THE END USES OF HOT WATER IN SINGLE FAMILY HOMES FROM FLOW TRACE ANALYSIS

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INTRODUCTION

The lack of detailed information on demand patterns for hot water in residences is an established obstacle to accurate designs of advanced hot water systems. An extensive literature review by Becker and Stogsdill (1990) found only seven articles with direct information on hot water use and these mainly provided data on aggregated daily and hourly hot water use in single family residences.[1] Recognizing the need for more detailed information, Hiller (1994) conducted a multi-year study of hot water use in 14 single-family homes.[2] This study collected hot water flow data at 15 second intervals from meters installed on the feed lines to the hot water tanks, in addition to temperature and energy consumption data. The results of the study included a methodology for design of hot water systems using "moving windows" of various lengths on a hot water flow database to generate worst-case hot water demands for intervals ranging from one minute to three hours.

Using the huge database of hot water use obtained in the 1994 Hiller study, work proceeded to find ways to extract information on the end uses of hot water based on the flow characteristics of the hot water demands. Lowenstein and Hiller (1996) described a technique for categorizing the end uses of water using flow data collected from the hot water tank feed line in 15 second intervals.[3] To place the water use into the proper end-use category, the volume of flow and the average flow rate for each hot water draw were grouped into tables where events with similar volume and average flow rate could be identified in a process referred to as "bin analysis". This technique appeared to work quite well for some water use events, but had limitations caused by simultaneous usage and the fact that different end uses can have similar draw characteristics.

In 1998 Lowenstein and Hiller published a second paper on disaggregation of hot water use from a single flow trace.[4] In this paper two methods of improving on the disaggregation technique were proposed. It was suggested that better accuracy could be achieved by making more use of the other characteristics of the "flow signature", or by placing thermocouples on individual hot water branch lines. The use of the flow signature characteristics, such as the time of day, were thought to help separate draws from similar uses such as clothes washers and showers (since presumably showers predominated in the morning while clothes washers were a later in the day use). The use of thermocouples allowed uses on main branches to be either included or excluded from specific end use categories, which helped resolve ambiguities. The approach laid out relies heavily on a purely mathematical analysis in which each water draw needs to be characterized according to its flow rate, volume and location in the system.

At the same time, DeOreo, Heaney, and Mayer (1996) independently examined the same basic approach to disaggregation of single family water demands from short duration flow data.[5] In these studies the recording interval was set at ten seconds and the data were obtained from the standard water meter of the home using a flow recorder capable of sensing the movement of interior magnets in the meter. These water meters were typically 5/8 or 3/4 inch in size and provided resolution ranging from 80 to 100 magnetic pulses per gallon. As such, these meters offer more than adequate resolution of water for the purpose of disaggregating into end uses. These data sets were typically obtained for two-week periods and are referred to as "flow traces." Instead of the bin analysis approach, the flow trace data for this study were analyzed with a computer program that relies on an expert systems approach in which the user (expert) educates the program as to which end use category individual events belong (Mayer et. al. 1996).[6] The program then searches through the remaining database and locates all other events with similar parameters and classifies them accordingly. In a recent EPA study in Seattle, Washington duplicate meters were installed on the feed lines to the hot water tanks, and simultaneous flow traces were obtained from both the hot and cold water lines (DeOreo, et. al. 2000).[7] This paper explains how these data were used to characterize the hot water demand according to end use, and it presents results from the Seattle homes. Additional studies that include hot water end use monitoring are being conducted in 2001 and these results will be published as they become available.

