Energy Research and Development Division
FINAL PROJECT REPORT

PILOT PHASE OF A FIELD STUDY TO DETERMINE WASTE OF WATER AND ENERGY IN RESIDENTIAL HOT WATER DISTRIBUTION SYSTEMS

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PREFACE

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Pilot Phase of Field Study to Determine Waste of Water and Energy in Residential Hot Water Distribution Systems is the final report for the Pilot Phase of Field Study to Determine Waste of Water and Energy in Residential Hot Water Distribution Systems project (contract number 500-06-036R) conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Buildings End-Use Energy Efficiency Program.

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ABSTRACT

A pilot study was conducted to determine the feasibility of directly measuring the waste of water and energy caused by current hot water distribution systems in California residences using wireless sensor network technologies. The project's tasks were to test and evaluate the proposed hardware, installation protocols, data collection and processing procedures. The techniques developed in this project provided a way to accurately measure temperature and flow of indoor water use events at one second resolution. The technologies used in this pilot phase study were also viable for use in a large field study to determine the energy and water efficiency of hot water distribution systems in California homes. The lessons learned from the experience will improve procedures, programming and wireless sensor network specifications.

Keywords: hot water distribution system, hot water end uses, water heating, wireless sensor network, water efficiency

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EXECUTIVE SUMMARY

Introduction

California's energy and water resources are both at a premium and the state's economic and environmental vitality depend on the efficient use of these resources. Heating water is one of the most energy-consumptive activities in a household, accounting for about 40 percent of California residential natural gas consumption. Water heating system designs often require users to run the water for a time before it achieves the desired temperature, wasting water in the process.

Project Purpose

The purpose of this project was to conduct a pilot study to determine the feasibility of directly measuring the waste of water and energy caused by current hot water distribution systems in California residences using wireless sensor network technologies. Researchers sought to gain experience with the field measurement process and collect actual data to understand the automated collection and processing protocol necessary to measure the waste of water and energy caused by current residential hot water distribution systems

Project Results

Monitoring was successfully completed on three houses for a total of 22 days. A wireless sensor network was developed to measure flow and temperature of water at the trunk (water heater) and twigs (individual end-use points) of a residential hot water distribution system (HWDS). Data were collected at one-second intervals while hot water was flowing. The monitored HWDS points were the inlet and outlet of the water heater and several hot water end-uses in single-family residences. The collected data were minimally processed on site and sent to a central server by cell modem for further processing. The one second interval field data were analyzed and aggregated into summary data about individual hot water draws.

All measurements were taken at points that were capable of being isolated by shutoff valves, such as sink faucets and clothes washers. This strategy allowed relatively simple installation. The appropriate shutoff valve was closed, the downstream plumbing was disconnected, the flow meter and thermistor mountings were installed and the plumbing was reconnected. Similar flow and temperature monitoring equipment was applied to the gas line supplying the water heater to measure energy use by the water heater.

The temperature and flow of water was measured into and out of the water heater and at the clothes washer, dishwasher, showerhead, and kitchen sink faucet. The temperature and flow of gas to the water heater was also measured.

Using wireless sensor network technology was clearly feasible for measuring water and gas flows and temperatures and will provide useful data for understanding the waste of energy and water in residential HWDS based on the results of this pilot phase study. The techniques developed in this project will provide a way to accurately measure temperature and flow at indoor water use events at one second resolution. The technologies used in this pilot phase study were also viable for use in a large field study to determine the energy and water efficiency of hot and cold water distribution systems in California homes.

The research team recommended proceeding with a field study to determine energy and water efficiency of residential hot and cold water distribution systems in California. They also recommended using the lessons learned from the experience in this pilot phase study to improve procedures, programming and wireless sensor network specifications.

Project Benefits

Detailed information about the energy and water efficiency of residential hot water distribution systems will allow the development of improved technologies, plumbing techniques, and building codes to reduce the waste caused by current construction practices. This could result in reduced energy use and increased water availability for homes and businesses in California.

CHAPTER 1: Introduction

The purpose of this project was to conduct a pilot study to determine the feasibility of directly measuring the waste of water and energy caused by current hot water distribution systems (HWDS) in California residences. The project's tasks were to test and evaluate the proposed hardware, installation protocols, data collection, and processing procedures.

This project sought to gain experience with the field aspects of the measurement process and collect actual data to understand the automated data collection and processing protocol necessary to directly measure the waste of water and energy caused by current residential hot water distribution systems. Activities included review and shakedown of the audit protocols, field tests, equipment installation, and limited monitoring of HWDS at four houses. The data collection period for each house measured in the pilot phase was much shorter than it will be in the field study phase; as few as five days per house. Results were generated, but were not relevant by themselves. The four houses used in the pilot study were those of volunteers from Lawrence Berkeley National Laboratory (LBNL). The importance of the pilot phase was to ensure that the entire process would work correctly.

This task started as a project funded by the California Department of Water Resources (DWR) with resources authorized by Proposition 50 Water Use Efficiency Grants.

1.1 Approach

A wireless sensor network was developed to measure flow and temperature of water at the trunk (water heater) and twigs (individual end-use points) of a residential HWDS. Data were collected at one-second intervals while hot water was flowing. The points in the HWDS that were monitored were the inlet and outlet of the water heater and several hot water end-uses in single-family residences. The collected data were minimally processed on site and sent to a central server by cell modem for further processing. At LBNL, the one second interval field data were analyzed and aggregated into summary data about individual hot water draws.

All measurements were taken at points that are capable of being isolated by shutoff valves, such as sink faucets and clothes washers. This strategy allowed relatively simple installation. The appropriate shutoff valve was closed, the downstream plumbing was disconnected, the flow meter and thermistor mountings were installed, and the plumbing was reconnected. Similar flow and temperature monitoring equipment was applied to the gas line supplying the water heater to measure energy use by the water heater.

The temperature and flow of water was measured into and out of the water heater and at the clothes washer, dishwasher, showerhead, and kitchen sink faucet. The temperature and flow of gas to the water heater was also measured. Figure 1 shows the points at which temperatures and flows were measured.

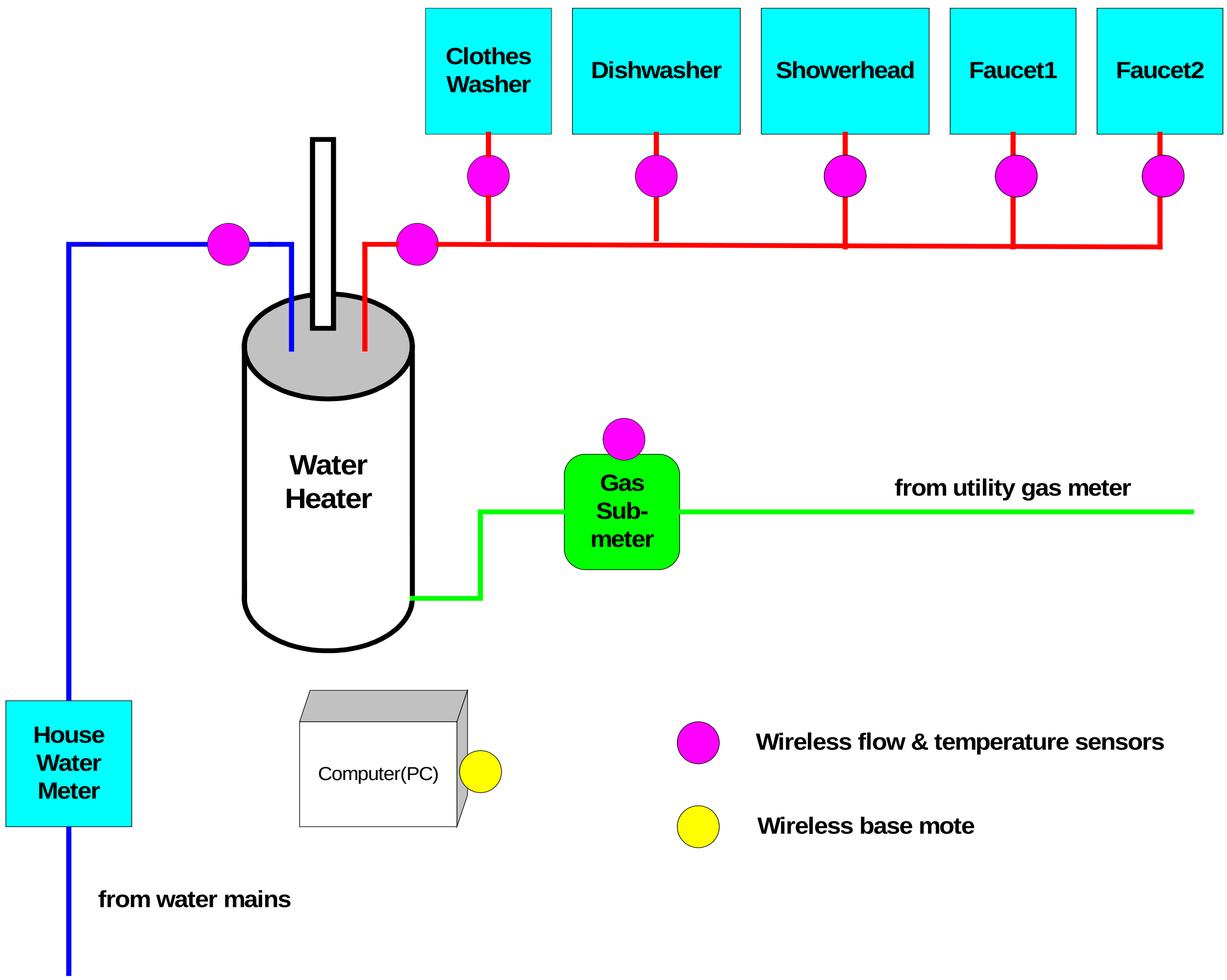

Figure 1: Measurement points

1.2 Monitoring Equipment

Water flow was measured with an inline turbine meter. The flow meter is manufactured for use in tankless water heaters.[1] The flow meter is small enough to be installed without trouble in most locations. See Figure 2 for a photograph of one of the flow meters.

The standard pickup for that flow meter is a Hall sensor, which detects a magnetic pulse each revolution from a magnet mounted on the turbine blades.[2] Another type of pickup, a Wiegand sensor was available from the manufacture.[3] Unlike a Hall sensor, this type of sensor does not need external power. The Wiegand sensor pickoff worked well with the equipment used in this

[1] Sika turbine flow sensor for potable water, series VTY 10 K5-30

[2] The Hall effect produces a voltage difference transverse to an electric current in a conductor in a magnetic field perpendicular to the current. That voltage signals a change of magnetic field.

[3] A Wiegand sensor is a coil near a specially processed wire subjected to a changing magnetic field. The magnetic polarity of the wire rapidly shifts and generates a strong, short electrical pulse in the coil.

study. No modifications to the data acquisition software or hardware were necessary to use the Wiegand sensor. Since energy management is an issue for the wireless sensor network, the Wiegand sensors were used to conserve energy and extend battery lifetime.

Figure 2: Flow meter

The output of the flow meters is rated at 515 pulses per liter (1950 pulses per gallon) at flow rates above 2 liter/minute (0.5 GPM). Since many of residential hot water flows at end uses are below that level, the flow meters were calibrated in the laboratory. Below about 0.5 liter/minute (0.13 GPM) the flow meter does not register any flow. Figure 3 is a sample calibration curve for one of the flow meters.

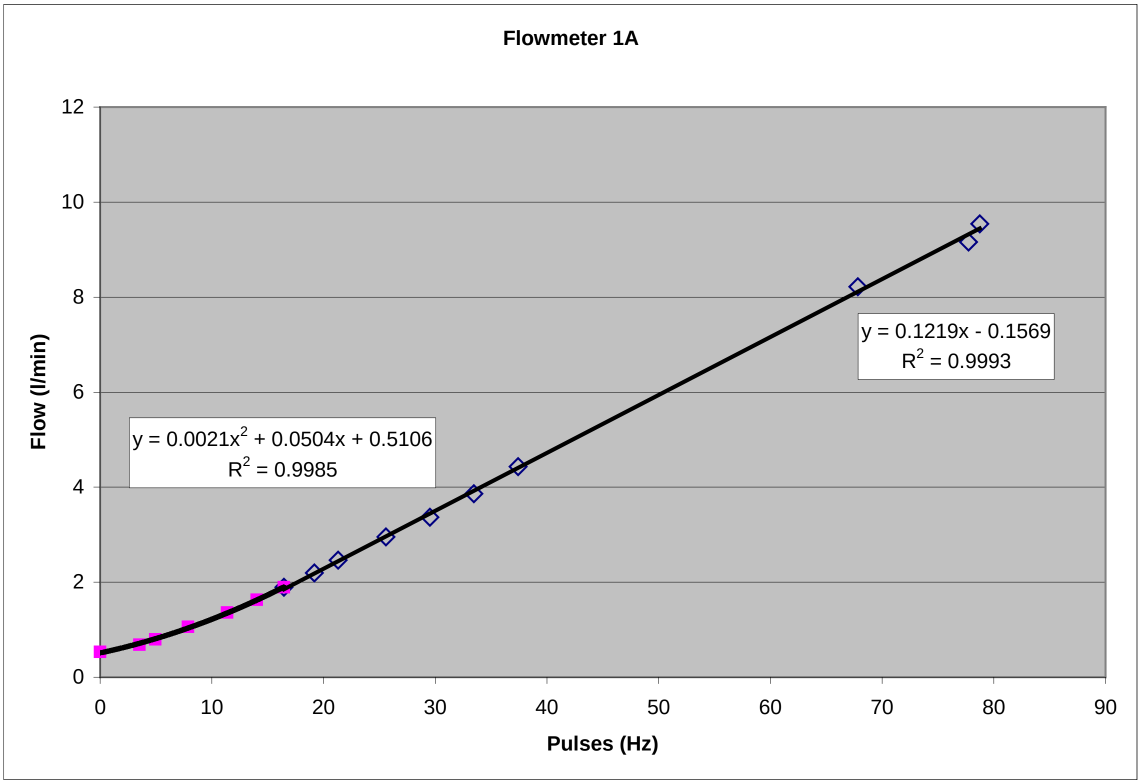

Figure 3: Calibration curve for flow meter 1A

Temperature was measured with a thermistor probe inserted into the water flow. Thermistors are ceramic semiconductors whose resistance drops nonlinearly as temperatures rise. The thermistors used for this project were model number QTLCB-14C3 from Quality Thermistors Inc. They are rated at 10,000 ohm (Ω) resistance at 25°C.

