS

Prepared for: California Energy Commission
Prepared by: Heschong Mahone Group, Inc.

JUNE 2013
CEC-500-2013-011

HESCHONG MAHONE GROUP

***Prepared by:***

***Primary Author(s):***
Yanda Zhang, PhD

Heschong Mahone Group, Inc.
11211 Gold Country Blvd, Suite 103
Gold River, CA 95670
916-962-7001
www.h-m-g.com

***Contract Number: 500-06-029***

***Prepared for:***

**California Energy Commission**

Bradley C. Meister, Ph.D., P.E.
***Contract Manager***

Virginia Lew
***Office Manager***
***Energy Efficiency Research Office***

Laurie ten Hope
***Deputy Director***
***RESEARCH AND DEVELOPMENT DIVISION***

Robert P. Oglesby
***Executive Director***

**DISCLAIMER**

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

# ACKNOWLEDGEMENTS

The author would like to acknowledge the following team members at Heschong Mahone Group, Inc., that contributed to the development of this study:

- Charlotte Bonneville
- Derrick Leung
- Jeff Staller
- Julianna Wei
- Matthew Haro
- Mike Maroney
- Owen Howlett (now with the California Energy Commission)
- Sophia Hartkopf
- Stephen Wilson

EDC Technology, Inc., subcontractor on the project, provided temperature modulation control equipment and access to its database of continuous monitoring data from many multifamily buildings. Saves You Energy, LLC and Enovative Group, Inc. provided demand control equipment to support the field performance evaluation of demand control technologies.

The research team would like thank the California Investor Owned Utilities (IOUs), Codes and Standards programs for providing additional funding to support the improvement of the recirculation system model developed by this study. The improved model was used to support the development of the 2013 Title 24 requirements for central domestic hot water systems in multifamily buildings and hotels/motels.

The project team is enormously appreciative of all the building owners and operators who participated in this study and allowed team members to survey their buildings, monitor their domestic hot water systems, and review their building plans. The study would not have been possible without their participation.

# PREFACE

The California Energy Commission 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 conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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

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

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

*Multifamily Central Domestic Hot Water Distribution Systems* is the final report for the Domestic Hot Water project (contract number 500-06-029), conducted by Heschong Mahone Group. The information from this project contributes to PIER's Buildings End-Use Energy Efficiency Program.

When the source of a table, figure or photo is not otherwise credited, it is the work of the author of the report.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

# ABSTRACT

This report examines recirculation systems in multifamily central domestic hot water systems. The purpose is to provide a good understanding of recirculation system performance and to assess the potential energy savings resulting from implementing recirculation system controls.

This project studied domestic hot water system operations in 28 multifamily buildings. These multifamily buildings had between 11 and 250 dwelling units each and ranged from two to five stories tall. Study buildings were located in both Northern and Southern California and covered five climate zones. About half of these buildings were built after 1990, and the other half was built before 1990.

This project developed a performance analysis method to measure energy consumption of major components in central domestic hot water systems. This method separated natural gas consumption for the domestic hot water system into four energy flow components: water heating equipment efficiency and standby heat loss, recirculation system heat loss, branch pipe heat loss, and delivered hot water energy. Percentages of natural gas consumption for these four energy flow components were calculated using field monitoring results.

While recirculation system controls can help to reduce heat loss from pipes, improving recirculation system designs is more important because it will ensure that domestic hot water systems will have small heat loss from initial startup. This study investigated recirculation system designs in central domestic hot water systems and developed a model to predict recirculation system performance based on recirculation system designs.

Additional research is needed to address branch pipe performance so that overall system optimization can be performed. Assessing the performance of these branches to the water fixture will further identify future opportunities for energy saving improvements.

Residential hot water systems use approximately 44 percent of residential natural gas use in California. Identifying ways to make all aspects of hot water systems more efficient can save California residents a significant amount of energy and water.

**Keywords:** Multifamily hot water distribution, hot water, central distribution, demand control, temperature modulation, efficient distribution, Cross over flow

Please use the following citation for this report:

Zhang, Yanda. (Heschong Mahone Group). 2013. ***Multifamily Central Domestic Hot Water Distribution Systems.*** California Energy Commission. Publication Number: CEC-500-2013-011.

# TABLE OF CONTENTS

**Acknowledgements** ..... **i**

**PREFACE** ..... **ii**

**ABSTRACT** ..... **iii**

**TABLE OF CONTENTS** ..... **iv**

**LIST OF FIGURES** ..... **vii**

**LIST OF TABLES** ..... **viii**

**EXECUTIVE SUMMARY** ..... **1**

Field Monitoring Study ..... 1

Performance Analysis ..... 1

Recirculation System Design ..... 3

System Operation Issues ..... 3

Recirculation System Model ..... 4

Performance of Recirculation System Controls ..... 4

Conclusions ..... 6

Next Steps ..... 6

Benefits to California ..... 6

**CHAPTER 1: Introduction** ..... **9**

1.1 Multifamily Central DHW Systems ..... 10

1.2 Recirculation System Controls ..... 11

1.2.1 Timer Control ..... 12

1.2.2 Temperature Modulation ..... 12

1.2.3 Demand Control ..... 13

1.2.4 Continuous Monitoring ..... 13

1.3 Previous Studies ..... 13

1.4 Research Goals and Objectives ..... 14

**CHAPTER 2: Research Plan** ..... **16**

2.1 Field Monitoring Study ..... 16

2.1.1 Field Monitoring Plan ..... 16
2.1.2 Evolution of Field Monitoring Plan ..... 17
2.2 Performance Analysis ..... 20
2.2.1 Energy Flow Analysis ..... 20
2.2.2 Historical Monitoring Data Analysis ..... 24
2.3 Recirculation System Model Development ..... 24
**CHAPTER 3: Field Monitoring Study ..... 27**
3.1 Field Monitoring Buildings ..... 27
3.2 Observations of Recirculation System Operation ..... 32
3.2.1 Hot Water Draw Flow ..... 32
3.2.2 Recirculation Flow ..... 32
3.2.3 HWS Temperatures ..... 32
3.2.4 HWR Temperatures ..... 33
3.2.5 CWS Temperatures ..... 33
3.3 Field Measurement Issues ..... 35
3.3.1 Temperature Measurement ..... 35
3.3.2 Water Flow Measurement ..... 37
3.3.3 Natural Gas Measurement ..... 38
3.4 Crossover Flow Investigation ..... 38
3.4.1 Reverse Flow Measurement ..... 38
3.4.2 System Pressure Analysis ..... 39
3.5 Recirculation System Piping Layout ..... 41
**CHAPTER 4: Performance Analysis Results ..... 44**
4.1 Overall System Performance ..... 44
4.2 Performance of Controls ..... 49
4.3 Hot Water Draw Analysis ..... 51
4.4 Historical Monitoring Data Analysis ..... 56
**CHAPTER 5: Recirculation System Model Development ..... 57**

5.1 Overview ..... 57
5.2 Recirculation System Configuration ..... 57
5.3 Pipe Heat Transfer Modes ..... 59
5.3.1 Pipe Heat Transfer with Hot Water Flows ..... 60
5.3.2 Pipe Heat Transfer without Hot Water Flows ..... 61
5.4 Recirculation System Heat Transfer Modes ..... 61
5.4.1 Recirculation Operation with Varying Hot Water Flows ..... 61
5.4.2 Recirculation Operation with Varying HWS Temperatures ..... 63
5.4.3 Mechanisms of Control Technologies ..... 64
5.5 Model of Controls ..... 64
5.5.1 Modeling of Continuous Pumping ..... 64
5.5.2 Continuous Pumping without Any Controls ..... 64
5.5.3 Modeling of Temperature Modulation ..... 65
5.5.4 Modeling of Timer Control and Demand Control ..... 65
5.6 Model Validation Procedures ..... 66
5.7 Model Validation Results ..... 69
5.7.1 Validation of HWR Temperature Prediction ..... 69
5.7.2 Validation of System Energy Flows ..... 71
5.8 Energy Savings of Controls ..... 74
**CHAPTER 6: Conclusion ..... 76**
6.1 Performance Analysis ..... 76
6.2 Recirculation System Piping Design ..... 77
6.3 Recirculation System Model ..... 78
6.4 Performance of Recirculation Controls ..... 79
6.5 Continuous Monitoring ..... 80
6.6 Next Steps ..... 81
**CHAPTER 7: Technology Transfer ..... 83**
7.1 Central DHW System Design Guide ..... 83

7.2 ACEEE Hot Water Forum Presentations ..... 83

7.3 2013 Title 24 Development ..... 83

**GLOSSARY ..... 85**

**REFERENCES ..... 86**

**APPENDIX A: Field Monitoring Study Buildings ..... A-1**

**APPENDIX B: Historical Monitoring Data Analysis ..... B-1**

**APPENDIX C: Recirculation System Model ..... C-1**

Pipe Heat Transfer Solutions ..... C-1

Pipe Heat Transfer Coefficient (UA) ..... C-1

Lumped Capacity Method for Pipe Cool Down ..... C-2

Excel Model Screenshots ..... C-3

Overall Setting and Output Summary ..... C-3

Settings of Controls ..... C-4

Model Pipe Section Configuration ..... C-5

Model Calculation Steps ..... C-6

## LIST OF FIGURES

Figure 1: Average Energy Flows in Monitored Central DHW Systems ..... 2
Figure 2: Illustration of a Central DHW System in a Multi-Family Building ..... 10
Figure 3: Schematics of Central DHW System Configuration ..... 11
Figure 4: Schematics of Field Measurement Locations ..... 17
Figure 5: Illustration of Major Energy Flow Components in Central DHW Systems ..... 21
Figure 6: Measured Recirculation System Operation – No Controls ..... 33
Figure 7: Measured Recirculation System Operation – Timer Control ..... 34
Figure 8: Measured Recirculation System Operation – Temperature Modulation ..... 34
Figure 9: Measured Recirculation System Operation – Demand Control ..... 35
Figure 10: Comparison of Water and Pipe Temperature Measurements ..... 36
Figure 11: Recirculation System Pressure Measurement Results ..... 40
Figure 12: Recirculation System Piping Layouts in Four Full On-Site Study Buildings ..... 43
Figure 13: Percentages of DHW System Natural Gas Consumption by Energy Flow Components ..... 45
Figure 14: Average Energy Flows in Multi-Family Central DHW Systems ..... 46
Figure 15: Statistics of Recirculation System Heat Loss ..... 49
Figure 16: Example of Measured Peak Hot Water Demand – Full Day ..... 53
Figure 17: Example of Measured Peak Hot Water Demand – Three Hours ..... 53

Figure 18: Peak Hot Water Demand Fractions ..... 54
Figure 19: Example of Pipe Section Configurations for a Simple Recirculation System ..... 58
Figure 20: Recirculation System Model for a Full On-Site Study Building ..... 59
Figure 21: Hot Water Temperature Distribution in a Recirculation System ..... 63
Figure 22: Model Validation – Temperature Modulation ..... 70
Figure 23: Model Validation – Timer Control ..... 70
Figure 24: Model Validation – Demand Control ..... 70
Figure 25: HWS Temperatures under Temperature Modulation Controls and Continuous Monitoring ..... B-2
Figure 26: Illustration of Pipe Heat Transfer ..... C-1

## LIST OF TABLES

Table 1: Summary of Measured Energy Savings from Control Technologies ..... 5
Table 2: Energy Savings from Control Technologies in Four Buildings Based on Modeling Study ..... 5
Table 3 Summary of Field Monitoring Plan ..... 17
Table 4: Summary of Field Monitoring Study Buildings ..... 28
Table 5: Detailed Characteristics of Field Monitoring Study Buildings – Full On-Site Study ..... 29
Table 6: Detailed Characteristics of Field Monitoring Study Buildings – Partial On-Site Study. 30
Table 7 Variations of Key Recirculation System Parameters of All Monitored Buildings ..... 44
Table 8 Summary of Field Monitoring and Performance Analysis Results – Full On-Site Study47
Table 9: Summary of Field Monitoring and Performance Analysis Results – Partial On-Site Study ..... 48
Table 10: Control Schedules for Full On-Site Studies ..... 51
Table 11: Measured Gas Energy Savings by Controls ..... 51
Table 12: Recirculation System Pipe Heat Loss Rates under Different Flow Conditions ..... 62
Table 13: Recirculation System Pipe Heat Loss Rates with Different HWS Temperature ..... 63
Table 14: Validation of Model Predictions of Recirculation System Pipe Heat Loss ..... 71
Table 15: Validation of Energy Savings from Controls ..... 72
Table 16: Comparison of Heat Loss of Flows in Recirculation Systems ..... 74
Table 17: Energy Savings from Control Technologies in Four Buildings Based on Modeling Study ..... 75
Table 18: Pictures of Field Monitoring Study Buildings – Full On-Site Study ..... A-2
Table 19: Pictures of Field Monitoring Study Buildings – Partial On-Site Study ..... A-8
Table 20: Average HWS Temperature under Temperature Modulation and Continuous Monitoring ..... B-6

# EXECUTIVE SUMMARY

## Field Monitoring Study

The study monitored central domestic hot water system operation in 28 multifamily buildings, selected from more than 50 buildings recruited by the research team. These monitored multifamily buildings had between 11 and 250 dwelling units each and were between two and five stories tall. They were located in both northern and southern California and covered five climate zones. About half of these buildings were built after 1990 and the other half was built before 1990.

The research team conducted two types of field studies: full on-site studies (performed in 8 buildings) and partial on-site studies (performed in 20 buildings). Full on-site study buildings were chosen to provide in-depth understanding of recirculation performance, while partial on-site study buildings were chosen to obtain performance information from a broad range of buildings. Both types of field studies monitored key recirculation system parameters, including hot water supply temperature, hot water return temperature, cold water supply temperature, recirculation flow, and hot water draw flow. These measurements allowed the research team to quantify recirculation system performance using an energy flow analysis method, described in the next section. Full on-site studies also monitored domestic hot water system natural gas consumption, investigated recirculation system piping designs, and assessed energy savings from recirculation system controls. Control technologies investigated by this study included timer control, temperature modulation, and demand control. The additional information provided by full on-site studies was essential to developing a recirculation system model.

## Performance Analysis

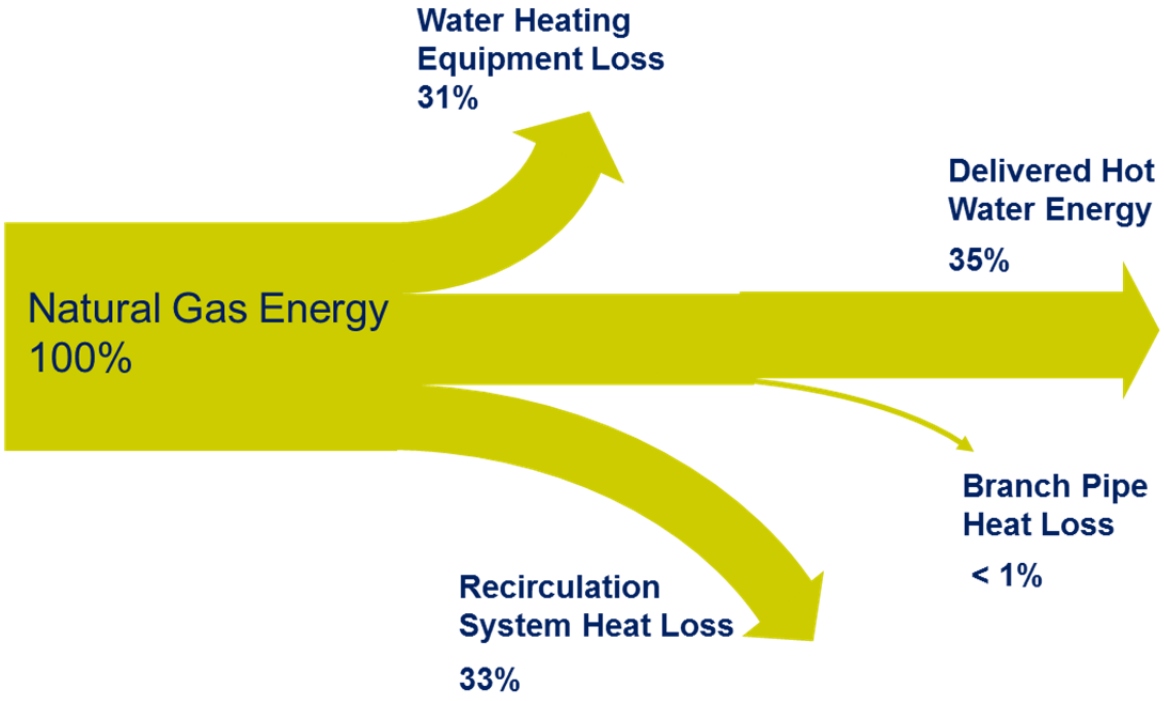
Previous studies relied on total system natural gas consumption to determine performance of overall central domestic hot water systems; this approach was unable to reveal the performance of recirculation systems as a component of the overall central domestic hot water system. This study developed a performance analysis method − energy flow analysis method − to quantify energy consumption of major components in central domestic hot water systems. This method separated the total domestic hot water system natural gas consumption into four energy flow components: water heating equipment efficiency and standby heat loss, recirculation system heat loss, branch pipe heat loss, and delivered hot water energy. Percentages of total domestic hot water system natural gas consumption for these four energy flow components were calculated using field monitoring results. Two performance metrics are established based on this performance analysis method:

- Overall domestic hot water system efficiency is represented by the percentage of total system natural gas consumption accounted for by delivered hot water energy.
- Performance of recirculation system is represented by the percentage of total system natural gas consumption taken up by recirculation system heat loss.

Energy flow analysis was performed for domestic hot water systems in all 28 monitored buildings. The analysis results revealed a very wide range of performance. Overall domestic hot water system efficiency ranged from 9 percent to 67 percent, and recirculation system heat loss ranged from 3 percent to 61 percent. As shown in **Error! Reference source not found.**, the overall average efficiency of central domestic hot water systems was 35 percent, and recirculation system heat loss represented 33 percent of the total domestic hot water system natural gas consumption.

The results showed that heat loss by branch pipes represented about 1 percent of the total natural gas consumption. However, this study did not monitor hot water usages at each branch and hot water fixture; therefore, it was un able to quantify hot water waste associated with draws to discharge cold water in the pipe and hot water cooled down in branches without being used. For this reason, branch pipe heat loss provided by this study represents only a low bound. If hot water wastes by branch pipes were included, overall domestic hot water system efficiency would be lower than 35 percent.  Future studies are needed to provide better information on branch pipe performance in multifamily central domestic hot water systems. This future research will result in a thorough investigation and assessment of the entire piping system performance and heat loss, natural gas consumption implications and strategies for optimization based on pipe size and run.

**Figure 1:  Average Energy Flows in Monitored Central DHW Systems**



## Recirculation System Design

The study investigated recirculation piping designs through field surveys, building plan reviews, and interviews with domestic hot water system designers. The research team inspected recirculation system designs, in terms of pipe sizes and locations, in more than 50 multifamily buildings as part of the initial screening process to identify field study candidates. For monitored buildings, the research team further reviewed building plans, if available, to obtain the recirculation design information that could not be observed through field inspection. Many types of designs were found. Some buildings used simple recirculation loops that stayed in one floor with long branch lines to reach to each hot water fixture, while other buildings used complicated designs to minimize branch lengths between recirculation pipes and dwelling units.

Interviews with several recirculation system designers found that there was no consensus on design guidelines for central domestic hot water recirculation systems. This explained why no consistent design trends were observed in the field. Some design approaches, for instance, using balancing valves to balance flows in parallel recirculation loops, were adopted from design guides for hydronic heating systems which transfers heat by circulating a hot fluid through a closed system of pipes. These approaches were not widely used and were not always suitable for central domestic hot water systems.

Detailed recirculation system designs in four full on-site study buildings were created based on field inspection and building plan review, and were used to support the development and validation of a recirculation system model developed by the study.

## System Operation Issues

This study investigated the system operations issue of crossover flows and recirculation pump failures, which were reported by previous studies to exist widely in central domestic hot water systems.

Bidirectional flow meters were installed on cold water supply and hot water return pipes to detect possible crossover flow[1] in these pipes. Field measurements did not indicate strong reverse flow signals (strong signals can be an indication of crossover flows in cold water supply pipes). In all surveyed central domestic hot water systems, check valves were in place on cold water supply pipes to prevent back flows into building cold water mains. Therefore, it was not surprising that no crossover flows in cold water supply pipes were found in these buildings. Previous studies relied on pipe temperature measurements to detect crossover flows. This study found that pipe temperature measurements, in some cases, were not reliable for copper pipes. Because of their high thermal conductivity, the temperature of copper pipes can rise very quickly when there is no water flow and the pipe is connected to a hot water pipe or a storage tank with a short pipe length. In this case, using temperature measurement alone may lead to a false conclusion of crossover flow of hot water into cold pipes.

1 Crossover flow is cold water flowing into hot water piping or hot water flowing into cold water piping

The study encountered only one event of recirculation pump failure during the field study period. The failure was related to a coupler between the pump and motor. The system operator identified the issue based on complaints of no hot water services from building occupants and fixed the problem very quickly.

The study also tried to identify crossover flows and recirculation pump failures from long-term monitoring data provided by EDC Technology Inc. (EDC), who implemented continuous monitoring of recirculation system in many multifamily buildings. Although many irregular monitoring results were found, the research team did not possess sufficient information to discern between system malfunctions and measurements issues. EDC informed the research team that extensive information on system configurations was needed for system diagnosis. Since system configuration information was not available to the research team, the study could not reach definitive conclusions from analyzing historical monitoring data obtained from EDC.

## Recirculation System Model

The study developed a recirculation system heat transfer model capable of predicting recirculation pipe heat loss with different recirculation designs and under different operation conditions. The model treated the recirculation system as a network of interconnected pipe sections, reflective of actual recirculation system designs. The study identified that pipe heat loss can be represented by two fundamental heat transfer modes: pipe with hot water flows and pipe without hot water flows. Depending on hot water draw schedules and recirculation pump control schedules, each pipe section can be in one of the two heat transfer modes and, therefore, have different heat loss characteristics. This unique modeling method avoided the use of complicated numerical methods, which could not provide clear explanation of the physical processes. More important, this modeling method can be adapted to simple algorithms to be implemented in Title 24 compliance software.

For model validation, four recirculation system models were configured based on detailed recirculation system designs of four on-site study buildings. Model-predicted hot water return temperatures, recirculation system heat loss, and total domestic hot water system natural gas consumption were compared to measured values from field studies. The validation results showed a close match between model prediction and field measurement, indicating the model could actually predict recirculation system performance.

## Performance of Recirculation System Controls

The study evaluated performance of three recirculation control technologies: timer control, temperature modulation, and demand control. Energy savings potentials from these control technologies were assessed through field measurement, heat transfer analysis, and model simulations.

Field measurements in eight full on-site study buildings provided a large range of energy savings including negative and zero energy savings, as shown in Table 1. These savings were calculated based on comparison to the domestic hot water system without any recirculation

system controls. Further investigation revealed that variations in system operation conditions, especially hot water usages, caused the large uncertainties in energy savings assessment.

**Table 1: Summary of Measured Energy Savings from Control Technologies**

| Controls | Min | Max | Median |
|---|---|---|---|
| Temperature Modulation | -11% | 14% | 7% |
| Timer Control | -4% | 18% | 1% |
| Demand Response | 0% | 32% | 11% |

Pipe heat transfer studies revealed how the control technologies saved energy. Fundamentally, pipe heat loss reduction depends on pipe temperature reduction. Temperature modulation controls reduce the temperature of the whole recirculation system. The amount of pipe temperature reduction is moderate and is for several hours a day, depending on detailed control settings. Timer controls allow recirculation pipes, especially hot water return pipes, to cool down substantially. Hot water draw flows, if existent, would prevent hot water supply pipes from cooling down so that heat loss reduction in hot water supply pipes can be much less and depends on hot water draw schedules. Timer controls are also usually active for several hours a day, depending on control schedule settings. Demand controls have the same effects on pipe temperature reduction as timer controls, since both technologies control recirculation pump operation. However, demand controls turn off recirculation pumps much more often than timer controls and, therefore, lead to higher heat loss reduction.

The study further used the validated recirculation models for four full on-site study buildings to assess energy savings from controls. Modeling studies have the advantages to keep system operation conditions, such as hot water draw schedules, cold water supply temperatures, and ambient temperatures, the same with and without recirculation controls, so that changes in domestic hot water system natural gas consumption reflect only energy savings from controls. Results of the modeling study showed that energy savings from controls strongly correlate to recirculation system performance as omdocated om Table 2. Buildings with higher recirculation system heat losses benefited more from controls than those with lower recirculation system heat losses. Since field studies revealed a wide range of recirculation system performance, energy savings from control in these building were expected to vary accordingly.

**Table 2: Energy Savings from Control Technologies in Four Buildings Based on Modeling Study**

| | A-SAM | B-SFD | C-SFH | D-SFF |
|---|---|---|---|---|
| **Temp Modulation** | 2.0% | 1.4% | 0.9% | 0.5% |
| **Timer Control** | 5.4% | 3.4% | 1.8% | 0.5% |
| **Demand Control** | 14.3% | 6.9% | 4.5% | 1.0% |
| | | | | |
| **Recirculation System Heat Loss** | 42% | 34% | 18% | 7% |

## Conclusions

Key observations and findings from the research project include:

- Water heater/boiler efficiency is still the most important component to system efficiency- Proper system sizing will help reduce standby and short-cycling losses
- Distribution system design is important especially placing the recirculation loop through the middle of the building (this is the same concept as placing water heater near fixture)
- Control and monitoring is important and even a simple temperature indicator on the hot water return can be very useful
- The key to energy savings is to reduce recirculation loop temperatures as much as possible since the return portion of the recirculation loop does not need to be warm
- Pipe insulation can keep recirculation loop warm for an extended period
- Hot water draws will help sustain recirculation loop temperatures
- Recirculation controls were not widely used and those that were in use were not configured properly.

## Next Steps

While recirculation system controls can help to reduce pipe heat loss, enhancing recirculation system designs is more important because it ensures the domestic hot water system will have small heat loss from the onset of equipment operation. This study, for the first time, began to investigate recirculation system designs in central domestic hot water systems and developed a model to predict recirculation system performance based on recirculation system designs. From the point of view of overall distribution system performance, there is a tradeoff between recirculation system design and branch pipe design since heat loss from the two cannot be minimized at the same time. Additional research is needed to address branch pipe performance so that overall system improvement can be performed.

This study provided a better understanding of energy savings mechanisms of control technologies. Further studies should be conducted to help improve existing control technologies and demonstrate new control technologies, based on the findings from this study.

## Benefits to California

Residential hot water systems use approximately 44 percent of residential natural gas use in California. In California, approximately one third of households reside in multifamily buildings and there are 2.4 million multifamily units according to the Multifamily Subcommittee of the California Home Energy Retrofit Coordinating Committee (www.builditgreen.org/_files/Admin/HERCC/MF_HERCC_report_10152010.pdf). Thus, identifying ways to make hot water systems more efficient can save California residents a significant amount of energy and water.

For existing multifamily buildings, the benefits of improved hot water systems include monetary savings, reduced energy usage, reduced water use, and reduced greenhouse gas

emissions due to energy savings and the embedded energy in water. As indicated in this report, recirculation system heat loss can range between 7% and 42%, with an average 33%. This means that on average 33% of the energy used to heat water is lost through the piping systems. Identifying effective control technologies and strategies can reduce this energy loss. For instance, installing a temperature indicator on hot water return piping and reducing the recirculation loop temperatures can lead to savings. Understanding that the return portion of the recirculation loop does not need to be kept warm and that pipe insulation can keep recirculation loop warm for extended periods will further result in reduced costs and energy use.

In addition to the savings mentioned previously, for planned multifamily buildings, additional savings can be realized through proper system design, sizing and the location of the distribution system. By placing the recirculation loop in the middle of the building (this is the same concept as placing a water heater near a fixture) both natural gas and water usage can be minimized.

# CHAPTER 1: Introduction

This report presents findings from the study on central domestic hot water (DHW) systems in multifamily buildings. The study was conducted by the Heschong Mahone Group (HMG) and was funded by the California Energy Commission (Energy Commission) through the Public Interest Energy Research (PIER) program.

Multifamily buildings, especially large buildings with many dwelling units, usually use a central DHW system to provide hot water to each dwelling unit. Such systems have centrally located water heating equipment and use recirculation systems to distribute hot water to individual dwelling units. Recirculation systems usually consist of long recirculation pipes with hot water circulating inside, even when there is no hot water draw in the building. As a result, recirculation systems in multi-family buildings incur a large amount of pipe heat loss and reduce overall DHW system efficiency. Several control technologies have been promoted by industry practitioners to improve the efficiency of DHW systems with recirculation systems.

A previous PIER study on multi-family central DHW system [HMG 2008] (hereafter referred to as the 2008 PIER study) tried to assess energy savings from these control technologies. The 2008 PIER study monitored recirculation systems in three multi-family buildings and provided preliminary assessment of energy savings from control technologies. The study identified factors that affected control technology performance and recommended that further investigation of central DHW systems be performed to provide better assessment of control technology savings.

This study was a continuation of the 2008 PIER study on central DHW systems in multi-family buildings. It aimed to provide thorough understanding of recirculation system operation and control technology performance. The study included three major components:

1. Conducting field monitoring in a broad range of multi-family buildings to collect performance data of central DHW systems
2. Performing in-depth analysis to characterize performance of central DHW systems
3. Developing a recirculation system model to facilitate performance assessment of systems with different designs and control technologies

This chapter provides basic information on central DHW system designs and controls and the overall research goals and objectives.

## 1.1 Multifamily Central DHW Systems

Figure 2 illustrates a central DHW system in a multifamily building, and Figure 3 presents the schematics of central DHW system configuration. In general, a central DHW system consists of:

- Central water heating equipment and a recirculation system. Common types of water heating equipment used in multi-family central DHW systems include the following:
- One or multiple commercial gas storage water heaters
- One or two hot water heating boilers coupled with a large storage tank

The following three types of water heating equipment were also observed, but they were less common:

- A storage tank heated by steam from a central plant (at a university campus)
- Solar water heater with gas water heater/boiler as backup (three buildings)
- Tankless water heater connected to recirculation system (one building)

**Figure 2: Illustration of a Central DHW System in a Multi-Family Building**

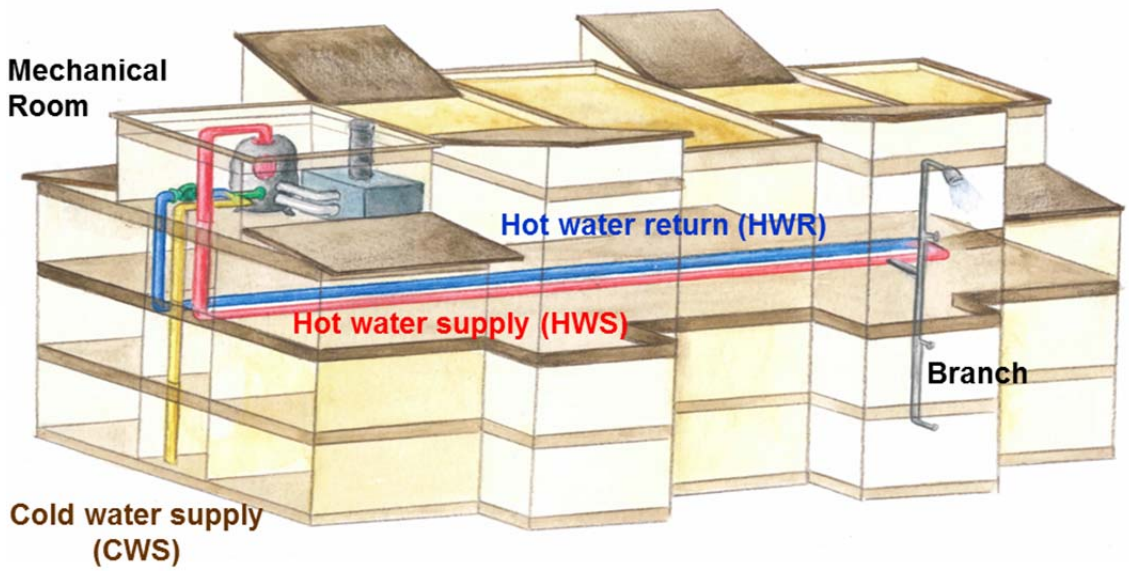
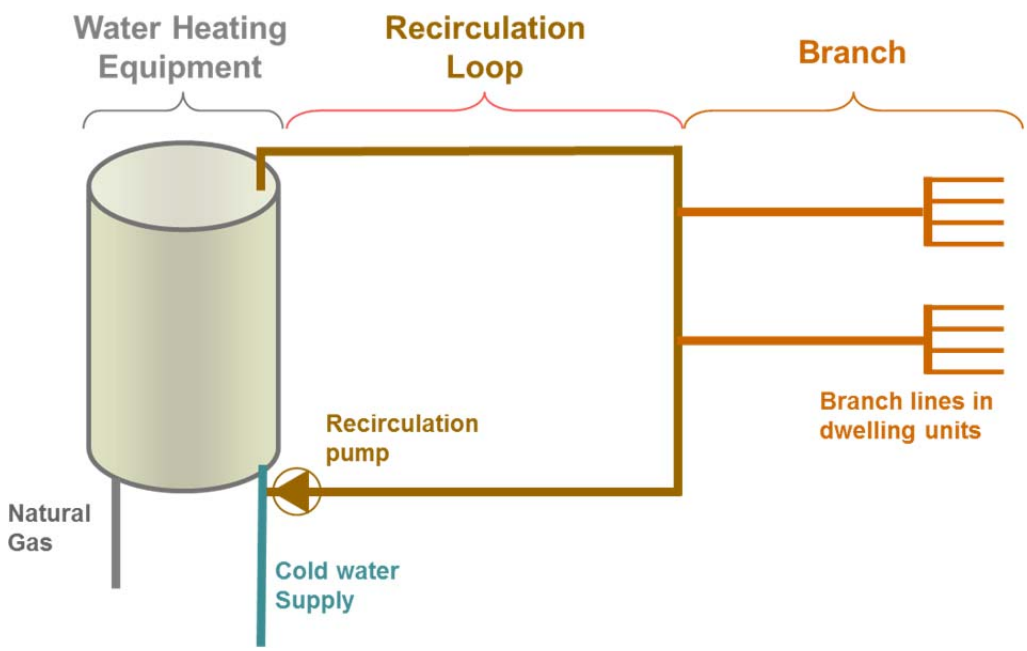


**Figure 3: Schematics of Central DHW System Configuration**




Detailed configurations of water heating equipment are not critical to the investigation of recirculation system performance, which is the focus of this study. As shown in Figure 3**Error! Reference source not found.**, water heating equipment can be represented by a simple storage tank that provides hot water supply to the recirculation system and takes hot water return from the recirculation system and cold water supply as input.