FLOW TRACE ANALYSIS

The disaggregation process used in this study is similar to that explained by Lowenstein and Hiller (1996). It starts with records of short interval flows, then assembles sets of flows down into water use draws or events, and assigns them to end use categories such as toilet, shower, faucet, or clothes washer. The main difference in the authors' approach is the linkage between end use categories and the water use events. Where the earlier approach appears aimed at a purely mathematical analysis, the authors' technique relies on a specialized expert systems computer program, which stores the parameters of each water use event, and assigns it to one of several end use categories. The program then finds all other water use events with the same parameters (within a range) and assigns them to the same category. A key to this approach is that a trained analyst works with each flow trace data set using a detailed graphical user interface (GUI) to train the program to identify the proper end uses for events which otherwise might be difficult or impossible to categorize unambiguously. This technique requires some effort during analysis, but it greatly reduces the set up time and hardware required at the individual sites and the amount of peripheral data that must be obtained from each customer (such as thermocouples). In most cases it is possible to accurately quantify the water used for each major end use category without ever entering the home or disturbing the residents.

The analysis software program is designed to identify three types of water use events: trickle events, primary events, and super-events. A trickle event is a very small event, most often a leak. A primary event is one that starts and ends at a baseline flow at or near zero. This is by far the most common and important type of water use event. A super-event is one that begins and ends at a non-zero baseline while a primary event is occurring. This is the case when a second water use begins while another is still in progress such as a toilet flush while someone is taking a shower. The super-events are treated as separate water uses having their own flow characteristics.

The computer program stores important statistical information about each water use event that are used in the classification process. These include the start time, stop time, duration, volume (gal), peak flow rate (gpm), mode flow rate, and the mode number (the number of times that the mode flow occurs during the event). The mode flow rate for each event is important since many times events like showers start off with a high flow and drop to a lower flow after the user either adjusts the water temperature or, for bathtub/shower combos, closes the diverter valve sending water from the high-flow tub faucet to the restricted flow shower.

The analyst, working with an established library of flow trace signatures and his own experience, can quickly and accurately classify toilets, showers, clothes washers, dishwashers, faucets, and leaks. The analyst also has the advantage of seeing the flow data presented in graphical form using the GUI. Using the GUI, flow graphs can be scrolled in windows across the screen, which helps the analysts take advantage of the association of water use events which might otherwise be impossible to properly identify. For example, the small pulses of water which often follow the rinse cycle of a clothes washer could be difficult to distinguish from toilets, or faucets, but can be easily identified because of their association with the rinse washing cycle. Typically, an analyst can complete analysis of a two-week flow trace (≈120,000 individual flow records) in approximately one hour. Experience has shown that, except to access water meters located inside, it is not normally necessary to enter the houses at set-up since the types of fixtures and appliances can be easily recognized.

The flow trace analysis approach was the primary data collection technique used in a large study of single family water use in 12 cities, the Residential End Uses of Water Study (REUWS), which was sponsored by the American Water Works Association Research Foundation (Mayer et. al. 1999).[8] In the REUWS, four weeks of water use data were collected from 1,188 homes in two separate two-week intervals in the winter and summer from 1996 to 1998. The resulting database of water use events contained over 1.9 million records.

The Seattle EPA study, on which the current paper is based, was a follow-up to the REUWS, aimed at measuring the impact of retrofitting existing fixtures and appliances with water efficient models. As a part of the Seattle study water meters were installed on the feed lines to the hot water tanks and simultaneous flow traces were obtained from both the main meter and the hot water feed meter. A total of ten homes were equipped with hot water meters, and were used for the analysis in this paper. There were an average of 2.6 residents in the homes studied. The main purpose of this hot water analysis was to determine the savings in hot water use effected by the water efficiency measures, however this analysis also provided detailed information on baseline hot water use patterns, which is of primary interest to the heating industry. All the data presented in this paper were recorded during the baseline sample period, prior to any retrofits, because this was deemed to be more representative of the population of single-family homes.

ANALYSIS OF HOT WATER TRACES IN COMBINATION WITH MAIN METER TRACES

Installation of the water meters on the hot water feed lines was a fairly simple task, which took a plumber less than 1/2 hour per installation. Once the meter was in place, simultaneous flow traces were obtained from the hot water feed and the main feed lines using two flow recorders. During analysis the two flow traces were analyzed simultaneously (see Figure 1). The analyst was able to examine the flow traces recorded from the main meter and the hot water meter in separate graph windows.