For this project, temperature was determined by measuring the resistance of the thermistor and applying the following equation:

$$\frac{1}{T} = a + b\ln(R_{therm}) + c\left(\ln(R_{therm})\right)^2 + d\left(\ln(R_{therm})\right)^3$$

where;

T = temperature (kelvins),

a = 0.001116401465500,

b = 0.000237982973213,

c = -0.000000372283234,

d = 0.000000099063233, and

R_{therm} = resistance of thermistor (Ohms).

Figure 4 shows the relation of temperature to resistance.

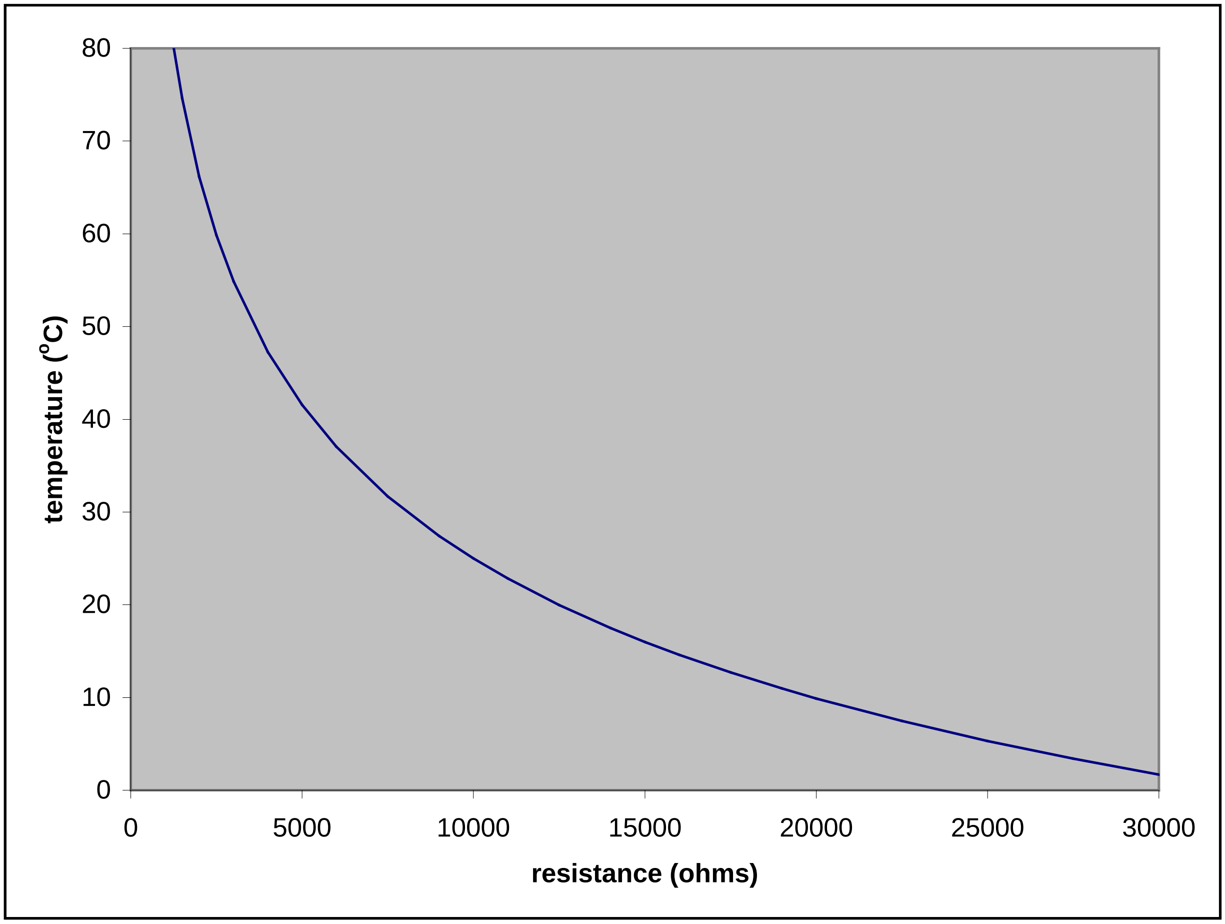

Figure 4: Temperature as a function of resistance for thermistors

Because of the potentially higher flow rates at the water heater, a different flow meter was used at that location. All hot water flows go through the water heater. This raises the possibility of higher flows due to coincident uses of hot water at different end use points. During concurrent hot water draws at different end uses, the flow of water at the water heater will be the sum of these flows.

Omega model FTB4705 flow meters were used at the inlet and outlet at the water heater. These flow meters are a rotor design with a single jet. They have a rated range of 0.8 to 38 liters per minute (0.3 to 10 GPM). An example of the installation of the Omega flow meters is shown in Figure 5.

The output of Omega flow meters is a square-wave pulsed voltage, at 87.2 pulses per liter (330 pulses per gallon). Since the output of these flow meters was in pulses, the same data acquisition system was used to read the output of these meters.

Figure 5: Flow meters at water heater

An auxiliary gas meter was installed on the gas line to the water heater to record gas use by just the water heater. An American Meter Dry Test Meter was used as the auxiliary gas meter.[4] A magnetic pulse generator attached to the gas meter generated 17.7 pulses per liter (500 pulses per cu.ft.) .[5] Gas consumption during gas draw events was recorded at one-second intervals. The pilot light to ignite the main burner of water heaters burns continuously. The gas use by the pilot light was recorded as single pulses at approximately 20-second intervals.

Figure 6 shows the auxiliary gas meter with pulse generator attached.

In addition to collecting pulses from the gas flow meter the temperature of the surface of the gas pipe was also monitored. This temperature can be used as a reasonable proxy for the ambient air temperature near the water heater. Ambient air temperature is not expected to change very rapidly. This would be sufficient to get a good record of the ambient temperature.

[4] American Meter Company, Model DTM-200A Non T.C., Serial# 06H865002, Calibration date: 7/11/2007

[5] IMAC Systems, Domestic Meter Pulser, 500 pulses per revolution.

Figure 6: Auxiliary gas meter with pulse generator attached

1.3 Wireless Data Acquisition System

The data acquired by the sensors was read and transmitted to a local on-site computer by a wireless sensor network. The individual units of the wireless sensor network are called motes. The motes did minimal data processing and sent the data to a base mote at an on-site dedicated computer. More processing of the data was done at the on-site computer. The data was sent via cell modem to a server at LBNL once a day. A schematic of the data collection and transmission scheme is shown in Figure 7.

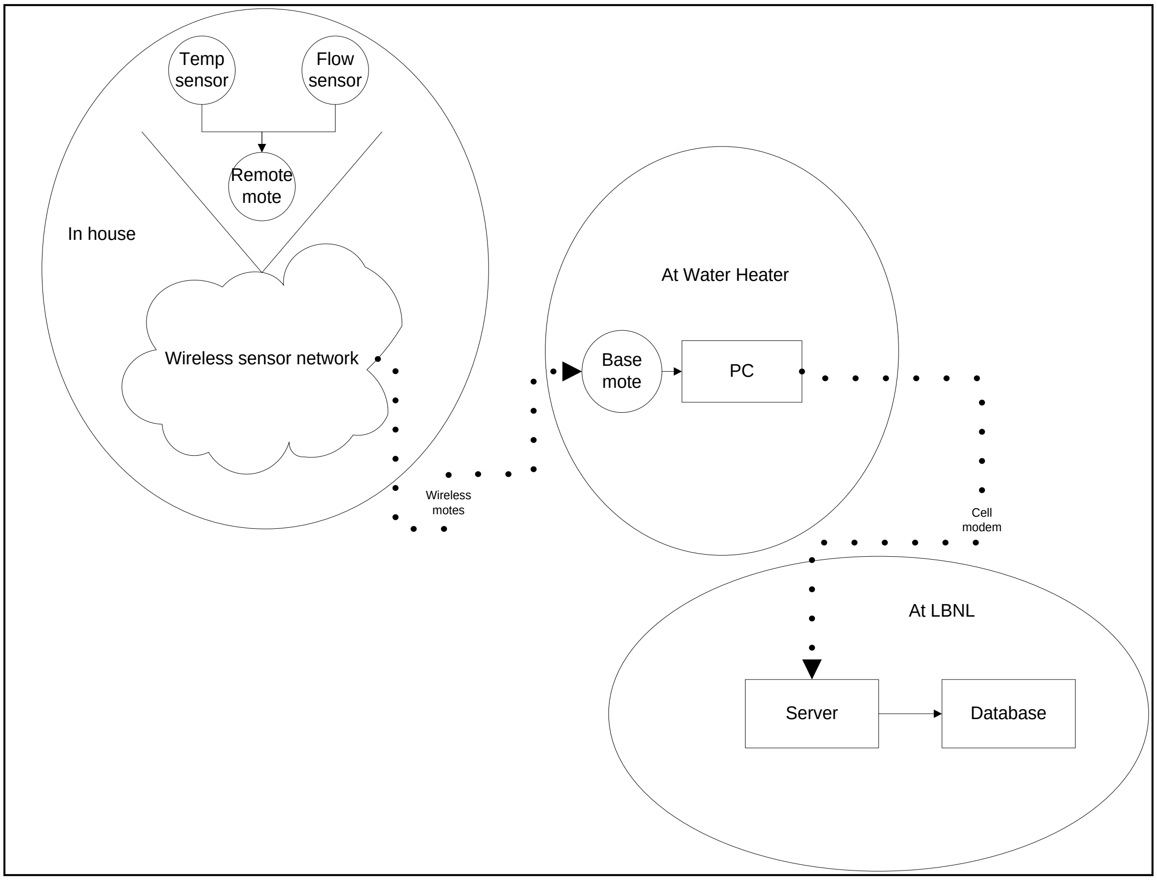

Figure 7: Data collection and transmission scheme

The motes were Tmote Sky platforms developed by Moteiv.[6] The Tmote Sky follows a design which was developed at the University of California, Berkeley, and operates with TinyOS. TinyOS is an embedded operating system developed for wireless sensor networks. Moteiv provided necessary components for the proper function of the Tmote Sky platform. The radio signal from the motes followed the IEEE 802.15.4 standard at 2.4 GHz.[1]

The circuit board for the motes is approximately 32 mm (1.27 in) by 65 mm (2.58 in) with a USB port at one end. Figure 8 shows a Tmote Sky circuit board.

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[6] In October 2007 Moteiv became Sentilla, www.sentilla.com. At that time they stopped producing Tmote Sky motes.

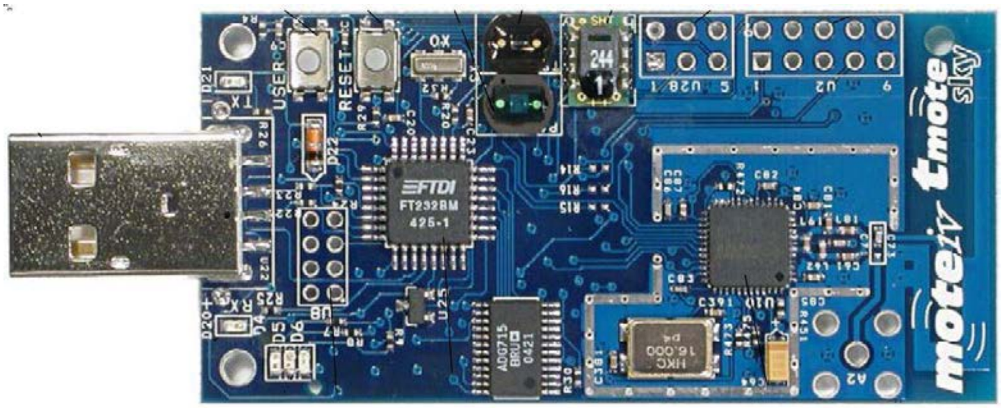


Figure 8: Tmote Sky circuit board

The motes assemble data in five-second intervals into packets during flow. During periods of no flow packets were sent at approximately 20-minute intervals. The data packets contain identification fields for the computer and the mote, a timestamp, five seconds of flow information, five seconds of temperature, and some clock synchronization flags. See Appendix A for a sample data packet.

Data acquisition software using wireless sensor networks has problems standard hard-wired data acquisition systems do not have. Among the problems faced in developing the software for the motes were: signal interference (making sure that concurrent signals from different motes did not result in data loss), time synchronization (making sure that all the motes were registering the same time and then applying corrections to the timestamp in the data packets if the mote was not time synchronized), and node reboots (making sure the motes rebooted automatically if the software running on them froze).

A base mote for the wireless sensor network was attached to a USB port on the onsite computer. The onsite computer was located near the water heater in all cases. The onsite computer unloaded the data packets from the base mote and performed some preliminary data processing. Packets were sorted into files by mote and duplicate packets were eliminated. Retroactive time synchronization was applied if necessary.

A rudimentary web front end was built for the pilot phase of the project. An initial graph of the recorded data from all the motes was created daily posted to a website to assist in diagnosis of any data collection problems. An example of this type of graph is shown in Figure 9.