A recirculation system helps to bring hot water closer dwelling units, which might be far away from the central water heating equipment, so that building occupants do not need to wait for a long time for hot water to reach their hot water fixtures, for instance showers and kitchen sinks, through branch lines. To completely achieve this function, a recirculation system needs to get close to most of the dwelling units in the building. This implies that the piping layout of a recirculation system can be fairly complicated. Instead of one simple recirculation loop illustrated in Figure 2 and Figure3, many recirculation systems observed in the field had multiple loops and went through several stories. Recirculation loops also need to be maintained at high temperatures by circulating hot water all the time so that occupants can have quick access to hot water all the time. High recirculation system temperatures, coupled with large pipe surface areas associated with complicated designs, cause recirculation systems to have high heat losses and a large impact to overall system efficiency.

## 1.2 Recirculation System Controls

This study investigated several recirculation system control technologies. These control technologies aim to reduce recirculation system heat loss by adjusting either recirculation pump

operations or hot water supply temperatures based on building hot water usage schedules. The following section describes the basic operation principles of these control technologies.

### 1.2.1 Timer Control

A timer control (or time clock control) automatically turns off the recirculation pump according to a fixed schedule set by the system operator. The common practice is to turn off the recirculation pump when a building is expected to have no hot water draws. The intention is to avoid having cold water in the recirculation loop when there are hot water draws. Since the same control schedule is used every day, this control is believed to be applicable to buildings with consistent window periods every day when there is no hot water draw.

The schedule of a timer control depends on building hot water usage schedules, which, in turn, depends on building occupant behaviors. It is generally expected that multifamily buildings have little to no hot water demand for some period during the night, so that the recirculation pump can be scheduled to be turned off by a timer control. For this reason, the timer control was specified in 2005 Title 24 Part 6 as the minimum control requirement for multifamily DHW systems. A building could have other times, when there is no hot water draw and the recirculation pump can be turned off, for instance during the time after morning peak hours and before lunch cooking time and/or the time after the lunch and before the evening cooking time. Ideally, timer control schedules should be carefully set by DHW system operators with observations of hot water demand patterns.

### 1.2.2 Temperature Modulation

A temperature modulation control reduces hot water supply (HWS) temperatures when the hot water demand is expected to be zero or very low. Recirculation pump operation is not affected and is kept on all the time.

There are two types of temperature modulation controls available in the market; one uses fixed control schedules and the other uses dynamic control schedules. For the one with fixed control schedules, the control schedule is determined in similar way as that of a timer control. Since the recirculation pump is not turned off, there is no concern for introducing cold water in the recirculation system. The control would work when there are low levels of hot water draws. A temperature modulation control with dynamic control schedules is designed to automatically set control schedule by detecting and learning hot water usage patterns. Control schedules may be automatically adjusted based on changes in hot water usage patterns. Potentially, temperature modulation control with a dynamic control schedule can more accurately reflect building hot water draw schedules and capture more times to reduce HWS temperatures.

Temperature modulation controls also need to determine the amount of HWS temperature reduction during zero or low hot water demands. Large reductions in HWS temperature help to reduce more pipe heat loss. However, by keeping HWS temperature too low, the system thermal storage might be too low to meet any unexpected demand and the lukewarm water temperature may not be able to satisfy hot water service needs of building occupants.

### 1.2.3 Demand Control

Demand controls change recirculation pump operation based on hot water demand. The recirculation pump is turned off when there is no hot water draws. It is turned on when hot water draws are detected by a flow sensor installed on the cold water supply (CWS) pipe. Some industry practitioners suggested that demand control systems need to use a powerful recirculation pump to bring hot water to occupants quickly, when hot water draws were detected and the recirculation pump was turned on.

Advanced demand control technologies also incorporate measurement of hot water return (HWR) temperature to determine recirculation pump operation in conjunction with hot water demands. The recirculation pump is kept off as long as the HWR temperature is above an upper threshold value, even when hot water draws are detected. The recirculation pump is turned on if the HWR temperature is below a lower threshold value to prevent the water temperatures in the recirculation system from becoming too low.

### 1.2.4 Continuous Monitoring

A continuous monitoring system installed in a recirculation system measures key system operation parameters. It may automatically identify system operation issues and alert system operators. If system operators take actions accordingly to correct reported problems, the system can be maintained to operate under expected conditions. Energy savings could be generated if the reported issues and corresponding correction actions prevent system performance degradation. Continuous monitoring itself is not a control technology. However, it has been integrated with other control technologies, for instance temperature modulation.

The research team collaborated with EDC Technology Inc. (EDC), a company that provides continuous monitoring equipment and services, to evaluate the benefits of continuous monitoring.

## 1.3 Previous Studies

Several studies have been conducted to assess energy savings from recirculation system controls. Bohac et.al. [Bohac 1992] assessed energy savings and cost effectiveness of several control technologies based on field studies at three multi-family buildings (all had about 40 dwelling units each) in Minnesota. Their study found that temperature modulation controls (referred to as the AQUASTAT in the study) was “worthwhile” and demand controls achieved more energy savings than timer controls. Heschong Mahone Group (HMG) conducted the 2008 PIER study [HMG 2008], which assessed performance of control technologies at three multi-family buildings in California. The study observed large variations of energy savings from controls, and some buildings even showed negative energy savings from certain controls. In addition, the study pointed out that crossover flows might exist in recirculation systems, which could lead to additional system energy losses. The Itron evaluation study [Itron 2006] of California utility multi-family boiler control programs concluded that energy savings from temperature modulation controls were lower than what were claimed by utility incentive programs and that energy savings varied substantially from building to building. A follow-up study by KEMA [KEMA 2008] suggested that demand control was more suitable for buildings

with 3-40 dwelling units and temperature modulation was more suitable for larger buildings. In summary, previous studies were not able to reach definitive conclusions on energy savings of recirculation control technologies.

## 1.4 Research Goals and Objectives

The goal of this project is to gain a better understanding of performance of recirculation systems in multi-family central DHW systems. Such knowledge may be used by industry practitioners to improve design practices and control technologies and by the Energy Commission to improve building energy codes for central DHW systems.

The objectives of this study are to:

- Characterize DWH recirculation system designs and operational parameters in multi-family buildings.
- Assess pipe heat loss of recirculation systems and the impact of recirculation system performance on overall DHW system efficiency.
- Evaluate energy savings potentials of control technologies and investigate the factors affecting performance of control technologies.
- Investigate the existence of crossover flows and their impact on DHW system efficiency.
- Evaluate the benefits of continuous monitoring of recirculation systems and identify common failure modes of central DHW systems.
- Develop a recirculation system model to predict performance of DHW recirculation systems and potential energy savings from control technologies.
- Inform the development of California building energy code (Title 24 Part 6) and utility energy efficiency programs.

The following research activities were carried out to achieve the above project objectives:

- Conducted two types of field monitoring studies:
  - Full on-site studies were performed at eight (8) multi-family buildings to collect detailed performance data of recirculation systems under different controls. In-depth performance analysis was conducted to provide comprehensive understandings of recirculation system performance.
  - Partial on-site studies were conducted at twenty (20) multi-family buildings. These studies involved less detailed monitoring and analysis. They provided more building samples and performance data to help characterize recirculation system designs and performance.
- Developed an energy flow analysis method to quantify heat loss components in central DHW systems and characterized recirculation system performance by comparing recirculation system heat loss to total system energy consumption.

- Analyzed hot water draw patterns collected from field studies to assess the applicability of control technologies.
- Investigated common design practices for recirculation system designs
- Compared central DHW system energy consumption under different recirculation system controls
- Analyzed historical monitoring data provided by EDC to understand long-term DHW system performance from a broad range of multi-family buildings and to assess the benefits of continuous system monitoring.
- Performed in-depth pipe heat transfer analysis to identify key modes of recirculation operation and revealed energy savings mechanisms of control technologies.
- Developed a recirculation system heat transfer model and validated the model using recirculation designs and performance data collected from four full on-site study buildings.

# CHAPTER 2:
# Research Plan

This chapter discusses the research plans for the three major tasks of the study: field monitoring, performance analysis, and recirculation system model development. Research plans for each of the three tasks were developed to ensure research results from each task could be used to support the other two tasks. For example, the field monitoring plan needed to ensure that enough process data and system design information were obtained to support performance analysis and model development. The method for performance analysis needed to be based on field measurement data and to provide in-depth information to support model development. Development of the recirculation system model needed to ensure that the model could be validated by field study results. As the methodologies for performance analysis and the recirculation model were refined, the field monitoring plan was adjusted accordingly.

## 2.1 Field Monitoring Study

### 2.1.1 Field Monitoring Plan

The study conducted the following two types of field monitoring studies:

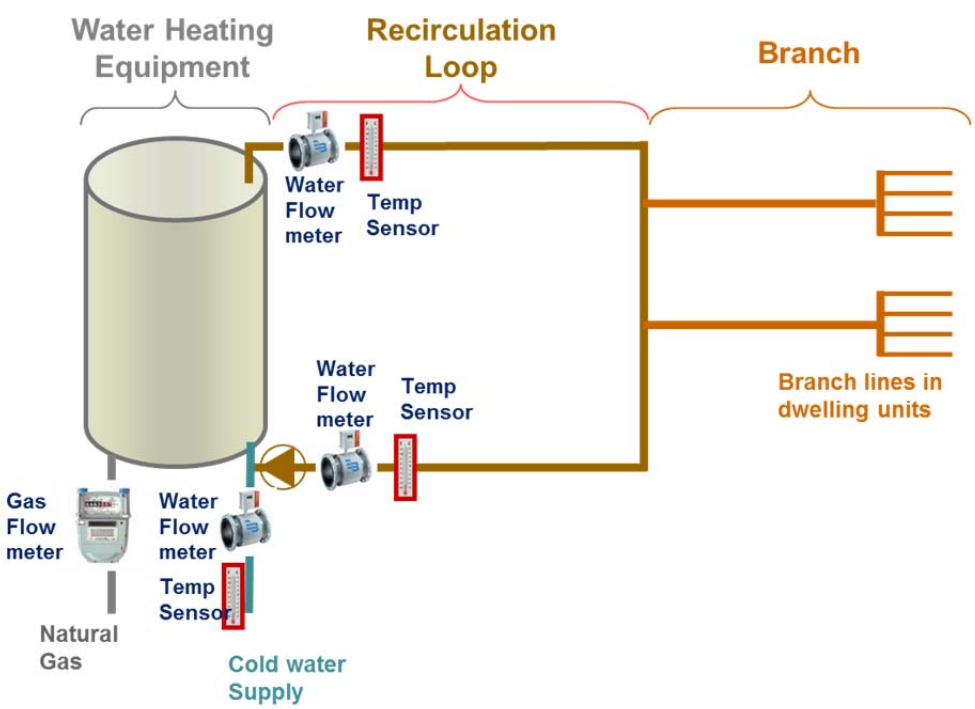
- **Full on-site studies** aimed to provide detailed recirculation system operation data and design information to support in-depth understandings of recirculation system performance. These field studies monitored central DHW system operation under different recirculation controls to assess their associated energy savings. Detailed information on recirculation system piping designs was collected to facilitate the development of a recirculation system model. The study planned to conduct full on-site studies in nine (9) multi-family buildings.
- **Partial on-site studies** aimed to obtain recirculation system performance from a broad range of buildings with different size, vintage, geographic location, and occupancy type. These monitoring studies only investigated recirculation system performance under the existing conditions without changing recirculation controls. The study planned to conduct partial on-site studies in 24 multi-family buildings.

Table 3 summarizes the monitoring plan for both full and partial on-site field studies. Figure 4 presents a schematic of the process parameters measured by the full and partial on-site studies.

**Table 3 Summary of Field Monitoring Plan**

| | Full On-site Study | Partial On-site Study |
|---|---|---|
| **Monitoring Parameters** | | |
| Temperature - Hot water supply (HWS) | Yes | Yes |
| Temperature - Hot water return (HWS) | Yes | Yes |
| Temperature - Cold water supply (CWS) | Yes | Yes |
| Temperature – Mechanical room | Yes | Yes |
| Flow – Hot water draw | Yes | Yes |
| Flow – Recirculation flow | Yes | Yes |
| Flow – Nature gas | Yes | No |
| Pressure – Recirculation system | At selected buildings | no |
| **Number of Building** | 9 | 24 |
| **Monitoring Period** | > 1 year | 2 month |
| **Data Collection Interval** | 30 second | 5 minutes |
| **Performance of Recirculation Controls** | Yes | No |
| **Investigate Recirculation System Design** | Field inspection + Plan check | Field inspection only |

**Figure 4: Schematics of Field Measurement Locations**




### 2.1.2 Evolution of Field Monitoring Plan

The initial objectives of field studies were slightly different and focused on assessing energy savings from control technologies and prevention of system operation issues. The original

approach was to measure energy savings from buildings with different characteristics, such as size, geographic location, and occupancy type, and to perform regression analysis to seek for patterns of energy savings. In the initial field monitoring plan, full on-site studies were designed to measure energy savings from the three control technologies, installation of check valves on CWS pipes to prevent crossover flows, and installation of air release values to prevent pump failure. Partial on-site studies were originally designed to assess long-term energy savings from recirculation controls that had already been installed. Partial on-site studies were also planned to test the capability of using limited process monitoring to identify system operation issues.

Findings from several preliminary research efforts indicated that some of the initial research approaches were not feasible and required modification. The preliminary research efforts included the implementation of a full on-site study, surveys of recirculation system designs, preliminary heat transfer analysis for model development, and analysis of historical continuous monitoring data provided by EDC. The following sections provide detailed discussions of identified issues related to the initial field monitoring plan. These issues and the proposed revisions to the research plan were discussed during the Project Advisory Committee (PAC) meeting on November 21, 2008. The field monitoring plan presented in the previous section reflected the revised research plan.

#### *2.1.2.1 Assess Energy Savings from Controls*

Preliminary research identified the following issues related to the approach of using regression analysis to assess energy savings from controls.

- Recirculation system heat loss strongly depends on recirculation system designs. Therefore, energy savings from recirculation controls depend on recirculation system designs. Similar buildings in terms of size, geographic location, and occupancy type can have completely different recirculation system designs. Therefore, there was not enough known about recirculation system designs to characterize recirculation system designs for regression analysis.
- Energy savings from controls depend on hot water draw schedules, especially the windows with zero hot water draw. Hot water draw schedules could not be adequately generalized by building characteristics and occupant types.
- Control settings for timer control and temperature modulation can vary, depending on system operators.

In summary, preliminary research found that energy savings from controls would be affected by factors not included in the initial research plan. These factors are very difficult, if not impossible, to characterize to support a regression type analysis of energy savings from controls. Even if these factors could be characterized, a much larger building sample size than initially planned would be needed to capture most possibilities for regression analysis. More importantly, results from a regression analysis would not be able to inform the market on how to improve recirculation designs and to improve control technologies.

Results from preliminary field studies also indicated the DHW system natural gas consumptions were affected by large day-to-day hot water draw variations to cause large uncertainties in energy savings assessment. Energy savings from controls may not be accurately obtained simply based on field measurement of DHW system energy consumption.

With the above considerations, the revised field monitoring plan focused on providing information to support performance analysis and model development, which would provide in-depth understandings of recirculation system operations and energy savings mechanisms of control technologies.

#### *2.1.2.2 Assess Energy Savings from Crossover Flows Prevention*

The 2008 PIER study [HMG 2008] indicated that there could be three types of crossover flows existing in a recirculation system. They included:

1. Crossover flows from a HWR pipe to the connected CWS pipe
2. Crossover flows from storage tanks or CWS pipe into the connected HWR pipe
3. Crossover flows, in a hot water fixture, from the hot water pipe into the cold water pipe through the leaking mixing valve

It was proposed that the first two types of crossover flows could be prevented by installing a check valve on affected CWS and HWR pipes. The initial monitored plan for full on-site studies planned to measure the energy savings from the installation of check valves. The initial field monitoring plan did not intend to investigate the third crossover flow.

Preliminary field studies provided the following findings:

- No obvious signs of crossover flows were found in monitored buildings. Therefore, there was no need to install check valves and measure energy savings.
- All central DHW systems in surveyed multi-family buildings were equipped with a check valve on the CWS pipe following plumbing code requirements. Therefore, installing check value on CWS pipes was already a common practice and crossover flows in CWS pipe should not exist or at least be very small.
- Crossover flows in HWR pipes should only happen when recirculation pumps are turned off. None of the building survey had any recirculation pump control prior to the study. Therefore, the chances for crossover flow in HWR pipes were very small.
- Crossover flows into HWR pipe have very small or zero impact on system energy consumptions. If hot water flows from storage tanks into a HWR pipe, it would eventually be delivered to hot water fixtures or be sent back to the storage tanks. If cold water flows into a HWR pipe, it would displace the hot water, which will be delivered as hot water draws. If cold water does reach fixtures through HWR pipes, it will cause occupants' unsatisfactory, but not cause any direct loss of hot water. In addition, a HWR pipe filled with cold water has no pipe heat loss.

Based on the above findings, the field monitoring plan was revised to investigate the existence of crossover flow, instead of measuring energy savings from the prevention measure of installing check valves.

#### *2.1.2.3 Assess Energy Savings from Pump Failure Prevention*

According to some industry practitioners [HMG 2008], many system operators would increase HWS temperature as a way to deal with hot water service issues. Recirculation pump failure was identified as a major operation issue for central DHW systems. Furthermore, the 2008 Title 24, Codes and Standards Enhancement (CASE) study on multi-family DHW system [HMG 2007] indicated that pump failures were often caused by propeller vane cavitation caused by trapped air bubbles in recirculation flows. Based on this information, the initial field monitoring plan intended to assess energy savings from installation of air release valves in recirculation systems.

Air release valves need to be installed at the highest point of the recirculation system to release trapped air bubbles. This is often not feasible because the highest recirculation pipes are not accessible in many existing buildings. In most buildings, hot water fixtures located at a higher altitude than the recirculation loop can effectively serve the same function as air release valves. Installing an air release valve may not be necessary at all.

Preliminary field studies did not observe any recirculation pump failures. It is highly uncertain if any pump failure event would be captured by the field studies. In addition, pump failures only impact system efficiency if they are not identified by system operators and lead to HWS temperature increase. The combined probability of all these events seemed to be very small.

For all above reasons, we did not anticipate to observe any energy savings from installation of air release valves. The revised field monitoring plan intended to merely assess the frequencies of pump failures from monitored buildings.

#### *2.1.2.4 Identify System Operation Issues*

Field studies planned to identify possible system operation issues during the course of system performance monitoring. The associated findings can be useful to the evaluation of benefits of continuous monitoring.

## 2.2 Performance Analysis

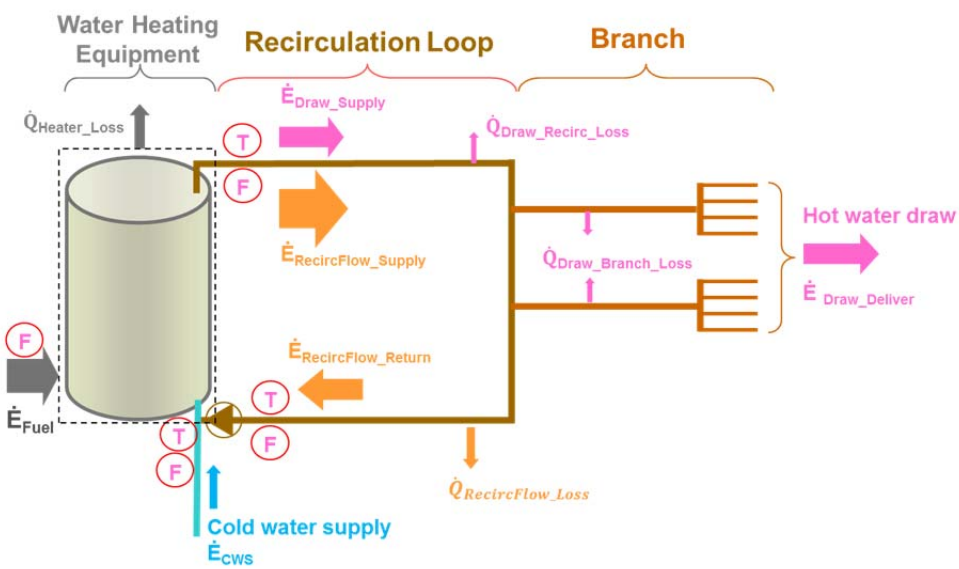
### 2.2.1 Energy Flow Analysis

Total DHW system natural gas consumptions are affected by several factors, including efficiency of water heating equipment, recirculation system heat loss, and branch pipe heat loss. In order to characterize recirculation system performance, field study data analysis needs to further quantify recirculation system heat loss and calculate it as a percentage of the total DHW system natural gas consumption. The research team developed the energy flow analysis method to achieve this goal by quantifying all major energy flow components in a central DHW system.

**Error! Reference source not found.** illustrates the different energy flow components in a central DHW system. In particular, thermal energy carried by hot water flows in the recirculation system is broken into two components. One is thermal energy associated the recirculation flow and the other is thermal energy associated with hot water draw flows. At the starting point of the recirculation system, the two energy flow components are labeled as $\dot{E}_{Recirc_Supply}$ and $\dot{E}_{Draw_Supply}$, respectively. The sum of these two is the hot water energy provided by the water

heating system. As the recirculation flow travels through the recirculation system, it loses part of its thermal energy, $\dot{Q}_{RecircFlow_Loss}$, due to recirculation system pipe heat loss. Thermal energy associated with the returned recirculation flow is $\dot{E}_{Recirc_Return}$. Hot water draw flows also suffer energy loss, $\dot{Q}_{Draw_Recirc_Loss}$, as they go through the recirculation system. They also suffer energy loss at branch pipes, $\dot{Q}_{Draw_Branch_Loss}$. The final delivered energy to water fixtures is $\dot{E}_{Draw_Deliver}$, which equals to $\dot{E}_{Draw_Supply}$ - $\dot{Q}_{Draw_Recirc_Loss}$ - $\dot{Q}_{Draw_Branch_Loss}$. Total recirculation pipe heat loss is the sum of $\dot{Q}_{RecircFlow-Loss}$ and $\dot{Q}_{Draw-Recirc-Loss}$.

**Figure 5: Illustration of Major Energy Flow Components in Central DHW Systems**




Energy flow components in a central DHW system can be correlated to each other using a control volume analysis. The control volume is defined as the water heating system, as illustrated by the dashed box in **Error! Reference source not found.**. According to the law of conservation of energy, the change of energy within the control volume equals to the difference between input and output energy. This relationship can be described by the equation shown below:

$$\Delta E_{Control\ Volume} =$$

$$\left(\sum \dot{E}_{Fuel} + \sum \dot{E}_{RecircFlow_Return} + \sum \dot{E}_{CWS}\right) - \left(\sum \dot{E}_{RecircFlow_Supply} + \sum \dot{E}_{Draw_Supply} + \sum \dot{Q}_{Heater_Loss}\right) \quad \text{(Eq. 1)}$$

Since all energy components vary with time, the summation operator, Σ, are used in the above equation to provide cumulative energy flows with the time period of interest. While the above equation holds for any length of time, daily analysis makes the most sense since hot water draw patterns are repetitive on a daily basis. In a full-day cycle, changes in thermal energy stored in

the water heating system is negligible, for example, $\Delta E_{control\ Volume} \approx 0$. The above equation can be re-arranged as:

$$\sum \dot{E}_{Fuel} = \sum \dot{Q}_{Heater_Loss} + \left(\sum \dot{E}_{RecircFlow_Supply} - \sum \dot{E}_{RecircFlow_Return}\right) + \left(\sum \dot{E}_{Draw_Supply} - \sum \dot{E}_{CWS}\right)$$

(Eq. 2)

Using

$(\dot{E}_{RecircFlow_Supply} - \dot{E}_{RecircFlow_Return}) = \dot{Q}_{RecircFlow_Loss}$, and

$\dot{E}_{Draw_Supply} = \dot{E}_{Draw_Deliver} + \dot{Q}_{Draw_Recirc_Loss} + \dot{Q}_{Draw_Branch_Loss}$

Eq. 2 can be further rearranged as follows:

$$\sum \dot{E}_{Fuel} = \sum \dot{Q}_{Heater_Loss} + \left(\sum \dot{Q}_{RecircFlow_Loss} + \sum \dot{Q}_{Draw_Recirc_Loss}\right) + \sum \dot{Q}_{Draw_Branch_Loss} + \left(\sum \dot{E}_{Draw_Deliver} - \sum \dot{E}_{CW}\right)$$

(Eq. 3)

The four components on the right side of the equation represent water heater loss, recirculation system pipe heat loss, branch pipe heat loss, and net delivered hot water energy, respectively.

Isolating the terms enclosed in the last parenthesis and dividing both sides of the above equation by the daily fuel energy input, the overall DHW system efficiency becomes:

$$\eta_{System} = \frac{\sum \dot{E}_{Draw} - \sum \dot{E}_{CWS}}{\sum \dot{E}_{Fuel}} = 1 - \frac{\sum \dot{Q}_{Heater_Loss}}{\sum \dot{E}_{Fuel}} - \frac{\sum \dot{Q}_{RecircFlow_Loss} + \sum \dot{Q}_{Draw_Recirc_Loss}}{\sum \dot{E}_{Fuel}} - \frac{\sum \dot{E}_{Draw_Branch_Loss}}{\sum \dot{E}_{Fuel}}$$

or

(Eq. 4)

$$\eta_{System} = \eta_{WH} - f_{RecircSystem_Loss} - f_{Branch_Loss}$$

(Eq. 5)

where

$\eta_{WH}$: efficiency of water heating system $(1 - \frac{\sum \dot{Q}_{Heater_{Loss}}}{\sum \dot{E}_{Fuel}})$

$f_{RecircSystem_Loss}$: recirculation system pipe heat loss fraction $(\frac{\sum \dot{Q}_{RecircFlow_Loss} + \sum \dot{Q}_{Draw_Recirc_Loss}}{\sum \dot{E}_{Fuel}})$

$f_{Branch_Loss}$: branch pipe heat loss fraction $(\frac{\sum \dot{E}_{Draw_Branch_Loss}}{\sum \dot{E}_{Fuel}})$

Equation Eq.4 and Eq.5 clearly illustrate that the overall DHW system efficiency is affected by three heat loss components: heat loss through water heating system, heat loss through recirculation system, and heat loss through branch pipes.

It should be noted that all hot water draws were considered to be used by building occupants in the above analysis. In practice, some hot water draws are wasted during to the following two reasons:

1. Building occupants may have to clear out the cold water in a branch pipe. More water is usually damped than the amount of cold water contained in the branch pipe, which leads to hot water waste.
2. Hot water left in a branch pipe from previous hot water draws cools down to cold water because there are no immediate hot water draws.

Since the field monitoring study did not intend to address the above two issues, the energy flow analysis did not include the consideration of heat loss associated with hot water waste. Therefore, the overall DHW system efficiency calculated according to equation Eq. 5 still represents an optimistic estimate of DWH system performance. This, however, does not affect the assessment of recirculation system performance.

In the above energy flow analysis method, recirculation system pipe heat loss is assessed from heat loss associated with two flow components in the recirculation system, hot water draws and recirculation flows. It is important to break the total recirculation system heat loss into these two components, because they provide great insight into energy savings mechanisms of control technologies.

The energy flow analysis method was developed to analyze field monitoring data. With the exception of water heater losses, all other energy flow components in equation Eq.3 can be calculated using field measurement data, as follows:

$$\sum \dot{E}_{Fuel} = HV_{Fuel} \cdot \sum \dot{V}_{Fuel}$$

$$\sum \dot{Q}_{RecircFlow_Loss} = \rho \cdot C_p \cdot \sum f_{Recirc} \cdot \Delta t \cdot (T_{HWS} - T_{HWR})$$

$$\sum \dot{Q}_{Draw_Recirc_Loss} = \rho \cdot C_p \cdot \sum f_{Draw} \cdot \Delta t \cdot (T_{HWS} - T_{HW_Branch})$$

$$\sum \dot{Q}_{Draw_Branch_Loss} = \rho \cdot C_p \cdot \sum f_{Draw} \cdot \Delta t \cdot (T_{HW_Branch} - T_{HW_Fixture})$$

$$\sum \dot{E}_{Draw_Deliver} - \sum \dot{E}_{CWS} = \rho \cdot C_p \cdot \sum f_{Draw} \cdot \Delta t \cdot (T_{HW_Fixture} - T_{CwS})$$

where

$HV_{Fuel}$: fuel heat value

$\dot{V}_{Fuel}$: natural gas volumetric flow rate

$f_{Recirc}$: recirculation flow rate

$\rho$: water density

$C_p$: water heat capacity

$\Delta t$: monitoring time interval

$f_{Recirc}$: recirculation flow rate

$f_{Drawc}$: hot water draw flow rate

$T_{CWS}$: cold water supply temperature

$T_{HWS}$: hot water supply temperature

$T_{HWR}$: hot water return temperature

$T_{HW_Branch}$: hot water temperature at the entrance of a branch

$T_{HW_Fixture}$: hot water temperature at a hot water fixture

Field studies did not measure $T_{HW_Branch}$ and $T_{HW_Fixture}$ and these temperatures were obtained based on measured temperature drop of recirculation flows and simple pipe heat transfer analysis. Since hot water travel through part of the recirculation system, $T_{HW_Branch}$ should be between HWS and HWR temperatures, as described by the following equation:

$$(T_{HWS} - T_{HW_Branch}) = f \cdot (T_{HWS} - T_{HWR})$$

The fraction, f, depends on detailed recirculation system configurations, hot water draw locations, and flow rates. As a first-order assumption, it was assumed that, on average, hot water was drawn from the middle branch. It was also assumed heat loss per unit pipe surface area was a constant because hot water flow temperatures had small variations. Based on detailed recirculation system configuration obtained from full on-site field study buildings, the average value of fraction f was estimated to be 0.6.

Branch pipes are usually shorter and smaller than recirculation pipes, so branch pipe heat loss is proportionally smaller than those of recirculation pipes. Based on pipe surface area comparison, branch pipe heat loss was assumed to be 10 percent of the heat loss in recirculation pipes. Therefore, $T_{HW_Fixture}$ is estimated according to the following equation:

$$(T_{HW_Branch} - T_{HW_Fixture}) = 10\% \cdot (T_{HWS} - T_{HW_Branch})$$

### 2.2.2 Historical Monitoring Data Analysis

The study collaborated with EDC on evaluating benefits of continuous monitoring systems. EDC provided commercial continuous monitoring products and services to multi-family and hotel/motel buildings and had cumulated large amount of monitoring data from buildings using its monitoring services. The study planned to analyze EDC's monitoring data to understand what system failure modes could be identified by continuous monitoring technologies. The study also planned to explore possible computer algorithms to automatically identify these system failures through monitoring results.

## 2.3 Recirculation System Model Development

The recirculation system model needed to accurately predict performance of system with different configurations and under different operational conditions. In addition, the model also needed to serve the following two purposes:

- Enhance the understanding of recirculation system operation and energy savings mechanisms of control technologies
- Facilitate the development of performance calculation algorithms to be incorporated into compliance software for California Building Energy Code (Title 24, Part 6).

The study considered two modeling approaches, regression model and physical model. A regression model was to be based on correlations between recirculation system performance and various factors affecting system performance. As explained above, preliminary research found that these correlations could not be easily established, because some of the factors, especially recirculation system pipe configurations, could not be easily quantified for developing correlations. Also, a regression model would provide very limited understandings of recirculation system operation.

A physical model would be based on heat transfer and mass transfer principles, as well as inputs of detailed system designs and operational parameters. In dealing with complicated systems with very dynamic changes of operational conditions, the building science community often uses finite element based modeling method. Such a method would break the complicated recirculation system into many small pipe pieces, for instance one-inch long pipe pieces. Within each pipe piece, water flow and temperature can be considered to be uniform so that the pipe piece can be simulated using equations reflecting fundamental physical processes. The model would simulate physical processes in each piece and the interaction between pieces in small time intervals, for instance one seconds, and integrate the solutions from all pipe pieces to obtain the overall system performance. A finite element model essentially provides a microscopic view of the system. However, it does not provide explicit understandings of system operation on macroscopic levels.

Further investigation revealed that finite element models required understandings of flow patterns in recirculation pipes. For example, at low flow rates, shear flows could take place to cause hot water to travel faster than cold water and to mix with cold water. Convection flows could form at junctions between recirculation pipe and branch pipes to enhance recirculation pipe heat loss. These flow patterns are complicated and not well understood. Inappropriate assumptions of these flow patterns could lead of large simulation errors.

Title 24 performance calculation requires relatively simple algorithms to estimate hourly energy consumption of a recirculation system. Finite element models are too complicated for conversion back into simple calculation algorithms to be implemented in Title 24. For the same reason, this modeling approach requires much more resources than available to the study. For all above reasons, an alternative method was needed.

After extensive investigation, the study decided to develop a physical model based on simulation of heat transfer of major pipe sections in recirculation systems. Major pipe sections were recirculation pipe sections between branch pipes and pipe section having the same diameter, insulation condition, and locations. Heat transfer of pipe sections can be calculated using established engineering solutions. By dividing a recirculation system into only several major sections, the overall model is much simpler than a finite element model. In addition,

dynamic changes in system operations are simplified as a sequence of system heat transfer mode. Recirculation system performance can be easily understood through heat transfer characteristics of each pipe sections. Such a simple model can be easily converted into Title 24 performance calculation algorithms. Detailed description of the process of Title 24 performance calculation rule set development is provided in Chapter 50.