The addition of the main meter flow trace was a tremendous help in disaggregating the hot water trace. Water uses recorded from the hot water meter in isolation could be difficult to accurately categorize, but with the main meter flow trace available the fixture or appliance responsible for each end use became readily apparent. For example, varying the wash setting on a clothes washer changes the volume of hot water used. This can make a single hot water draw from a washer have the same statistical characteristics of a faucet or a shower. Also, it was found that many people use the warm/cold setting, so that hot water is only used during the wash cycle, which can result in a single hot water use event, which can be ambiguous to place. However, no matter which setting the user chooses, the main trace will still maintain the same unmistakable multi-cycle clothes washer pattern, so the analyst could easily determine that the single hot water event is part of a clothes washer.

Showers, when viewed by themselves can be deceptive, but they stand out when seen in conjunction with the main flow trace. In Figure 1, the flow trace from the main meter is on top and the hot water flow trace is on the bottom. There are a total of eight events shown in the main trace: a shower, two toilet flushes, four faucet uses, and a final toilet flush. Only three of these events include hot water: the shower and two of the faucets. The shower event in this example consumed a total of 16.2 gallons of water, of which 9.5 gallons (59%) were hot water. Adjusting the water temperature consumed almost half of the shower duration. Initially more cold water was used and the hot water was gradually increased; then decreased a bit until the proper temperature was finally reached. After this the flow rates of hot and cold water remained constant for the remainder of the shower. The mode flow for hot water was 1.7 gpm and 2.4 gpm for the main meter. About 70% of the total water draw for this shower event was for hot water.