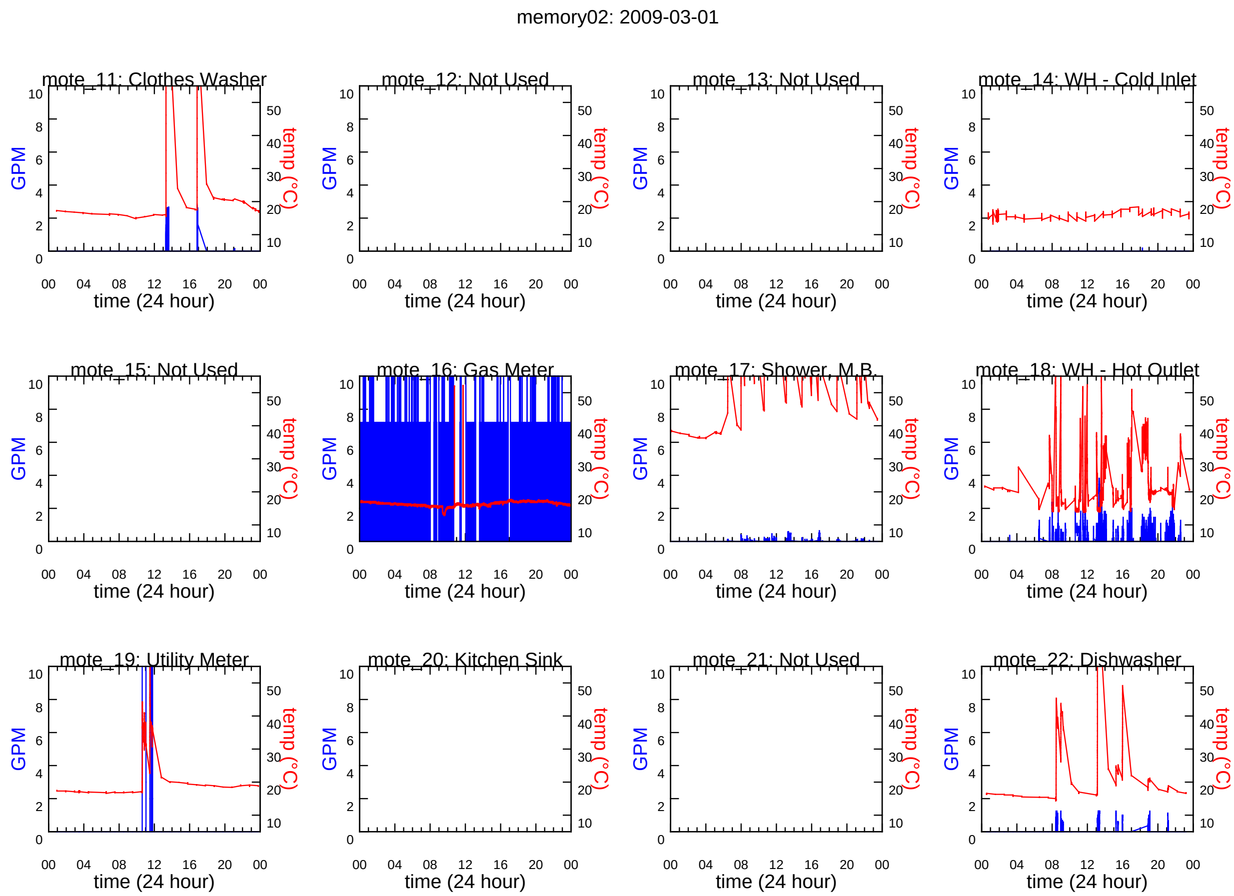


Figure 9: Example of Diagnostic Graph

The local computer was rebooted automatically four times per day. This was to enable unattended recovery if the computer operating system locked up. The data was sent once per day via cell modem to a central server at LBNL. The scheme to process the data and transmit it to the central server included several automated scripts and batch files. A schematic flowchart of this is included in Appendix B. Wireless Sensor Network Data Handling Scheme

1.4 Monitored Houses

Monitoring was done on four houses during the pilot period. The houses, all single-family detached homes built from 1970s through 1990s, were of volunteer LBNL employees. The water heater for each house is in the garage, as is standard for homes of this vintage in California. All houses are slab–on-grade. A short description of each, along with the number of residents, house is shown in Table 1.

Table 1:Attributes of monitored houses

	Concord	**Richmond**	**Martinez**	**Moraga**
Area, estimated, m^2 (sq. ft.)	232 (2,500)	149 (1,600)	124 (1,330)	185 (1,990)
Stories	2	2	2	1
Baths	2.5	2.5	2.5	2
Bedrooms	4	3	3	4
Adults	2	4	2	3
Children	2	0	1	0
Foundation	slab-on-grade	slab-on-grade	slab-on-grade	slab-on-grade
Year built	1974	1990	1983	1965
Siding style	stucco	wood	stucco & composite	wood siding
Water heater location	garage	garage	garage	garage
Pipe type	copper	copper	copper	copper
Pressure reducer	None	None	Yes	None
Faucet type (at measured faucets)	single handle faucets	kitchen - single	single handle faucets	single handle faucets
To water heater, estimated distance, m (ft.)				
Clothes washer	6.1 (20)	3.0 (10)	3.7 (12)	5.2 (17)
Dishwasher & Kitchen Sink	7.6 (25)	5.5 (18)	11.3 (37)	4.6 (15)
Shower	9.1 (30)	8.8 (29)	11.3 (37)	10.7 (35)

A sketch of the floor plan for each house is shown below in figures 10–13. Each floor plan shows a schematic of the house and the location of the water heater, clothes washer, dishwasher, kitchen sink, and shower.