The original scope of the research did not include the performance of branch pipes connecting to a recirculation loop, and field monitoring studies did not monitor performance of branch pipes. As a result, the recirculation model developed by this PIER study did not cover branch pipes.

# CHAPTER 3:
# Field Monitoring Study

This chapter describes characteristics of multi-family buildings monitored by the study, observations of recirculation system operations, and field measurement issues. Results of quantitative performance analysis are provided in Chapter 4.

## 3.1 Field Monitoring Buildings

The following criteria were used by the study to select field monitoring buildings:

- The building must have a central DHW system using a recirculation system to distribute hot water. The recirculation system could include one or more recirculation loops. The study focused on recirculation systems and did not impose any limits on water heating systems.
- The DHW systems were dedicated to DHW services and not for other uses such as hydronic space heating, adjacent commercial applications, or pool heating. Systems that served the building's laundry facility were eligible. Performance of recirculation systems heavily depended on hot water usage patterns, therefore, inclusion of other hot water usages would distort the overall research findings.
- The recirculation system must be insulated. The study was intended to provide information to inform further improvements to systems that met the 2005 Title 24 codes at the least; 2005 Title 24 required recirculation pipes to be insulated. However, field surveys could only verify that pipes accessible by the research team were insulated.
- Straight pipe sections must be available near water heating equipment for any two of the following three pipes: CWS, HWS, and HWR pipes. Length of straight sections needed to be as least 25 times of the pipe diameter because adequate straight pipe sections were essential to accurate measurement of water flows.

The research team recruited field study participants through several different channels, to avoid any bias that might arise from using only one or two sources. These channels included:

- Developers known to HMG through implementation of utility multi-family building incentive programs
- Building owners known to HMG staff
- HMG's contacts at utilities including SMUD, PG&E, SDG&E, and the Southern California Gas Company
- Members of the Project Advisory Committee for this project
- Recirculation system control manufacturers

After initial screening, the study visited more than 50 multi-family buildings to select field study candidates. The research team tried to collect the following information from survey visits:

- Building information: number of dwelling units, size of units, number of bedrooms, number and type of hot water fixtures, number of occupants.
- Water heating system: water heating equipment type and specifications, storage tank capacity and insulation.
- Recirculation system configuration: pipe location, length, diameter, material, and insulation condition, recirculation pump power, and existing controls.
- Types of DHW fixtures: number of bathtubs, showers, faucets, clothes washers, and dishwashers.

The research team was not able to collect all above information for each building. Also, not all information collected could be fully verified.

The study successfully conducted full on-site monitoring in 8 buildings and partial on-site study in 20 buildings. Table 4 summarizes the building types of field study buildings in terms of building size, number of story, vintage, occupancy type, and geographic area. This summary shows that field monitoring studies covered a wide range of buildings. Table 5 and Table 6 provide more detailed information on building characteristics and water heating systems of each field study building.

**Table 4: Summary of Field Monitoring Study Buildings**

| | Full On-site | Partial On-site |
|---|---|---|
| **By Building Size (number of units)** | | |
| ≤20 | 2 | 7 |
| > 20 to ≤ 60 | 2 | 8 |
| >60 | 4 | 5 |
| **By Number of Stories** | | |
| Low-rise (≤ 3 stories) | 5 | 14 |
| High-rise (> 3 stories) | 3 | 6 |
| **By Vintage** | | |
| Built after 1990 | 5 | 10 |
| Built before 1990 | 3 | 10 |
| **By Occupancy Type** | | |
| Market Rate | 2 | 8 |
| Senior | 2 | 2 |
| Affordable | 3 | 7 |
| College Dormitory | 1 | 3 |
| **By Area** | | |
| Northern California | 6 | 15 |
| Southern California | 2 | 5 |

**Table 5: Detailed Characteristics of Field Monitoring Study Buildings – Full On-Site Study**

| Site Index | Climate Zone | Occupancy Type | Number of Unit | Average Unit Area (sq ft) | Building Floor Area (sq ft) | Number of Story | Vintage | Water Heating System | Mechanical Room Location |
|---|---|---|---|---|---|---|---|---|---|
| A-SAM | 12 | Senior | 87 | 600 | 52,380 | 3 | 1999 | 3 commercial gas storage water heaters | Top floor |
| B-SFD | 3 | Affordable | 98 | 787 | 79,152 | 4 | 2005 | 2 water heaters and 1 storage tank | Garage (ground floor) |
| C-SFH | 3 | Senior | 44 | 750 | 39,749 | 3 | 2008 | 2 water heaters and 1 storage tank | Garage (ground floor) |
| D-SFF | 3 | Affordable | 82 | 900 | 107670 | 5 | 1993 | 1 boiler with 1 storage tank | Garage (ground floor) |
| E-DAE | 12 | College | 250 | 150 | NA | 3 | Before 1980 | 1 boiler with 1 storage tank | First Floor |
| F-SAA | 12 | Affordable | 49 | 770 & 1190 | NA | 5 | 1993 | 1 boiler with 1 storage tank | Top floor |
| G-LAB | 9 | Market rate | 20 | 550 | 8,900 | 2 | 1965 | 1 boiler with 1 storage tank | Garage (ground floor) |
| H-LAR | 10 | Market rate | 20 | 685 | NA | 2 | 1960 | 1 boiler with 1 storage tank | First floor |

**Table 6: Detailed Characteristics of Field Monitoring Study Buildings – Partial On-Site Study**

| Site Index | Climate Zone | Occupancy Type | Number of Unit | Average Unit Area (sq ft) | Building Floor Area () | Number of Story | Vintage | Water Heating System | Mechanical Room Location |
|---|---|---|---|---|---|---|---|---|---|
| 1-SFB | 3 | Senior | 40 | 712 | 28480 | 4 | 2006 | 2 commercial gas storage water heaters | Ground floor |
| 2-BKS | 3 | Senior | 27 | 475 | 25,000 | 4 | 1999 | 1 commercial gas storage water heater | Ground floor |
| 3-BKU | 3 | Affordable | 35 | 995 | 34825 | 3 | 2005 | 2 boilers with 1 storage tank | First floor |
| 4-SAP | 12 | Market rate | 11 | 700 | 7700 | 2 | 1950 | 2 commercial gas storage water heaters | Garage (ground floor) |
| 5-SAC | 12 | Market rate | 16 | 650 | 10400 | 2 | 1950 | 1 commercial gas storage water heater | Garage (ground floor) |
| 6-DAK | 12 | College | 88 | 200 | ~ 18000 | 4 | 2005 | Central campus steam supply to 2 storage tanks | Ground floor |
| 7-DAL | 12 | College | 88 | 200 | ~ 18000 | 4 | 2005 | Central campus steam supply to 2 storage tanks | Ground floor in the neighboring building |
| 8-OAL | 3 | Affordable | 22 | 643 | ~ 15000 | 2 | 2008 | 2 boilers with 1 storage tank | In stand-alone structure next to the building |
| 9-OAL | 3 | Affordable | 28 | 643 | ~ 18000 | 3 | 2008 | 2 boilers with 1 storage tank | Garage (ground floor) |
| 10-SFF | 3 | Affordable | >60 | N/A | N/A | 5 | After 1990 | 2 boilers with 1 storage tank | Garage (ground floor) |
| 11-HOB | 9 | Market rate | 20 | 550 | 8,900 | 2 | 1965 | 1 boiler with 1 storage tank | Garage (ground floor) |
| 12-HOB | 9 | Market rate | 12 | 700 | 10,000 | 2 | 1965 | 1 boiler with 1 storage tank | First floor (in a room attached to the building) |

| Site Index | Climate Zone | Occupancy Type | Number of Unit | Average Unit Area (sq ft) | Building Floor Area () | Number of Story | Vintage | Water Heating System | Mechanical Room Location |
|---|---|---|---|---|---|---|---|---|---|
| 13-HOL | 9 | Affordable | 25 | 580 | 15,000 | 3 | 1960 | 1 commercial gas storage water heater and a solar water heating system | Basement |
| 14-HOC | 8 | Market rate | 16 | 550 | 8,900 | 2 | 1935 | 1 boiler with 1 storage tank | First Floor |
| 15-HOL | 8 | Affordable | 35 | N/A | N/A | 3 | 2003 | 2 boilers with 1 storage tank | Garage (ground floor) |
| 16-DAR | 12 | College | >60 | 100 | N/A | 2,3 | 1965 | Central campus steam supply to 2 storage tanks | In a stand-alone building serving multiple buildings |
| 17-SAP | 12 | Market rate | 16 | 700 | 11200 | 2 | 1960 | 1 commercial gas storage water heater | First floor (a separate room attached to the building) |
| 18-SFP | 3 | Affordable | >60 | N/A | N/A | 5 | After 1990 | 2 boilers with 1 storage tank | On the roof |
| 19-OAO | 3 | Market rate | <30 | N/A | N/A | 2 | Before 1990 | 1 commercial gas storage water heater | First Floor |
| 20-LAE | 10 | Market rate | <30 | N/A | N/A | 2 | Before 1990 | 1 commercial gas storage water heater | First Floor |

## 3.2 Observations of Recirculation System Operation

**Error! Reference source not found.** through **Error! Reference source not found.** present a sample of temperature and flow measurements to illustrate daily activities of recirculation systems without control and under the three types of controls. These four figures are based on monitoring results from the same full on-site study building. Recirculation system operations in other buildings had similar trends, except that hot water draw pattern had large variations among different buildings. Field monitoring studies provided the following general observations of operation parameters of recirculation systems in multi-family buildings.

### 3.2.1 Hot Water Draw Flow

As expected, hot water draw flows had large fluctuations throughout the day since occupant hot water demands were not constant. Hot water draws were very low during night time. However, there was hardly an extended window period when hot water draws stayed at zero. Even in buildings with small number of dwelling units, there were usually some scattered hot water draw events during night.

### 3.2.2 Recirculation Flow

Recirculation flow rates were constant (whenever the pump was on)and were not affected by variations of hot water draw flows. In this building, system operations during the demand control and the timer control used a recirculation pump provided by the demand control manufacturer, while system operations under continuously pumping and temperature modulation used the existing recirculation pump in the building. Therefore, two different recirculation flows were obtained. In buildings where the same recirculation pump was used for all controls, recirculation flows were the same under all controls.

### 3.2.3 HWS Temperatures

HWS temperatures fluctuated in a narrow range around the set point of the water heating system. Magnitude of fluctuations was determined by the controls of the water heating system. Frequency of the fluctuations depended on hot water draws and standby heat loss of the water heating system. When there were high hot water draws, storage tank temperature dropped more often so that the burners were turned on more often. As a result, the frequency of HWS temperature fluctuations was relatively high. In contrast, the frequency of HWS temperature fluctuations was much lower when there were low or zero hot water draws. The reason was that storage tank temperatures could be maintained for a long time, since standby loss of water heating systems were usually small. For the same reason, HWS temperature changed slowly from the high setting point to the low setting point during temperature modulation controls, as shown in **Error! Reference source not found.**.

In **Error! Reference source not found.**, HWS temperature dropped below its normal fluctuation range for some brief time around 11:00AM. The figure also showed high hot water draws during the same period. The measurement indicated that the heating capacity of the water heating system was not able to completely keep up with the high demand. However, the drop of HWS was very moderate.

### 3.2.4 HWR Temperatures

HWR temperatures were lowered than HWS temperatures because of the recirculation system pipe heat loss. The time offsets between the HWR and HWS temperature patterns were due to the traveling time of the recirculation flow in the recirculation system. When there were no hot water draws, the product of the time offset and the constant recirculation flow rate gave an estimated volume of the recirculation system.

### 3.2.5 CWS Temperatures

CWS temperatures were expected to be constant during each day. However, field measurements showed that CWS temperature increased at times when there were no hot water draws. CWS pipe temperature increased due to heat conducted from the adjacent, connected HWR pipes and the warm ambient condition of the mechanical room. Once cold water started to flow due to hot water draws, CWS pipe temperature were back to the cold water temperature.

**Figure 6: Measured Recirculation System Operation – No Controls**

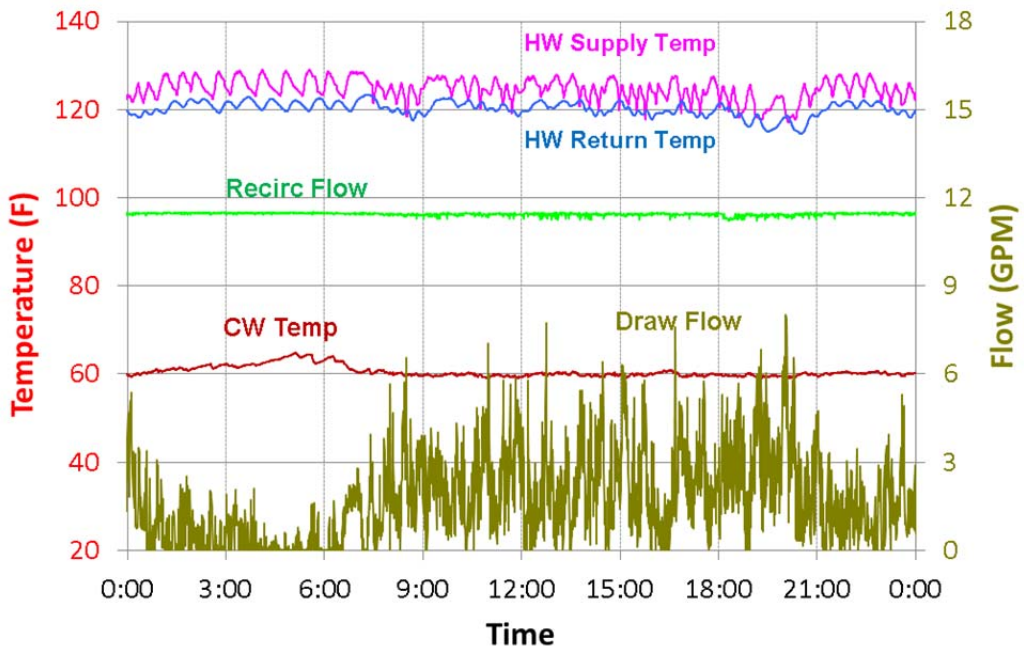


**Figure 7: Measured Recirculation System Operation – Timer Control**

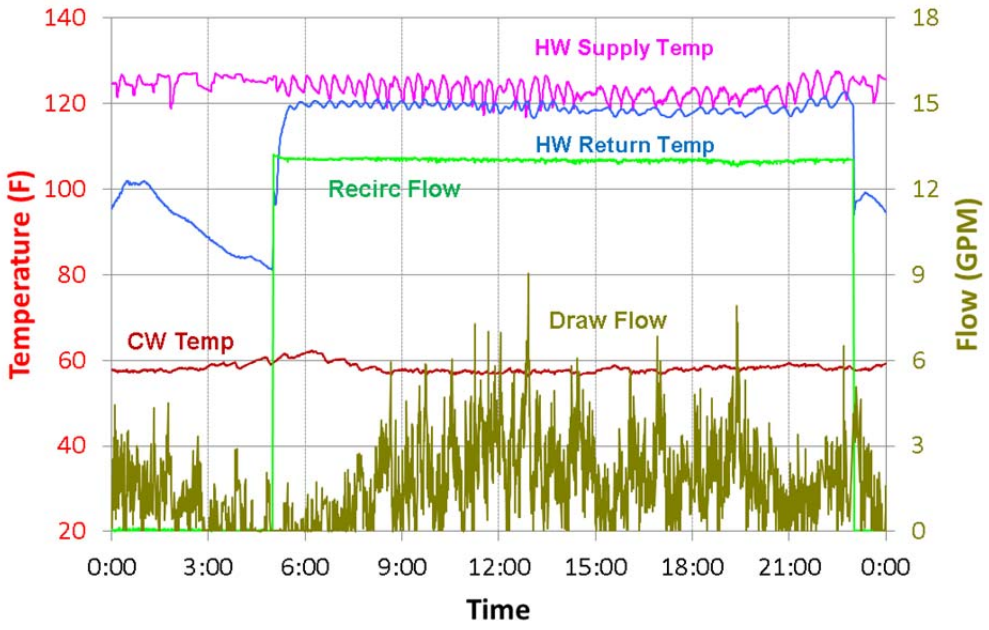



**Figure 8: Measured Recirculation System Operation – Temperature Modulation**

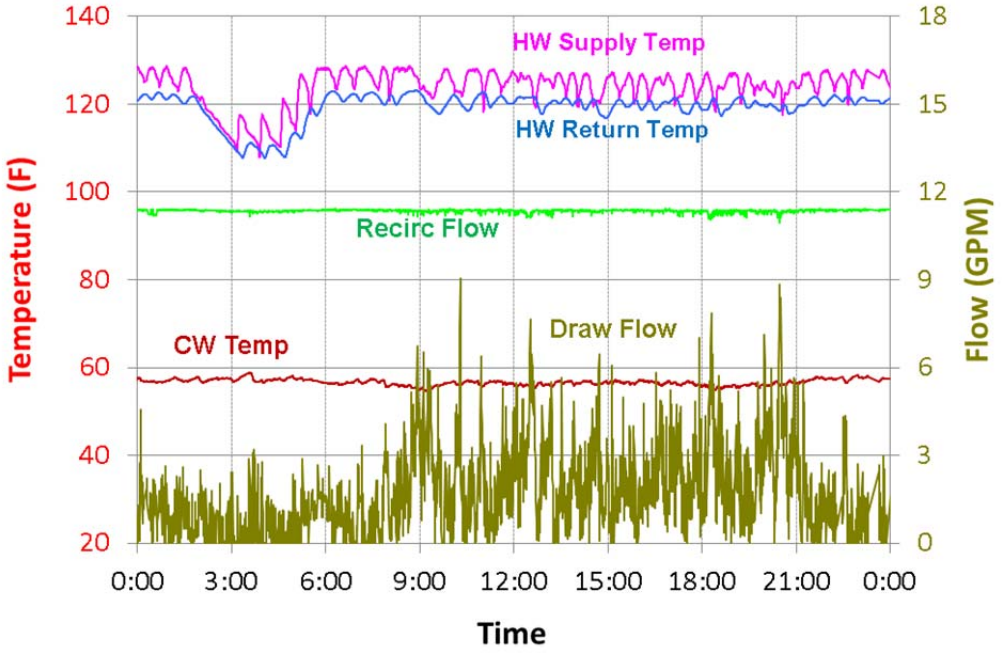
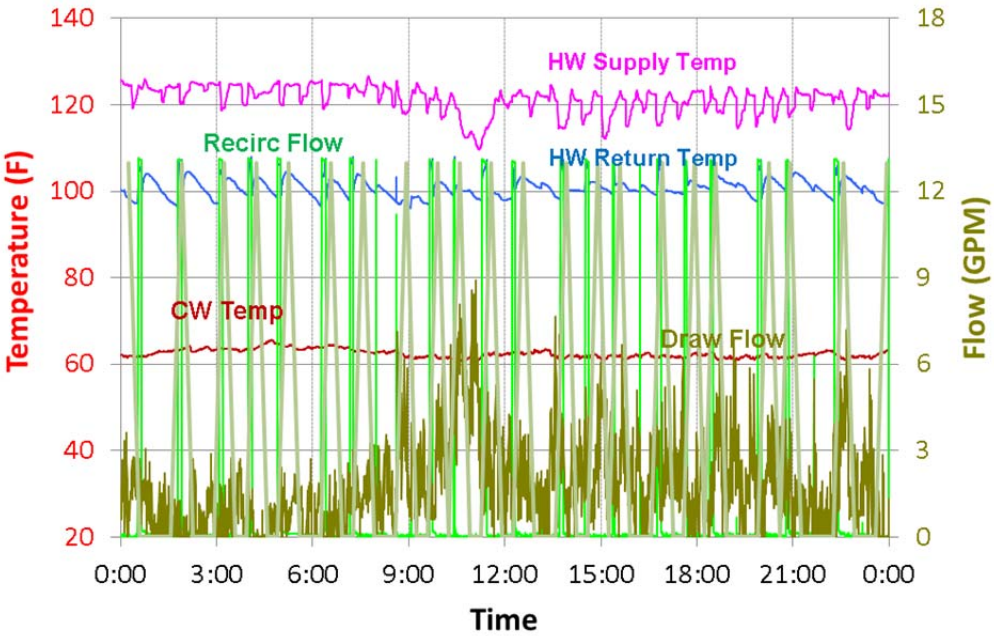


**Figure 9: Measured Recirculation System Operation – Demand Control**




## 3.3 Field Measurement Issues

This section discusses the important field measurement issues the study had encountered and their implications to performance evaluation.

### 3.3.1 Temperature Measurement

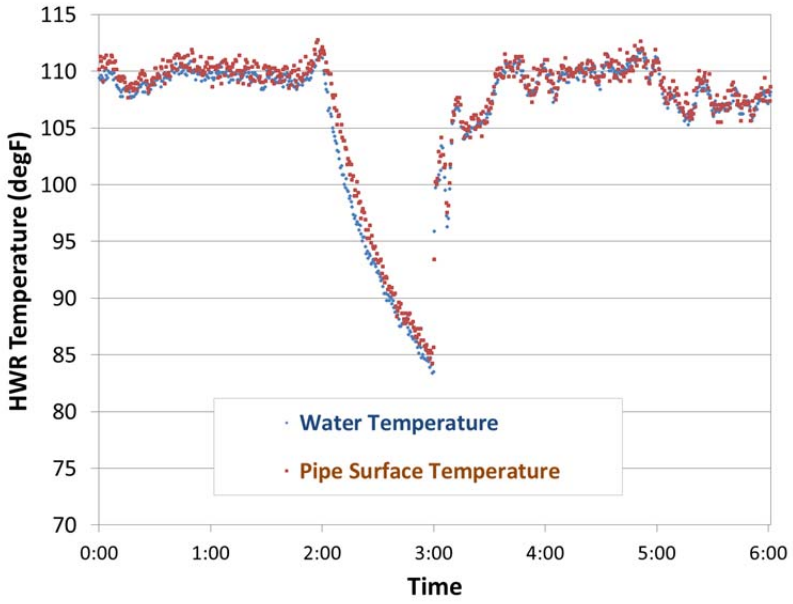
Water temperatures were measured using either thermocouples or thermistors. The selection of these two types of temperature sensors were based on the types of data loggers, which may only work with thermocouples or thermistors. Installation methods of temperature sensors were carefully considered to ensure temperature measurements. Attaching temperature sensors to pipe outside surface was easy to do. However, temperature sensors installed in this way measured pipe temperature, instead of water temperature. Copper water pipes were used in all field monitoring buildings and copper has very high thermal conductivities. Therefore, copper pipe surface temperature should be very close to water temperature. However, the research team was not sure if copper pipe surface temperatures would follow fast changes in water temperature. Field tests were performed to compare pipe surface temperatures to water temperatures with fast changes in water temperature.

In the first full on-study building, the research team attached a thermocouple on the HWR pipe and inserted a thermocouple inside the same pipe at the same location. To ensure fast response, all temperature sensors were less than 1/8 inch in diameter. For surface-attached installation, temperature sensors were tightly attached to the pipe using tapes wrapping around the pipe. Thermal grease was applied to enhance heat conduction between the temperature sensor and

the pipe. The surface-attached temperature sensor was well insulated to avoid the influence from ambient air. The recirculation pump was turned off first to let the pipe temperature to cool down and then turned on to facilitate the sudden water temperature increase. The comparison between pipe surface temperatures (measured by the surface attached thermocouple) and water temperatures (measured by the inserted thermocouple) are shown **Error! Reference source not found.**. The figure showed that the two temperature measurements gave almost the identical results. Therefore, copper pipe temperatures measured by the attached temperature sensor were a close proxy to the water temperatures even when temperature changes were fast. Water temperature measurements in all field study buildings were from surface-attached temperature sensors, installed following the same procedure as described above.

Because of the high conductivity of copper pipe, cold water pipes connected to storage tanks or hot water pipes can heat up quickly when there were no cold water flows in the pipe. During a field test, the team measured CWS pipe temperatures at a location about two feet from the connected hot water pipe. After the cold water flow was stopped by a shut-off valve for the CWS pipes, the measured CWS pipe temperatures quickly increased and exceeded the room ambient temperature. The temperature increase was clearly due to heat conduction, because there were no water flows. All CWS temperature measurements were made on CWS pipe at least five feet away from the connected storage tanks or HWR pipes, if possible. To avoid influence of ambient temperatures, all temperature sensors were well insulated. When CWS temperature sensors could not be placed far away from storage tanks or HWR pipes, rising CWS temperatures were detected and they were replaced with the normal CWS temperatures measured when there were hot water draws for performance analysis.

**Figure 10: Comparison of Water and Pipe Temperature Measurements**



### 3.3.2 Water Flow Measurement

Hot water flow measurements were essential to energy flow analysis. However, hot water draw flows occur constantly and often very sporadically, making accurate measurements of flow challenging. For this reason, the research team carefully considered different flowmeter options to obtain the most accurate flow measurements within the allowance of project budget and field installation feasibility.

Displacement type flowmeters can accurately measure unstable flows. That is why they are used to meter water usages and at gas stations for billing purposes. However, they are made only for small pipes (< 2 inches). Also, due to internal flow measurement mechanisms, they cause large pressure drops when flows are high, which could cause hot water service interruption. Therefore, they could not be used in most multi-family buildings where cold water or HWS supply pipes are at least 2 inches and hot water draw flows could be high.

The research team decided to use magnetic flowmeters in full on-site field studies for several reasons. This type of flowmeter has relatively high accuracy (±0.5 percent) and can handle high fluid temperatures up to 212 $^{o}$F. Magnetic sensors were placed inside the wall of a flowmeter so that the overall flowmeter looks just like a short pipe with a thick wall. Because there is no moving part in these flowmeters, they do not introduce any pressure drop if the flowmeter size matches with the water pipe diameter. For this reason, and very low pressure drop, magnetic flowmeters were easily accepted by the participants of full on-site studies. Another reason of using magnetic flowmeters is because they can measure bi-directional flows, which was needed to test the existence of crossover flows.

The team used ultrasonic flow meters for partial on-site studies. Ultrasonic flow meters have the least interruption to hot water services. Unlikely all other types of flowmeters, which require existing water pipes to be cut to install flow sensors, ultrasonic flow sensor can be simply strapped onto existing water pipes without any plumbing work. This nonintrusive technology greatly reduces cost and, more important, makes the field monitoring study more acceptable to participants. However, there were concerns regarding the accuracy of this type of flowmeters, especially for measuring low flows, that it may not be able to be detected by certain ultrasonic flow meters. Ultrasonic flow meters were used during the 2008 PIER study. It was found through that study that ultrasonic flow meters were accurate as along as strong ultrasonic signals could be detected by the embedded ultrasonic receivers. The research team further identified an ultrasonic flowmeter, made by Fuji Electronics, having relative good accuracy in the lower flow range. Based on both lab test and field use, this flowmeter was found to have good ultrasonic signal reception, good sensitivity in detecting low flows, and good measurement accuracy. Therefore, it was used in partial on-site studies.

Almost all flowmeters, except displacement flowmeters, are based on measurement of flow velocity. In order to obtain accurate measurements, certain length of straight pipes must be available upstream and downstream of the flowmeter to ensure fully developed flows exist in the flowmeter. For both partial and full on-site studies, the research team only selected DHW systems, where long straight cold water and recirculation loop pipe sections existed and were easily accessible for flowmeter installation. However, it should be noted that sudden changes in

hot water draws, which are normal in DHW systems, tend to cause flow patterns deviate from a fully developed flow. Therefore, inaccuracies of flow measurements were still inevitable even if very long straight pipes were used. The only way to deal with this flow-pattern induced inaccuracy is to use a displacement type flowmeter, which, however, is not available in large pipe sizes needed for multi-family DHW system.

Magnetic flowmeters used in this study were calibrated for measuring water flow rates by the corresponding vendors. Their calibration was further verified in selected full on-site study buildings.

### 3.3.3 Natural Gas Measurement

Full on-site studies monitored DHW system natural gas consumptions, either using gas meters or by monitoring the status of gas valve relays in water heaters or boilers. While the use of gas meters was preferred, under the following situations, the research team had to monitor gas valve relay instead:

- Heat input rate of the boiler was larger than 300kBtu/hr, exceeding the capacity of the largest gas meters used by the research team.
- Location of the water heating equipment and gas supply pipe did not provide enough space for installing a gas meter
- Installation of a gas meter created enough pressure drop that prevented water heating equipment from working properly. This problem occurred in two buildings.

Gas valve relays status, measured by detecting the electric current going through the relay, was used to determine the amount of time when the burner was turned on. Since all monitored water heating equipment had a constant firing rate, the product of water heater heat input rate and burner-on time could be used as an estimate of gas consumption during the time of interest.

## 3.4 Crossover Flow Investigation

The previous multi-family central DHW system PIER study [HMG 2008] indicated that three types of crossover flows may exist in a recirculation system. These are:

1. Hot water flow from tank into the cold water supply pipe
2. Hot water from tank into the recirculation return pipe
3. Hot water flow from the hot water supply into the cold water supply at a hot water fixture, for instance shower or faucet mixing valve

This study conducted several types of research activities to investigate the above crossover flow issues.

### 3.4.1 Reverse Flow Measurement

The first two types of crossover flows listed above involve hot water flowing in the opposite direction of normal flows. Both types of flowmeters used in this study, magnetic and ultrasonic flowmeters, could measure bi-directional flows and, therefore, could detect flows in reverse

directions. In addition, neither types of flowmeter would cause any flow pressure loss, so they would not change the existing flow patterns to potentially dampen or stop crossover flows.

None of the field flow measurements from full on-site and partial on-site buildings showed clear signs of reverse flows in either cold water supply or recirculation retune pipes. It should be noted that improper interpretation of flow measurement values, especially those of cold water supply flows, could lead to incorrect understandings of flow characteristics. Measured flow signals were based on instantaneous water velocities, which were very dynamic for cold water supply flow. There could be significant amount of jittering water movements due to fast changes in water velocity, fluctuations in water pressures, and water volume expansion or contraction due to temperature changes. The net cumulative sum of these fluctuating water movements was negligible compared to actual hot water draws. However, at very low or zero flows, these fluctuating water movements caused flowmeters to register scattered small negative values in water velocity measurements, which should not be incorrectly considered as crossover flows that effectively transferred water and energy in an opposite direction.

It should be noted that signals of recirculation flow measurements had little fluctuations, since recirculation flows were mostly determined by recirculation pump performance characteristics and were less susceptible to changes in hot water draw, pressure, and temperature. Consistent measurements of recirculation flow also indicated the flowmeters used in this study did not contribute to additional measurement fluctuations.

### 3.4.2 System Pressure Analysis

In the test full on-site study, the research team measured the hot water pressures at three key locations along the recirculation loop:

- Starting point of the hot water supply
- Entrance of the recirculation pump
- Exit of the recirculation pump

Pressure measurements at these three locations provided a complete understanding of pressure distribution in the recirculation system and facilitated the identification of crossover flows.

**Error! Reference source not found.** presents an example of typical pressure measurement results. Several observations can be made from these results:

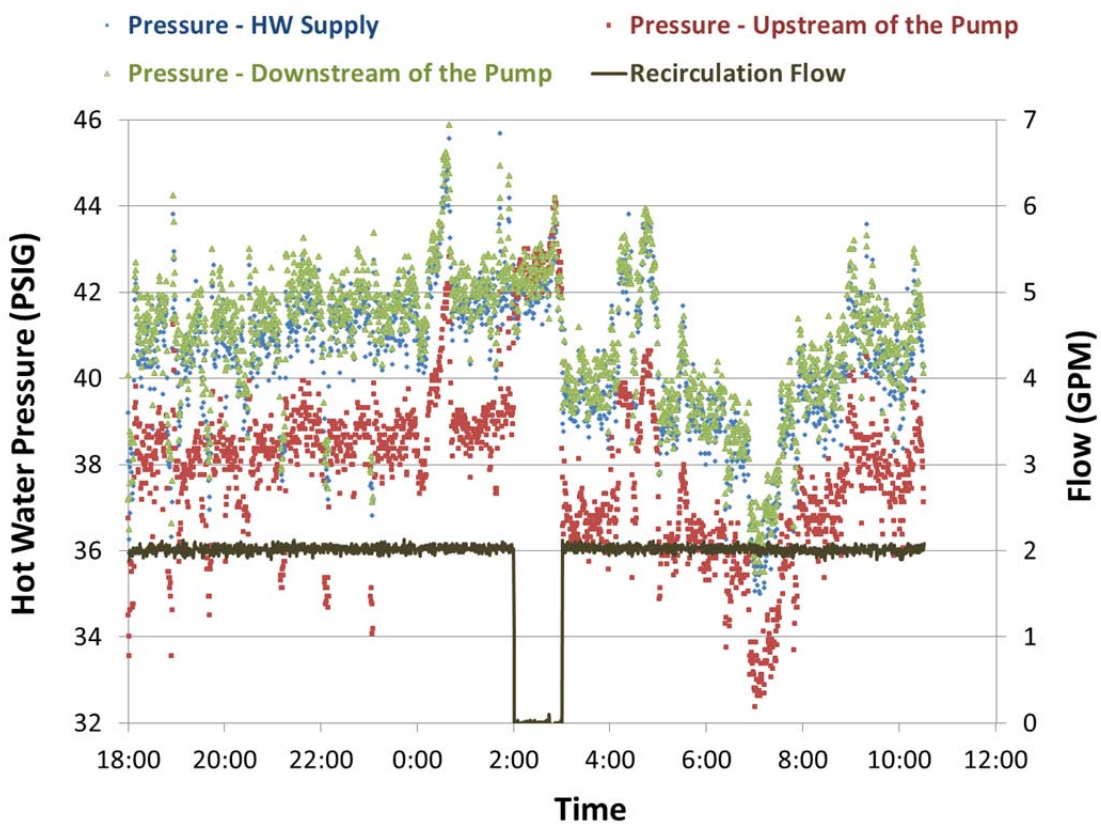
- Hot water pressures at the exit of the recirculation pump were the highest among the three locations. As shown in **Error! Reference source not found.**, this location is essentially the same as the entrance of cold water supply. Pressures at this location should be the highest of the hot water system to drive hot water deliveries.
- Hot water supply pressures was only very slightly below the recirculation pump pressures, or cold water supply pressures, indicating the storage tanks introduced very small amount of pressure losses.
- Recirculation pump entrance had the lowest pressure in the recirculation system, because the recirculation flow through the long recirculation pipes introduced large

pressure drops. Furthermore, when the recirculation flow was turned off, the recirculation pump entrance and exit had the same pressure.