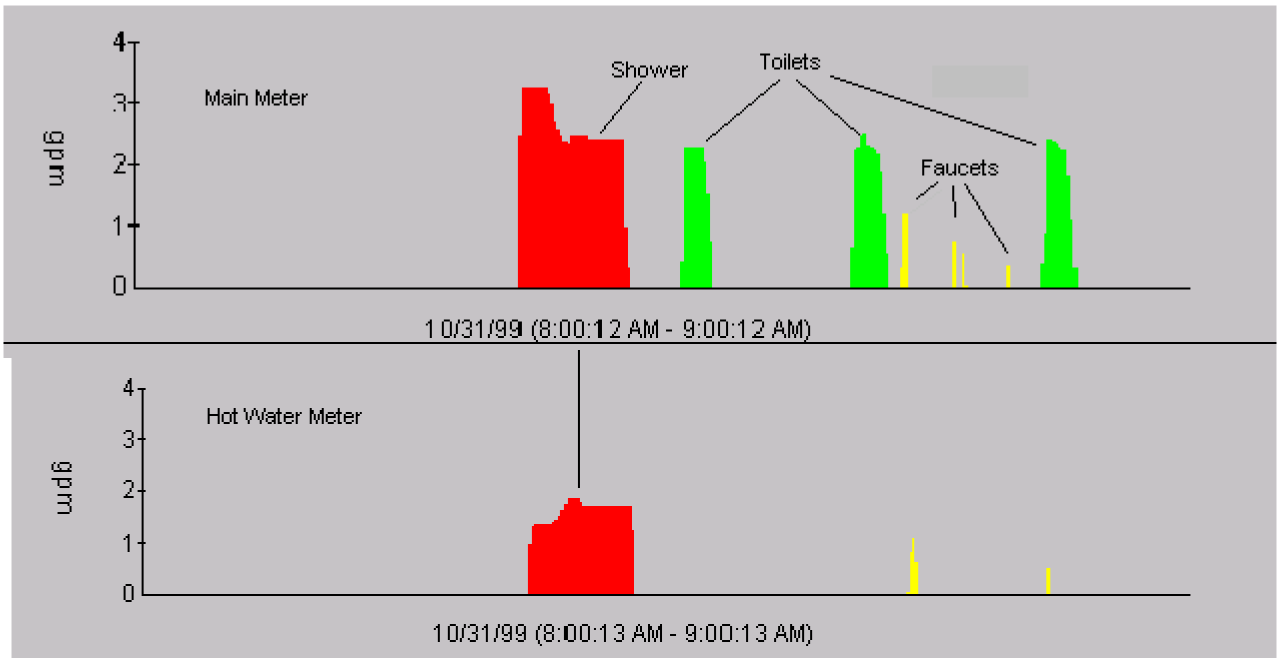

Figure 1: Simultaneous Flow Traces from Main (top) and Hot Water (bottom) Meters

HOT WATER USE BY END USE

The summary statistics for the hot water use in the ten hot water study homes recorded over the fourteen-day observation period are provided in Table 1. This table shows the peak hot water flow rate (gpm), volume (gal), duration (min), and the average flow rate (gpm) of the recorded hot water events (draws) for each of the identified end-uses: baths, dishwashers, showers, faucets and clothes washers. The 95% confidence interval for each mean value is also shown, providing an accuracy estimate of the mean. The data for dish washers and clothes washers are for individual draws; not for the entire appliance use cycle. The accuracy of these data is evident from the fact that the confidence intervals were normally 10% or less than the value of the means.

Table 1: Hot Water End Use Statistics in Ten Seattle Homes over 14 Days

Hot Water Use Events		Peak Flow (gpm)		Volume (gal)		Duration (min)		Avg. Flow (gpm)	
	n	Mean	Conf Int (95%)	Mean	Conf Int (95%)	Mean	Conf Int (95%)	Mean	Conf Int (95%)
Baths	101	3.16	0.34	9.48	1.42	4.60	0.73	2.23	0.28
Dishwashers	164	1.67	0.07	1.47	0.11	1.19	0.08	1.23	0.05
Showers	181	2.23	0.12	11.62	1.15	7.40	0.59	1.51	0.06
Faucets	4329	1.24	0.02	0.59	0.02	0.72	0.03	0.91	0.02
Clothes washers	168	2.43	0.14	7.28	0.88	3.17	0.33	2.10	0.13

HOUSEHOLD AND PERCAPITA HOT WATER USE

Table 2 provides information on daily hot water use by end-use on a per capita and per household basis. Faucet use is the largest hot water end use, followed by showers, baths and clothes washers. While dishwashers are the only appliance to use 100% hot water for their operation, they consume a relatively small fraction of the total hot water use (3.6%). Overall, the household hot water use measured in these home is in the same range as the homes studied by Lowenstein (1996).

Table 2: Household and per capita hot water use

Category	Per Capita (gcd)	Household Use (gal per day)	Percent of Total Hot Water Use	Percent of Overall Water Use that is Hot Water
Bath	4.2	10.9	16.7	78.2
Clothes Washer	3.9	10.1	15.5	27.8
Dishwasher	0.9	2.3	3.6	100
Faucet	8.6	22.4	34.3	72.7
Leak	1.2	3.1	4.8	26.8
Shower	6.3	16.4	25.1	73.1
Toilet	0.0	0	0	0.0
Other	0.01	.03	0	35.1
Indoor Total	25.1	65.3	100%	39.6%
Sample size	*10*			
Avg. # of residents	*2.6*			

HOURLY USE PATTERNS BY END-USE

Knowing the time of day when each end use occurs can be a useful design criterion and analysis parameter. Figure 2 shows the percent of each end use, which occurs during each hour of the day. This figure is based on water use in a sample of 1,188 homes studied in the late 1990s in the REUWS (Mayer et. al., 1999). The values represent the percentage of each category which occurs during each hour of the day. For example, just under 12% of the total shower usage occurs between 5 and 6 AM and just under 24% of shower use occurs between 5 and 7 AM. Thus 24% of the hot water used for showers will be used during this period. The peak period for clothes washing occurs slightly later, between 9 and 11 AM.

CONCLUSIONS

Collecting simultaneous flow traces from the main water meter and a meter installed at the feed line to the hot water tank can provide accurate data on the end uses of hot water in single family homes. This is an efficient and effective data collection methodology that eliminates the need for thermocouples or other intrusive devices. The expert systems software developed to disaggregate and categorize water uses greatly simplifies the analysis and provides statistics on peak flow, mode flow, and duration of each water use event. This approach can distinguish simultaneous water use events, and yields a detailed database of individual water use events for customized analyses.