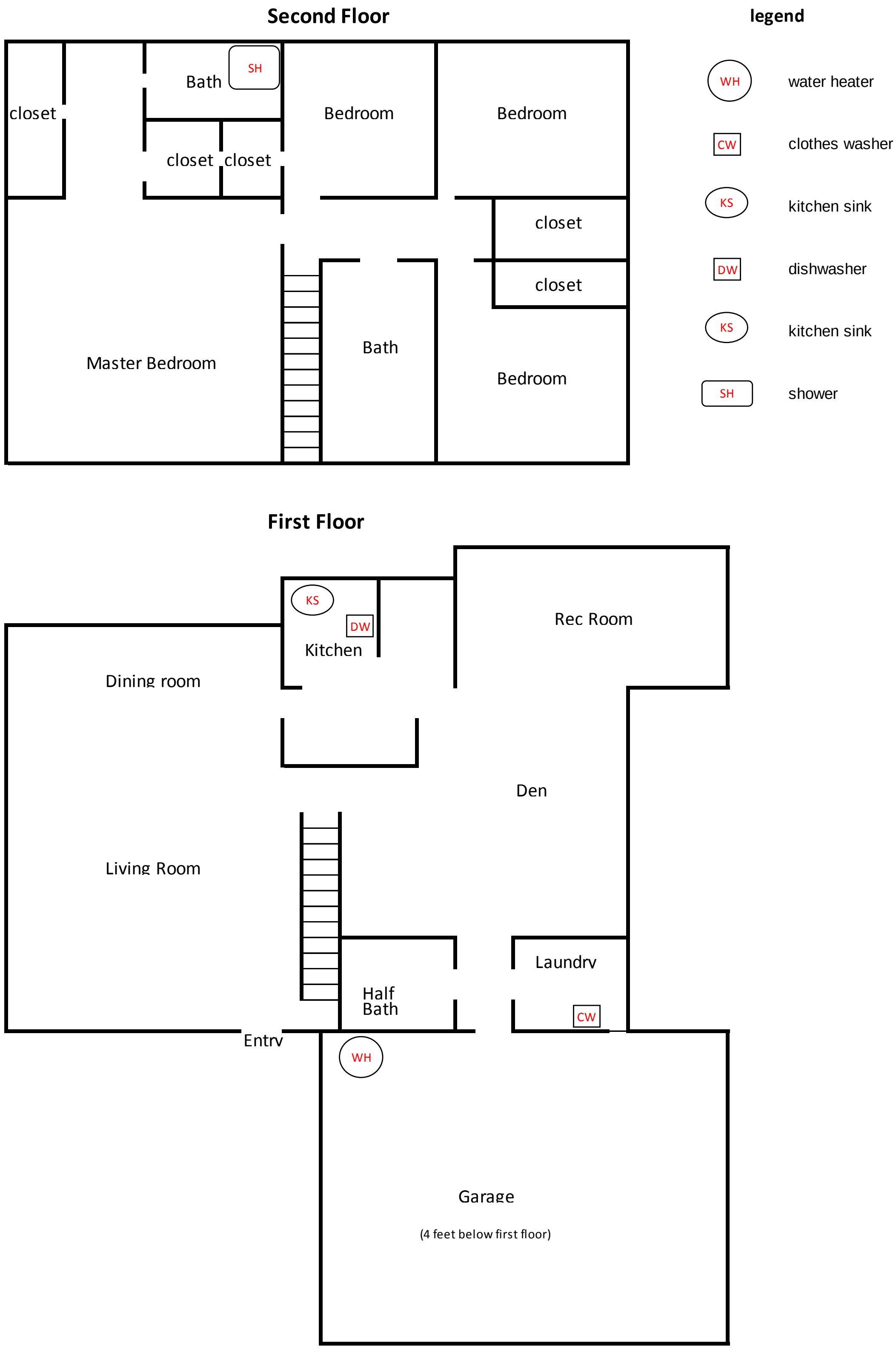


Figure 10: Concord House floor plan

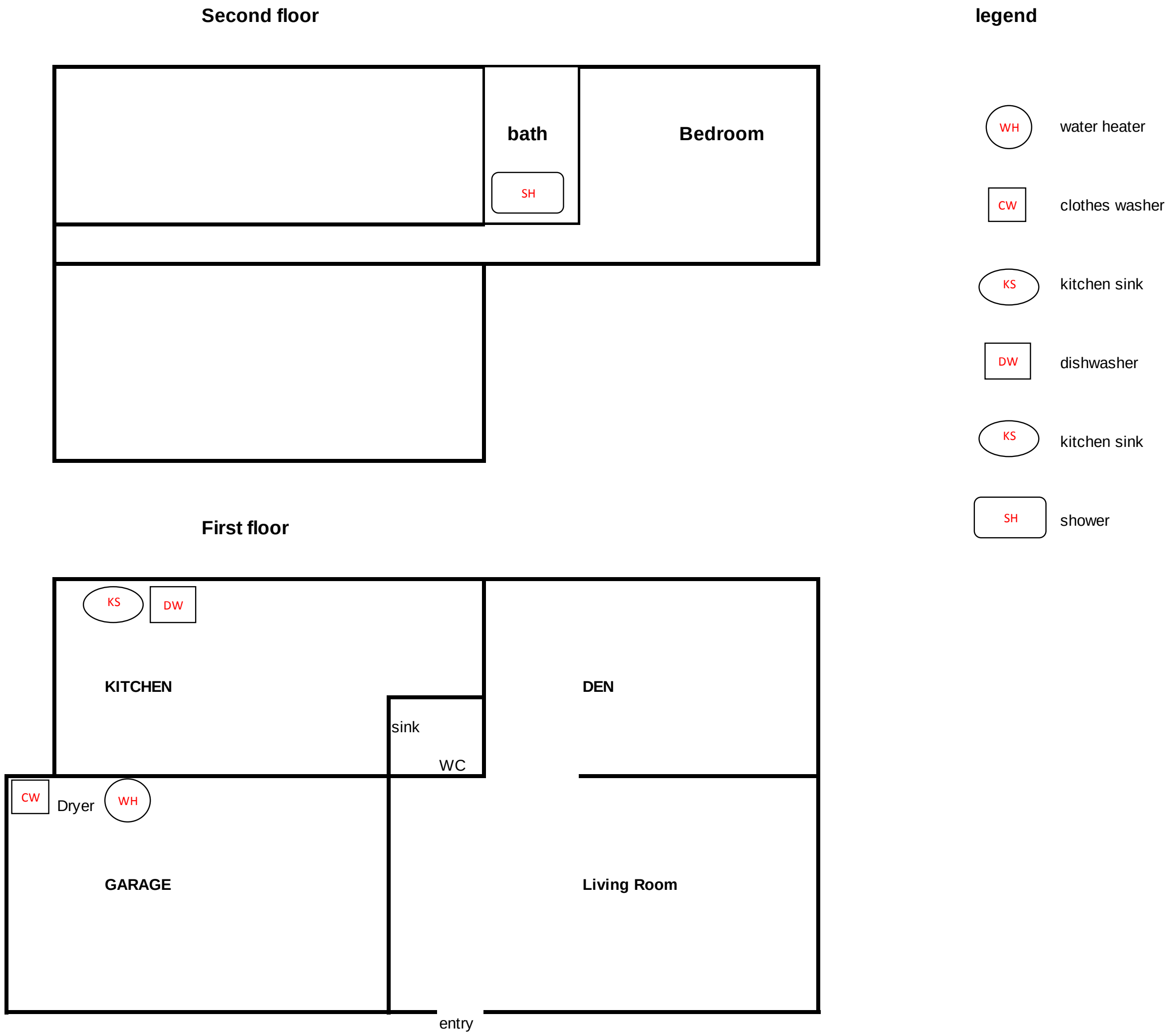


Figure 11: Richmond House floor plan

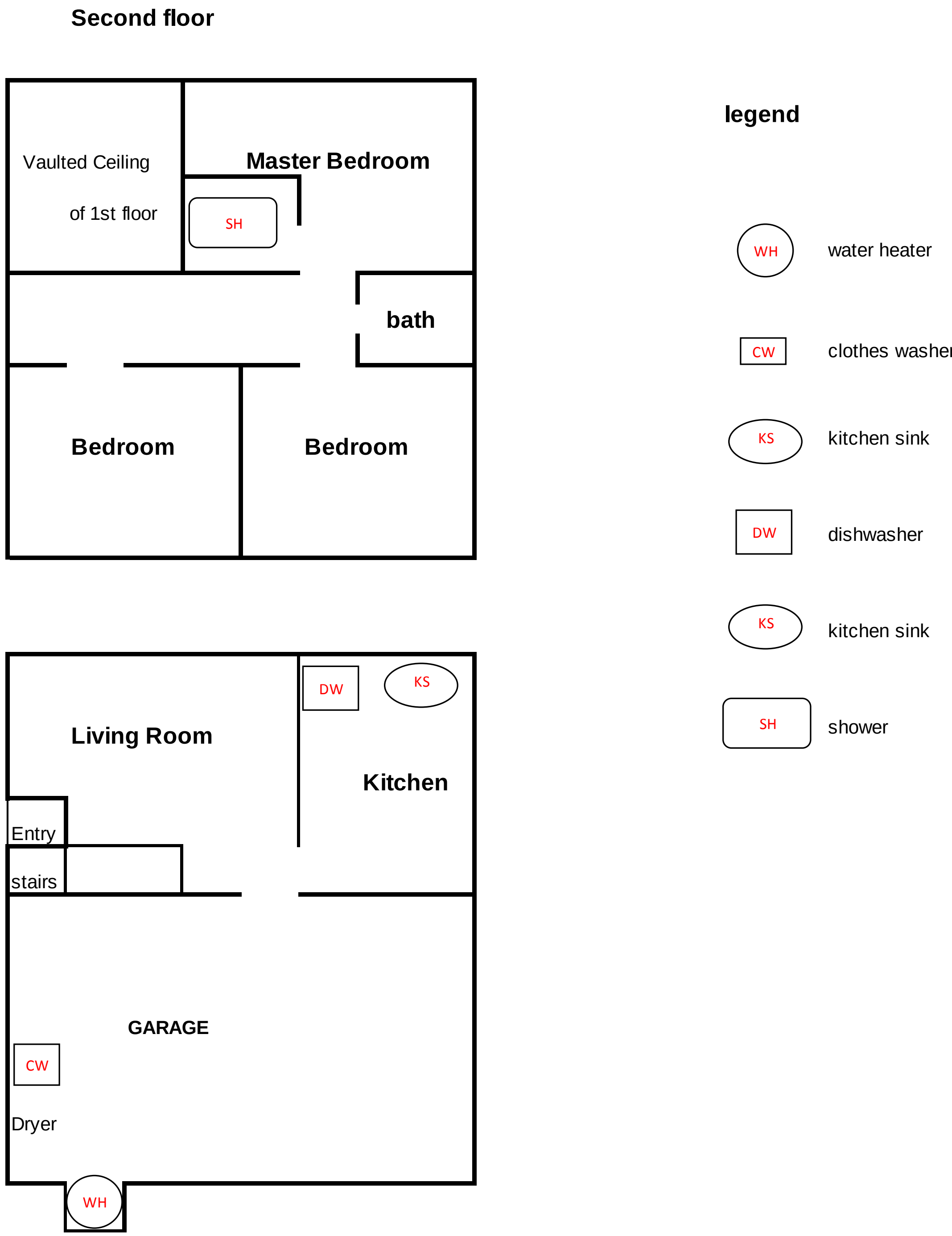


Figure 12: Martinez House floor plan

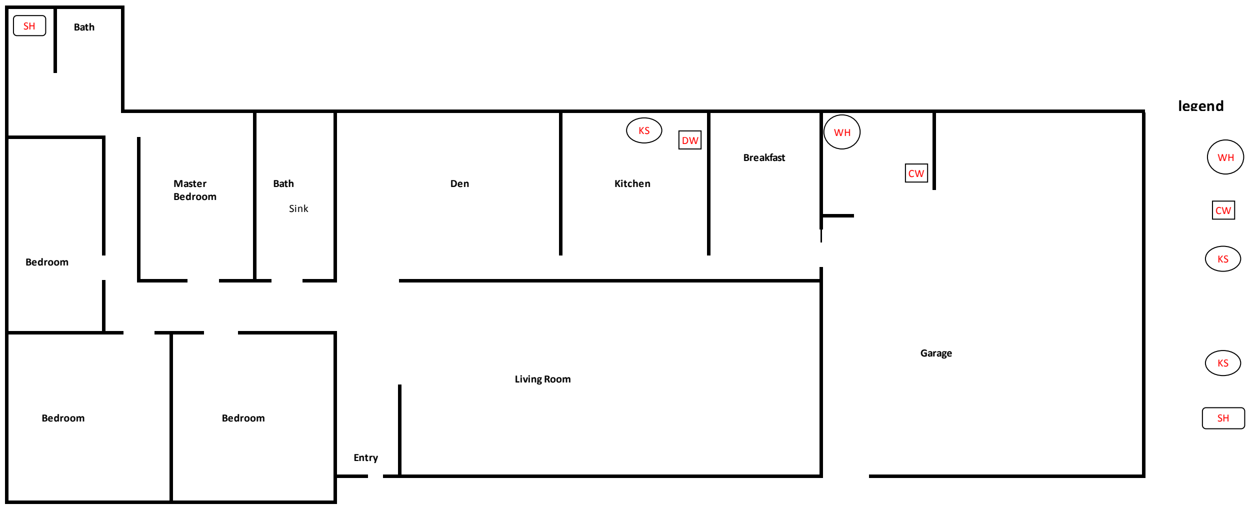


Figure 13: Moraga House floor plan

The data collection at the house in Moraga was not successful. No transmission was received from the mote in the shower. The L-shape of the house meant that transmission from that mote would have gone through two layers of exterior siding. It is probable this prevented signal transmission. There were problems with getting data from other motes at this site as well.

1.5 Collected Data

The collected data included flow rates and temperatures from hot water end use points at one second intervals during draws. The hot water use points monitored in the pilot study were kitchen sinks, showers, dishwashers, and clothes washers. Water flows into and out of the water heater were measured. Water temperature was measured at each end use point and at the inlet and outlet of the water heater. Data was only collected for those periods when draws were occurring. Table 2 lists the points where measurements were taken in pilot phase houses and the type of sensor.

Table 2: Measurement points in Pilot Phase Houses

End Use	Location	Monitored	Flow meter	Temperature
Water Heater Inlet	garage	cold water	Omega	thermistor, in water
Water Heater Outlet	garage	hot water	Omega	thermistor, in water
Water Heater Gas	garage	gas	American Meter	thermistor, outside of gas line
Kitchen Sink	kitchen	hot water	Sika	thermistor, in water
Dishwasher	kitchen	hot water	Sika	thermistor, in water

Shower	master bath	mixed water	Sika	thermistor, in water
Clothes Washer	garage	hot water	Sika	thermistor, in water

Monitoring was successfully completed for a total of 22 full days at three houses. The successful monitoring days and dates are listed in Table 3.

Table 3: Pilot Phase Monitoring Days and Sites

Site	Dates	Days
Concord	1/6–1/9, 1/13	5
Martinez	2/26–3/6	8
Richmond	3/19–3/26	9
Moraga	Not successful	0
total		22

Data was collected for 9416 water draw events. These water draw events include measurements of flow into and out of the water heater as well as at the end use points. Because of the standing pilot light, the flow meter on the gas line was sending data packets much more frequently. This resulted in 77260 additional data packets being sent that weren't associated with water draws.

1.6 Data Processing

The raw measurement data collected by the motes and uploaded to the server at LBNL was processed sequentially by several computer scripts. The processing was done for one day at a time. At this point the data was in multiple separate files for each mote. First the data files sent over from each mote were concatenated into one data file per mote. Because of the uncertain nature of the wireless data transmission, occasionally multiple data packets would be received. Duplicate data packets were removed at this stage.

Next the information from the data packets was converted into a simpler format for analysis. In this format each record contained the data from one second; the timestamp, one flow measurement and one temperature measurement.

After this, the flow data from the motes is translated from pulses to volumes. This is based on the calibrations that were done in the laboratory. Each flow meter has a different calibration curve. The conversion of the thermistor resistances to temperature was done at the motes. For consistency, this would be the stage in the processing that the temperature conversion would be done.

The interval data of flow and temperature of water at each measured point was then converted into information about draws. The data is processed record by record. There are four possibilities after reading a data line; a draw is about to start, a draw has ended, a draw is continuing, or a draw is not happening. A time gap longer than the standard time step between the timestamps from the previous and next record indicates that a draw has ended. The condition of a draw is also dependent on whether water is flowing or not. The algorithm used by the program to convert and aggregate the interval measurement data into draw information is shown in Figure 14, Flow Chart of Algorithm to Convert Measurements to Draws.

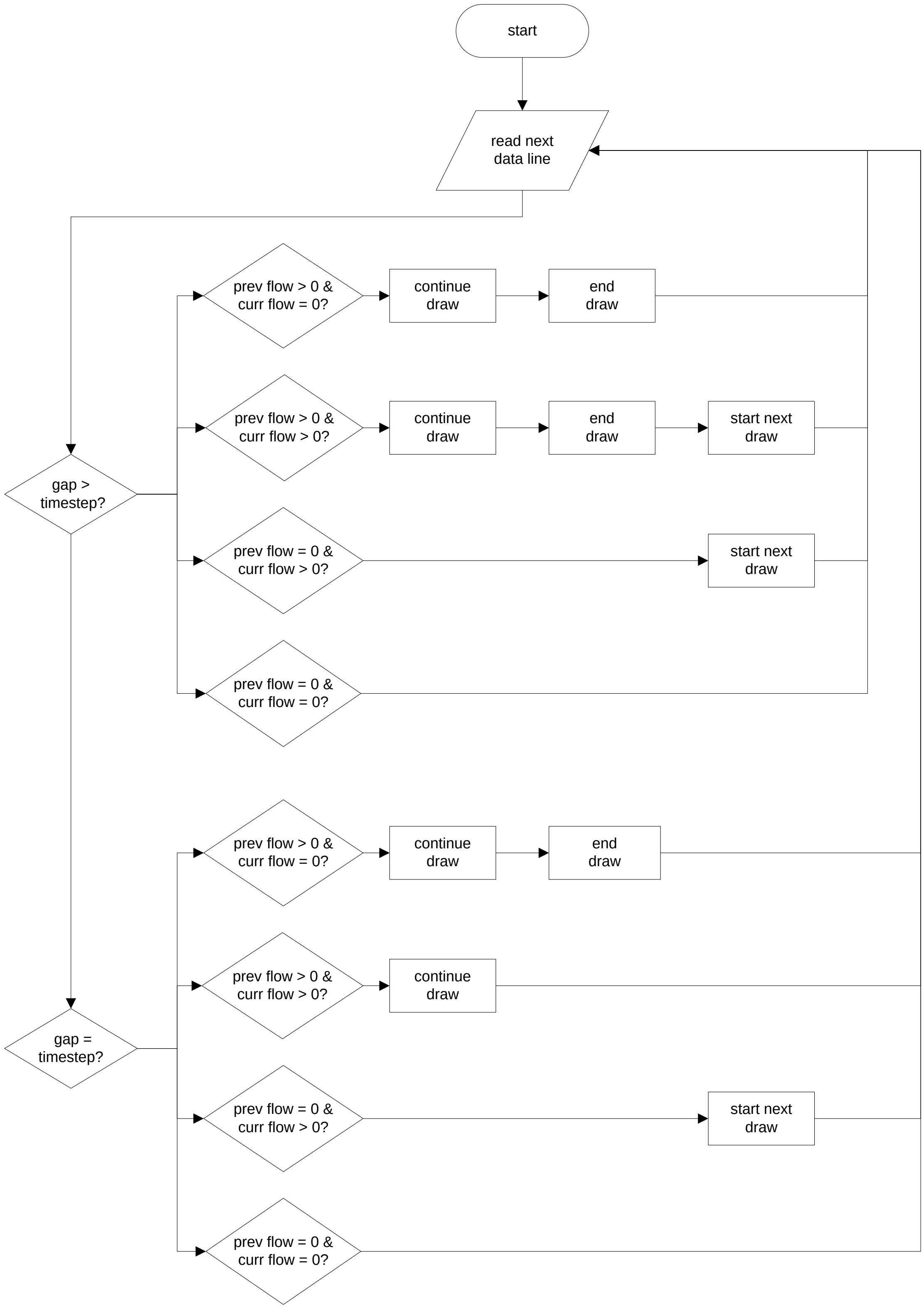


Figure 14: Flow Chart of Algorithm to Convert Measurements to Draws

The time at the start of the draw, the total duration of the draw, the total volume of water for the draw, the weighted average temperature during the draw, and the time since the previous draw were calculated and recorded for each draw.

CHAPTER 2: Outcomes

Information about the hot water draws is presented in this section. The efficiency calculations for a sample hot water event are explained in detail.

The daily hot water use, measured at the water heater inlet, for the monitored houses is shown in figure 15. There is striking variation of hot water use between houses. The variability of hot water use from day to day within the same house can be quite large as well.