- Overall system pressure varied with hot water draws. Large hot water draws would open the hot water system to the ambient and result in low hot water pressures.

When there were no hot water draws, the hot water system would form a close system. Any hot water temperature increases due to storage tank temperature controls would cause water volume and pressure to increase. This effect could not be easily captured by the pressure measurement in this study. All monitored DHW systems were equipped with an expansion tank, installed on the cold water supply line, to absorb the occasional hot water volume expansions.

**Figure 11: Recirculation System Pressure Measurement Results**




### 3.4.3 Hot Water Drain Test

This study did not plan to monitor hot water flows at individual hot water fixtures to determine if the third type crossover flows existed. However, a whole building hot water drain test was performed at several field study buildings to detect the existence of the third type of crossover flows. This test method was recommended by the EDC Technology staff.

This test was conducted in conjunction with the initial monitoring equipment installation. Building tenants were informed that hot water service would be stopped for several hours. HMG field study staff would turn off the cold water supply flow to the water heating system and shut off the recirculation pump. Water supply to the cold water system was not turned off. Then, one of the hot water faucet located on the lowest floor (in a laundry room or public bathroom) would be turned on to only drain hot water. If there was no leaking mixing valves in the building, hot water flow would eventually stop, because there was not make-up flow into the hot water system. Otherwise, it was expected that cold water would flow from the cold water system through a leaking mixing valve in a shower or a single-level faucet into the hot water system, so that the drain at the rest faucet would never stop.

This drain test was only allowed by the building owners or operators at four (4) field study buildings. At all these buildings, hot water drains eventually stopped after different amounts of time. Since only four (4) buildings were tested and all of them were built after 1990, this study can only conclude that the third type of crossover flows did not take place in any building, at least not in any newer buildings. This study did not yield any evidence of the existence of the third type of crossover flows.

## 3.5 Recirculation System Piping Layout

The original scope of this PIER project did not include the task to investigate recirculation system designs. Through preliminary research, the research team recognized that recirculation system design was the most important key factor in determining recirculation system performance. The team brought up this issue at the mid-term critical project review (CPR) meeting and suggested to investigate recirculation system designs to obtain full understanding of recirculation system performance. Following the approval by the Energy Commission project manager, the research team carried out the following research activities to collect information on recirculation system piping designs:

- Interviewed mechanical system designers to understand common design practices.
- Conducted visual inspection of recirculation system designs for all on-site study buildings.
- Reconstruct detailed recirculation system designs based on field visual inspection and building plumbing system plans (if available) for each full on-site study building.
- Collected and reviewed building plumbing plans from utility multi-family energy efficiency programs to gather more information on recirculation system design practices.

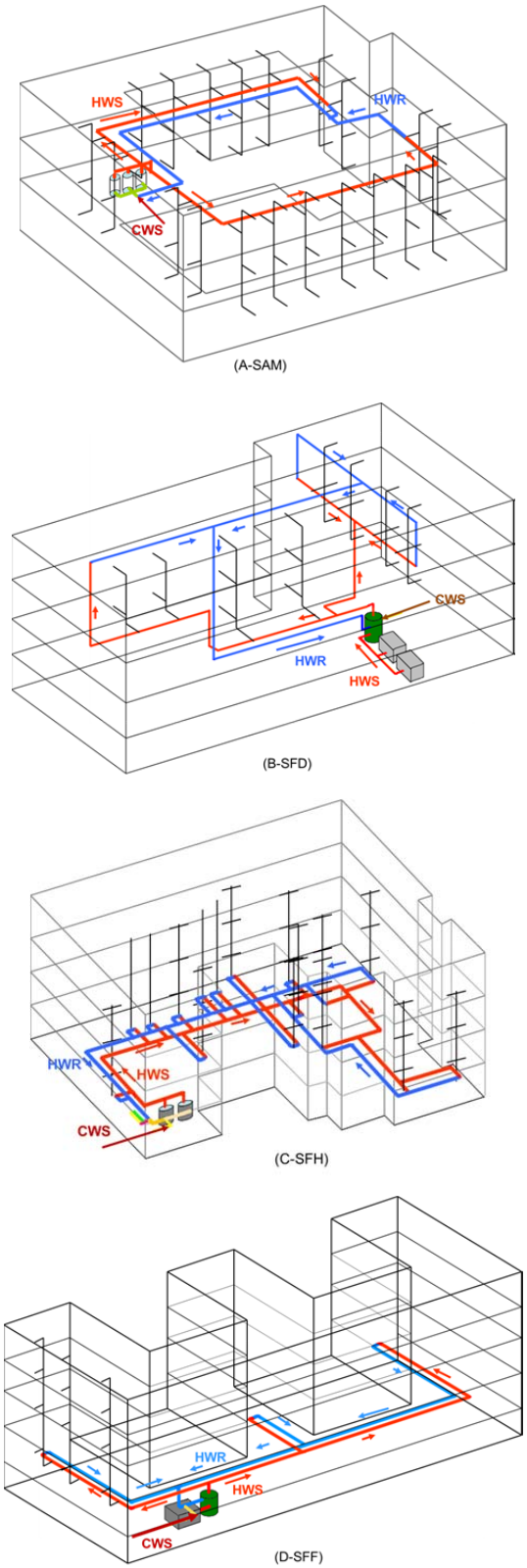
These research activities provided the following findings on general practices of recirculation system designs:

- There were no widely accepted guidelines on recirculation system designs for multi-family central DHW system. Different designers tended to have their own design preferences. The research team found no design guidelines intended to improve system efficiency, probably because there was little systematic knowledge of distribution system performance.

- Some design guidelines were created based on design guidelines for recirculation systems in hydronic heating systems. However, these design guidelines were not reflected in buildings monitored by this study. Hydronic heating recirculation systems have different operational requirements. These systems need to deliver hot water to every dwelling unit and, therefore, are more complicated. They are closed systems in that no water leaves the system. Recirculation flows for hydronic heating need to be carefully balanced to make sure they evenly reach each dwelling unit. In contrast, DHW recirculation systems are open systems and also rely on branch lines to deliver hot water to dwelling units. Recirculation pipes do not need to directly reach every dwelling unit. As a result, DHW recirculation loops can be much simpler and system balance is not as critical as for hydronic systems.
- Field studies observed many different types of recirculation system configurations. In general, DHW recirculation systems were not designed to reach every dwelling unit, unless the building only had only one or two stories. Some designs tried to reach most part of the building, while others only placed recirculation pipes in one of the building stories and used long branch lines to reach dwelling units on other building stories.
- Locations of recirculation pipes varied from building to building. Most monitored buildings did not have underground piping, unless water heating systems were located in a detached building. If a building had parking garage, on the first floor or basement floor, the mechanical room tended to locate on the garage floor and at least part of the recirculation pipes were located in the garage floor ceiling. When recirculation pipes were installed to be within a building, they were usually located in the ceiling spaces on one or multiple floors.
- Recirculation systems could consist of one or multiple loops. The splits of multiple recirculation loops started from the beginning of the hot water supply pipe in some buildings, while the splits occurred at different locations along the supply line in other buildings.

For full on-site study buildings, the research team intended to obtain detailed recirculation system design specifications, such as pipe length, diameter, and insulation thickness for each piping section. In selecting full on-site study buildings, the research team tried to only choose buildings, for which detailed recirculation system designs can be obtained from field inspection and/or building plan review. However, there were only a limited number of full on-site study participants and not all of them could meet the above selection criteria. For buildings with recirculation pipes buried in walls, detailed design specifications could not be verified even if a detailed plumbing plan was available. In the end, the research team identified four (4) full on-site buildings with visible recirculation pipes and a detailed plumbing plan. The recirculation system design were re-created, shown in **Error! Reference source not found.**, based on both plan check and field inspection. Section 50 discusses how the detailed recirculation system designs, along with the corresponding measured system operation parameters, were used to validate the recirculation system model.

**Figure 12: Recirculation System Piping Layouts in Four Full On-Site Study Buildings**



# CHAPTER 4:
# Performance Analysis Results

This chapter presents the analysis results based on data collected from field monitoring studies and historical monitoring data provided by EDC Technology.

## 4.1 Overall System Performance

Table 7 provides a summary of the ranges of the measured values of these parameters. Detailed monitoring results of key recirculation system operation parameters are shown in Table 8 and Table 9.

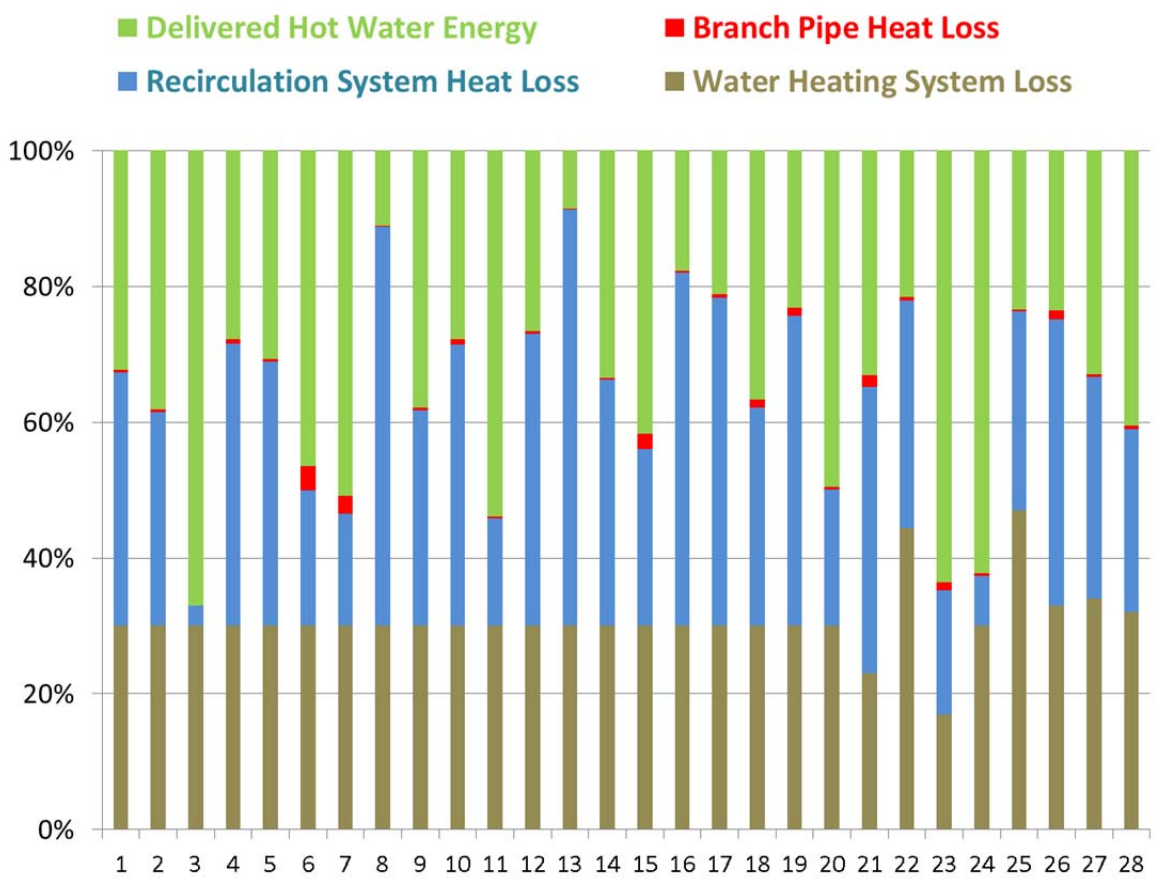
**Table 7 Variations of Key Recirculation System Parameters of All Monitored Buildings**

| | Minimum | Maximum | Median |
|---|---|---|---|
| **HWS Temp ($^oF$)** | 97 | 150 | 122 |
| **HWR Temp ($^oF$)** | 82 | 144 | 116 |
| **Recirculation System Temperature Drop** | 0.5 | 18 | 5 |
| **Recirculation Flow (GPM)** | 2 | 17 | 6 |
| **Daily Hot Water Draw (Gallon/unit)** | 4 | 55 | 29 |

Performance of overall DHW systems and recirculation systems was analyzed using the energy flow analysis method presented in Chapter 2.

**Error! Reference source not found.** presents the results of energy flow analysis by showing percentages of total DHW system natural gas consumption by four major energy components: water heating system loss, recirculation system heat loss, branch pipe heat loss, and delivered hot water energy. The figure clearly shows that there were large variations in central DHW system among different buildings. In particular, the recirculation system heat loss varied from 7 percent to 49 percent and delivered hot water energy varied from 21 percent to 62 percent.

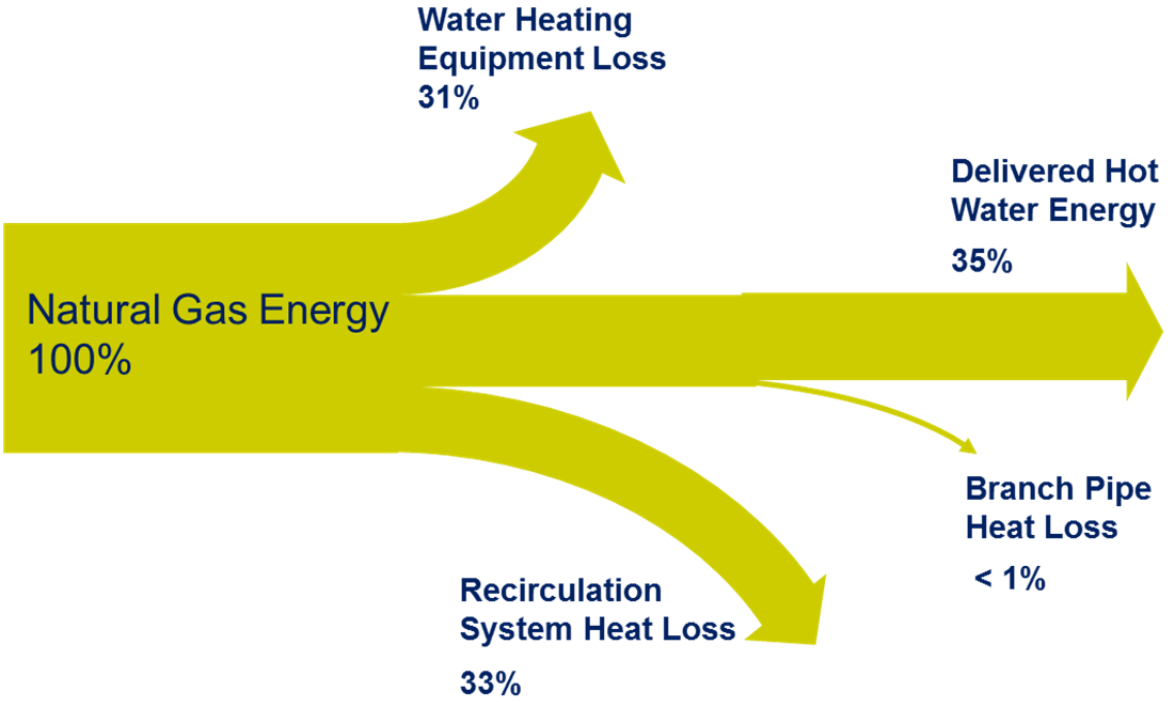
**Figure 13: Percentages of DHW System Natural Gas Consumption by Energy Flow Components**




**Error! Reference source not found.** illustrates the average energy flows among all buildings monitored by the study. It shows that, on average, 33 percent of the DHW system natural gas energy was lost by recirculation systems. The average overall DHW system efficiency, represented by the delivered hot water energy, was 35 percent.

The analysis results showed that branch pipe heat loss represented less than one percent of the total DHW system natural gas consumption. It should be noted that this loss only counted for pipe heat loss when there were hot water draws in branch pipes. It did not include energy loss associated with hot water wasted for discharging cold water in branch pipes and hot water cooled down in the pipe without further hot water flows. The study did not perform any measurements at individual hot water fixtures and, therefore, was un able to quantify this loss.

**Figure 14: Average Energy Flows in Multi-Family Central DHW Systems**



able 8 Summary of Field Monitoring and Performance Analysis Results – Full On-Site Study

| S p ) | HWR Temp ($^oF$) | Average Recirc. Loop Temp Drop ($^oF$) | Recirc. Flow (GPM) | Average Daily HW Draw per Unit (Gallon) | Water Heating Equipment Loss | Recirculation System Heat Loss | | | Branch Pipe Heat Loss | HW Delivered Energy |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Total | Recirc. Flow | HW Draw | | |
| 3 | 115 | 12.2 | 2.2 | 7 | 23% | 42% | 37% | 5.2% | 1.7% | 33% |
| 5 | 117 | 8.3 | 12.1 | 16 | 44% | 34% | 32% | 1.8% | 0.6% | 22% |
| 3 | 114 | 4.2 | 5.1 | 55 | 17% | 18% | 15% | 3.6% | 1.2% | 64% |
| 2 | 120 | 2.1 | 7.7 | 38 | 30% | 7% | 6% | 1.2% | 0.4% | 62% |
| 1 | 137 | 4.0 | 16.2 | 4 | 47% | 29% | 29% | 0.8% | 0.3% | 23% |
| 4 | 113 | 11.5 | 4.7 | 21 | 33% | 42% | 38% | 3.8% | 1.3% | 24% |
| 3 | 110 | 2.9 | 6.1 | 24 | 34% | 33% | 32% | 1.1% | 0.4% | 33% |
| 7 | 123 | 4.5 | 3.3 | 26 | 32% | 27% | 25% | 1.8% | 0.6% | 40% |

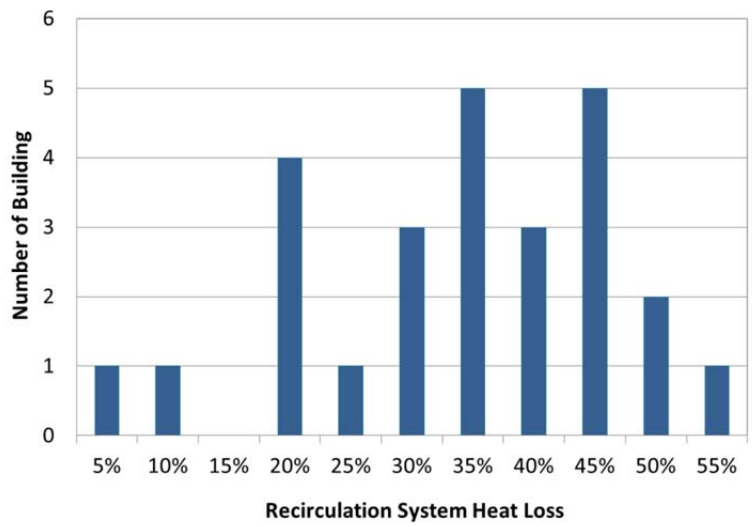
**Table 9: Summary of Field Monitoring and Performance Analysis Results – Partial On-Site Study**

| Site Index | CWS Temp (°F) | HWS Temp (°F) | HWR Temp (°F) | Average Recirc. Loop Temp Drop (°F) | Recirc. Flow (GPM) | Average Daily HW Draw per Unit (Gallon) | Water Heating Equipment Loss[2] | Recirculation System Heat Loss | | | Branch Pipe Heat Loss | HW Delivered Energy |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | Total | Recirc. Flow | HW Draw | | |
| 1-SFB | 63 | 120.9 | 117.2 | 3.7 | 9.1 | 19 | 30% | 37% | 36% | 1.3% | 0.4% | 32% |
| 2-BKS | 59 | 126.4 | 123.6 | 2.8 | 5.4 | 15 | 30% | 31% | 31% | 1.0% | 0.3% | 38% |
| 3-BKU | 70 | 114 | 113.8 | 0.2 | 11.4 | 33 | 30% | 3% | 3% | 0.2% | 0.1% | 67% |
| 4-SAP | 74 | 137.3 | 131.1 | 6.2 | 3.8 | 35 | 30% | 42% | 40% | 1.8% | 0.6% | 28% |
| 5-SAC | 73 | 121 | 118.1 | 2.9 | 5.5 | 25 | 30% | 39% | 38% | 1.2% | 0.4% | 31% |
| 6-DAK | 67 | 105.8 | 94.4 | 11.4 | 3.6 | 53 | 30% | 20% | 9% | 10.7% | 3.6% | 46% |
| 7-DAL | 67 | 116.4 | 105.8 | 10.6 | 4.1 | 54 | 30% | 16% | 9% | 7.9% | 2.6% | 51% |
| 8-OAL | 63 | 122.4 | 116.7 | 5.7 | 14.6 | 19 | 30% | 59% | 58% | 0.7% | 0.2% | 11% |
| 9-OAL | 63 | 115.8 | 113.2 | 2.6 | 9.8 | 31 | 30% | 32% | 30% | 1.2% | 0.4% | 38% |
| 10-SFF | 61 | 125.5 | 117.0 | 8.5 | 14.7 | 32 | 30% | 41% | 39% | 2.5% | 0.8% | 28% |
| 11-HOB | 57 | 113.6 | 112.1 | 1.5 | 5.7 | 39 | 30% | 16% | 15% | 0.9% | 0.3% | 54% |
| 12-HOB | 66 | 116.6 | 112.9 | 3.7 | 4.4 | 25 | 30% | 43% | 42% | 1.2% | 0.4% | 27% |
| 13-HOL | 92 | 112.8 | 110.5 | 2.3 | 10.3 | 12 | 30% | 61% | 61% | 0.6% | 0.2% | 9% |
| 14-HOC | 60 | 123.3 | 121.3 | 2.0 | 4.6 | 12 | 30% | 36% | 36% | 0.7% | 0.2% | 33% |
| 15-HOL | 64 | 143.9 | 126.1 | 17.8 | 3.6 | 32 | 30% | 26% | 19% | 6.8% | 2.3% | 42% |
| 16-DAR | 70 | 120.9 | 115.8 | 5.1 | 23.1 | 9 | 30% | 52% | 51% | 1.2% | 0.4% | 18% |
| 17-SAP | 67 | 131 | 123.9 | 7.1 | 7.1 | 34 | 30% | 48% | 47% | 1.6% | 0.5% | 21% |
| 18-SFP | 69 | 127.8 | 119.8 | 8.0 | 15.4 | 50 | 30% | 32% | 29% | 3.4% | 1.1% | 37% |
| 19-OAO | 69 | 115.4 | 105.4 | 10.0 | 3.9 | 31 | 30% | 46% | 42% | 3.6% | 1.2% | 23% |
| 20-LAE | 75 | 107.5 | 106.2 | 1.3 | 10.2 | 50 | 30% | 20% | 19% | 1.2% | 0.4% | 50% |

[2] Field studies did not measure DHW system natural gas consumption in partial on-site study buildings. Efficiencies of water heating equipment in partial on-site study buildings were assumed to be 30 percent for energy flow analysis. (The average efficiency of water heating equipment in full on-site buildings was 67 percent.)

The variation of recirculation system performance is further illustrated by **Error! Reference source not found.**, which shows the distribution of number of buildings in different ranges of recirculation system heat loss. Obviously, recirculation system heat loss depends on recirculation system piping designs. However, field studies were unable to collect enough design information to further correlate recirculation system designs to their performance.

**Figure 15: Statistics of Recirculation System Heat Loss**




The energy flow analysis revealed how recirculation system performance was related to hot water usages. Table 8 and Table 9 show the two components of recirculation system heat loss: heat loss associated with recirculation flows and hot water draw flows. The analyses, on average, represented 31 percent and 2 percent of the total DHW system natural gas consumptions. This result showed that majority of the recirculation system heat loss was associated recirculation flows. As hot water usages increase, recirculation system heat loss would increase slightly and its weight in the total DHW system natural gas consumption would decrease, leading to lower percent values.

## 4.2 Performance of Controls

The study assessed performance of recirculation controls in the eight full on-site study buildings. The three types of controls were tried at all these buildings when they were allowed by the building owners/operators.

Table 10 provides the control schedules for the three control technologies at the eight buildings. For timer controls and temperature modulation controls, the research team developed control schedules based on measured hot water usage patterns.

**Table 10: Control Schedules for Full On-Site Studies**

| Site Index | Timer Control (Hours of pump off / day) | Temperature Modulation (Temperature reduction / Hours of reduction) | Demand Control (Minutes of pump-on time/day) |
|---|---|---|---|
| A-SAM | 6 hours | 20°F / 6 hours | N/A |
| B-SFD | 6 hours | 10°F / 5 hours | 90 min |
| C-SFH | 6 hours | Not feasible | 265 min |
| D-SFF | 6 hours | 20°F / 6 hours | 346 min |
| E-DAE | 6 hours | 10°F / 6 hours | 477 min |
| F-SAA | 6 hours | 10°F / 6 hours | 170 min |
| G-LAB | N/A | N/A | 62 min |
| H-LAR | N/A | N/A | 62 min |

Energy savings were calculated by comparing the total DHW system energy consumption with and without controls being activated. The results, presented in Table 11, showed very large variations and some negative savings in some buildings. Table 11 also shows the recirculation system heat loss in each building for comparison. These energy savings results hardly show any trend and do not correlate well with recirculation system heat loss.

**Table 11: Measured Gas Energy Savings by Controls**

| Site Index | Timer Control | Temperature Modulation | Demand Control | Recirculation System Heat Loss (No Control) |
|---|---|---|---|---|
| A-SAM | 2.1% | 0.0% | N/A | 42% |
| B-SFD | 7.6% | -4.4% | 24% | 34% |
| C-SFH | 14% | N/A | 32% | 18% |
| D-SFF | -11% | 18% | 11% | 7% |
| E-DAE | 7.1% | 1.2% | 3.4% | 29% |
| F-SAA | 6.9% | 3.6% | 0.0% | 42% |
| G-LAB | N/A | N/A | 16% | 33% |
| H-LAR | N/A | N/A | 11% | 27% |

## 4.3 Hot Water Draw Analysis

This study analyzed the hot water draw measurements to characterize peak hot water demand. This information is important to the development of design guidelines for determining water heating capacities, tank sizes and water heater/boiler heat input, in multi-family buildings.

The research team followed a method provided in ASHRAE Application Handbook (Section 49.9) to characterize peak hot water demand by assessing the highest hot water draws for different time ranges. As an example, **Error! Reference source not found.** shows the maximum hot water demands for time ranges from one (1) minute to one (1) day. In addition, **Error! Reference source not found.** also shows maximum rates of hot water demand, which was

obtained by dividing the maximum hot water demand by the corresponding time range. It is clear that the maximum hot water demand increases with time range, because more hot water draws can be expected in a longer observation period. It is also clearly indicated by **Error! Reference source not found.** that the maximum rate of hot water demand decreases with time range, because high demands usually only last for short periods of time. It is those high rates of demand that determine the design capacity of a water heating system. Therefore, peak hot water demands during short time periods are more relevant and deserve careful investigation.

**Error! Reference source not found.** presents the same trend of maximum hot water demand as shown in **Error! Reference source not found.**, but only for up to three (3) hours of time range. It provides a detailed view of the correlation between maximum hot water demands and time ranges. However, information provided in this figure only represents peak demand characteristics of one building. In order to compare and summarize peak demand patterns of all the buildings monitored in this study, maximum hot water demands were normalized by the daily hot water demand to produce peak hot water demand fractions. These fractions represent the maximum fractions of daily hot water usages that occur during the corresponding time range. The slopes of a peak hot water demand fraction curve (**Error! Reference source not found.**) represent rates of hot water demand. Both values and slopes of a peak hot water demand fraction curve, along with building daily hot water demand, are needed to properly size the water heating system.

For each monitored building, peak hot water demand fractions were assessed on a daily basis. The day with the highest values of peak hot water demand fractions was used to represent the peak demand of the building. The corresponding peak hot water demand fractions for all buildings are presented in **Error! Reference source not found.**.

**Figure 16: Example of Measured Peak Hot Water Demand – Full Day**

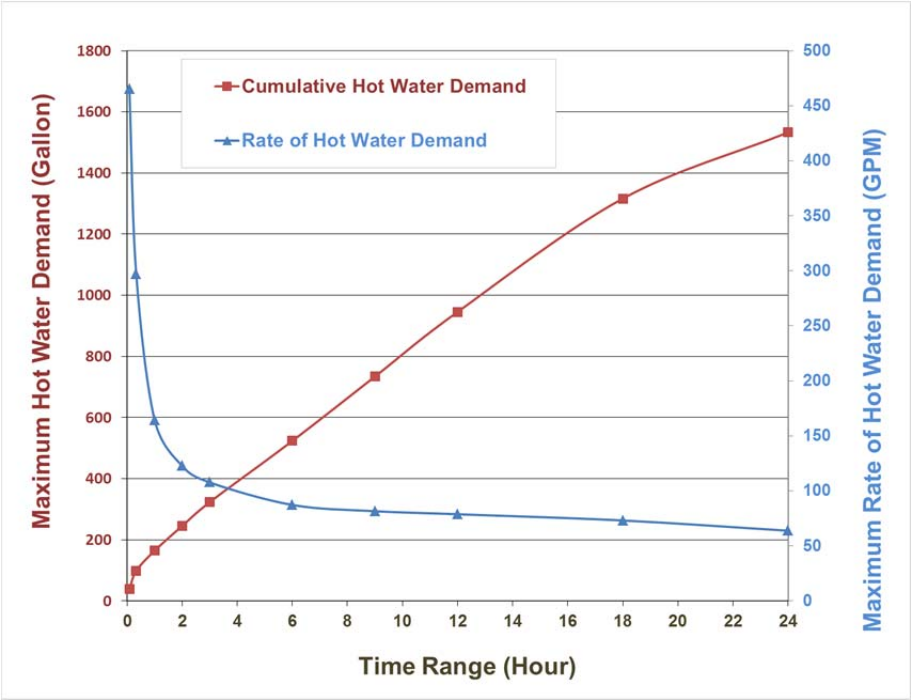
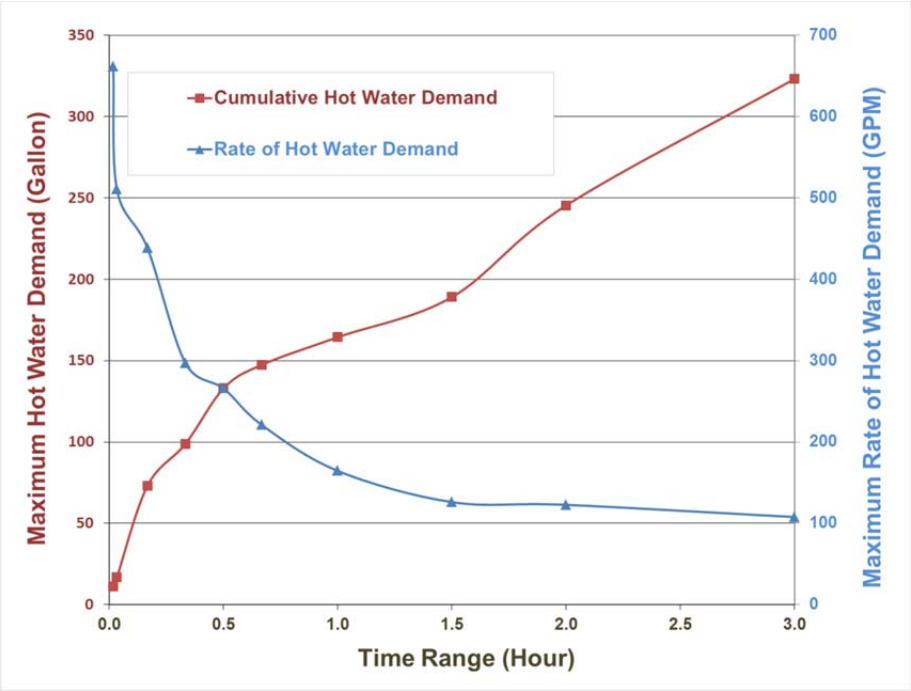



**Figure 17: Example of Measured Peak Hot Water Demand – Three Hours**



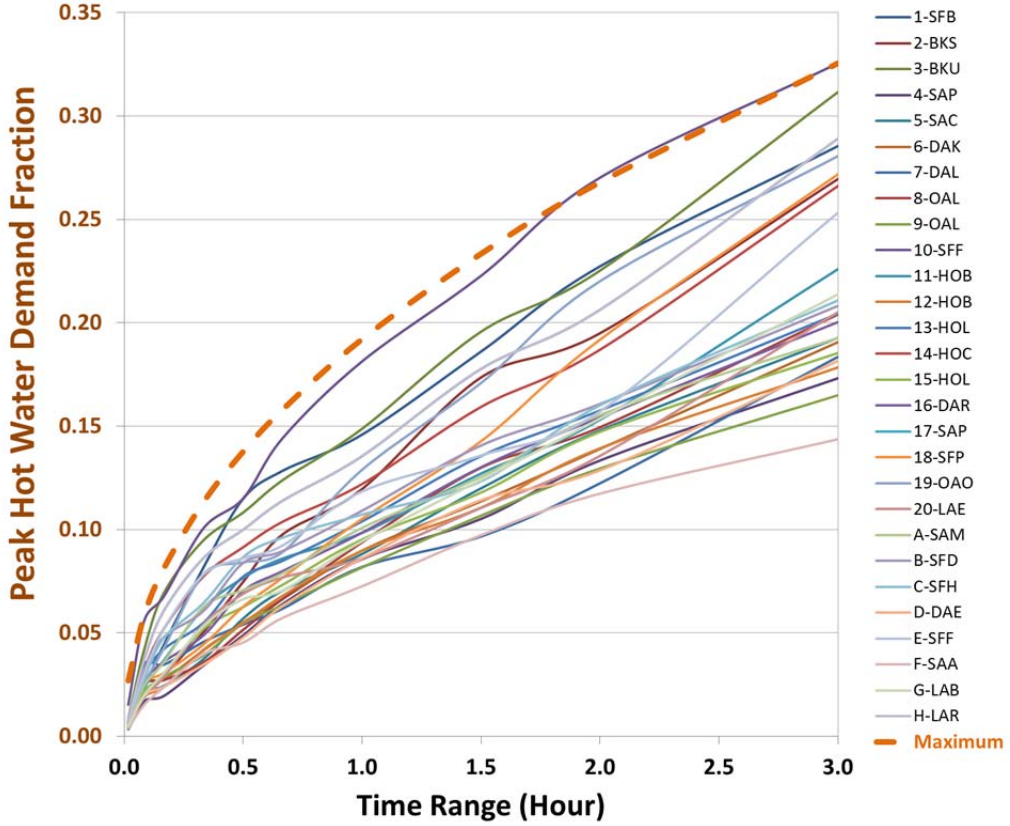
**Error! Reference source not found.** shows that buildings have large variations in peak hot water demand fractions. This is mostly due to differences in hot water usage behaviors of users in those buildings. If occupants in a building have relatively similar schedules, for instance all go to work and come home at similar times, it is more likely that hot water usages from different occupants will overlap and high peak hot water demand fractions are expected. If building occupants have different hot water usage schedules, there would be less dramatic increases in hot water draws. In this case, peak hot water demand curves would be expected to be relatively flat with low values.