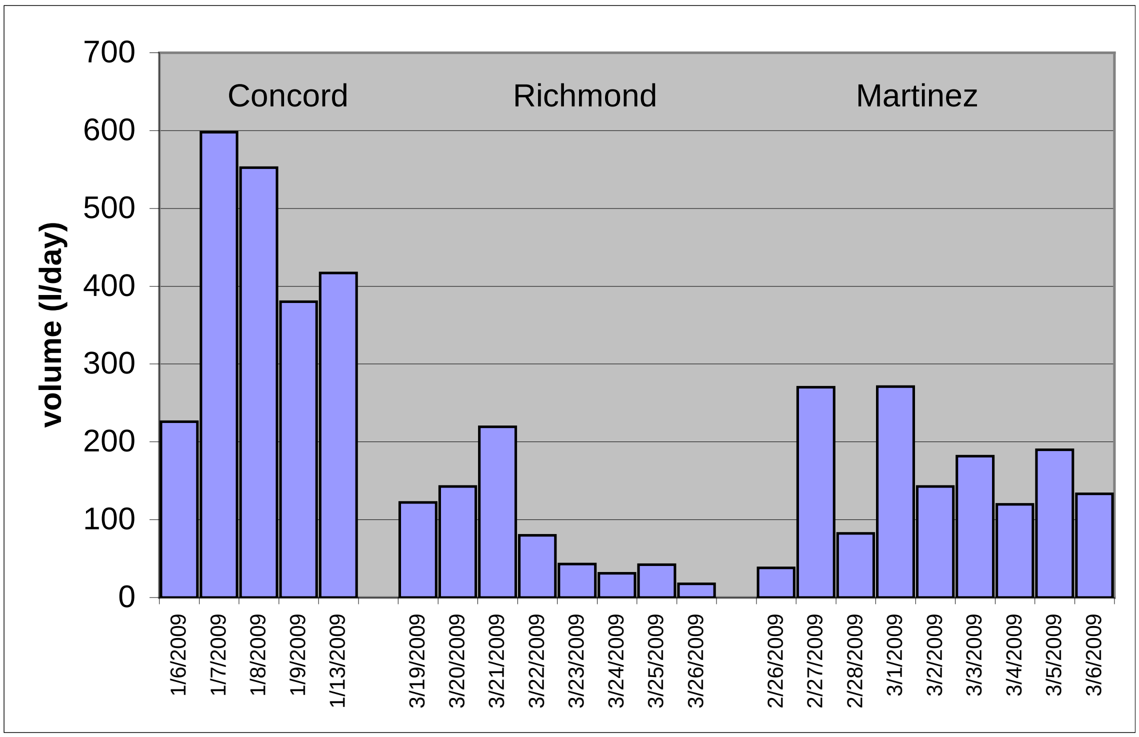


Figure 15: Daily Hot Water Use

A summary of the hot water use per day by end use across all 3 houses is shown in table 4. As expected showers are the largest average daily hot water end use by volume. Of the end uses monitored here, kitchen sinks have the highest average number of draws per day.

Table 4: Average Hot Water Use Per Day by End Use

location	volume (liters)	draws (number)
kitchen sink	20.6	30.6
DW	8.5	3.6
shower	105.3	5.2
CW	7.5	7.3

Dishwashers were not used every day, so the daily average volume is lower than the volume of hot water used for one load of dishes. Also there are several draws for one load of dishes in a dishwasher or one load of clothes in a clothes washer.

Because not every hot water end use was monitored, the total average daily volume of hot water end uses does not match the total average daily volume delivered from the water heater. See figure 16, Average Daily Hot Water Flow at the Water Heater and at End Uses. Two meters were used to measure water flow at the water heater. One meter was on the inlet and one was on the outlet. Surprisingly, the two flows were not identical. This is particularly true for the Martinez house. Several possible causes for this discrepancy are also discussed in the Recommendations section.

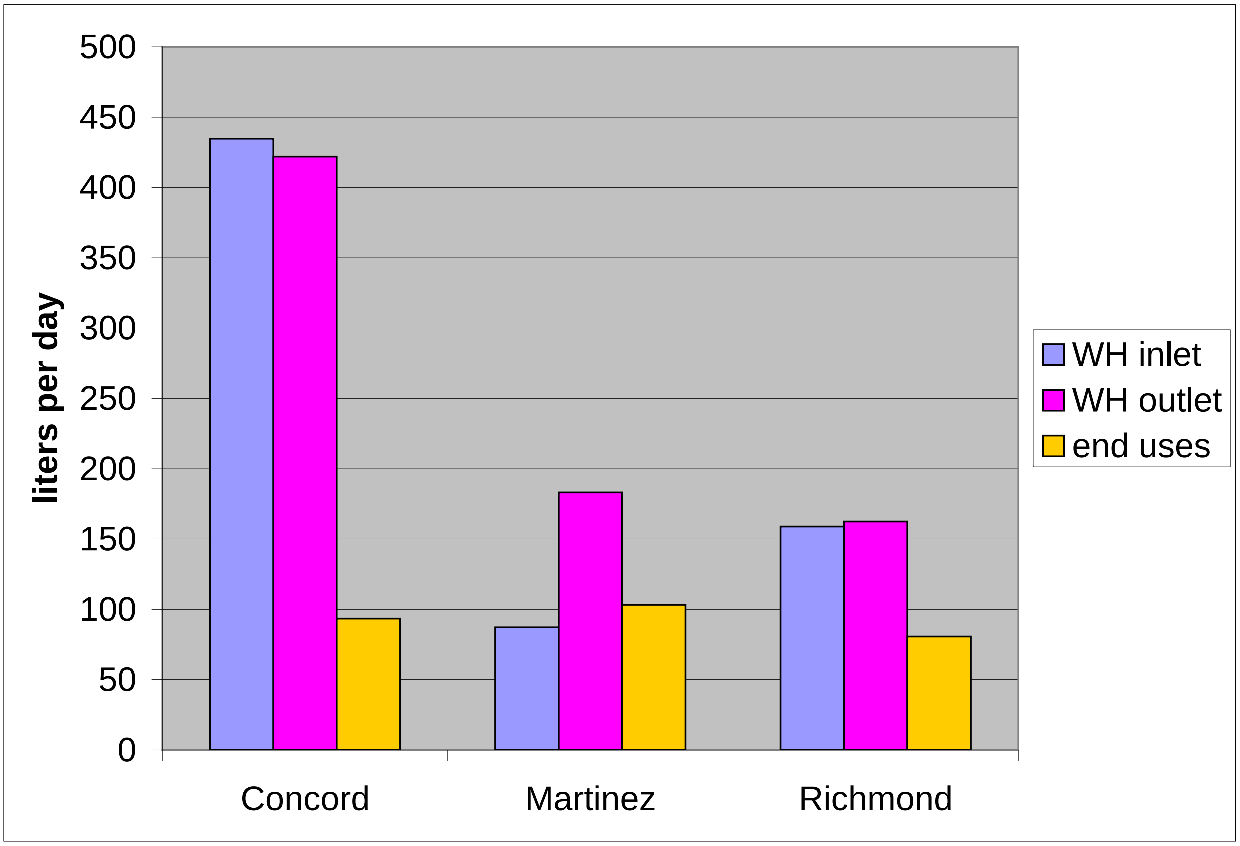


Figure 16: Average Daily Hot Water Flow at the Water Heater and at End Uses

A similar plot of average daily hot water use, but showing the number of draws, is shown in figure 17. Here the number of draws by end uses is smaller than the draws at the water heater. This is consistent with not all the end uses being monitored. However the number of draws per day is higher at the water heater inlet than at the water heater outlet, significantly so for the Concord house. Possible reasons for this discrepancy, along with potential solutions, are discussed in the Recommendations section.

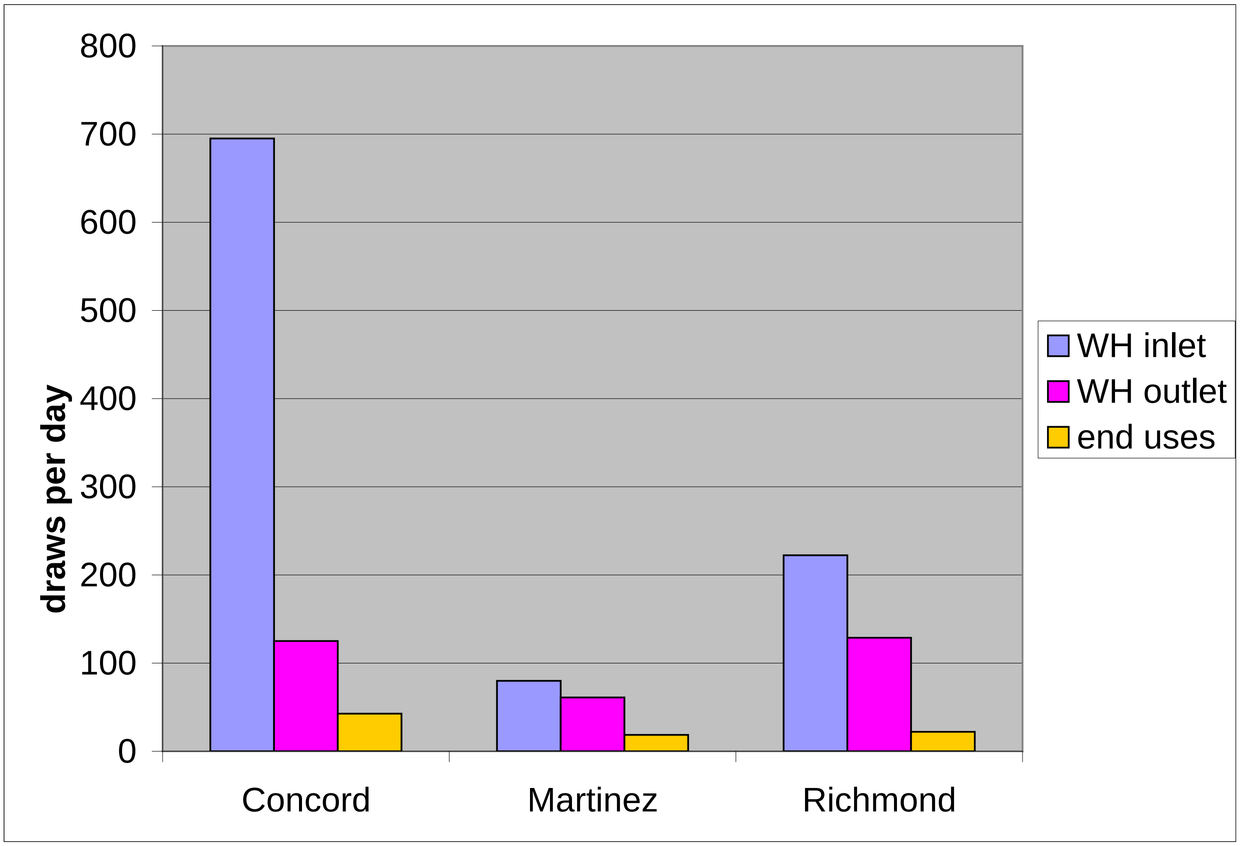


Figure 17: Average Daily Hot Water Draws at the Water Heater and at End Uses

The average volume per draw is shown in figure 18. From this figure it is clear that hot water draws for showers are significantly longer than draws for other end uses. However, the volume of water per draw for showers is lower than expected, especially for the Concord house. This may be due to data packets occasionally not being transmitted successfully. If a data packet in the middle of a draw did not get recorded, it would cause the appearance of two short draws instead of one longer draw. Sending totalized flow data instead of interval flow data, as discussed in the Recommendations section may allow correction of some of these problems.

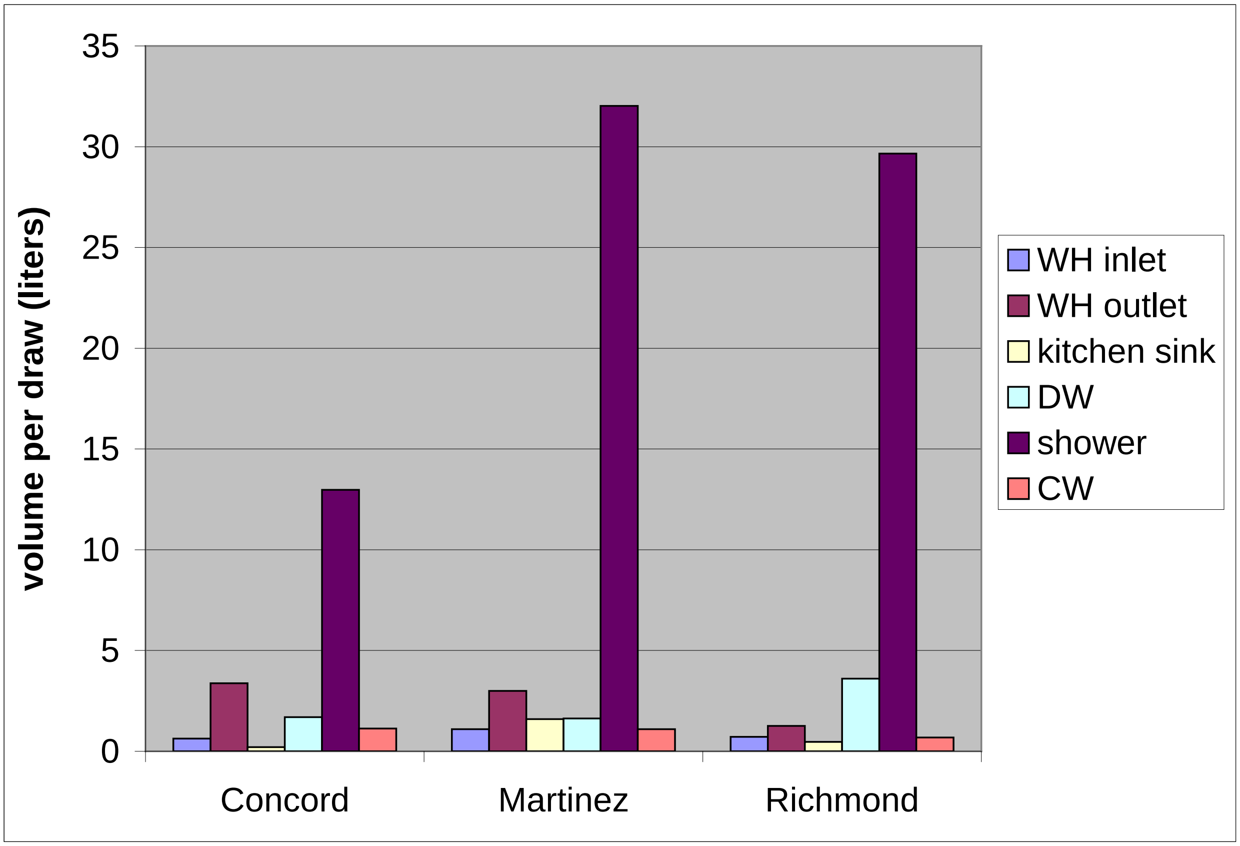


Figure 18: Average Volume per Draw by End Use

As an example of the details for hot water use, the following three charts show details of three end uses. This sample is for six minutes and shows use at a kitchen sink, dishwasher and clothes washer.

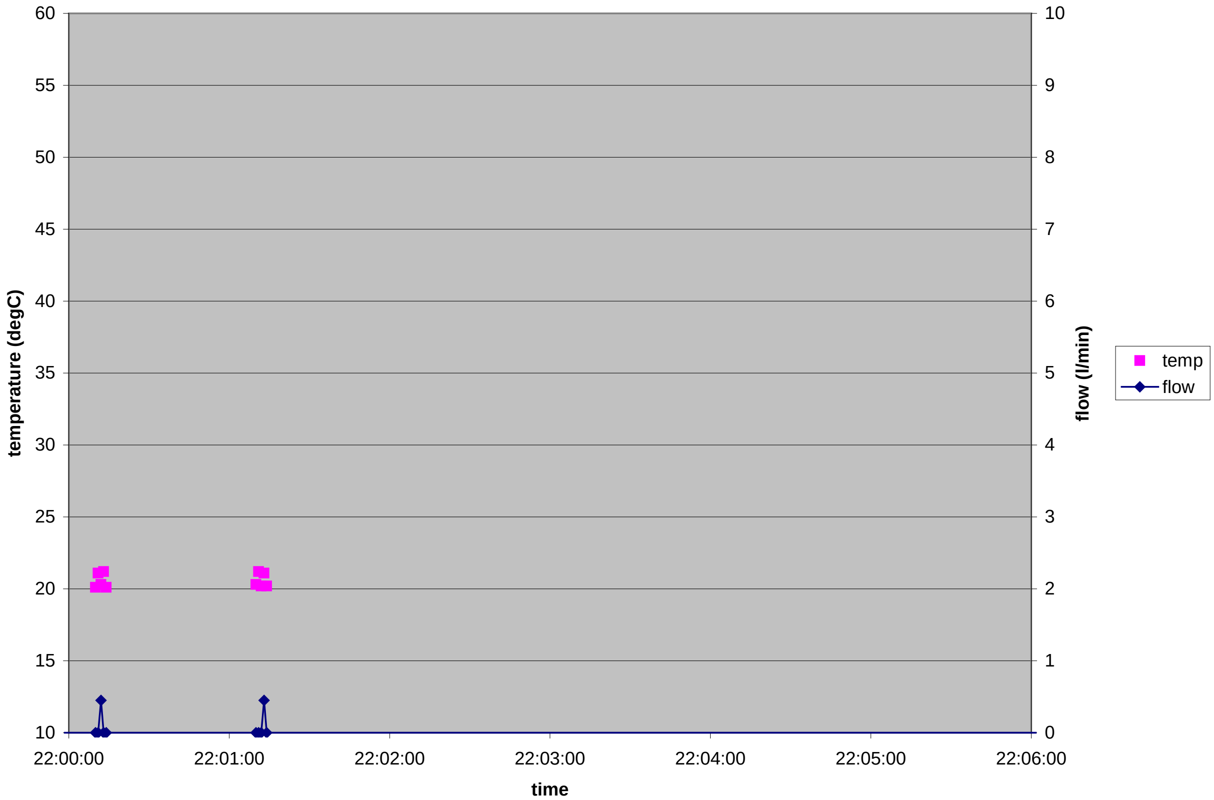


Figure 19: Kitchen Sink, Hot Water Flow and Temperature

Figures 19, Kitchen Sink, Hot Water Flow and Temperature shows two short hot water draws were taken at the kitchen sink about a minute apart. The temperature of the delivered water was room temperature. This is the temperature the hot water in the pipes cooled off to. The water at the faucet never got hot for these draws.

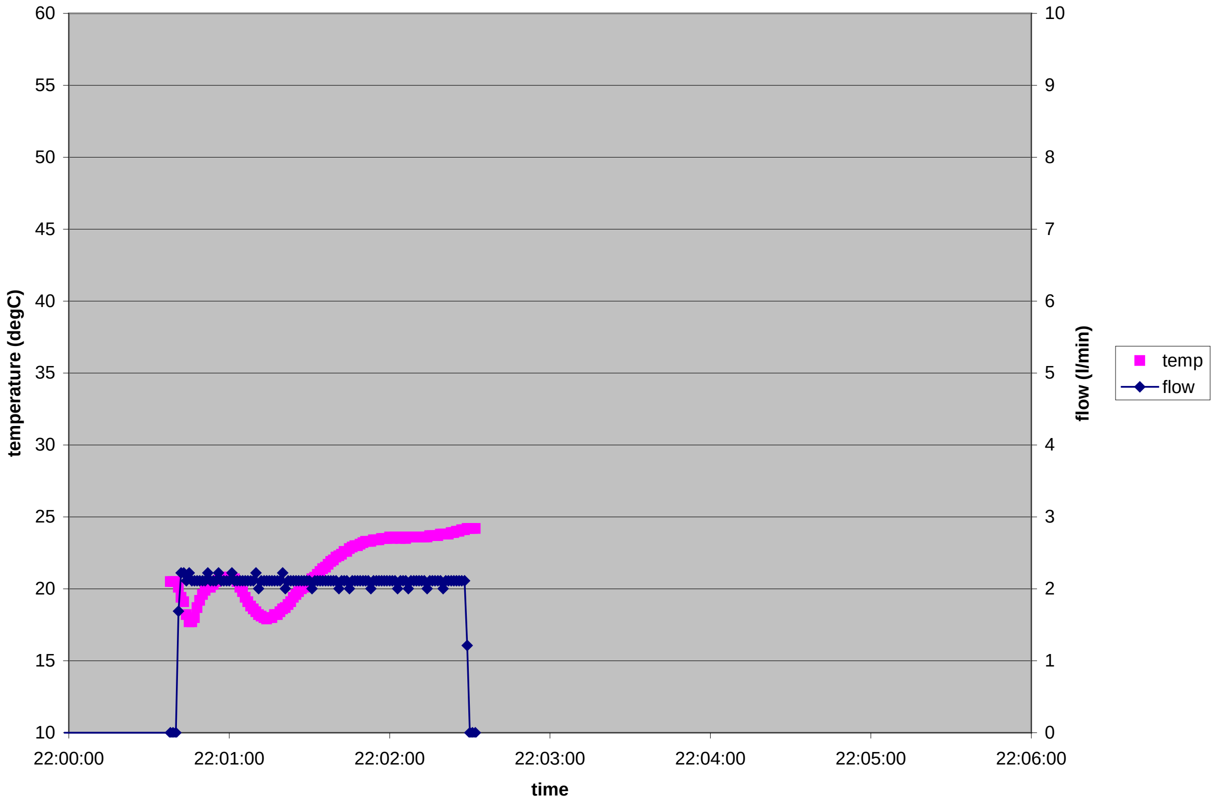


Figure 20: Dishwasher Hot Water Flow and Temperature

Figure 20, Dishwasher Hot Water Flow and Temperature, shows a two minute draw of hot water for the wash cycle of a dishwasher. The flow rate is very constant throughout the draw. Although it does increase in temperature, the water temperature does not get hot for this draw.

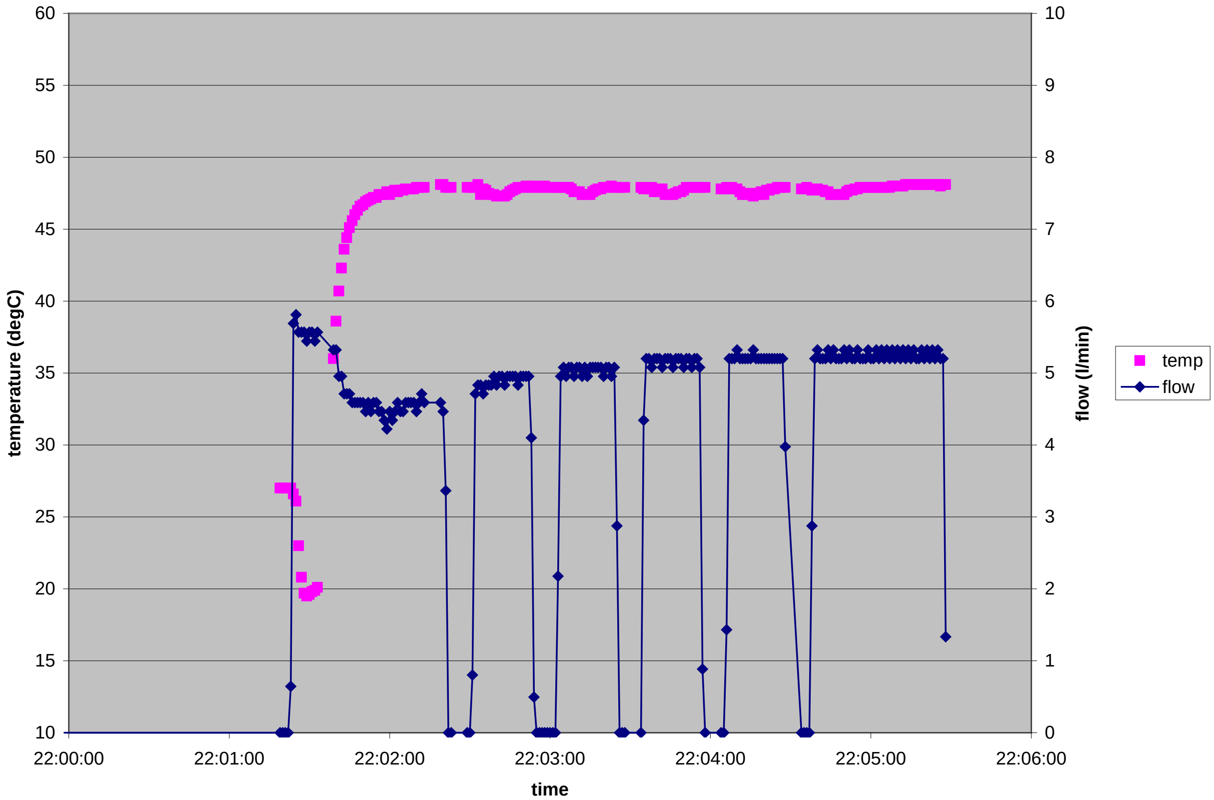


Figure 21: Clothes Washer Hot Water Flow and Temperature

Figure 21, Clothes Washer Hot Water Flow and Temperature, shows six individual draws by the clothes washer to fill for washing a load. Unlike the dishwasher, the draws are not all at the same flow rate. The temperature of the water arriving at the clothes washer actually drops briefly as cooled off water is cleared from the line. After about 30 seconds hot water has arrived at the clothes washer. The time between draws is not long enough for the water in the line to cool off.

For comparison the flow of water out of and into the water heater for the same time are shown in Figures 22 and 23.

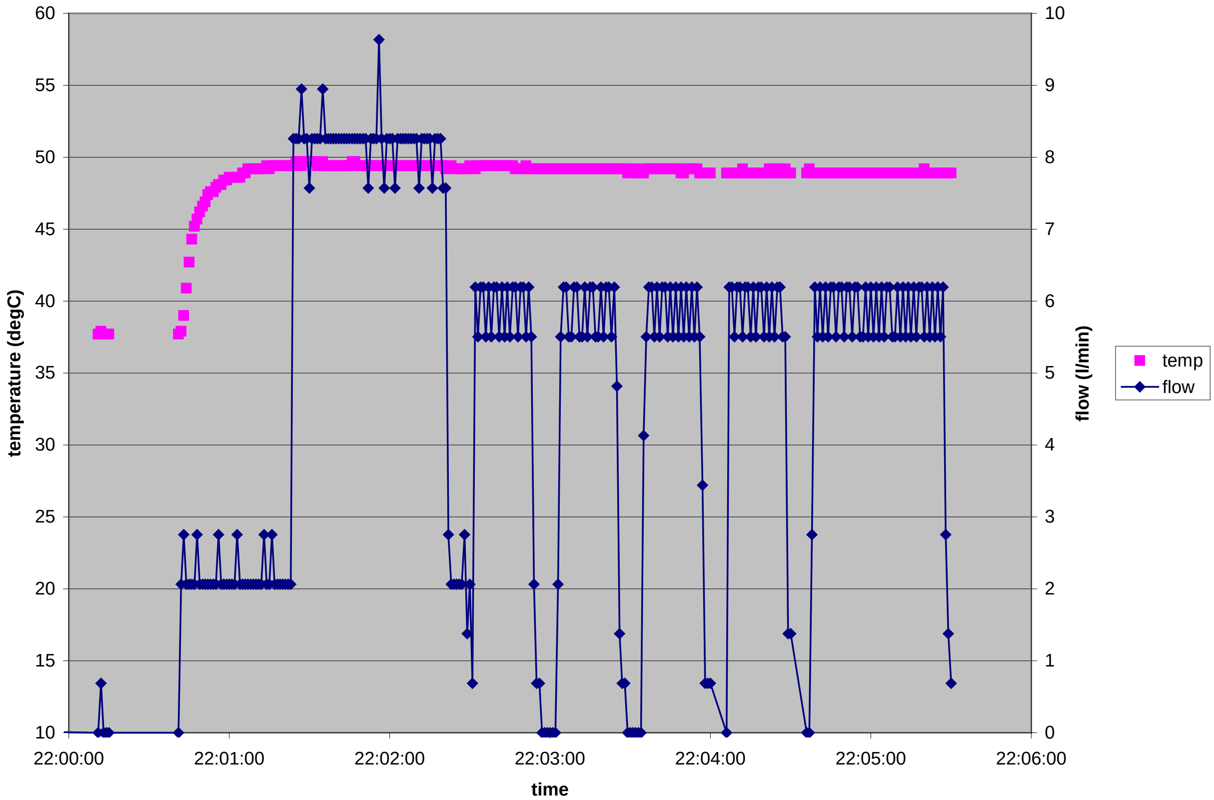


Figure 22: Flow and Temperature of Water out of Water Heater

In figure 22, Flow and Temperature of Water out of Water Heater, the three different end uses are now superposed, but still clearly visible. Even with the temperature sensor mounted near the water heater it still takes several seconds for the water temperature to rise to fully hot.