It is very difficult, if not impossible for DHW system designers to predict future occupant behaviors with regard to hot water usages. Therefore, capacity of a water heating system needs to meet the largest peak demand possible. For this purpose, a maximum peak hot water demand curve was generated to capture the maximum peak demand observed in this study. This curve is presented in **Error! Reference source not found.** and can be described by the following equation:

$$Maximum\ Peak\ Hot\ Water\ Demand\ Fraction = 3.26 \times Time\ Range^{0.48}$$

The peak hot water demand curve can be calculated as:
$$Peak\ Hot\ Water\ Demand\ (Gallon) = Daily\ Hot\ Water\ Demand \times 3.26 \times Time\ Range^{0.48}$$

**Figure 18: Peak Hot Water Demand Fractions**


Peak Hot Water Demand Fraction
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Time Range (Hour)
1-SFB
2-BKS
3-BKU
4-SAP
5-SAC
6-DAK
7-DAL
8-OAL
9-OAL
10-SFF
11-HOB
12-HOB
13-HOL
14-HOC
15-HOL
16-DAR
17-SAP
18-SFP
19-OAO
20-LAE
A-SAM
B-SFD
C-SFH
D-DAE
E-SFF
F-SAA
G-LAB
H-LAR
Maximum

## 4.4 Historical Monitoring Data Analysis

EDC's monitoring systems measured hot water supply temperature, hot water return temperature, and cold water temperature. In some buildings, status of relays for natural gas valves in water heater or boilers were also measured and they provided indirect indication of natural gas consumption. Measurements were made at every second and data were recorded every 15 minutes.

EDC monitoring systems did not measure water flows and, therefore, we could not conduct energy flow analysis, as described in the previous section, to reveal system energy performance or recirculation system heat loss. For some DHW system, EDC monitoring systems measured and recorded the status of gas value relay status, which can be used to determine the daily burner firing time of the corresponding water heating equipment. Most hot water heating equipment were expected to have a constant firing rate, knowing daily burner firing time, along with heating equipment heat input ratings (Btu/hr), we could estimate daily natural gas consumption by the monitored systems. Unfortunately, EDC monitoring data did not contain information of heating equipment heat input ratings. As a result, we could not estimate system gas consumptions. Another way to use the daily burner firing time information is calculate its relative changes as a way to assess savings achieved by the corresponding system improvement, such as installation of a temperature modulation control, reduction in supply temperature settings, fix of a pipe leak, and so forth. All EDC monitoring was started along with the installation of an EDC temperature modulation control and there was no monitoring data indicating system performance before installation of the control. Other possible system improvements were not explicitly indicated by the EDC monitoring data. As a result, we could not use the monitoring data to assess savings from system improvements.

Without being able to performing energy performance related calculation, this study analyzed the variations of hot water supply temperatures, hot water return temperatures, and recirculation loop temperature drops. The results provided a picture of common hot temperature settings and hot water temperatures delivered by recirculation systems. We also developed Excel programs to search for abnormal trends in temperature measurements, which were used to identify possible system operation issues, for instance recirculation pump failures.

# CHAPTER 5:
# Recirculation System Model Development

## 5.1 Overview

This chapter describes the recirculation system model developed by this study. This model was developed based on heat transfer principles and could predict recirculation system performance based on system designs, operational conditions, and control schedules. The development process of this model also provided in-depth understandings of recirculation system operation and revealed energy savings mechanisms of recirculation system designs and controls.

The general approach of this recirculation model, as discussed in Section 2.3, was to simulate heat transfer of each pipe section in recirculation systems. The overall model development consisted of the following steps of consideration:

1. Construct recirculation system using pipe sections
2. Understand and solve for heat loss of simple linear pipes
3. Understand heat loss characteristics of recirculation systems, considered as consisting of interconnected pipe section, with steady flows
4. Understand heat loss characteristics of recirculation systems without recirculation flows
5. Develop assumptions to simulate overall recirculation operation as a sequence of different heat loss modes

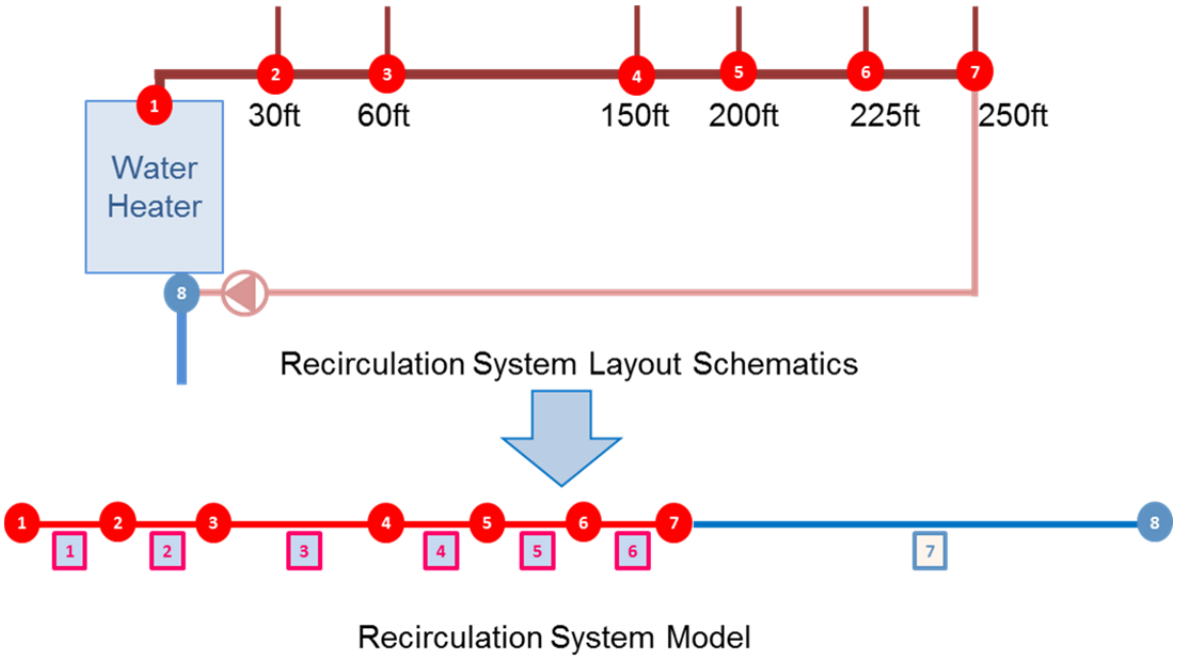
At the end, complicated recirculation systems were modeled as a set of interconnected pipe sections with a sequence of heat loss modes. This simple modeling approach was implemented using Excel.

The study validated the model to ensure accuracy by comparing model results to field monitoring results from four full on-site study buildings under different controls. Using the validated model, the study was able to provide more accurate assessment of energy savings from control technologies than those obtained from field studies, because operational conditions could be kept the same under different controls.

## 5.2 Recirculation System Configuration

Recirculation systems were modeled as a network of interconnected pipe sections. **Error! Reference source not found.** shows an example of pipe section configurations for a simple recirculation loop with six branch lines. In this example, the system is divided into seven pipe sections, denoted by the numbers enclosed in squares. Separation and interconnection between pipe sections are specified through pipe nodes, denoted by the numbers enclosed in circles. For example, pipe section number 1 has the node number 2 as the output node, which also serves as the input node for pipe section number 2. The model would pass flow and temperature information from pipe section number 1 to pipe section number 2 through pipe node number 2.

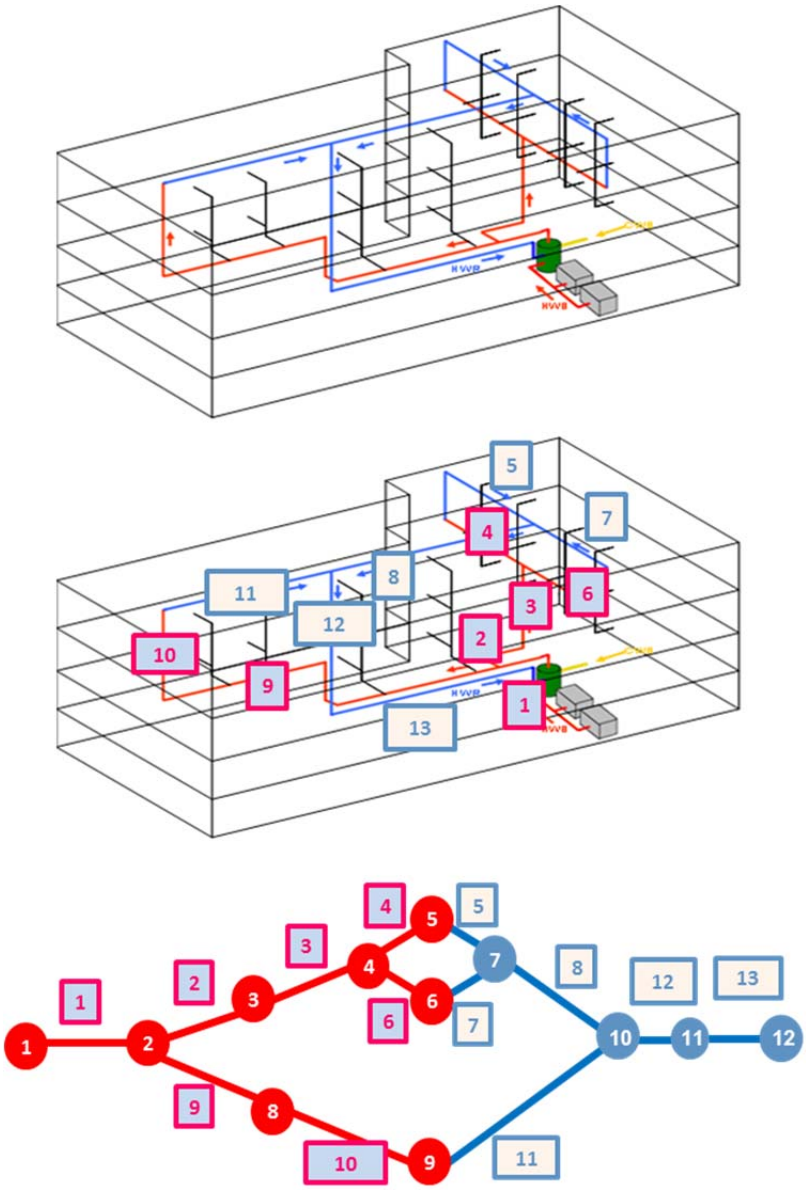
**Figure 19: Example of Pipe Section Configurations for a Simple Recirculation System**




Continuous linear pipe with the same physical configurations (pipe diameter and insulation), ambient conditions, and flows can be treated as a unique pipe section in the model, because such a pipe section would have a uniform heat transfer characteristics. Water flow in HWS pipes reduces as hot water is drawn branch pipes. For this reason, HWS pipes between different branches should be modeled as separate pipe sections. However, as explained in the following section, since pipe heat loss is not very sensitive to variations of hot water flows, HWS pipes between several branches can be modeled as one pipe section, with hot water draws from the branches in between may be relocated to the branches at the beginning and end of the combined pipe section. In this way, the overall model can be simplified down to having fewer pipe sections. HWR pipes can be modeled as one pipe section because they often have the same physical configurations and the same ambient conditions.

Using the above-described simplification method, **Error! Reference source not found.** illustrates how pipe section configurations were simplified from the complicated recirculation system design (for the full on-site building B-SFD) to a relatively simple model configuration. This example shows how a recirculation loop is split into two, at both pipe nodes #2 and #4, to form two sets of parallel recirculation loops.

**Figure 20: Recirculation System Model for a Full On-Site Study Building**




## 5.3 Pipe Heat Transfer Modes

Recirculation pipes have two distinctive heat transfer modes: pipe heat transfer with hot water flows and pipe heat transfer without hot water flows (with stagnant water). These two heat transfer models have very different heat loss characteristics, which can be used to explain the differences in system performance under controls. Pipe temperatures and heat loss for both heat transfer modes can be predicted from material and flow properties, using well-developed engineering solutions available from most heat transfer text books.

### 5.3.1 Pipe Heat Transfer with Hot Water Flows

A pipe with a steady hot water flow will achieve a stable temperature distribution, with pipe temperature decreasing gradually from the inlet to the outlet. Flow temperature at a distance *L* from the inlet can be calculated using the following equation [Incropera 2002]:

$$\boldsymbol{T_{flow}(L) = (T_{in} - T_{amb}).\, e^{-\frac{UA_L}{\rho \cdot c_p \cdot Flow} \cdot L} + T_{amb}}$$

where

$T_{in}$ is pipe inlet temperature;

$T_{amb}$ is ambient temperature;

$UA_L$ is pipe heat transfer coefficient per unit length of pipe. It depends on pipe physical configurations, such as pipe diameter and insulation conditions, and ambient conditions. Calculation of UA is discussed in Appendix C.

ρ is hot water density;

$C_p$ is hot water specific heat; and

Flow is hot water volumetric flow rate (GPM).

The average temperature of pipe with length *L* can be calculated as:

$$\boldsymbol{T_{avg} = (T_{in} - T_{amb}).\left(\frac{1 - e^{-\frac{UA_L}{\rho \cdot c_p \cdot Flow} \cdot L}}{\frac{UA_L \cdot L}{\rho \cdot c_p \cdot Flow}}\right) + T_{amb}}$$

Pipe heat loss rate (Btu/hr), $\boldsymbol{\dot{Q}_{loss\,rate}}$, can be calculated based on the formula for either pipe heat transfer or hot water energy loss, as shown below:

$$\boldsymbol{\dot{Q}_{loss\,rate} = UA \cdot (T_{avg} - T_{amb}) = \rho \cdot c_p \cdot Flow \cdot (T_{in} - T_{out,flow})}$$

The total pipe heat loss (Btu), $\boldsymbol{Q_{loss,flow}}$, during a period of Δt, when hot water has a constant flow rate, is:

$$\boldsymbol{Q_{loss,flow} = \dot{Q}_{loss\,rate} \cdot \Delta t}$$

The above equations indicate that pipe heat loss depends on pipe physical configurations, such as heat transfer coefficient and pipe length, and on operational parameters, such as inlet temperature, ambient temperatures, and flow. It will be shown in the next section that both pipe heat loss and the exit temperature increase with water flow rate. One way to explain this trend is that hot water has less time to lose heat as it travels through the pipe at a high flow rate, so that the exit water temperature and the average pipe temperature are higher. On the other hand, the overall pipe heat loss is higher due to the increased average pipe temperature.

### 5.3.2 Pipe Heat Transfer without Hot Water Flows

Without hot water flows, pipe heat loss will cause water and pipe temperatures to decrease. As pipe temperature is reduced, pipe heat loss slows down accordingly. Eventually, water and pipe temperatures will be the same as ambient temperature and pipe heat loss will be zero. As a result, stopping hot water flows can dramatically reduce pipe heat loss.

Pipe cool-down process can be analyzed using the lumped capacity method, which is one of the standard methods for analyzing transient heat transfer in simple systems. Using this method, average temperature of a pipe section after time t from the beginning of the cool-down process can be calculated as:

$$\boldsymbol{T_{avg}(t) = \left(T_{avg}(0) - T_{amb}\right).\, e^{-\frac{UA_L}{Cap_L}.t} + T_{amb}}$$

where

$T_{avg}$ (0) is the average temperature of the pipe section at the beginning of the cool-down process;

$Cap_L$ is thermal capacity (mass × specific heat) per unit length of pipe, including thermal capacity of both water and pipe.

Total pipe heat loss (Btu) during the cool-down period equals the total thermal energy reduction of hot water and the pipe, as shown in the following equation.

$$\boldsymbol{Q_{loss,cool} = Cap_L \cdot L \cdot \left(T_{avg}(0) - T_{avg}(t)\right)}$$

## 5.4 Recirculation System Heat Transfer Modes

Using the two pipe heat transfer modes presented above, several system operation modes were constructed to illustrate the overall recirculation system performance. These system operation modes help to explain energy savings mechanisms of control technologies.

### 5.4.1 Recirculation Operation with Varying Hot Water Flows

Water flow rate is the determining operational parameter in deciding pipe heat loss mode. Therefore, system operation modes are determined by flow conditions. Changes in hot water flows in a recirculation system are determined by hot water draw schedules and by recirculation pump control schedules.

Using the system design shown in **Error! Reference source not found.** as an example, the study calculated the recirculation system temperature distribution and pipe heat loss under several representative flow conditions, as listed in Table 12. For each pipe section of the system, pipe heat loss mode was determined based on water flow rate. Pipe temperatures and heat loss rate were calculated accordingly using the equations provided in the previous section. Temperature and flow data were passed from an upstream pipe section to a downstream one following the pipe section configurations presented in **Error! Reference source not found.**. When there was a hot water draw in a branch pipe, hot water flows in downstream pipe sections were reduced accordingly. The recirculation system was assumed to be located in conditioned spaces with

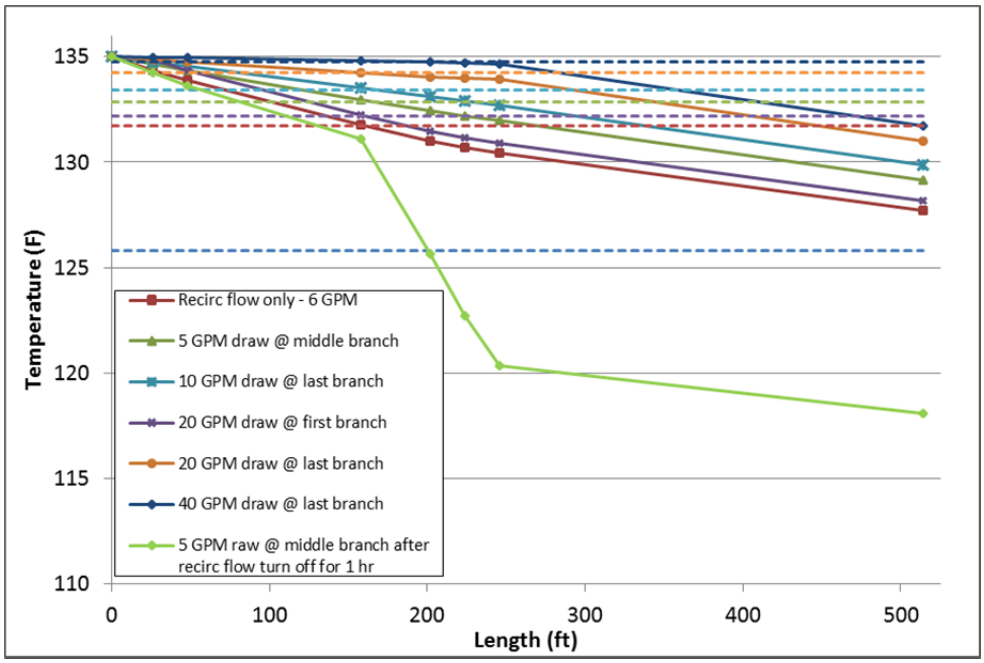
ambient temperature at 70$^{O}$F. The whole recirculation system was assumed to have perfect pipe insulation according to the 2005 Title 24 requirement. **Error! Reference source not found.** shows temperature distributions of the whole recirculation system under the selected flow conditions. Table 12 compares the rate of recirculation system pipe heat loss under the selected flow conditions. These heat transfer analysis provide the following findings:

- Pipe exit temperatures and system heat loss increased with increasing hot water flows. Hot water draws from the last branch resulted in higher system pipe heat loss than the same amount of hot water drawn from other branches.
- When the recirculation pump was on, variations of system pipe heat loss due to draw flow changes were relatively small. As the hot draw flow increased from 0 gpm to 5 gpm (expected to be the average draw flow rate based on field study findings), system pipe heat loss increased only by 1.8 percent. As the hot water draw flow increased from 5 GPM to 40 gpm (expected to be maximum possible draw flow rate), system heat loss increased by 3 percent. This finding implied that system operations with moderate draw flow variation can be modeled as having a constant flow and the simulation error is small.
- When the recirculation flow was stopped, HWR pipe sections and some HWS pipe sections had no water flows and cooled down. After one hour without the recirculation flow, system pipe heat loss rate reduced by 13.4 percent. Pipe temperatures of all pipes were still above 115$^{O}$F, which was warm enough for most general hot water services.
- HWR pipe temperatures were affected the most by recirculation pump controls. When the recirculation pump was turned off, HWS pipe temperatures had a large dependence on hot water draw locations.

**Table 12: Recirculation System Pipe Heat Loss Rates under Different Flow Conditions**

| Operation Conditions | Change in Pipe Heat Loss Rate (Compared to the Reference Condition) |
|---|---|
| Reference Condition:<br>Recirculation flow only (6GPM),<br>HWS temperature = 135$^{o}$F | 0% |
| 5 GPM draw at the middle branch | 1.8% |
| 10 GPM draw at the middle branch | 2.7% |
| 20 GPM draw at the middle branch | 3.5% |
| 20 GPM draw at the middle branch | 4.1% |
| 40 GPM draw at the middle branch | 4.8% |
| 5 GPM draw at the middle branch after recirculation flow being turned off for 1 hour | -13.4% |

**Figure 21: Hot Water Temperature Distribution in a Recirculation System**




### 5.4.2 Recirculation Operation with Varying HWS Temperatures

The analysis above assumed a constant HWS temperature of 135°F. As the HWS temperature changes, recirculation system pipe temperatures would float up and down with the HWS temperature. However, the trends presented in **Error! Reference source not found.** and Table 12 stay the same. Temperature distributions along the pipe length remain the same as those shown in **Error! Reference source not found.**.

Table 13 compares recirculation system pipe heat loss rates under one draw condition, but with different HWS temperatures. The results quantitatively show the energy savings benefit of lowering HWS temperatures.

**Table 13: Recirculation System Pipe Heat Loss Rates with Different HWS Temperature**

| Operation Conditions | Change in Pipe Heat Loss Rate (Compared to the Reference Condition) |
|---|---|
| Reference Condition:<br>HWS temperature = 135°F<br>Recirculation flow only (6GPM) | 0% |
| HWS temperature = 130°F<br>Recirculation flow only (6GPM) | -7.7% |
| HWS temperature = 125°F<br>Recirculation flow only (6GPM) | -15% |
| HWS temperature = 120°F | -23% |

| | |
|---|---|
| Recirculation flow only (6GPM) | |

### 5.4.3 Mechanisms of Control Technologies

The discussions in Section 5.3 on recirculation system operation modes help to understand energy savings mechanisms of control technologies.

Both timer controls and demand controls enable pipe cooling down to reduce pipe heat loss. The amount of pipe heat loss reduction depends on how often and how long pipes have no flow and are allowed to cool down. Hot water flows in HWR pipes solely depend on recirculation pump operation. Hot water flows in HWS pipes also depend on hot water draw schedules. Therefore, recirculation pump controls have a large impact to HWR pipes than to HWS pipes. The percentage reduction of recirculation system pipe heat loss depends on the ratio of HWR pipes to HWS pipes, which is determined by recirculation system designs. Cool-down process for HWS pipes depend on hot water draw schedules and locations, so energy savings from recirculation pump control also depends on occupant behaviors.

Temperature modulation controls reduce pipe temperatures of the whole recirculation system. Therefore, the percentage reduction of recirculation system pipe heat loss only depends on the amount of the HWS temperature reduction and duration of temperature reduction, and not on recirculation system designs. For a fixed temperature modulation control schedule, energy savings are not sensitive to hot water draw variations, because recirculation system pipe heat loss is not sensitive to hot water draw flows when the recirculation pump is turned on.

Quantitative assessment of energy savings from controls are provided later in this chapter based on recirculation system designs, draw schedules, and control schedules obtained from four full on-site study buildings.

## 5.5 Model of Controls

### 5.5.1 Modeling of Continuous Pumping

The daily operations of recirculation systems are simulated to have a sequence of different operation modes as discussed in the prior section. Different controls have different combinations of operation modes.

### 5.5.2 Continuous Pumping without Any Controls

Recirculation system operation without any control is the simplest scenario to model. Table 12 revealed that variation of hot water draws had a relatively small impact on recirculation system pipe heat loss when the recirculation pump was on. Based on this finding, the model simulates daily recirculation system operation as a sequence of steady-state operations with constant hot water draws along with a constant recirculation flow. The detailed modeling process is as follows:

- A day is divided into 48 time steps. Time steps were selected to capture periods with relatively small variations in draw flow. For this reason, durations of each time step were not always the same. For example, a time step at midnight could be two hours long

if hot water draws are very low or zero during the whole period. A time step for a peak-demand period could be only twenty minutes to include high hot water draws in that period. No time step is less than ten minutes, because it takes at least ten minutes for most recirculation systems to transition from one steady-state operation to another.

- For each time step, average hot water draws in each branch pipes are calculated according to detailed hot water draw schedules. The recirculation system is modeled to have a steady-state operation with constant hot way draws in each branch pipe.
- If the schedule of total hot water draw was known but branch locations of hot water draws were unknown, each time step included three scenarios of hot water draw locations to reflect possible variation of hot water draw locations: at the first branch, at the middle branch, and at the last branch. System pipe heat loss of the three scenarios is averaged to represent the recirculation system performance of the time period.
- Daily recirculation system heat loss was obtained by summing up system pipe heat loss from all 48 time steps.

### 5.5.3 Modeling of Temperature Modulation

The modeling process for system under temperature modulation control was very similar. Because temperature modulation controls do not turn off the recirculation pump, modeling method for dealing with variations in hot water draws stayed the same. Selection of time steps was based on both hot water draw schedule, as well as the temperature modulation schedule. Adjustment of HWS temperature was a slow process because it took considerable time to cool down and heat up water in large storage tanks in multi-family DHW systems. This effect was evident in field monitoring results, as shown in **Error! Reference source not found.**. The model designated two 30-minute time steps to cover the slow transitions for tank temperature cool down and ramp up. HWS temperatures for the two transition time steps are assumed to be the average between the normal HWS set temperature and the set temperature of the modulation control.

### 5.5.4 Modeling of Timer Control and Demand Control

Timer controls and demand controls involved two important, alternating processes: pipe cooling down and recovery from pipe cooling down. These two processes inflicted large changes in temperature and heat loss rate (as shown in **Error! Reference source not found.** and Table 12) that cannot be properly modeled using steady-state assumptions. They were modeled using the solutions to pipe cooling mode provide in Section 5.2.

First, time steps were selected such that the recirculation was either turned on or off during the whole time step. The recirculation system was assumed to start from a steady-state status so that the system initial condition can be used for further transient process modeling. Hot water flows and HWS temperature were the same as those of the last time step since the model simulated daily performance with the inherent assumption that the same operational conditions cycle from one day to another. The initial status provided average pipe temperature and heat loss rate of each pipe section.

Second, the model calculated pipe temperature and heat loss rate based on the following three possible scenarios:

1. If the recirculation pump was turned on for the current and preceding time steps, the recirculation system is treated as in transition from one steady-state status to another. The modeling method was essentially the same as that used for continuous pumping. Average temperature of each pipe section was calculated and saved for possible use in the next time step.
2. If the recirculation pump was turned off in the current time step, pipe sections without draw flows will cool down. For those pipe sections, the model performed cool-down mode calculation following the equations provided in Section 5.2, using the average pipe temperature of the last time step as the initial condition and the time step duration as the cool-down time. For pipe sections with hot water draw flows, the model used steady-state mode calculation. For all pipe sections, average temperature at the end of the time step was calculated and saved for possible use in the next time step.
3. If the recirculation pump is turned on in the current time step, but was turned off in the preceding step, pipe sections without flows previously would recover from a cool-down process. The model first calculated the steady-state performance for the whole recirculation system. For pipe sections without flows in the last time step, the model assumed a transition period between the end of the last time step and new steady-state operation. Pipe temperature and heat transfer rate were assumed to vary linearly with time. The length of the transition period was calculated as the total volume of pipe sections without flows in the last time step divided by the flow rate of the recirculation flow. Therefore, it was an estimate of the time needed to fill the pipes, which were previously cooled down with hot water. If the transition time was longer than the time step, the recirculation system did not reach the steady-state.

   As discussed in modeling for continuous pumping, the model considered three scenarios of hot water draw locations at each time step, such as at the first branch, at the middle branch, and at the last branch. They were used to reflect variations in hot water draw locations. Simulation results of the three scenarios were averaged to represent the performance of the time step.

## 5.6 Model Validation Procedures

To ensure that the developed model was able to accurately predict recirculation system performance, this study validated the model by comparing model output to field measurement results. The validation was performed for the four (4) full on-site study buildings with detailed recirculation system plumbing designs from the field monitoring studies. First, for each building, a recirculation system model was developed based on the system plumbing configurations. Pipe insulation conditions were calibrated based on system performance without controls. Second, the model was used to predict system performance under different controls, using same control schedules and hot water draws obtained from the corresponding

field studies. The predicted HWR temperature, recirculation system heat loss, and overall system natural gas energy consumption were compared to field measurement values.

The detailed validation procedures are discussed here:

### Step 1. Develop a Recirculation System Model

For each validation building, a recirculation system configuration model was developed following the method described in Section 5.2. **Error! Reference source not found.** presented an example.

### Step 2. Develop of Validation Data Set

For each validation building, one day of monitoring data under each control was selected for model validation comparison. Each data set was broken in 48 time steps following methods discussed in previous sections. Average values of all monitored parameters in each time step were calculated. Average values of the following parameters were used as input to the recirculation model as they represented the system operational conditions and control schedules:

- CWS temperature
- HWS temperature
- Hot water draw flow rate
- Recirculation pump on/off time

Ambient temperatures for pipes in conditioned spaces were assumed to be 70$^{O}$F. For pipes in unconditioned spaces, ambient temperatures were obtained from a weather database.

The average HWR temperatures were used to validate model accuracy.

### Step 3. Calibrate of Pipe Heat Transfer Coefficient

Field studies found that all four buildings had one-inch fiberglass based pipe insulations, at least for exposed pipes. However, the study found that using this insulation condition alone would substantially underestimate recirculation system pipe heat loss. Two other factors needed to be considered to properly model overall pipe heat transfer coefficients. One is pipe insulation quality and the other is heat loss through branch pipes.

Most straight pipes in these buildings had good insulation with the help of pre-fabricated pipe insulation products. Low-quality insulations were observes at elbows or other types of joints, where field-installed loose insulation materials were used. It was also uncertain whether pipes inside walls were insulated well.

Heat loss through branch pipes increased recirculation pipe heat loss. When there were hot water draws, branch pipe heat loss was associated with hot water flows in branch pipes and, therefore, would be considered independent from recirculation pipes. When there was no hot water flow, thermal energy lost by branch pipes was from hot water in recirculation pipes, through heat conduction and convection and should therefore be included in recirculation system modeling. Heat loss caused by conduction is relatively easy to quantify. Convection heat loss is very difficult to predict, because convection flows caused by temperature differences in branch pipes are extremely uncertain.

The two factors discussed above effectively increase heat transfer coefficients of recirculation pipes. In the model, their effects were represented by a multiply factor, applied to the heat transfer coefficients that were calculated based on perfect pipe insulation of straight pipes without branch pipes. For each validation building, the multiple factor was obtained through a calibration process using the validation data set for continuous pumping (no control). The multiplier was varied until the modeled HWR temperature marched with the measured HWR temperature. The calibrated multiply factors were in the range of 2.0 to 2.5 for the four validation buildings.

#### Step 4 Validate Model Prediction for Controls

For each validation building, the recirculation system model was to simulate system operation under the three types of controls, using the corresponding validation data set developed in Step 2. To determine model accuracy, the study compared modeled and measured results of HWR temperature, recirculation system heat loss, and total DHW system energy consumption.

## 5.7 Model Validation Results

### 5.7.1 Validation of HWR Temperature Prediction

**Error! Reference source not found.** through **Error! Reference source not found.** present comparisons between modeled and measured HWR temperatures under three recirculation system controls. In addition to HWR temperatures, these figures also show model inputs and the corresponding measured values for hot water draws, HWS temperatures, and recirculation flows. These figures were based results from the full on-site study building of B-SFD, and results from other buildings were similar.

It can be seen from these figures that the model accurately predicted HWR temperatures when the recirculation pump was turned on. When the recirculation pump was turned off, during either timer control or demand control, the model correctly predicted the trends of HWR temperature changes, but seemed to have predicted lower HWR temperatures than measured.

The measured HWR temperature was observed in the mechanical room, with considerably high ambient temperatures than the rest of the HWR pipes, due to the water heating equipment inside. High ambient temperatures slowed down the temperature drop for the short HWR pipe in the mechanical room. On the other hand, the model only simulated large pipe sections. The short HWR pipe section in the mechanical room was not treated as a separate pipe section, since its impact to overall recirculation system heat loss was small. The modeled HWR temperatures represented the performance of overall HWR pipes and, therefore, they were lower than the measured values obtained from values in the mechanical room. Prediction of overall recirculation system heat loss should still be relatively accurate, as shown below. It should also be pointed out that the high ambient temperature in mechanical room had small impact on HWR temperatures with recirculation flow, for the same reason that the short HWR pipes in the mechanical room only represented a small fraction of the recirculation system.