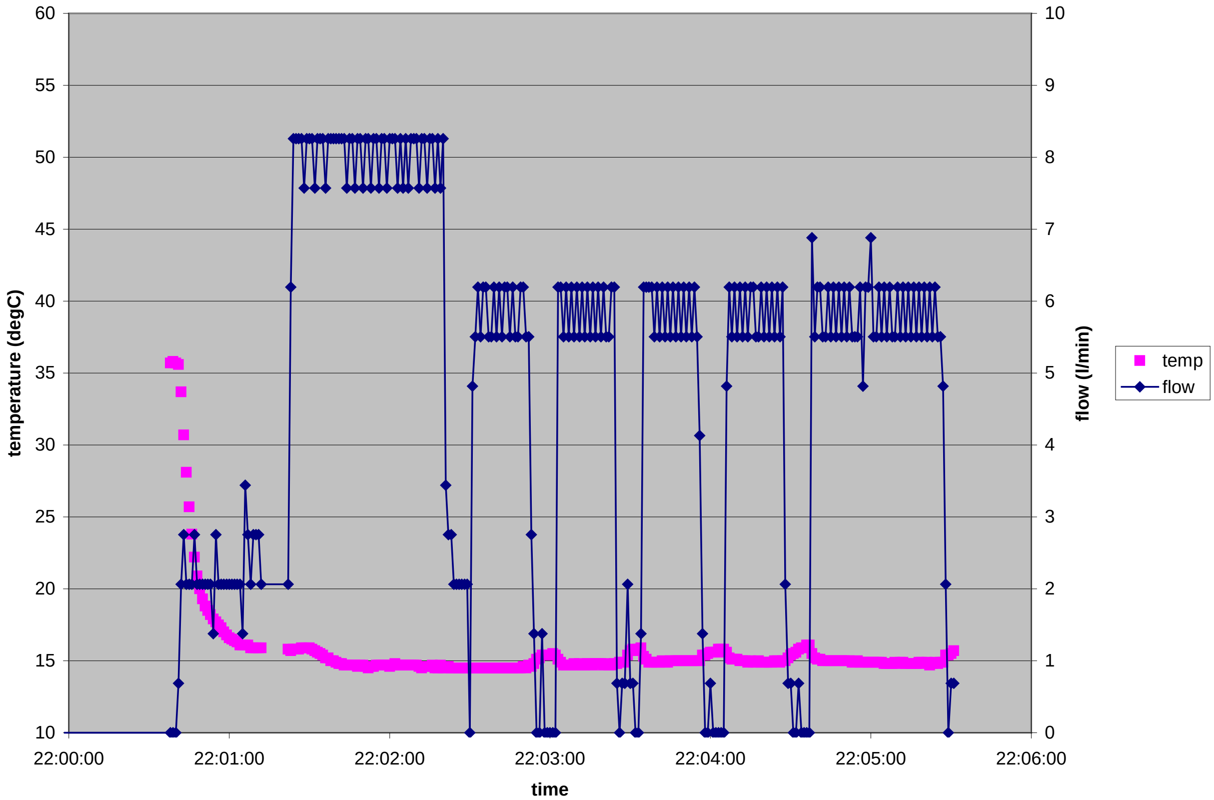


Figure 23: Flow and Temperature of Water Into Water Heater

The same superposed flow pattern shown on the outlet water flow is also visible on the inlet water flow in Figure 23, Flow and Temperature of Water Into Water Heater. The pronounced drop in water temperature at the beginning of the draw shows that nearly a liter of water in the inlet line upstream of the water heater had been warmed significantly. Warming the water in this pipe will contribute to the standby losses of the water heater. The lower resolution of the flow meters at the water heater mean less detail is captured by the flow meters.

From this data the efficiency of the hot water distribution system for these draws was calculated. The efficiency of draws was calculated as the ratio of the energy out of the pipes at the end use point to the energy into the pipes at the water heater outlet. The energy was calculated as the change in enthalpy for water from 15 °C at atmospheric pressure multiplied by the volume of water drawn.[7] The volume was based on water drawn at the end use point because the flow meters at the water heater were lower resolution and were not calibrated. The reference temperature of 15 °C was chosen as a representative temperature of the inlet water to

7 The enthalpy and density of water were calculated as a cubic fit of data from E.W. Lemmon, M.O. McLinden and D.G. Friend, "Thermophysical Properties of Fluid Systems" in NIST Chemistry WebBook, NIST Standard Reference Database Number 69, Eds. P.J. Linstrom and W.G. Mallard, National Institute of Standards and Technology, Gaithersburg MD, 20899, http://webbook.nist.gov, (retrieved August 17, 2009).

the heater after the pipe had been cleared of pre-warmed water. The results are shown in Table 5, Hot Water Distribution System Efficiencies for Selected Draws

Table 5: Hot Water Distribution System Efficiencies for Selected Draws

End Use	Start time	End time	Efficiency
Kitchen Sink	22:00:10	22:01:30	20.1%
Dishwasher	22:00:40	22:02:32	19.1%
Clothes Washer	22:01:21	22:05:28	90.5%

CHAPTER 3: Recommendations

The following recommendations for the field study are based on the results of this pilot phase project. The experience gained in the pilot phase study using wireless sensor networks demonstrates that it is clearly feasible to use this technology for measuring water and gas flows and temperatures.

The goal was to reliably collect water flow and temperature data from every indoor water end use point, at the water heater and at the whole house meter in one second intervals when water was flowing. The overall success of the pilot phase study indicates that this technique can work. However, the pilot phase study did reveal shortcomings in many areas. These recommendations address those shortcomings and provide ways to improve the outcomes of the follow-on field study.

Because most hot water end use points, such as sinks and clothes washers, have an adjacent cold water end use point, adding cold water monitoring to the data acquisition system would require adding two additional data channels to the motes and installing another sensor set at each end use point. This effort would not require significant additional programming or field work. The value of additional information about cold water end uses compared to the incremental cost justify that this capability be included.

The recommendations are grouped into three broad categories; data collection, data transmission and data analysis. These groupings can also be considered analogous to the key hardware involved. The data collection corresponds to the sensors used to initially gather the flow and temperature data. The data transmission corresponds to the getting the data collected by the sensors onto the motes then wirelessly transmitted to the local processing and storage units on site and then transmitted to the server at LBNL. The data analysis means screening, cleaning and processing the monitored interval data from each house into results that can be used for policy recommendations. The analysis would occur on the server at LBNL.

The sensors used for data collection in the pilot phase study were more than adequate. Recommendations at this stage fall into areas of increasing the ease and robustness of installing system and improving the calibration of the flow meters.

The 10k ohm thermistor probes worked quite well at measuring water temperature in the pipes. The main shortcoming was the leads to connect the thermistors to the motes were fragile. The leads should be hardened and protected, perhaps by encasing them in plastic shrink tubing as they leave the probe. Another option would be to install a jack on the thermistor. Then a separate wire could be run to the mote after all the sensors have been installed in the plumbing.

The Sika flow meters with a Wiegand pickoff also worked quite well. The Omega flow meters used at the water heater did not have as high resolution. This caused difficulties in some of the calculations. Either find higher resolution jet flow meters or consider using the Sika turbine meters at the water heater as well.

The anomalous flows at the water heater, with different amounts of water apparently flowing into and out of the water heater, could have been caused by back flow from the HWDS into the cold water system. One way of determining if this is in fact happening would be to add pressure sensors at the inlet and outlet of the water heater. A differential pressure sensor across the water heater may be just as useful, but less expensive. This capability should be added to the data collection system. Pressure transducers that give a signal as a resistance would be capable of being read by the motes just as the thermistors are. This would preclude having special programs for the motes for this application.

Calibration of all the flow meters prior to data collection is important. This would be easiest to do at a dedicated installation in a lab. The set of sensors, motes, and local processing unit for each house should be tested before installation. A temporary plumbing loop should be set up with all the sensors installed in series. Water should be drawn through this loop at a graduated set of flow rates ranging from about one half l/min up to 20 l/m. The time constant and calibration of the thermistors should be checked by a series approximately 5°C step changes in temperatures starting at 20°C going up to about 60°C. A dedicated calibration bench using high quality sensors and a separate, automated data collection system based on LabVIEW should be used.

The motes used in the pilot phase performed adequately but upgrading to take advantage of recent developments in wireless sensor network technology is strongly recommended. It is also important that the motes used in the field study be physically more robust than the early prototypes used in the pilot phase. Since they will be installed in relatively uncontrolled field conditions and may be subjected to occasional rough handling, the motes should be rugged enough to be considered "plumber-proof". The motes must be battery powered, as there is no guarantee of power nearby. It is important that changing batteries in the field be possible and not risk damaging the motes.

The mote platforms used in the pilot phase were able to detect the pulse signals from the Wiegand pickoff on the Sika flow meter. Pulses from the Wiegand pickoff are roughly triangular voltage spikes with peaks of about 3.3 V. The duration of the spike above 1.5V is about 10 microseconds. The maximum expected frequency in this application is approximately 300 Hz. Any new platform must be able to detect these pulses as well. It is expected that this will be standard.

In the pilot phase the pulses were summed for each second of flow. The number of pulses from the flow meter for each second was sent to the onsite computer. A better strategy would be to keep a running total of the pulses and send the new total for each second. That would allow partial reconstruction of flow if some data is lost.

In the pilot phase the resistance of the thermistor was translated to temperature by the mote. To reduce the work load of the mote, this translation should be done on the server once the data gets there.

To reduce the number of transmissions and to increase redundancy in case of missed transmissions, as much data should be stored at the mote as possible. The exact amount of data to be stored at the mote will depend on the balance of energy and reliability between memory and transmission for the platform used in the field study. Sending packets with overlapping data, such that each recorded data point is send in two or more sequential packets, would provide additional redundancy to the transmission process.

From experience gained during the pilot phase, the software program on the motes should have features to assure robust operations, reliable signal transmission, and synchronization to within less than one second across the whole wireless sensor network. The target for reliable data acquisition should be loss of less than one datum per million.

Given the intermittent nature of hot water use, it is important to have a regular signal from each mote that it is still operational. A lack of data received at the local processing unit could be due to the lack of any hot water draws at that end use, or it could be due to failure of the mote. A way to solve this is to require a "heartbeat" signal from the motes every 15 or 20 minutes. This heartbeat signal would be a basic report on the status of the mote. One crucial piece of data to include in the "heartbeat" signal is the remaining voltage on the mote's battery. This will give an indication of the remaining life of the mote.

To assure that the motes are working as intended when installed, it is imperative to include some local indication of the status of the mote. One possible solution is to have LED indicators show the installer vital information such as whether the signal strength to and from the local computer is adequate, if the battery voltage is acceptable, whether data from the sensors is valid, and if time synchronization has been successful. To conserve energy in the mote battery, the LED indicators should be turned off after proper operation is assured. If the signal to the local computer is too weak, it may be necessary to add relay motes. This should be known at the time of installation so the relay motes can be added then.

The on-site processing unit should be a simple computer running the Linux open-source operating system. The computers used for pilot phase were salvaged PCs running Windows XP. That operating system proved to be unreliable.

The local computer would store all data on-site as a local backup to the data that is passed to the central server each day.

The on-site processing units would be the connection between the local wireless sensor network and the Internet. Connections to the Internet would depend on the situation at the house being monitored. The possible network connection protocols could be cell phone modem (GSM), IEEE 802.11-wireless LAN standards (WiFi), or modems on land line telephone service (POTS) , whichever provides the easiest, most reliable service from that house. The motes should be IPv6 capable. This will allow remote access all the way to the motes for diagnostics and remote reprogramming without having to visit the site.

Each mote should be able to transmit data collected from four channels. For most motes this will be hot water flow, hot water temperature, cold water flow and cold water temperature. Each data set will be identified by a mote ID and a timestamp. The timestamps should be synchronized for all the motes to within a half second. The targeted data collection period for each site will be three months. The choice of how much data to store in the motes memory and how often to transmit data to the local computer will be made to maximize battery life. Understanding and minimizing the power use of the mote in all the modes of operation (data collection, data transmission, synchronization, initial start, data relaying, watching for data, wakeup cycles, sleep mode, etc) will be important.

The wireless sensor network should be capable of operating as a mesh. This would allow additional 'relay' motes to be installed if the signal is too weak in any part of the network.

From experience with the pilot phase, the importance of having a mote designer and programmer on staff cannot be stressed strongly enough. The field study should start with clear specifications of the necessary capabilities of the wireless sensor network. The implementation should be phased with the first five installations to confirm the system is meeting the design criteria. The second phase of 10 more houses will allow for any final configuration changes necessary to cover a wider range of applications. The third phase of 15 additional homes will allow methodical preparation and installation of the complete field monitoring phase. The mote designer and programmer will be involved at minimum in the design and implementation of the first 15 wireless sensor network installations.

The data coming in daily from each house will need to be checked, processed and entered into a database in an automated fashion. Each data point will be associated with a specific house, mote, and end use point. The date and time each data point was collected will also be noted. Because of the intermittent nature of hot water use combined with the indeterminacy of a wireless network, quality review of the data will be crucial. After being collected and stored, the raw interval data should be checked for consistency and plausibility. Initial diagnostic graphs will be required for daily review by project staff. After the interval data has been checked, cleaned, and stored in another data table, it will be divided into draws. Summary information will be calculated and stored for each draw. Draws at the water heater and the whole house meter will be associated with end use draws. At this point the energy and water efficiency of the HWDS will be calculated for each draw.

The vast amounts of data that will be collected by the field study mean that all the data processing and analysis procedures should be written as programs, scripts or macros and automated. To that end it will be necessary to have an experienced database programmer as part of the staff of this project.

Because of its reliability, widespread availability and lack of cost, open source software should be used for all stages possible in the project. This will allow widespread sharing and analysis of the data by parties not involved in the original project. Using open source software and providing copies of all programs and scripts will allow future extensions of the study. Use of open source software is also compatible with the public purpose goals of this project.

CHAPTER 4:
Conclusions

From the experience gained in the pilot phase study, using wireless sensor network technology is clearly feasible for measuring water and gas flows and temperatures and will provide useful data for understanding the waste of energy and water in residential HWDS.

REFERENCES

IEEE 802.15.4-2006, IEEE Standard for Information technology- Telecommunications and information exchange between systems- Local and metropolitan area networks- Specific requirements Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs).
http://ieeexplore.ieee.org/servlet/opac?punumber=11161

GLOSSARY

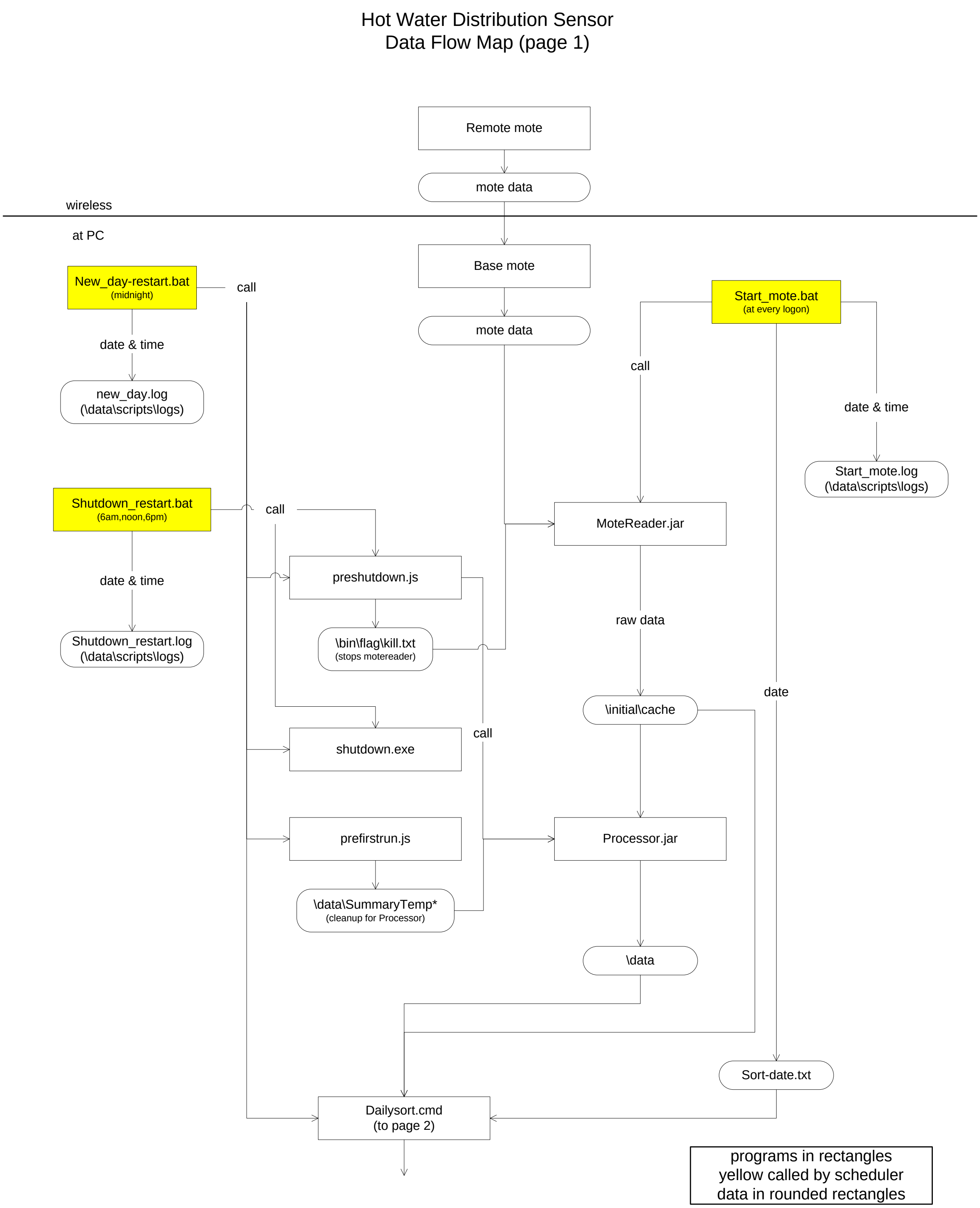
CW	clothes washer
DW	dishwasher
GPM	gallons per minute
HWDS	hot water distribution system
IEEE	Institute of Electrical and Electronics Engineers
LBNL	Lawrence Berkeley National Laboratory
LED	light emitting diode
Mote	data acquisition unit in a wireless sensor network
PC	personal computer
USB	Universal Serial Bus
WH	water heater

Appendix A:
Contents of Data Packets

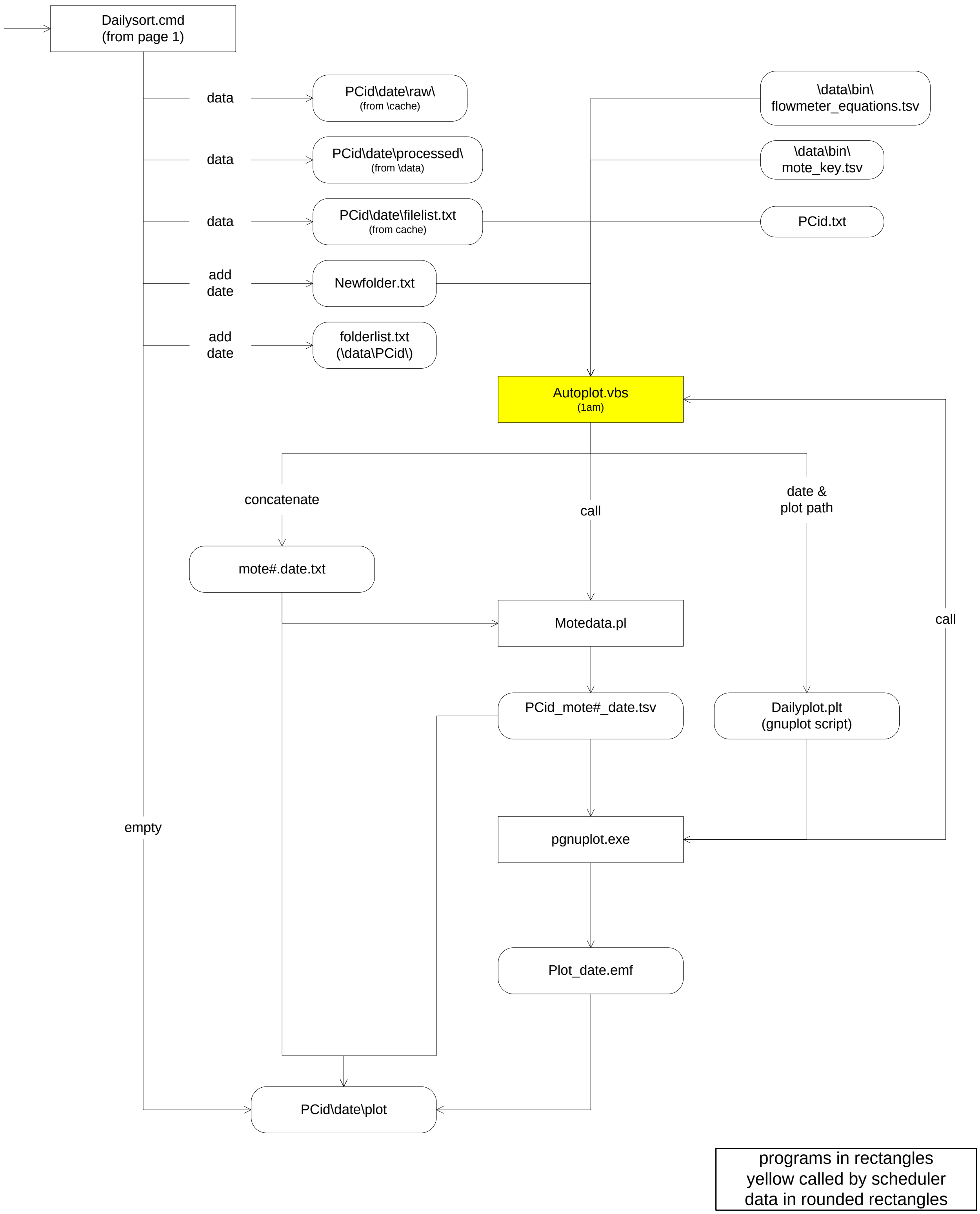
PC id	mote #	time stamp	water flow (pulses / second)					water temperature (^{o}C)					time synch flags			Unix time (1)
memory02	22	Sat Mar 21 11:03:33 PDT 2009	0	0	0	0	28	16.8	16.9	16.8	16.8	16.8	0	1	1	1237658613509

(1) represented as milliseconds since midnight January 1, 1970

Appendix B:
Wireless Sensor Network Data Handling Scheme

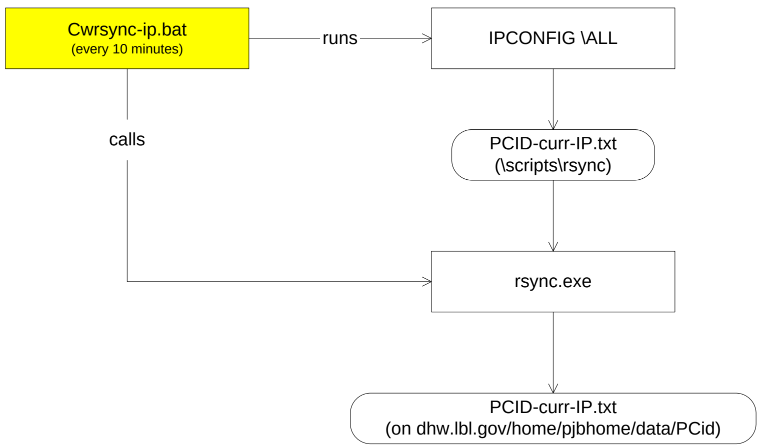


Hot Water Distribution Sensor
Data Flow Map (page 2)

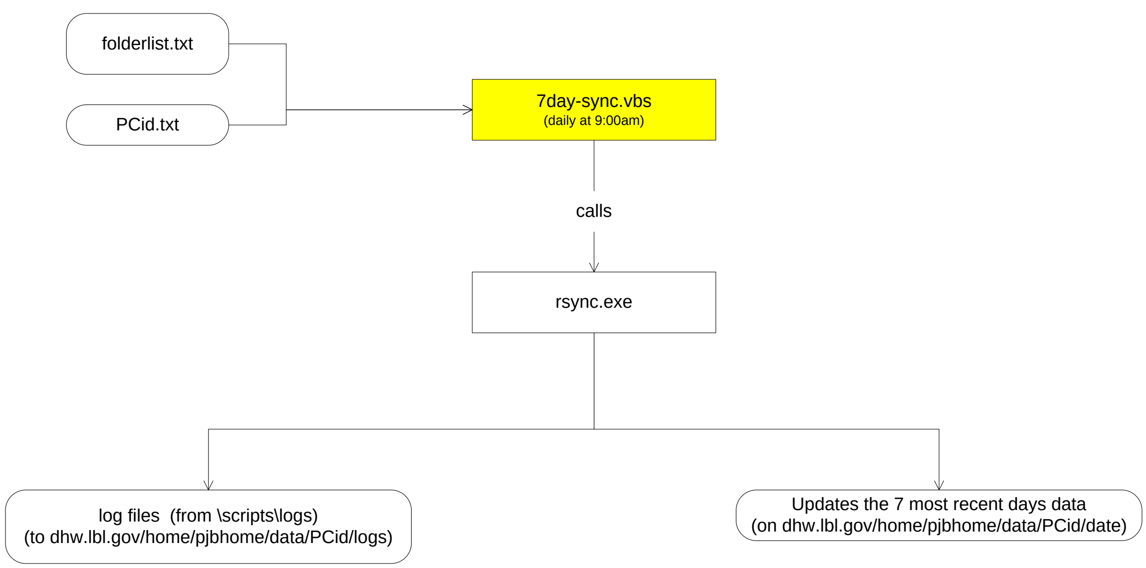


Hot Water Distribution Sensor
Data Flow Map (page 3)

IP update



data update



programs in rectangles
yellow called by scheduler
data in rounded rectangles