**Figure 22: Model Validation – Temperature Modulation**

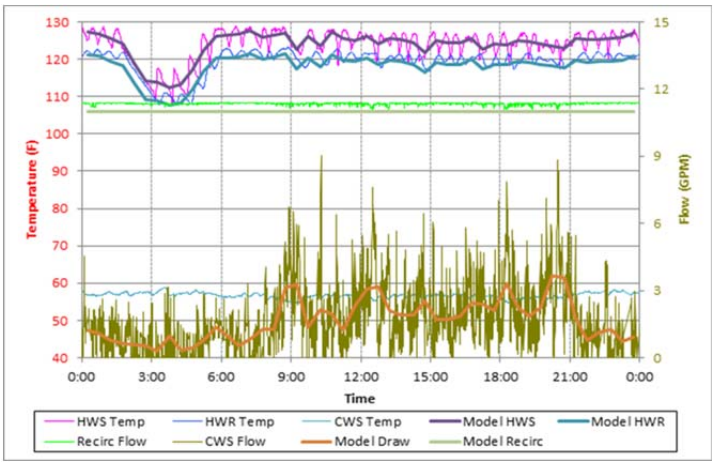



**Figure 23: Model Validation – Timer Control**

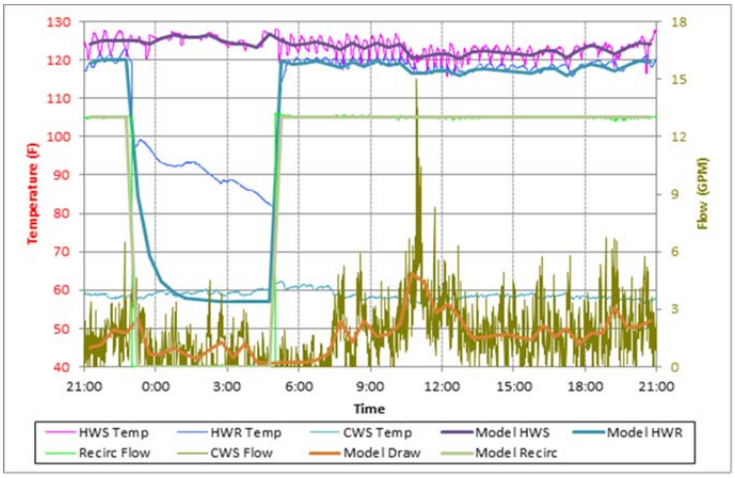
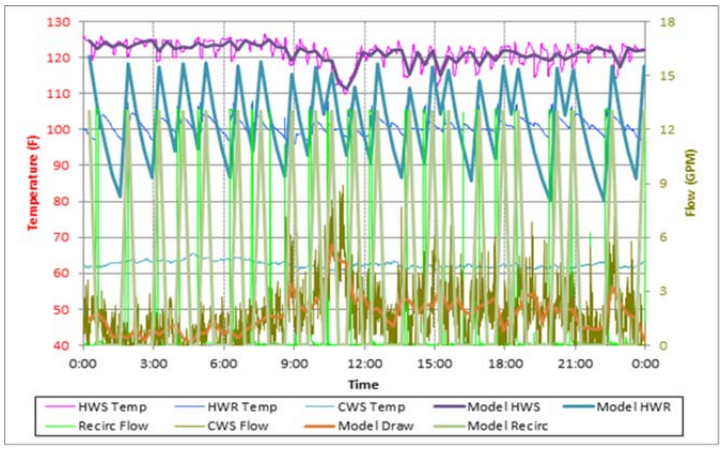



**Figure 24: Model Validation – Demand Control**



### 5.7.2 Validation of System Energy Flows

Table 14 presents the compassion between model predictions and field measurements of recirculation system pipe heat loss and overall DHW system natural gas consumptions. The maximum difference between modeled and measured values was 10.3 percent, which was for the case of demand control in the building B-SFD. For most other cases, the percentage differences between modeled and measured values were less than five percent. Considering the complexity of the recirculation system operation, the model predictions were fairly accurate.

**Table 14: Validation of Model Predictions of Recirculation System Pipe Heat Loss**

| | Measured (Btu/day) | Modeled (Btu/day) | % Difference |
|---|---|---|---|
| **A-SAM** | | | |
| Temp Modulation | 442,840 | 435,949 | -1.6% |
| Timer Control | 421,494 | 419,521 | -0.5% |
| Demand Control | Not monitored | - | - |
| **B-SFD** | | | |
| Temp Modulation | 633,433 | 616,266 | -2.7% |
| Timer Control | 600,803 | 562,822 | -6.3% |
| Demand Control | 411,903 | 453,556 | 10.1% |
| **C-SFH** | | | |
| Temp Modulation | Not monitored | - | - |
| Timer Control | 187,240 | 194,233 | 3.7% |
| Demand Control | 180,478 | 173,723 | -3.7% |
| **D-SFF** | | | |
| Temp Modulation | 204,820 | 204,057 | -0.4% |
| Timer Control | 220,452 | 228,777 | 3.8% |
| Demand Control | 178,093 | 179,729 | 0.9% |

Table 15 compares the modeled and measured DHW system natural gas consumptions under different controls for the four validation buildings. The results showed that the energy savings predicted by the models were very close to measured values. In-depth investigation revealed that changes in DHW system natural gas consumptions were dominated by changes in hot water draws. Because the measured hot water draws were used as model validation input, it is not surprising the modeled and measured energy savings were consistent. Although these comparison results did not further demonstrate model accuracy, they clearly showed that energy savings from control technologies could be easily offset by variations in hot water draws.

**Table 15: Validation of Energy Savings from Controls**

| | Measured DHW System Gas Consumption (Btu/day) | % Energy Savings | Modeled DHW System Gas Consumption (Btu/day) | % Energy Savings | Difference in Energy Savings |
|---|---|---|---|---|---|
| **A-SAM** | | | | | |
| Temp Modulation | 1,030,039 | 0.0% | 1,023,148 | -1.9% | -1.9% |
| Timer Control | 1,008,693 | -2.1% | 1,006,720 | -3.5% | -1.4% |
| Demand Control | Not monitored | - | - | - | - |
| **B-SFD** | | | | | |
| Temp Modulation | 1,958,764 | 4.4% | 1,941,597 | 3.3% | -1.1% |
| Timer Control | 1,732,428 | -7.6% | 1,694,446 | -10% | -2.4% |
| Demand Control | 1,423,628 | -24% | 1,465,281 | -22% | 2.0% |
| **C-SFH** | | | | | |
| Temp Modulation | Not monitored | - | - | - | - |
| Timer Control | 942,592 | -14% | 949,586 | -14% | 0% |
| Demand Control | 742,710 | -32% | 735,955 | -33% | -1% |
| **D-SFF** | | | | | |
| Temp Modulation | 2,564,910 | -18% | 2,564,146 | -18% | 0% |
| Timer Control | 3,443,807 | 11% | 3,452,131 | 11% | 0% |
| Demand Control | 2,784,551 | -11% | 2,786,187 | -11% | 0% |

Using the validated models, the study further analyzed the two components of recirculation pipe heat loss: recirculation flow heat loss and hot water draw heat loss in recirculation pipes. As discussed in Section0 2.2.1 on energy flow analysis, these two components correspond to the energy flow components of $\dot{Q}_{\mathrm{RecircFlow-Loss}}$ and $\dot{Q}_{\mathrm{Draw-Recirc-Loss}}$, respectively, shown in **Error! Reference source not found.**. The analysis results are shown in

Table 16. Relative changes of these two components under different controls provided another perspective to understand energy savings of control technologies.

The results showed that recirculation flow heat loss was much larger than heat loss of hot water draws, when there was no recirculation control. Temperature modulation control caused similar reduction of heat loss of both recirculation flows and hot water draw flows. The percentages of reduction were moderate. Timer controls and demand controls substantially reduced heat loss of recirculation flows, but dramatically increased the heat loss of hot water draw flows. One way to understand this effect is to consider that, when recirculation flows were stopped, heat loss by HWS pipes was all used to cool hot water draws instead of shared between hot water draws and the recirculation flow.

These results indicated the energy savings from temperature modulation controls has less dependence on hot water draws than those for timer controls and demand controls.

**Table 16: Comparison of Heat Loss of Flows in Recirculation Systems**

| | Recirculation Flow Heat Loss | | Draw Flow Heat Loss | |
|---|---|---|---|---|
| | Modeled Results (Btu/day) | % Change from no Control | Modeled Results (Btu/day) | % Change from no Control |
| **A-SAM** | | | | |
| No Control | 368,536 | - | 87,654 | - |
| Temp Modulation | 355,698 | -3.5% | 80,251 | -8.4% |
| Timer Control | 279,559 | -24% | 139,962 | 60% |
| Demand Control | Not monitored | - | - | - |
| **B-SFD** | | | | |
| No Control | 608,711 | - | 34,776 | - |
| Temp Modulation | 582,695 | -4.3% | 33,572 | -3.5% |
| Timer Control | 461,656 | -24% | 101,166 | 191% |
| Demand Control | 191,328 | -69% | 262,228 | 654% |
| **C-SFH** | | | | |
| No Control | 177,796 | - | 29,404 | - |
| Temp Modulation | Not monitored | - | - | - |
| Timer Control | 145,345 | -18% | 48,889 | 66% |
| Demand Control | 82,244 | -54% | 91,479 | 211% |
| **D-SFF** | | | | |
| No Control | 176,588 | - | 51,679 | - |
| Temp Modulation | 159,541 | -10% | 44,516 | -14% |
| Timer Control | 147,709 | -16% | 81,068 | 56.9% |
| Demand Control | 78,002 | -56% | 101,727 | 97% |

## 5.8 Energy Savings of Controls

The previous section revealed that to determine the impact of control technologies to overall DHW system gas energy consumptions, the hot water usages had to be kept the same under all test conditions. This requirement is very difficult, if not impossible, to meet in actually field studies. However, the requirement can be easily achieved in simulation efforts. Using the models created for validation, the research team simulated recirculation system operation with consistent hot water draw schedules, same as those used during continuous pumping (no control). Pump operations or HWS temperatures were varied according to the corresponding control schedules.

Table 17 shows the reduction in overall DHW system gas energy consumption achieved by different controls in four full on-site study buildings, while holding the hot water draw schedules constant. Compared to the results in Table 11, all control technologies showed positive energy savings, because the variations caused by hot water draws were eliminated.

In general, demand controls achieved the highest levels of energy savings, and there was a large variation in the levels of energy savings from different controls. Table 17 also demonstrates that

that the percentage of energy savings from controls highly depends on recirculation system pipe heat loss, which depends on recirculation system designs and building hot water usages.

**Table 17: Energy Savings from Control Technologies in Four Buildings Based on Modeling Study**

| | A-SAM | B-SFD | C-SFH | D-SFF |
|---|---|---|---|---|
| **Temp Modulation** | 2.0% | 1.4% | 0.9% | 0.5% |
| **Timer Control** | 5.4% | 3.4% | 1.8% | 0.5% |
| **Demand Control** | 14% | 6.9% | 4.5% | 1.0% |
| | | | | |
| **Recirculation System Pipe Heat Loss (No Recirculation Control)** | 42% | 34% | 18% | 7% |

# CHAPTER 6: Conclusion

The research team conducted successful field studies in 28 multi-family buildings. Full on-site studies were performed in eight (8) of these buildings to provide detailed DHW system process measurements, investigate recirculation system designs, and assess energy savings from controls. Partial on-site studies were conducted in the rest of the multi-family buildings to assess recirculation system performance and identify system failure modes in a broader range of multi-family buildings. Key observations from the field studies include:

- Recirculation flow rates are constant when the recirculation pump is turned on. They are not sensitive to variations of hot water draw flows. The observed recirculation flow rates were in the range of 2 to 17 GPM, with a median of 6 GPM.
- Hot water draws were spread out throughout the day. In general, there were no extended window periods when hot water draw flows were zero.
- Daily hot water draw per dwelling unit had large variations among monitored buildings and between different days for the same building. The average daily hot water draws per dwelling unit were between 4 and 55 Gallons/day for the 28 monitored buildings, with a median of 29 Gallons/day.
- HWR temperatures were lower than the corresponding HWS temperatures due to recirculation system pipe heat loss. The amount of temperature reduction depends on several factors, including recirculation system piping designs, pipe insulation conditions, recirculation flow rate, and hot water draw flow rates. The field measured temperature reductions were in the range of 0.2 to 18 $^{o}$F, with a median of 4.8 $^{o}$F.
- Recirculation controls were not widely used. Of more than 50 buildings surveyed by the research team, four (4) buildings had timer controls and one (1) building had temperature modulation control. None of the four timer controls was configured properly to actually achieve recirculation pump controls.

## 6.1 Performance Analysis

The study developed an energy flow analysis method to analyze field monitoring data. This method provided a clear illustration of central DHW system performance by breaking down total DHW system natural gas consumption into four components: water heating system heat loss, recirculation system heat loss, branch pipe heat loss, and delivered hot water energy. DHW system efficiency is indicated by the percentage of total DHW system natural gas consumptions accounted by the delivered hot water energy. Recirculation performance is indicated by the percentage of total DHW system natural gas consumption accounted for by the recirculation system heat loss. This quantity is also termed the recirculation system heat loss fraction.

DHW system efficiencies and recirculation system heat loss fractions for the monitored buildings showed very large variations. These large variations were due to differences in recirculation system designs, as well as the amount of hot water draws. Buildings with shorter recirculation pipes are expected to have less pipe heat loss and, therefore, a smaller recirculation heat loss fraction than those with longer recirculation pipes. Once recirculation system designs are fixed, recirculation system heat loss represents a fixed operation cost of the total DHW system operation. As DHW system natural gas consumptions increase with hot water usages, the weight of the recirculation system heat loss becomes smaller. Therefore, buildings with higher hot water usages had lower recirculation system heat loss fractions than those with low hot water usages.

The average DHW system efficiency of all the monitored buildings was 35 percent. The average recirculation system heat loss fraction of all monitored buildings was 33 percent. The remaining 32 percent of total DHW system natural gas consumption was mostly accounted by heat loss by water heating systems.

This study did not perform detailed monitoring of hot water draws at each branch and each hot water fixture. Therefore, the study was not able to quantify energy loss associated with hot water wastes at hot water fixtures (excessive water use by building occupants to displace cold hot water in the branch pipe) or in branch pipes (hot water cooling down without being used). If these two types of wastes were included, overall DHW system efficiency would be lower. However, assessment of recirculation system heat loss fraction was independent of these issues.

## 6.2 Recirculation System Piping Design

This study investigated recirculation system plumbing designs through field survey, buildings plan check, and interviews with recirculation system designers. The study found:

- There were no widely accepted design guidelines for recirculation systems in central DHW recirculation systems. Some of the design guidelines used by the industry were those for hydronic space heating systems and were not suitable for central DHW system. The study did not find any design guidelines intended for improving system efficiencies.
- Field studies observed many different types of recirculation system piping designs. In general, DHW recirculation systems were not designed to reach every dwelling unit, unless the building only had only one or two stories. Some designs tried to reach most part of the building, while others only placed recirculation pipes in one of the building stories and used long branch lines to reach dwelling units on other building stories.
- Recirculation systems could consist of one or more recirculation loops. All recirculation loops shared the same HWR pipe section connected to the hot water system, so that only one recirculation pump was used even if there were multiple recirculation loops.

## 6.3 Recirculation System Model

The research team developed a heat transfer model to predict recirculation system performance. The model was successfully validated by field monitoring data obtained from four full on-site study buildings.

The model broke each recirculation system down to a combination of interconnected pipe sections. Pipe heat loss was calculated using two basic heat transfer modes, depending on whether there was hot water flowing in the pipe. These two heat transfer modes have the following characteristics:

- With hot water flows, pipe temperature and heat loss increase slightly with hot water flow rates.
- Without hot water flows, pipe temperatures gradually declines due to pipe heat loss and pipe heat loss rate decreases accordingly. Significant pipe temperature reduction would lead to large pipe heat loss reduction, if the pipe has zero hot water flow for a long period.

In the model, heat transfer modes of pipe sections were determined by hot water draw schedules and recirculation pump operation schedules. The interconnections between pipe sections ensured temperature and flow information being passed from upstream to downstream pipe sections. The model used 48 time intervals to simulate the sequence of the daily operation of a recirculation system. Overall recirculation system performance was calculated by summing up the heat losses from all pipe sections during the 48 time intervals.

The study validated the recirculation model for four full on-site study buildings with different size and recirculation system designs. Recirculation models for these four buildings were created according to detailed piping configurations obtained from field surveys. Hot water draw schedules and control schedules obtained from the field monitoring study were used as the model inputs. The differences between measured and predicted recirculation system heat loss and DHW system natural gas consumption were all less than 7 percent. There were some discrepancies between predicted and measured values of HWR temperatures, primarily because the measured HWR temperatures represented those in mechanical rooms, but the majority of the HWR pipes were located outside of the mechanical rooms.

The validated recirculation system models provided a better assessment of energy savings from controls, because (biased) variations in system natural gas consumption introduced by other operational parameters, especially hot water draws, can be eliminated by keeping all other operational conditions constant, with and without controls. The validated model indicated that all three control technologies saved energy. Percentage reduction of DHW system natural gas consumptions was proportional to recirculation system heat loss fraction. Consistent with monitored data, the model also predicted that Demand controls have the highest energy savings.

## 6.4 Performance of Recirculation Controls

This study investigated the performance of three recirculation control technologies: timer control, temperature modulation, and demand control. Energy savings from these control technologies were measured in the eight (8) full on-site study buildings. The efforts in energy flow analysis and recirculation model development further provided in-depth understanding of energy savings mechanisms of controls.

Field measurement of energy savings from controls found:

- Percentage energy savings were calculated as percentage energy reduction in DHW system natural gas consumption from the baseline of no recirculation system controls. The average measured percentage energy savings for timer control, temperature modulation, and demand control were 4.5 percent, 3.7 percent, and 14 percent, respectively. However, measured energy savings for the controls in different buildings showed significant variations. In some buildings, negative or zero energy savings were observed. Uncertainties in field energy savings measurements were due to large variations in daily hot water usages.
- Energy savings from timer controls and temperature modulation controls depended on control schedule settings. The field studies only monitored control technology performance under one set of control schedule settings. Control schedule of demand controls were determined by building hot water usage patterns, sensitivity of the flow sensor, and location of the HWR temperature sensor.
- Field studies did not observe increases in hot water usages due to the deployment of recirculation controls. The research team did not receive any complaints when controls were activated.

Pipe heat transfer analysis revealed that pipe heat loss reduction was determined by the amount and duration of pipe temperatures reduction. The three control technologies have different mechanisms in reducing recirculation pipe temperatures:

- Temperature modulation controls reduce temperatures of the whole recirculation system. The amount of temperature reduction is almost uniform across the whole recirculation system and equals to the HWS temperature reduction set by the control.
- Both timer controls and demand controls stop recirculation flows. If there is neither hot water circulation nor hot water draw flow in a recirculation pipe, pipe temperature cools down and pipe heat loss rate is reduced. The amount of pipe temperature reduction and heat loss reduction depend on how long the pipe is allowed to cool down, which further depends on recirculation pump control schedules as well as hot water draw schedules. Temperature reduction is usually not uniform across the recirculation system, due to the existence of hot water draw flows. HWR pipes are not affected by hot water draws and, therefore, are affected mostly by recirculation pump controls.
- Timer controls have fixed control schedules to reduce pipe temperatures and demand controls have dynamic control schedules to reduce pipe temperatures.

By analyzing pipe heat transfer of each pipe section of the system under different operational and control conditions, the research team obtained the following findings of energy savings mechanisms of control technologies:

- Under temperature modulation controls, there are always hot water flows in recirculation pipes. Temperatures in all pipe sections are relatively stable, and they float with the HWS temperature set by the control. Reductions in pipe heat loss are about 25 percent during control periods, if the HWS temperature reduction by the control is 15°F and the temperature difference between recirculation pipes and the ambient is 60°F.
- Timer controls allow recirculation pipes to cool down for extended periods. However, the control has different impact to HWS and HWR pipe. All HWR pipes cool down for the full period when the recirculation pump is turned off and the reduction of pipe heat loss can be more than 50 percent. HWS pipes may have hot water draw flows, which prevent the pipe from cooling down or prolong the amount of cool down time. Heat loss reduction in HWS pipe depends on hot water draw schedules and, in general, is less than those in HWR pipes.
- Demand controls have the similar energy savings mechanisms as those of timer controls. However, demand controls turn off recirculation pump much more frequently to generate more opportunities for energy savings.

The validated recirculation system model was able to provide more accurate assessment of energy savings from controls. This is because operation conditions, except the ones directly affected by controls, could be kept the same by the simulation studies, so that changes in system natural gas consumption would be solely due to controls. Energy savings assessment through modeling studies reached the following conclusions:

- All three control technologies were able to savings energy through reduction in pipe heat loss in all buildings.
- Percentages of energy savings depended highly on a building's baseline recirculation system loss fractions. DHW systems with high recirculation loss fractions benefited more from control technologies.
- The average energy savings were 1.2 percent, 2.8 percent, and 6.6 percent for timer control, temperature modulation, and demand control, respectively, in the four full on-site study buildings used for the modeling efforts.

## 6.5 Continuous Monitoring

This study investigated benefits of continuous monitoring through field monitoring studies and analysis of continuous monitoring data provided by EDC.

The field monitoring studies provided the following observations on DHW system operation issues:

- For most DHW systems, the research team did not indicate any system malfunctions during their monitoring periods. Though some recirculation systems seemed to be less efficient than others, they were due to system designs, not operational issues.

- The research team did not observe crossover flows between cold water supply pipes and hot water return pipes. The field monitoring studies were not designed to investigate the existence of crossover flows at water fixtures.
- High CWS supply temperatures were measured in many buildings. However, they were caused by heat conduction from the connected hot water return pipes or hot water tanks, not due to crossover flows.
- One building was identified to have a constant 0.2 GPM hot water leakage. However, the issue was not able to be corrected because the location of the leakage could not be found.
- In one building, the flue damper for a water heater was never turned on because the system operator did not know the existence of the flue damper. This issue was identified by the research team during initial field survey, but not by the monitoring system.
- Four buildings were found to have timer controls, but all of them were disabled. These issues were identified by the research team during initial field survey, but not by the monitoring system.

Continuous monitoring systems implemented by EDC provided a vast amount of monitoring data, including measurements of HWS, HWR, and CWS temperatures, as well as gas relay times. In an attempt to identify DHW system failure modes, for instance recirculation pump failures, commonly happened in the field, the research team developed an Excel tool to look for abnormal measurement results from thirty buildings installed with EDC continuous monitoring systems. Although many abnormal measurement results were identified, the research team could not tell if they were due to measurement issues or system failures. EDC indicated that system operation issues could not be identified solely based on a data analysis algorithm and the research team also needed to have a good understanding of DHW system configurations to perform system diagnosis using continuous monitoring data. Since detailed system configuration information was not available to the research team, we were not able to identify system operation issues solely based on continuous monitoring data and we were therefore unable to assess potential energy savings from continuous monitoring.

## 6.6 Next Steps

While recirculation system controls can help to reduce pipe heat loss, optimizing recirculation system designs should take even higher priority as it ensures small DHW system heat loss to start with. This study, for the first time, began to investigate recirculation system designs in central DHW systems and developed a model to predict recirculation system performance based on recirculation system designs. From the overall distribution system performance point of view, there is a tradeoff between recirculation system design and branch pipe design because heat loss from the two cannot be minimized at the same time. Additional research is needed to address branch pipe performance so that overall system optimization can be achieved. Assessing the performance of these branches to the water fixture will further identify future opportunities for energy and water saving improvements.

This study provided a better understanding of energy savings mechanisms of control technologies. Further studies should be conducted to help improve existing control technologies and to demonstrate new control technologies, based on the findings from this study.

# CHAPTER 7:
# Technology Transfer

## 7.1 Central DHW System Design Guide

The study developed guidelines for central DHW system designs and improvement. They were organized and printed as a 10-page brochure and a one-page flyer with professional graphic designs. The brochure provided details information to guide mechanical system designer to design and retrofit DHW systems. The flyer was a condensed version of the brochure to convey main energy efficiency measures to developers, building owners, and operators.

## 7.2 ACEEE Hot Water Forum Presentations

The following presentations have been made on this research area:

***2008 ACEEE Hot Water Forum***

"Multifamily Central DHW Field Study for Title 24 Implementation" by Owen Howlett

Available at http://www.aceee.org/files/pdf/conferences/hwf/2008/4b_howlett.pdf

***2009 ACEEE Hot Water Forum***

- "PIER Multifamily Central Domestic Hot Water Systems - Central vs. Distributed Architectures" by Yanda Zhang

Available at http://www.aceee.org/files/pdf/conferences/hwf/2009/1B-Multifamily1-Zhang.pdf

- "PIER Multifamily Central Domestic Hot Water Systems – Recirculating System Controls", by Yanda Zhang

Available at http://www.aceee.org/files/pdf/conferences/hwf/2009/2B-Multifamily2-Zhang.pdf

***2010 ACEEE Hot Water Forum***

"Central Domestic Hot Water Systems in Multi-Family Buildings" by Charlotte Bonneville

Available at http://www.aceee.org/files/pdf/conferences/hwf/2010/3C_Charlotte_Bonneville.pdf

***2011 ACEEE Hot Water Forum***

"DHW Recirculation System Performance in Multi-Family Buildings" by Yanda Zhang

Available at http://www.aceee.org/files/pdf/conferences/hwf/2011/1C%20-%20Yanda%20Zhang.pdf.

## 7.3 2013 Title 24 Development

With additional funding provided by IOU Codes and Standards (C&S) programs, the research team conducted two Codes and Standards Enhancement (CASE) studies. The Space and Water Heating CASE study developed and proposed, along with other measures, the performance

calculation algorithms for recirculation systems in multi-family and hotel/motel buildings. The multifamily DHW CASE study developed and proposed prescriptive requirements for recirculation systems, along with solar water requirements for DHW systems, in multi-family and hotel/motel buildings. In both CASE studies, recirculation system related development was based on research findings from this study. The draft reports for these two studies are available at the Energy Commission 2013 Title 24 rulemaking home page.

http://www.energy.ca.gov/title24/2013standards/prerulemaking/documents/current/Reports/Residential/Water_Heating/2013_CASE_NR_Space_and_Water_Heating_Oct_2011.pdf

http://www.energy.ca.gov/title24/2013standards/prerulemaking/documents/current/Reports/Residential/Water_Heating/2013_CASE_R_MF_DHW_and_Solar_Water_Heating_Oct_2011.pdf

# GLOSSARY

| | |
|---|---|
| 2008 PIER | Pier Study on Multi-Family Central DHW System (HMG 2008) |
| Btu | British thermal unit |
| C&S | Codes and Standards |
| CASE | Codes and Standards Enhancement |
| CPR | Critical Project Review |
| CWS | Cold Water Supply |
| DHW | Domestic Hot Water |
| EDC | EDC Technology, Inc. |
| Energy Commission | California Energy Commission |
| GPM | Gallons Per Minute |
| HMG | Heschong Mahone Group |
| HWR | Hot Water Return |
| HWS | Hot Water Supply |
| IOU | California Investor Owned Utilities |
| PAC | Project Advisory Committee |
| PIER | Public Interest Energy Research |

# REFERENCES


Gutierrez, Jorge and Woo, Kevin 2008. EDC, Inc. Hot Water Recirculating System Study. June 1-3, 2008 – ACEEE Water Heating Conference.

Heschong Mahone Group (HMG) 2007. Codes and Standards Enhancement Initiative (CASE), Revised Report: Central Hot Water Distribution Systems in Multifamily Buildings.

Heschong Mahone Group (HMG) 2008. Water Heaters and Hot Water Distribution Systems, PIER Final Project Appendices, Appendix A, Energy Commission-500-2005-007-APA

Incropera, Frank P. and DeWitt, David P. 2002. Fundamentals of Heat and Mass Transfer, 5th Edition, ISBN 0-471-38650-2

Itron 2006. Impact Evaluation of the 2004-2005 Statewide Multifamily Boiler Control Measure.

KEMA 2008. Multifamily Boiler Controls – Process Evaluation SoCal Gas' and SDG&E's 2006-2008 Multifamily Energy Efficiency Rebate Program, CALMAC Study ID: SDG0227.01,

Lobenstein, M.S, Bohac, D.L., Staller T.J., Dunsworth T.S., and Hancock M.W. 1992. Measured Savings from Domestic Hot Water Temperature Control Strategies in Multi-family Buildings with Recirculation Loops. Report to Energy Resource Center, Legislative Committee on Minnesota Resources, Contract # 02140-03535.

Stone, Nehemiah 2008. Central Domestic Hot Water System Study. June 1-3, 2008 – ACEEE Water Heating Conference.

# APPENDIX A:
# Field Monitoring Study Buildings

Table 18 presents pictures of field monitoring study buildings and their DHW systems. Some of these pictures had been edited to remove the information that may lead to the disclosure of the identities of the buildings.

**Table 18: Pictures of Field Monitoring Study Buildings – Full On-Site Study**

| Site Index | Building | DHW System |
|---|---|---|
| A-SAM | <br> <br>Senior Housing<br>Three Conventional Tank Water Heaters | |
| **Site Index** | **Building** | **DHW System** |

| | | |
|---|---|---|
| B-SFD | <br> <br>Non-Senior Housing<br>Multiple Boilers and Storage Tank | |
| **Site Index** | **Building** | **DHW System** |

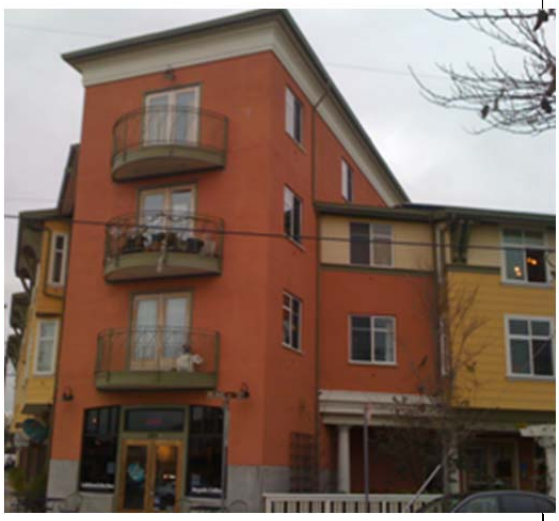
| | | |
|---|---|---|
| C-SFH | <br> <br>Senior Housing<br>Two Conventional Tank Water Heaters | |
| **Site Index** | **Building** | **DHW System** |

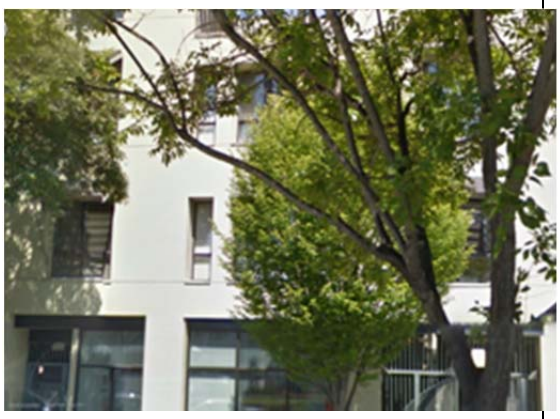
| | | |
|---|---|---|
| D-SFF | <br> <br><br>Non-Senior Housing<br>Boiler and Storage Tank | |
| **Site Index** | **Building** | **DHW System** |

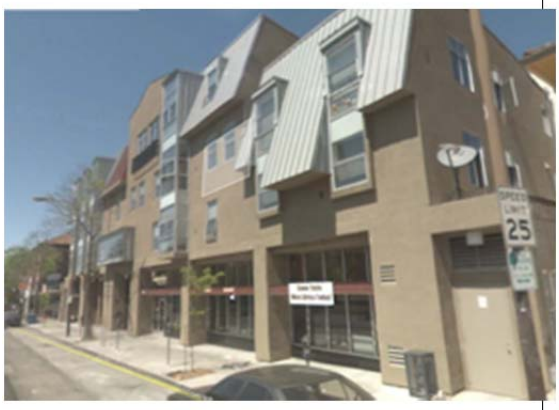
| | | |
|---|---|---|
| E-DAE | <br> <br>Non-Senior Housing<br>Boiler and Storage Tank | |
| **Site Index** | **Building** | **DHW System** |

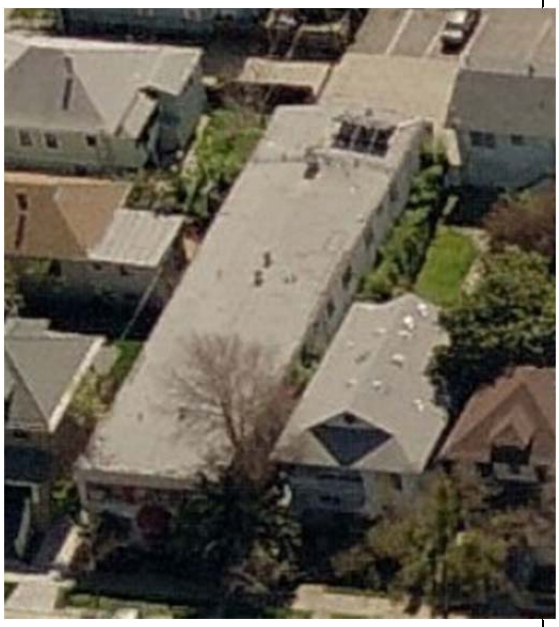
| | | |
|---|---|---|
| H-<br>LAR | <br> <br>Non-Senior Housing<br>Conventional Tank Water Heater | |

**Table 19: Pictures of Field Monitoring Study Buildings – Partial On-Site Study**

| Site Index | Building | DHW System |
|---|---|---|
| 1-SFB | <br>  <br>Non-Senior Housing<br>Two Conventional Tank Water Heaters | |

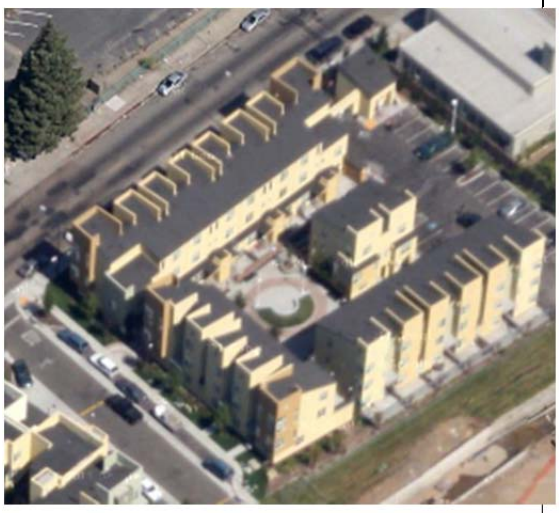
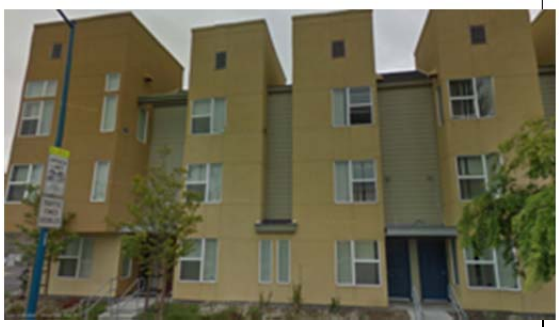
| Site Index | Building | DHW System |
|---|---|---|
| 2-BKS | <br>  <br>Senior Housing<br>Conventional Tank Water Heater<br>Multiple Boilers and Storage Tank | |

| Site Index | Building | DHW System |
|---|---|---|
| 3-BKU | <br>  <br>Non-Senior Housing<br>Two Conventional Tank Water Heaters | |

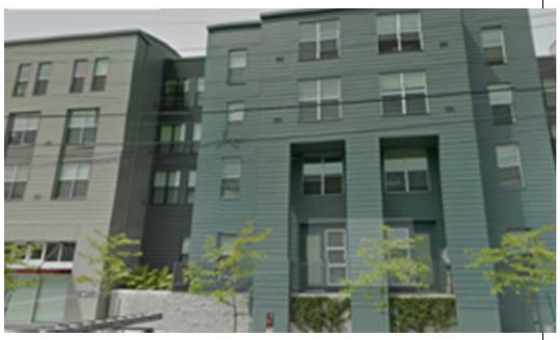
| Site Index | Building | DHW System |
|---|---|---|
| 4-SAP |  <br> <br>Non-Senior Housing<br>Two Conventional Tank Water Heaters | <br> |

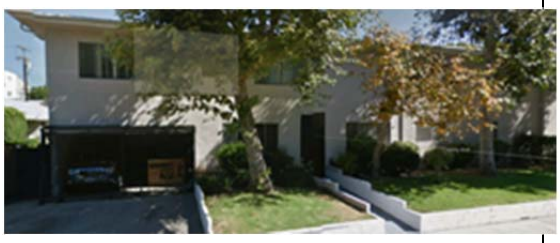
| Site Index | Building | DHW System |
|---|---|---|
| 5-SAC | <br> <br>Non-Senior Housing<br>Conventional Tank Water Heater | |

| Site Index | Building | DHW System |
|---|---|---|
| 6-DAK | <br> <br>Large Non-Senior Housing<br>Multiple Boilers and Storage Tanks | <br> |

| Site Index | Building | DHW System |
|---|---|---|
| 8-OAL |  <br>  <br>Large Non-Senior Housing<br>Multiple Boilers and Storage Tanks | |

| Site Index | Building | DHW System |
|---|---|---|
| 9-OAL | <br> <br>Non-Senior Housing<br>Condensing Water Heater | <br> |

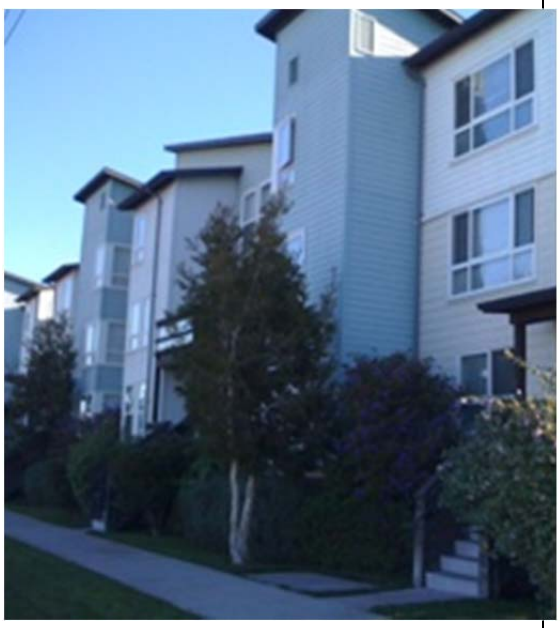
| Site Index | Building | DHW System |
|---|---|---|
| 10-SFF | <br>  <br>Non-Senior Housing<br>Boiler and Storage Tank | <br> |
| Site Index | Building | DHW System |

| | | |
|---|---|---|
| 11-HOB | <br>  <br><br>Non-Senior Housing<br>Conventional Tank Water Heater | |

| Site Index | Building | DHW System |
|---|---|---|
| 12-HOB | <br> <br>Non-Senior Housing<br>Conventional Tank Water Heater | |

| Site Index | Building | DHW System |
|---|---|---|
| 13-HOL | <br>Non-Senior Housing<br>Multiple Conventional Tank Water Heaters | <br> |

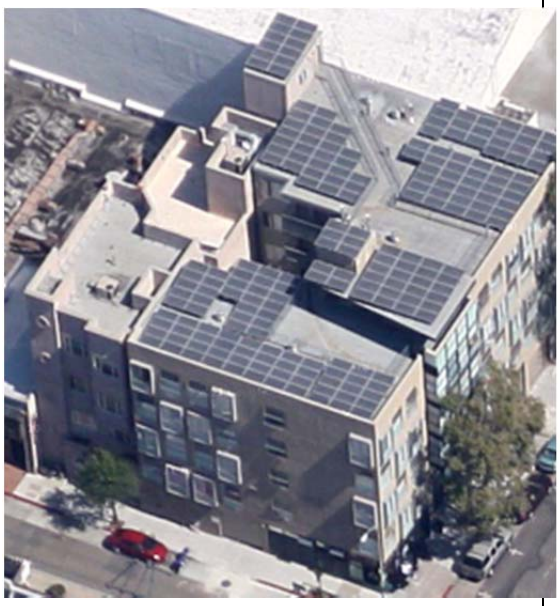
| Site Index | Building | DHW System |
|---|---|---|
| 14-HOC | <br> <br>Non-Senior Housing<br>Multiple Conventional Tank Water Heaters | |

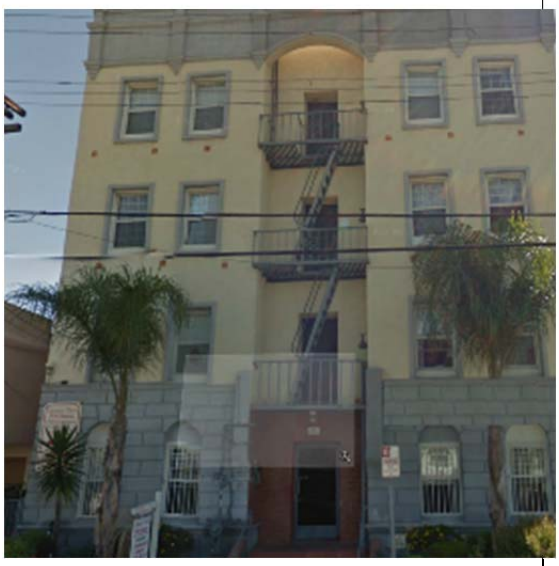
| Site Index | Building | DHW System |
|---|---|---|
| 15-HOL | <br>  <br>Non-Senior Housing<br>Multiple Boiler and Storage Tank | |

| Site Index | Building | DHW System |
|---|---|---|
| 16-DAR | <br> <br>Non-Senior Housing<br>Boiler and Storage Tank | <br> |

| Site Index | Building | DHW System |
|---|---|---|
| 17-SAP | <br> <br>Non-Senior Housing<br>Multiple Conventional Tank Water Heaters | <br> |

| Site Index | Building | DHW System |
|---|---|---|
| 18-SFP | <br> <br>Senior Housing<br>Boiler and Storage Tank | |

| Site Index | Building | DHW System |
|---|---|---|
| 19-OAO |  <br> <br>Non-Senior Housing | |

| Site Index | Building | DHW System |
|---|---|---|
| 20-LAE | <br>  <br>Non-Senior Housing<br>Multiple Boiler and Storage Tanks | |

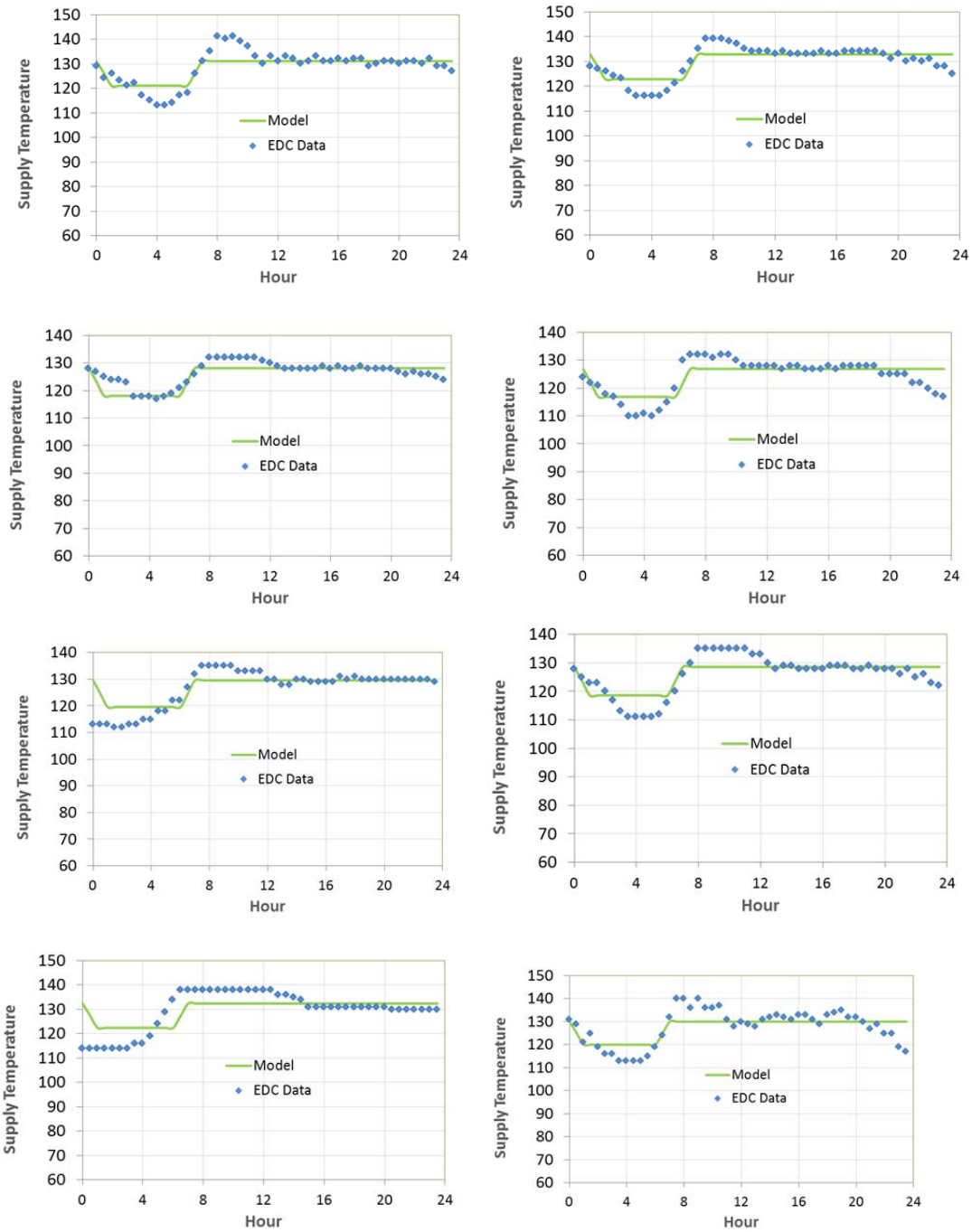
# APPENDIX B:
# Historical Monitoring Data Analysis

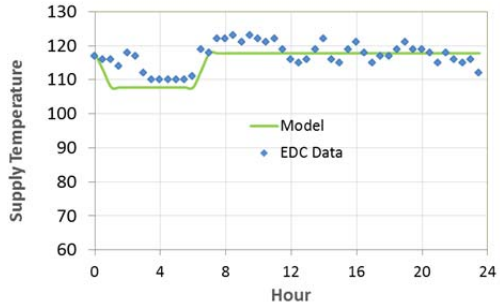
This appendix summarizes HWS temperature settings in buildings using the temperature modulation and continuous monitoring technology from EDC Technology Inc. (EDC). In general, HWS temperatures were reduced at night to save energy and were increased above daytime average temperatures early in the morning to meet the morning peak demand. EDC's continuous monitoring services aimed to help system operators to promptly identify and fix system operational issues and to avoid the use of high HWS temperatures.

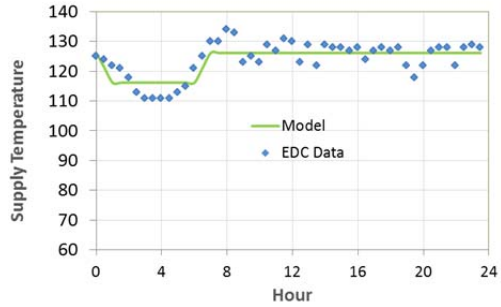
On average, HWS temperatures were reduced for 5 hours during the night, with a 1-hour transition period on both ends of the 5-hour period. Using this averaged control scheme to curve fit the measured HWS temperatures, the amounts of temperature reduction at night were obtained. **Error! Reference source not found.** presents the curve fitting results for 30 buildings using the control and monitoring technology from EDC.

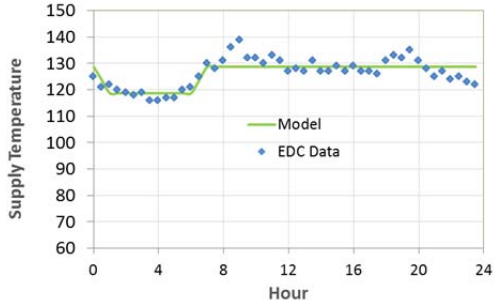
Table 20 summarizes the average HWS temperatures and HWS temperature reductions at night, presented in graphical form in Figure 25. The average daytime HWS temperature represents the HWS temperature achieved by the continuous monitoring function. The average temperature reduction at night represents the typical amount of temperature modulation.

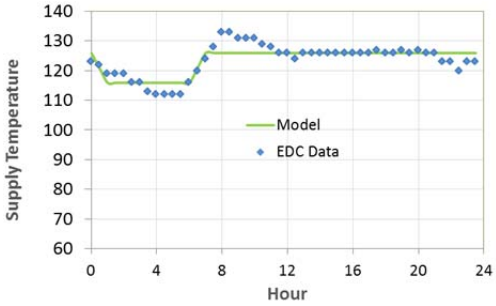
**Table 20Figure 25: HWS Temperatures under Temperature Modulation Controls and Continuous Monitoring**

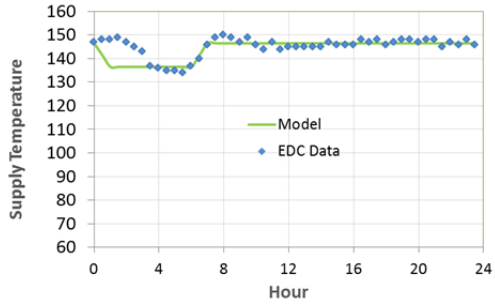


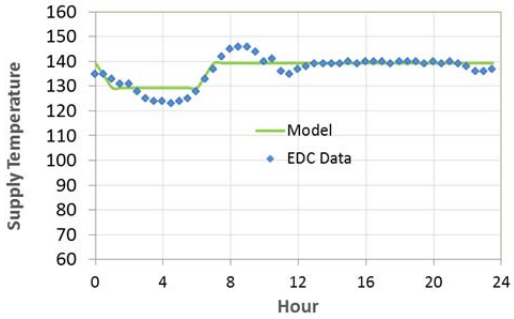

Supply Temperature
Hour
Model
EDC Data

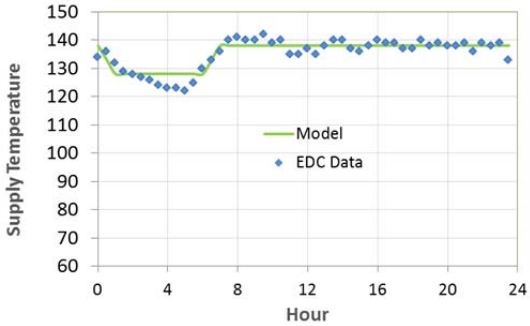

Supply Temperature
Hour
Model
EDC Data

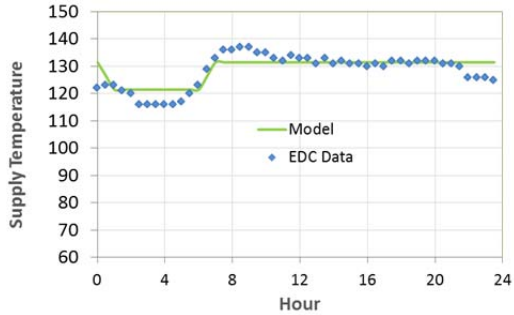

Supply Temperature
Hour
Model
EDC Data

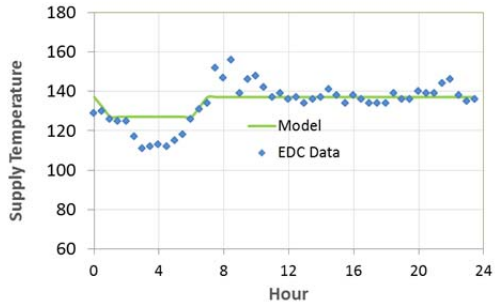

Supply Temperature
Hour
Model
EDC Data

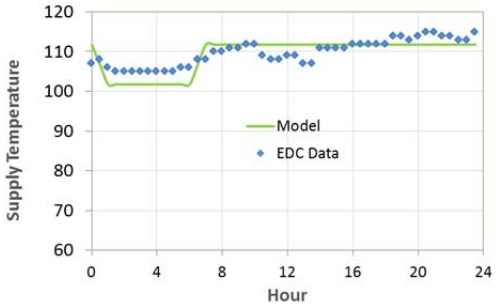

Supply Temperature
Hour
Model
EDC Data

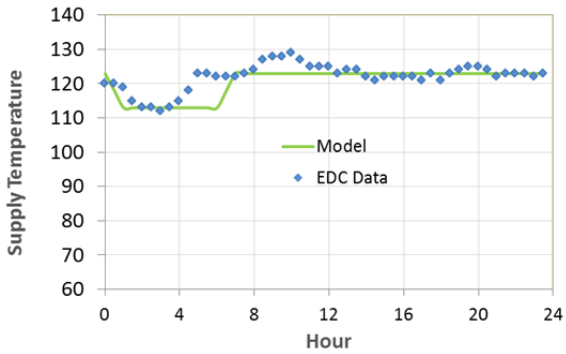

Supply Temperature
Hour
Model
EDC Data

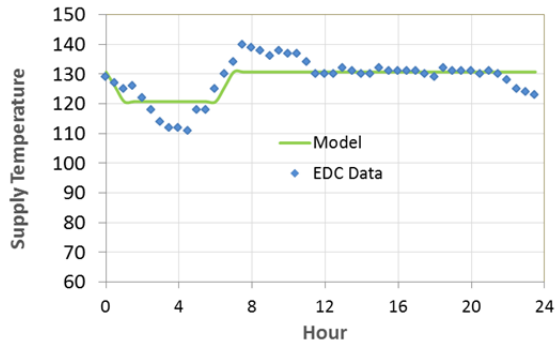

Supply Temperature
Hour
Model
EDC Data

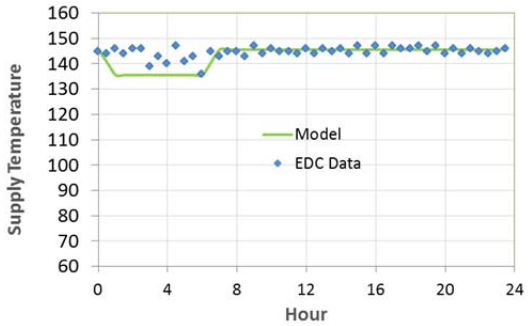

Supply Temperature
Hour
Model
EDC Data

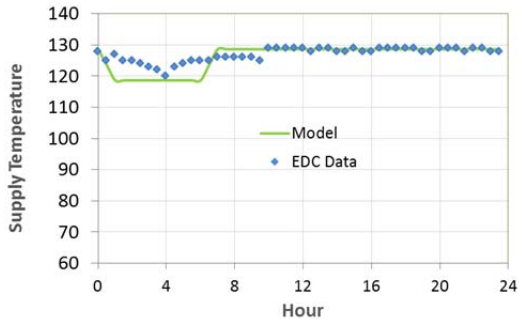

Supply Temperature
Hour
Model
EDC Data

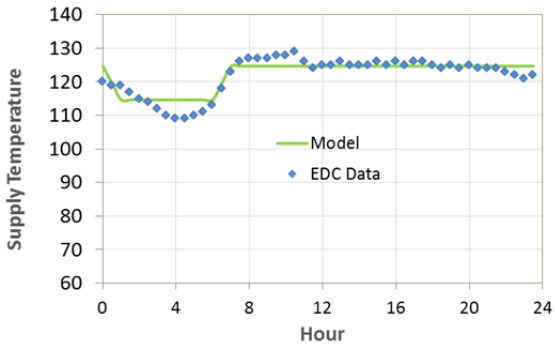

Supply Temperature
Hour
Model
EDC Data

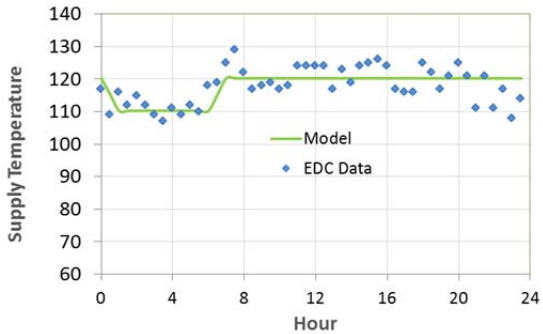

Supply Temperature
Hour
Model
EDC Data

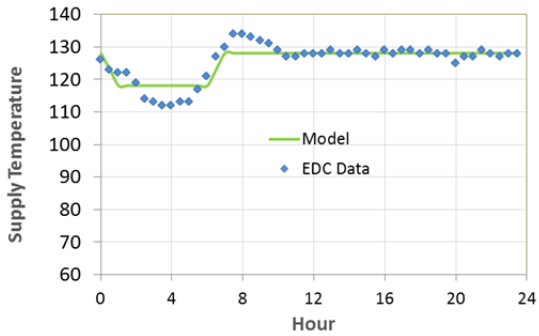

Supply Temperature
Hour
Model
EDC Data

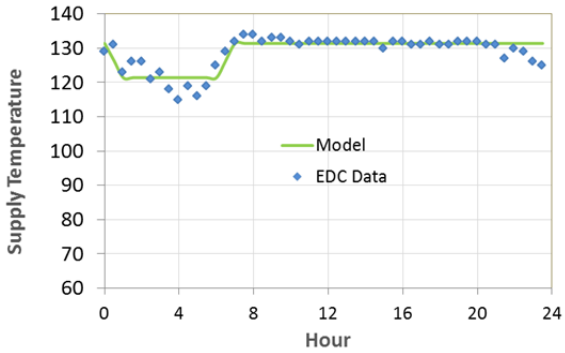

Supply Temperature
Hour
Model
EDC Data

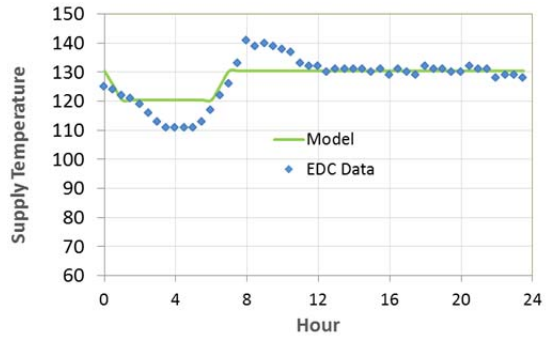

Supply Temperature
Hour
Model
EDC Data

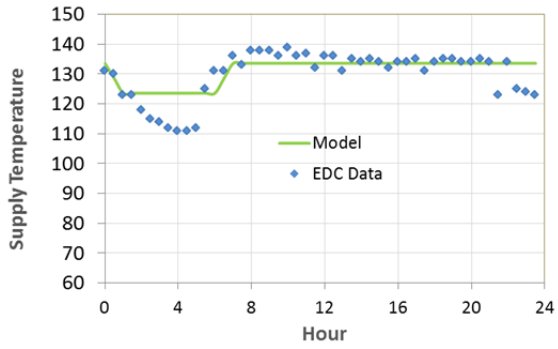

Supply Temperature
Hour
Model
EDC Data

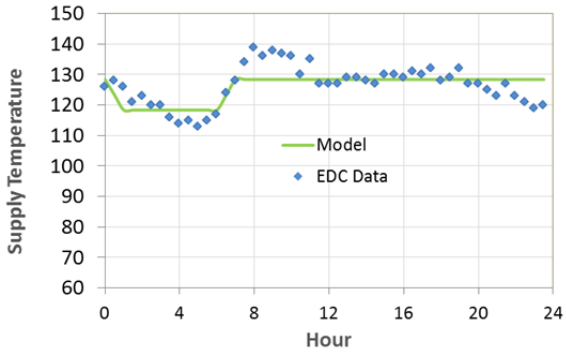

Supply Temperature
Hour
Model
EDC Data


Supply Temperature
Hour
Model
EDC Data


Supply Temperature
Hour
Model
EDC Data


Supply Temperature
Hour
Model
EDC Data


Supply Temperature
Hour
Model
EDC Data


Supply Temperature
Hour
Model
EDC Data

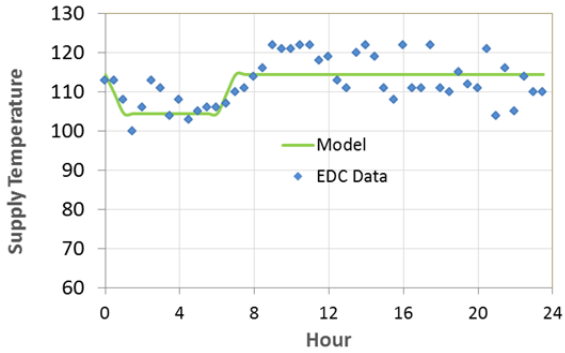

Supply Temperature
Hour
Model
EDC Data

**Table 20: Average HWS Temperature under Temperature Modulation and Continuous Monitoring**

| Site Index | Average HWS Temperature During Daytime ($^oF$) | Average HWS Temperature Reduction at Night ($^oF$) |
|---|---|---|
| 1 | 130.7 | 9.1 |
| 2 | 133.0 | 11.6 |
| 3 | 128.1 | 6.1 |
| 4 | 126.9 | 11.3 |
| 5 | 129.5 | 11.5 |
| 6 | 128.6 | 10.7 |
| 7 | 132.4 | 11.1 |
| 8 | 130.0 | 8.9 |
| 9 | 117.8 | 2.9 |
| 10 | 126.2 | 8.3 |
| 11 | 128.7 | 9.3 |
| 12 | 125.9 | 9.3 |
| 13 | 125.5 | 13.4 |
| 14 | 139.3 | 11.9 |
| 15 | 138.1 | 11.4 |
| 16 | 131.5 | 12.6 |
| 17 | 137.1 | 12.8 |
| 18 | 111.8 | 7.8 |
| 19 | 122.9 | 3.7 |
| 20 | 145.6 | 3.6 |
| 21 | 128.6 | 6.2 |
| 22 | 124.8 | 11.5 |
| 23 | 124.6 | 11.0 |
| 24 | 120.2 | 9.4 |
| 25 | 128.1 | 9.6 |
| 26 | 131.4 | 10.2 |
| 27 | 130.4 | 11.4 |
| 28 | 133.6 | 15.3 |
| 29 | 128.4 | 7.7 |
| 30 | 114.5 | 7.1 |
| **Average** | **128.4** | **9.6** |

# APPENDIX C:
# Recirculation System Model

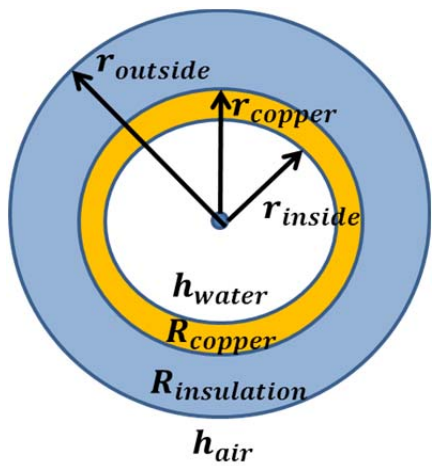
## Pipe Heat Transfer Solutions

### Pipe Heat Transfer Coefficient (UA)

The heat losses from hot water to the surrounding environment include the following four heat transfer steps, as illustrated in **Error! Reference source not found.**:

- Heat convection (or conduction with there is no flow) from hot water to the pipe
- Heat conduct through the pipe
- Heat conduction through the pipe insulation
- Heat transfer between insulation outer surface and the surrounding environment (including both convection and radiation)

**Figure 26: Illustration of Pipe Heat Transfer**




The overall pipe heat transfer coefficient per unit pipe length, $UA_L$, can be calculated by combining the heat transfer effects of all these four steps, in the following way:

$$\boldsymbol{UA_L = \frac{1}{R_{water_convection} + R_{pipe_conduction} + R_{insulation_conduction} + R_{air}}}$$

where:

$R_{water_convection} = \frac{1}{2\pi r_{inside} h_{water}}$ represents heat transfer resistance due to heat convection between hot water and pipe inside surface.

$R_{pipe_conduction} = ln(\frac{r_{copper}}{r_{inside}})\frac{1}{2\cdot\pi\cdot k_{copper}}$ represents heat transfer resistance due to heat conduction through the copper pipe wall.

$R_{insulation_conduction} = ln(\frac{r_{outside}}{r_{copper}})\frac{1}{2\cdot\pi\cdot k_{insulation}}$ represents heat transfer resistance due to heat conduction through the insulation material. For good insulation installation, the heat transfer resistance caused by the air gap between the pipe surface and pipe insulation is smaller than that of the insulation material and, therefore, is neglected.

$R_{air} = \frac{1}{2\pi r_{outside}(h_{air_convection}+h_{radiation})}$ represents heat transfer resistance due to air convection and pipe radiation to the ambient.

For insulated copper pipe, $\boldsymbol{R_{insulation_conduction}}$ is much larger than the other three heat transfer resistance in the above equation for $UA_L$. Therefore, hot water heat loss rate is determined by pipe insulation conditions and $UA_L$ can be simplified as:

$$\boldsymbol{UA_L} = \frac{\boldsymbol{2\cdot\pi\cdot k_{insulation}}}{ln(\frac{\boldsymbol{r_{outside}}}{\boldsymbol{r_{copper}}})}$$

where:

$k_{insulation}$ is thermal conductivity of the insulation material.

## Lumped Capacity Method for Pipe Cool Down

When there is no flow, hot water temperature will decline due to pipe heat loss. It can be assumed that water temperatures remand equal to pipe temperatures during the cool down process, so the thermal energy stored in hot water and copper pipe can be represented as ($Cap_L \cdot T_{avg}$). The rate of reduction of ($Cap_L \cdot T_{avg}$) equals to the rate of pipe heat loss $UA_L \cdot (T_{avg} - T_{amb})$. Since $T_{avg}$ varies with time during the cool down process, this relationship can be described with a different equation:

$$\boldsymbol{\frac{d}{dt}\left(Cap_L \cdot T_{avg}(t)\right) = UA_L \cdot \left(T_{avg}(t) - T_{amb}\right)}$$

By integrating the above equation, obtain:

$$\boldsymbol{T_{avg}(t) = \left(T_{avg}(0) - T_{amb}\right).e^{-\frac{UA_L}{Cap_L}.t} + T_{amb}}$$

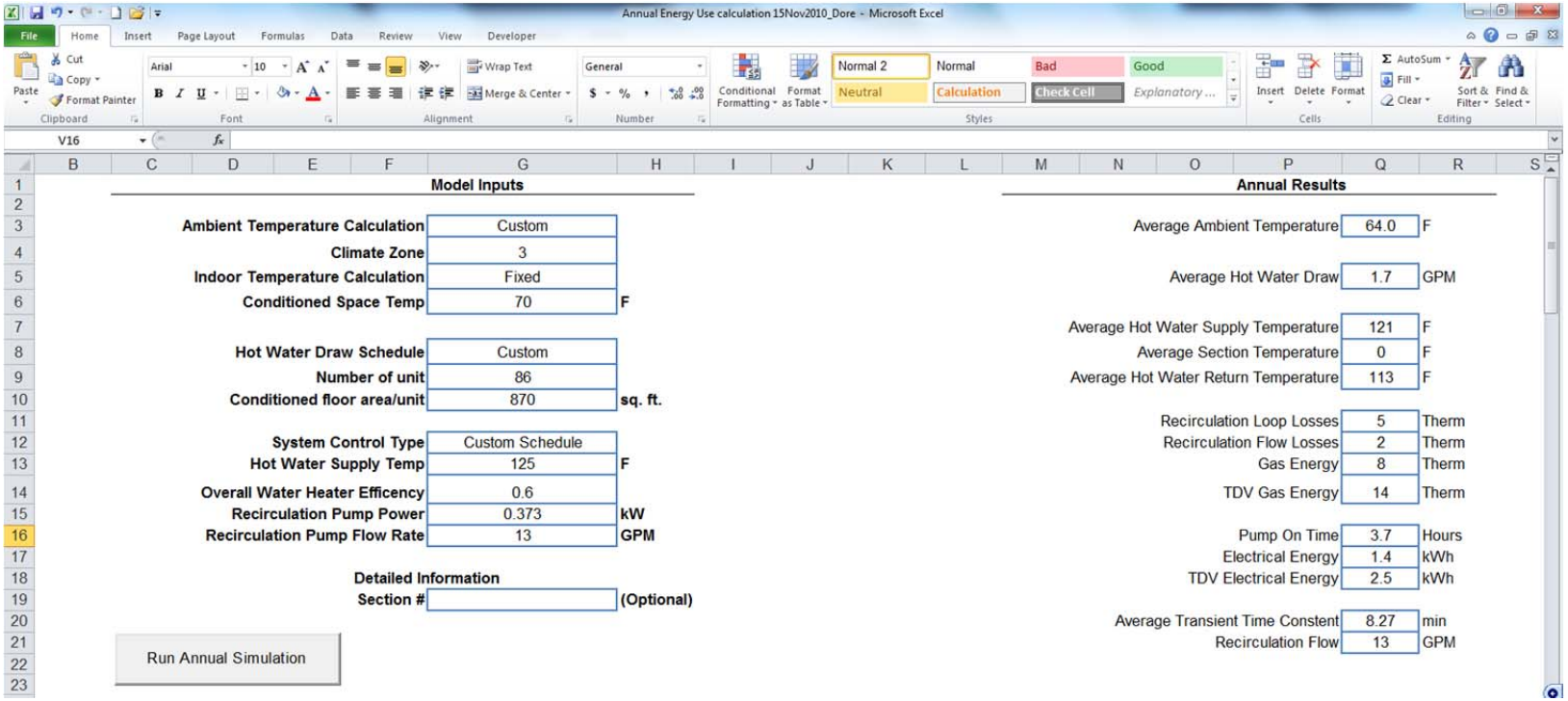
where:

$T_{avg}$ (0) is the average temperature of the pipe section at the beginning of the cool-down process;

$Cap_L$ is thermal capacity (mass × specific heat) per unit length of pipe, including thermal capacity of both water and pipe.

# Excel Model Screenshots

## Overall Setting and Output Summary



**Model Inputs**

| | | |
|---|---|---|
| Ambient Temperature Calculation | Custom | |
| Climate Zone | 3 | |
| Indoor Temperature Calculation | Fixed | |
| Conditioned Space Temp | 70 | F |
| Hot Water Draw Schedule | Custom | |
| Number of unit | 86 | |
| Conditioned floor area/unit | 870 | sq. ft. |
| System Control Type | Custom Schedule | |
| Hot Water Supply Temp | 125 | F |
| Overall Water Heater Efficency | 0.6 | |
| Recirculation Pump Power | 0.373 | kW |
| Recirculation Pump Flow Rate | 13 | GPM |
| Detailed Information | | |
| Section # | | (Optional) |

Run Annual Simulation

**Annual Results**

| | | |
|---|---|---|
| Average Ambient Temperature | 64.0 | F |
| Average Hot Water Draw | 1.7 | GPM |
| Average Hot Water Supply Temperature | 121 | F |
| Average Section Temperature | 0 | F |
| Average Hot Water Return Temperature | 113 | F |
| Recirculation Loop Losses | 5 | Therm |
| Recirculation Flow Losses | 2 | Therm |
| Gas Energy | 8 | Therm |
| TDV Gas Energy | 14 | Therm |
| Pump On Time | 3.7 | Hours |
| Electrical Energy | 1.4 | kWh |
| TDV Electrical Energy | 2.5 | kWh |
| Average Transient Time Constent | 8.27 | min |
| Recirculation Flow | 13 | GPM |

## Settings of Controls

| HVAC | | | Custom Inputs Draw | | Control Inputs | | |
|---|---|---|---|---|---|---|---|
| Step index | Conditioned Space Temp | Measured HWR Temp (F) | HW Draw (GPM) | Ambient Temperature (F) | Time Interval (Min) | HWS Temp (F) | Pump On/Off |
| 1 | 70 | 100.0 | 1.59 | 57.8 | 10 | 125.2 | On |
| 2 | 70 | 100.7 | 1.60 | 57.5 | 45 | 123.6 | Off |
| 3 | 70 | 100.2 | 0.54 | 57.3 | 45 | 123.3 | Off |
| 4 | 70 | 98.4 | 0.54 | 57.2 | 10 | 124.2 | On |
| 5 | 70 | 101.5 | 0.64 | 57.0 | 70 | 123.9 | Off |
| 6 | 70 | 100.8 | 0.60 | 56.8 | 10 | 123.4 | On |
| 7 | 70 | 101.4 | 0.91 | 56.7 | 50 | 122.7 | Off |
| 8 | 70 | 104.0 | 0.80 | 56.4 | 10 | 123.9 | On |
| 9 | 70 | 101.8 | 0.30 | 56.1 | 50 | 123.2 | Off |
| 10 | 70 | 102.7 | 0.92 | 55.6 | 10 | 121.4 | On |
| 11 | 70 | 101.0 | 0.87 | 55.3 | 70 | 124.0 | Off |
| 12 | 70 | 102.1 | 0.24 | 55.1 | 10 | 120.0 | On |
| 13 | 70 | 101.6 | 0.87 | 54.9 | 50 | 124.3 | Off |
| 14 | 70 | 103.7 | 1.37 | 54.9 | 10 | 123.5 | On |
| 15 | 70 | 101.4 | 1.56 | 55.1 | 35 | 124.0 | Off |
| 16 | 70 | 99.3 | 1.63 | 54.6 | 35 | 123.0 | Off |
| 17 | 70 | 97.4 | 3.26 | 53.9 | 10 | 120.4 | On |
| 18 | 70 | 97.8 | 2.29 | 54.7 | 50 | 121.4 | Off |
| 19 | 70 | 103.3 | 1.37 | 56.2 | 10 | 121.6 | On |
| 20 | 70 | 101.2 | 3.13 | 58.0 | 30 | 120.0 | Off |
| 21 | 70 | 101.6 | 4.77 | 60.1 | 10 | 121.1 | On |
| 22 | 70 | 99.8 | 4.99 | 63.6 | 50 | 113.2 | Off |
| 23 | 70 | 103.1 | 2.57 | 65.9 | 10 | 114.2 | On |
| 24 | 70 | 99.2 | 2.33 | 68.6 | 50 | 120.2 | Off |
| 25 | 70 | 102.1 | 2.19 | 71.1 | 10 | 122.8 | On |
| 26 | 70 | 101.3 | 1.75 | 73.5 | 70 | 121.7 | Off |
| 27 | 70 | 102.4 | 3.61 | 73.6 | 10 | 114.8 | On |
| 28 | 70 | 100.9 | 1.87 | 75.4 | 50 | 118.9 | Off |
| 29 | 70 | 102.1 | 1.05 | 77.2 | 10 | 121.2 | On |
| 30 | 70 | 100.7 | 3.26 | 79.0 | 30 | 117.4 | Off |
| 31 | 70 | 102.2 | 1.90 | 79.3 | 10 | 118.9 | On |
| 32 | 70 | 100.7 | 2.07 | 76.9 | 70 | 120.6 | Off |
| 33 | 70 | 101.0 | 2.89 | 77.1 | 10 | 118.3 | On |
| 34 | 70 | 100.5 | 2.27 | 75.3 | 50 | 119.7 | Off |
| 35 | 70 | 102.4 | 0.94 | 73.6 | 10 | 121.1 | On |
| 36 | 70 | 101.4 | 1.31 | 72.4 | 30 | 122.1 | Off |
| 37 | 70 | 102.7 | 0.99 | 71.1 | 10 | 121.6 | On |
| 38 | 70 | 102.3 | 2.84 | 69.2 | 45 | 121.1 | Off |
| 39 | 70 | 100.5 | 1.93 | 67.7 | 45 | 119.0 | Off |
| 40 | 70 | 101.5 | 0.93 | 67.5 | 10 | 120.0 | On |
| 41 | 70 | 102.5 | 2.30 | 66.9 | 30 | 120.5 | Off |
| 42 | 70 | 101.9 | 2.04 | 66.1 | 10 | 122.7 | On |
| 43 | 70 | 103.1 | 1.14 | 65.6 | 45 | 121.1 | Off |
| 44 | 70 | 99.9 | 0.95 | 65.0 | 45 | 122.2 | Off |
| 45 | 70 | 102.3 | 2.34 | 65.0 | 10 | 121.9 | On |
| 46 | 70 | 101.1 | 2.17 | 64.1 | 70 | 120.8 | Off |
| 47 | 70 | 97.4 | 0.59 | 63.1 | 10 | 122.1 | On |
| 48 | 70 | 97.0 | 0.02 | 62.8 | 10 | 122.1 | Off |

Default Control Schedules

| Temperature Modulation | | | | Timer Control | | | | Demand Control | | | | No Control | | | | Temperature Modulation + Monitoring | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Step index | Time Interval (Min) | HWS Temp | Pump On/Off | Step index | Time Interval (Min) | HWS Temp | Pump On/Off | Step index | Time Interval (Min) | HWS Temp | Pump On/Off | Step index | Time Interval (Min) | HWS Temp | Pump On/Off | Step index | Time Interval (Min) | HWS Temp | Pump On/Off |
| 1 | 30 | 110 | On | 1 | 30 | 125 | Off | 1 | 10 | 125 | On | 1 | 30 | 125 | On | 1 | 30 | 115 | On |
| 2 | 30 | 110 | On | 2 | 30 | 125 | Off | 2 | 50 | 125 | Off | 2 | 30 | 125 | On | 2 | 30 | 115 | On |
| 3 | 30 | 110 | On | 3 | 30 | 125 | Off | 3 | 10 | 125 | On | 3 | 30 | 125 | On | 3 | 30 | 115 | On |
| 4 | 30 | 110 | On | 4 | 30 | 125 | Off | 4 | 50 | 125 | Off | 4 | 30 | 125 | On | 4 | 30 | 115 | On |
| 5 | 30 | 110 | On | 5 | 30 | 125 | Off | 5 | 10 | 125 | On | 5 | 30 | 125 | On | 5 | 30 | 115 | On |
| 6 | 30 | 110 | On | 6 | 30 | 125 | Off | 6 | 50 | 125 | Off | 6 | 30 | 125 | On | 6 | 30 | 115 | On |
| 7 | 30 | 110 | On | 7 | 30 | 125 | Off | 7 | 10 | 125 | On | 7 | 30 | 125 | On | 7 | 30 | 115 | On |
| 8 | 30 | 110 | On | 8 | 30 | 125 | Off | 8 | 50 | 125 | Off | 8 | 30 | 125 | On | 8 | 30 | 115 | On |
| 9 | 30 | 110 | On | 9 | 30 | 125 | Off | 9 | 10 | 125 | On | 9 | 30 | 125 | On | 9 | 30 | 115 | On |
| 10 | 30 | 117.5 | On | 10 | 30 | 125 | Off | 10 | 50 | 125 | Off | 10 | 30 | 125 | On | 10 | 30 | 120 | On |
| 11 | 30 | 125 | On | 11 | 30 | 125 | On | 11 | 10 | 125 | On | 11 | 30 | 125 | On | 11 | 30 | 125 | On |
| 12 | 30 | 125 | On | 12 | 30 | 125 | On | 12 | 50 | 125 | Off | 12 | 30 | 125 | On | 12 | 30 | 125 | On |
| 13 | 30 | 125 | On | 13 | 30 | 125 | On | 13 | 10 | 125 | On | 13 | 30 | 125 | On | 13 | 30 | 125 | On |
| 14 | 30 | 125 | On | 14 | 30 | 125 | On | 14 | 50 | 125 | Off | 14 | 30 | 125 | On | 14 | 30 | 125 | On |
| 15 | 30 | 125 | On | 15 | 30 | 125 | On | 15 | 10 | 125 | On | 15 | 30 | 125 | On | 15 | 30 | 125 | On |
| 16 | 30 | 125 | On | 16 | 30 | 125 | On | 16 | 50 | 125 | Off | 16 | 30 | 125 | On | 16 | 30 | 125 | On |
| 17 | 30 | 125 | On | 17 | 30 | 125 | On | 17 | 10 | 125 | On | 17 | 30 | 125 | On | 17 | 30 | 125 | On |
| 18 | 30 | 125 | On | 18 | 30 | 125 | On | 18 | 50 | 125 | Off | 18 | 30 | 125 | On | 18 | 30 | 125 | On |
| 19 | 30 | 125 | On | 19 | 30 | 125 | On | 19 | 10 | 125 | On | 19 | 30 | 125 | On | 19 | 30 | 125 | On |
| 20 | 30 | 125 | On | 20 | 30 | 125 | On | 20 | 50 | 125 | Off | 20 | 30 | 125 | On | 20 | 30 | 125 | On |
| 21 | 30 | 125 | On | 21 | 30 | 125 | On | 21 | 10 | 125 | On | 21 | 30 | 125 | On | 21 | 30 | 125 | On |
| 22 | 30 | 125 | On | 22 | 30 | 125 | On | 22 | 50 | 125 | Off | 22 | 30 | 125 | On | 22 | 30 | 125 | On |
| 23 | 30 | 125 | On | 23 | 30 | 125 | On | 23 | 10 | 125 | On | 23 | 30 | 125 | On | 23 | 30 | 125 | On |
| 24 | 30 | 125 | On | 24 | 30 | 125 | On | 24 | 50 | 125 | Off | 24 | 30 | 125 | On | 24 | 30 | 125 | On |
| 25 | 30 | 125 | On | 25 | 30 | 125 | On | 25 | 10 | 125 | On | 25 | 30 | 125 | On | 25 | 30 | 125 | On |
| 26 | 30 | 125 | On | 26 | 30 | 125 | On | 26 | 50 | 125 | Off | 26 | 30 | 125 | On | 26 | 30 | 125 | On |
| 27 | 30 | 125 | On | 27 | 30 | 125 | On | 27 | 10 | 125 | On | 27 | 30 | 125 | On | 27 | 30 | 125 | On |
| 28 | 30 | 125 | On | 28 | 30 | 125 | On | 28 | 50 | 125 | Off | 28 | 30 | 125 | On | 28 | 30 | 125 | On |
| 29 | 30 | 125 | On | 29 | 30 | 125 | On | 29 | 10 | 125 | On | 29 | 30 | 125 | On | 29 | 30 | 125 | On |
| 30 | 30 | 125 | On | 30 | 30 | 125 | On | 30 | 50 | 125 | Off | 30 | 30 | 125 | On | 30 | 30 | 125 | On |
| 31 | 30 | 125 | On | 31 | 30 | 125 | On | 31 | 10 | 125 | On | 31 | 30 | 125 | On | 31 | 30 | 125 | On |
| 32 | 30 | 125 | On | 32 | 30 | 125 | On | 32 | 50 | 125 | Off | 32 | 30 | 125 | On | 32 | 30 | 125 | On |
| 33 | 30 | 125 | On | 33 | 30 | 125 | On | 33 | 10 | 125 | On | 33 | 30 | 125 | On | 33 | 30 | 125 | On |
| 34 | 30 | 125 | On | 34 | 30 | 125 | On | 34 | 50 | 125 | Off | 34 | 30 | 125 | On | 34 | 30 | 125 | On |
| 35 | 30 | 125 | On | 35 | 30 | 125 | On | 35 | 10 | 125 | On | 35 | 30 | 125 | On | 35 | 30 | 125 | On |
| 36 | 30 | 125 | On | 36 | 30 | 125 | On | 36 | 50 | 125 | Off | 36 | 30 | 125 | On | 36 | 30 | 125 | On |
| 37 | 30 | 125 | On | 37 | 30 | 125 | On | 37 | 10 | 125 | On | 37 | 30 | 125 | On | 37 | 30 | 125 | On |
| 38 | 30 | 125 | On | 38 | 30 | 125 | On | 38 | 50 | 125 | Off | 38 | 30 | 125 | On | 38 | 30 | 125 | On |
| 39 | 30 | 125 | On | 39 | 30 | 125 | On | 39 | 10 | 125 | On | 39 | 30 | 125 | On | 39 | 30 | 125 | On |
| 40 | 30 | 125 | On | 40 | 30 | 125 | On | 40 | 50 | 125 | Off | 40 | 30 | 125 | On | 40 | 30 | 125 | On |
| 41 | 30 | 125 | On | 41 | 30 | 125 | On | 41 | 10 | 125 | On | 41 | 30 | 125 | On | 41 | 30 | 125 | On |
| 42 | 30 | 125 | On | 42 | 30 | 125 | On | 42 | 50 | 125 | Off | 42 | 30 | 125 | On | 42 | 30 | 125 | On |
| 43 | 30 | 125 | On | 43 | 30 | 125 | On | 43 | 10 | 125 | On | 43 | 30 | 125 | On | 43 | 30 | 125 | On |
| 44 | 30 | 125 | On | 44 | 30 | 125 | On | 44 | 50 | 125 | Off | 44 | 30 | 125 | On | 44 | 30 | 125 | On |
| 45 | 30 | 125 | On | 45 | 30 | 125 | On | 45 | 10 | 125 | On | 45 | 30 | 125 | On | 45 | 30 | 125 | On |
| 46 | 30 | 125 | On | 46 | 30 | 125 | On | 46 | 50 | 125 | Off | 46 | 30 | 125 | On | 46 | 30 | 125 | On |
| 47 | 30 | 117.5 | On | 47 | 30 | 125 | Off | 47 | 10 | 125 | On | 47 | 30 | 125 | On | 47 | 30 | 120 | On |
| 48 | 30 | 110 | On | 48 | 30 | 125 | Off | 48 | 50 | 125 | Off | 48 | 30 | 125 | On | 48 | 30 | 115 | On |

## Model Pipe Section Configuration

| F | G | H | I | J | K | L | M | N | O | P | Q | R | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Loop Characteristics** | | | | | | | | | | | | | |
| **Number of Node** | 12 | | | | | | | | | | | | |
| **Number of Section** | 13 | | | | | | | | | | | | |
| **Effective Area Correction** | 2.77 | | | | | | | | | | | | |
| **Section Name** | First | B1-1 | B1-1 | B1-1 | B1-1 | B1-1 | B1-1 | B1-1 | B1-1 | B1-1 | B1-1 | B2-2 | Return |
| **Section #** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| **Beginning Node** | 1 | 2 | 3 | 4 | 5 | 4 | 6 | 7 | 2 | 8 | 9 | 10 | 11 |
| **End Node** | 2 | 3 | 4 | 5 | 7 | 6 | 7 | 10 | 8 | 9 | 10 | 11 | 12 |
| **Copper Pipe** | | | | | | | | | | | | | |
| Pipe Diameter (in) | 3 | 2 | 2 | 1.5 | 0.75 | 1.5 | 0.75 | 1 | 2.5 | 2.5 | 0.85 | 1.25 | 1.25 |
| Length (ft) | 20.63 | 95.9 | 22.7 | 49.18 | 84.49 | 76.73 | 53.79 | 89.6 | 103.42 | 147.53 | 139.12 | 19.25 | 97.1 |
| Pipe type (Supply/Return) | S | S | S | S | R | S | R | R | S | S | R | R | R |
| **mCp (Btu/ft/F)** | 184.5 | 395.6 | 93.6 | 118.3 | 58.4 | 184.6 | 37.2 | 102.9 | 652.0 | 930.2 | 119.7 | 33.1 | 167.0 |
| **UA/mCp** | 0.06 | 0.11 | 0.11 | 0.16 | 0.42 | 0.16 | 0.42 | 0.28 | 0.08 | 0.08 | 0.35 | 0.21 | 0.21 |
| **UAL/rCp** | 0.03 | 0.10 | 0.02 | 0.04 | 0.05 | 0.07 | 0.03 | 0.06 | 0.13 | 0.18 | 0.09 | 0.02 | 0.08 |
| **Insulation** | | | | | | | | | | | | | |
| Thickness | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Insulation conductivity | 0.271 | 0.271 | 0.271 | 0.271 | 0.271 | 0.271 | 0.271 | 0.271 | 0.271 | 0.271 | 0.271 | 0.271 | 0.271 |
| UA-model steady state | 0.254 | 0.191 | 0.191 | 0.159 | 0.109 | 0.159 | 0.109 | 0.126 | 0.223 | 0.223 | 0.116 | 0.143 | 0.143 |
| UA-model cool down | 0.200 | 0.163 | 0.163 | 0.142 | 0.104 | 0.142 | 0.104 | 0.117 | 0.183 | 0.183 | 0.109 | 0.130 | 0.130 |
| **Ambient** | Boiler | Garage | Inside | Inside | Inside | Inside | Inside | Inside | Garage | Inside | Inside | Inside | Garage |
| Ambient Temp (F) | P | O | S | P | P | P | P | P | O | S | P | S | O |
| | **Section #** | | | | | | | | | | | | |
| **Node #** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 4 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 1 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 1 | 1 | 1 | 0.5 | 0.5 | 0.5 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| 9 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| 10 | 1 | 0.5 | 0.5 | 0.25 | 0.25 | 0.25 | 0.25 | 0.5 | 0.5 | 0.5 | 0.5 | 0 | 0 |
| 11 | 1 | 0.5 | 0.5 | 0.25 | 0.25 | 0.25 | 0.25 | 0.5 | 0.5 | 0.5 | 0.5 | 1 | 0 |
| 12 | 1 | 0.5 | 0.5 | 0.25 | 0.25 | 0.25 | 0.25 | 0.5 | 0.5 | 0.5 | 0.5 | 1 | 1 |

## Model Calculation Steps

| 41 | Step Index | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 80 | 1 | Ambient Temp | 70 | 57.75 | 66.9375 | 70 | 70 | 70 | 70 | 70 | 57.75 | 66.9375 | 70 | 66.9375 | 57.75 | Total |
| 81 | | Recirculation Flow (GPM) | 13 | | | | | | | | | | | | | |
| 82 | | Input Temp (F) | 125.1800003 | | | | | | | | | | | | | |
| 83 | | Flow (GPM) | 14.58614998 | 7.406371415 | 7.179778561 | 3.476592854 | 3.25 | 3.4765929 | 3.25 | 6.5 | 6.953186 | 6.726592854 | 6.5 | 13 | 13 | |
| 84 | | Recirculation Flow (GPM) | 13 | 6.5 | 6.5 | 3.25 | 3.25 | 3.25 | 3.25 | 6.5 | 6.5 | 6.5 | 6.5 | 13 | 13 | |
| 85 | | UAL/ρ¥Cp | 0.00 | 0.01 | 0.00 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | 0.02 | 0.03 | 0.01 | 0.00 | 0.01 | |
| 86 | | T_in (F) | 125.1800003 | 125.069256 | 124.1431078 | 123.9499324 | 123.2743424 | 123.94993 | 122.8995895 | 122.401259 | 125.0693 | 123.8330944 | 122.299267 | 121.7353001 | 121.6704582 | |
| 87 | | T_out (F) | 125.1 | 124.1 | 123.9 | 123.3 | 122.4 | 122.9 | 122.4 | 121.9 | 123.8 | 122.3 | 121.6 | 121.7 | 121.3 | **3.9** |
| 88 | | Q_loss (Btu/hr) | 133 | 566 | 114 | 194 | 225 | 301 | 143 | 273 | 710 | 852 | 387 | 70 | 408 | **4376** |
| 89 | | Q_Loss_Recirc (Btu/hr) | 119 | 497 | 104 | 181 | 225 | 282 | 143 | 273 | 663 | 823 | 387 | 70 | 408 | **4175** |
| 90 | | Cool-down/partial cool down | | | | | | | | | | | | | | |
| 91 | | Flow (GPM) | 1.59 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 92 | | UAL/¥Cp | 0.02 | na | na | na | na | na | na | na | na | na | na | na | na | |
| 93 | | T_in begin (F) | 125.18 | 125.06 | 124.00 | 123.79 | 123.07 | 123.79 | 122.67 | 122.19 | 125.06 | 123.73 | 122.15 | 121.56 | 121.49 | |
| 94 | | T_out begin (F) | 125.06 | 124.00 | 123.79 | 123.07 | 122.23 | 122.67 | 122.14 | 121.68 | 123.73 | 122.15 | 121.43 | 121.49 | 121.11 | |
| 95 | | T_in end (F) | 125.2 | 123.8 | 123.0 | 122.3 | 119.5 | 122.3 | 119.1 | 119.8 | 124.2 | 123.0 | 119.2 | 119.7 | 119.3 | |
| 96 | | T_out end (F) | 124.2 | 122.8 | 122.8 | 121.6 | 118.7 | 121.3 | 118.7 | 119.3 | 122.9 | 121.4 | 118.5 | 119.6 | 118.9 | **6.2** |
| 97 | | Q_loss (Btu) | 132 | 479 | 97 | 170 | 206 | 264 | 130 | 246 | 578 | 692 | 352 | 62 | 364 | **3772** |
| 98 | | Q_loss recirculation (Btu) | 0 | 0 | 0 | 0 | 206 | 0 | 130 | 246 | 0 | 0 | 352 | 62 | 364 | **1360** |
| 99 | | Flow (GPM) | 1.586149976 | 1.057433318 | 0.528716659 | 0 | 0 | 0 | 0 | 0 | 0.528717 | 0 | 0 | 0 | 0 | |
| 100 | | UAL/¥Cp | 0.02 | 0.10 | 0.05 | na | na | na | na | na | 0.24 | na | na | na | na | |
| 101 | | T_in end (F) | 125.2 | 124.2 | 118.0 | 122.3 | 119.5 | 122.3 | 119.1 | 119.8 | 124.2 | 123.0 | 119.2 | 119.7 | 119.3 | |
| 102 | | T_out end (F) | 124.2 | 118.0 | 115.7 | 121.6 | 118.7 | 121.3 | 118.7 | 119.3 | 109.8 | 121.4 | 118.5 | 119.6 | 118.9 | **6.2** |
| 103 | | Q_loss (Btu) | 132 | 536 | 100 | 170 | 206 | 264 | 130 | 246 | 627 | 692 | 352 | 62 | 364 | **3882** |
| 104 | | Q_loss recirculation (Btu) | 0 | 0 | 0 | 0 | 206 | 0 | 130 | 246 | 0 | 0 | 352 | 62 | 364 | **1360** |
| 105 | | Flow (GPM) | 1.586149976 | 1.057433318 | 1.057433318 | 0.528716659 | 0 | 0.5287167 | 0 | 0 | 0.528717 | 0.528716659 | 0 | 0 | 0 | |
| 106 | | UAL/¥Cp | 0.02 | 0.10 | 0.02 | 0.08 | na | 0.13 | na | na | 0.24 | 0.35 | na | na | na | |
| 107 | | T_in end (F) | 125.2 | 124.2 | 118.0 | 116.9 | 119.5 | 116.9 | 119.1 | 119.8 | 124.2 | 109.8 | 119.2 | 119.7 | 119.3 | |
| 108 | | T_out end (F) | 124.2 | 118.0 | 116.9 | 113.1 | 118.7 | 111.2 | 118.7 | 119.3 | 109.8 | 97.2 | 118.5 | 119.6 | 118.9 | **6.2** |
| 109 | | Q_loss (Btu) | 132 | 536 | 101 | 163 | 206 | 248 | 130 | 246 | 627 | 549 | 352 | 62 | 364 | **3717** |
| 110 | | Q_loss recirculation (Btu) | 0 | 0 | 0 | 0 | 206 | 0 | 130 | 246 | 0 | 0 | 352 | 62 | 364 | **1360** |
| 111 | | T_in end (F) | 125.2 | 124.1 | 119.7 | 120.5 | 119.5 | 120.5 | 119.1 | 119.8 | 124.2 | 118.6 | 119.2 | 119.7 | 119.3 | |
| 112 | | T_out end (F) | 124.2 | 119.6 | 118.5 | 118.8 | 118.7 | 117.9 | 118.7 | 119.3 | 114.2 | 113.3 | 118.5 | 119.6 | 118.9 | |
| 113 | | Q_loss (Btu) | 132.2 | 517.0 | 99.3 | 167.4 | 205.7 | 258.6 | 130.3 | 246.2 | 610.5 | 644.7 | 352.2 | 62.0 | 364.0 | **3790** |
| 114 | | Q_loss recirculation (Btu) | 0.0 | 0.0 | 0.0 | 0.0 | 205.7 | 0.0 | 130.3 | 246.2 | 0.0 | 0.0 | 352.2 | 62.0 | 364.0 | **1360** |
| 115 | | Section Temp | 125.1 | 124.6 | 124.0 | 123.6 | 122.9 | 123.4 | 122.6 | 122.1 | 124.5 | 123.1 | 121.9 | 121.7 | 121.5 | |
| 116 | | | | | | | | | | | | | | | | |
| 117 | | | | | | | | | | | | | | | | |
| 118 | 2 | Ambient Temp | 70 | 57.54 | 66.885 | 70 | 70 | 70 | 70 | 70 | 57.54 | 66.885 | 70 | 66.885 | 57.54 | Total |
| 119 | | Recirculation Flow (GPM) | 13 | | | | | | | | | | | | | |
| 120 | | Input Temp (F) | 123.5833335 | | | | | | | | | | | | | |
| 121 | | Flow (GPM) | 14.59793333 | 7.41310476 | 7.18482857 | 3.47827619 | 3.25 | 3.4782762 | 3.25 | 6.5 | 6.956552 | 6.72827619 | 6.5 | 13 | 13 | |
| 122 | | Recirculation Flow (GPM) | 13 | 6.5 | 6.5 | 3.25 | 3.25 | 3.25 | 3.25 | 6.5 | 6.5 | 6.5 | 6.5 | 13 | 13 | |
| 123 | | UAL/ρ¥Cp | 0.00 | 0.01 | 0.00 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | 0.02 | 0.03 | 0.01 | 0.00 | 0.01 | |
| 124 | | T_in (F) | 123.5833335 | 123.4758803 | 122.5695823 | 122.3816751 | 121.7260391 | 122.38168 | 121.3623531 | 120.878417 | 123.4759 | 122.2657018 | 120.7730823 | 120.2287018 | 120.1655805 | |
| 125 | | T_out (F) | 123.5 | 122.6 | 122.4 | 121.7 | 120.9 | 121.4 | 120.8 | 120.4 | 122.3 | 120.8 | 120.1 | 120.2 | 119.8 | **3.8** |
| 126 | | Q_loss (Btu/hr) | 583 | 2496 | 501 | 847 | 984 | 1317 | 624 | 1191 | 3127 | 3730 | 1692 | 305 | 1801 | **19198** |
| 127 | | Q_Loss_Recirc (Btu/hr) | 519 | 2188 | 454 | 792 | 984 | 1231 | 624 | 1191 | 2922 | 3604 | 1692 | 305 | 1801 | **18305** |
| 128 | | Cool-down/partial cool down | | | | | | | | | | | | | | |
| 129 | | Flow (GPM) | 1.597933329 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | |
| 130 | | UAL/¥Cp | 0.02 | na | na | na | na | na | na | na | na | na | na | na | na | |
| 131 | | T_in begin (F) | 125.18 | 125.07 | 124.14 | 123.95 | 123.27 | 123.95 | 122.90 | 122.40 | 125.07 | 123.83 | 122.30 | 121.74 | 121.67 | |
| 132 | | T_out begin (F) | 125.07 | 124.14 | 123.95 | 123.27 | 122.44 | 122.90 | 122.37 | 121.89 | 123.83 | 122.30 | 121.58 | 121.67 | 121.29 | |
| 133 | | T_in end (F) | 123.6 | 119.7 | 119.6 | 117.7 | 109.0 | 117.7 | 108.7 | 112.4 | 121.1 | 120.5 | 110.2 | 113.8 | 112.3 | |
| 134 | | T_out end (F) | 122.6 | 118.9 | 119.4 | 117.1 | 108.4 | 116.8 | 108.4 | 112.0 | 120.0 | 119.1 | 109.6 | 113.7 | 112.0 | **11.6** |
| 135 | | Q_loss (Btu) | 578 | 2096 | 423 | 731 | 826 | 1137 | 524 | 1026 | 2549 | 3054 | 1439 | 264 | 1552 | **16199** |
| 136 | | Q_loss recirculation (Btu) | 0 | 0 | 0 | 0 | 826 | 0 | 524 | 1026 | 0 | 0 | 1439 | 264 | 1552 | **5630** |
| 137 | | Flow (GPM) | 1.597933329 | 1.065288886 | 0.532644443 | 0 | 0 | 0 | 0 | 0 | 0.532644 | 0 | 0 | 0 | 0 | |
| 138 | | UAL/¥Cp | 0.02 | 0.10 | 0.05 | na | na | na | na | na | 0.24 | na | na | na | na | |
| 139 | | T_in end (F) | 123.6 | 122.6 | 116.6 | 117.7 | 109.0 | 117.7 | 108.7 | 112.4 | 122.6 | 120.5 | 110.2 | 113.8 | 112.3 | |
| 140 | | T_out end (F) | 122.6 | 116.6 | 114.4 | 117.1 | 108.4 | 116.8 | 108.4 | 112.0 | 108.6 | 119.1 | 109.6 | 113.7 | 112.0 | **11.6** |
| 141 | | Q_loss (Btu) | 578 | 2364 | 439 | 731 | 826 | 1137 | 524 | 1026 | 2767 | 3054 | 1439 | 264 | 1552 | **16700** |
| 142 | | Q_loss recirculation (Btu) | 0 | 0 | 0 | 0 | 826 | 0 | 524 | 1026 | 0 | 0 | 1439 | 264 | 1552 | **5630** |

Dashboard | Output | Calculator | UA calculation | Outside weather file