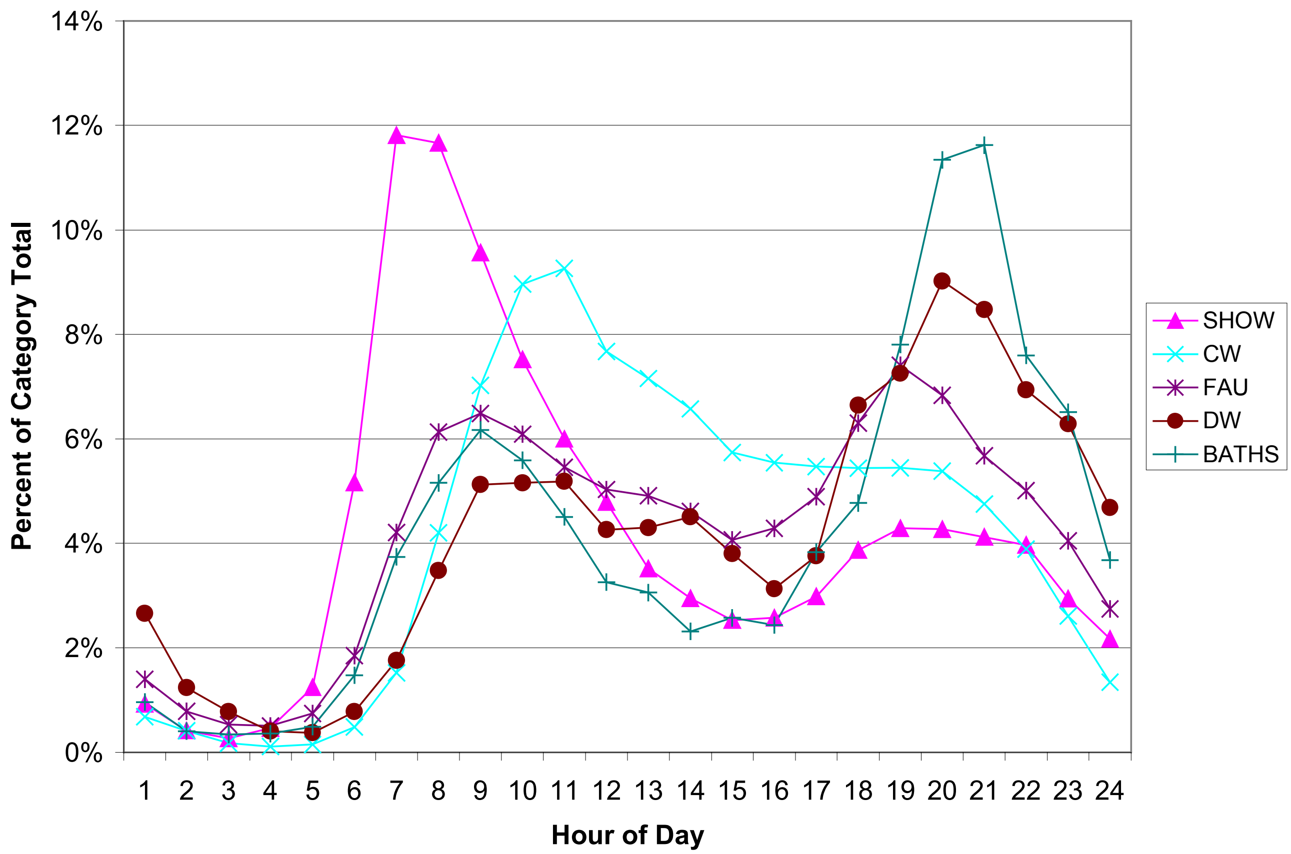

Figure 2 : Hourly Percent of Use by Category

The data on peak flow rate, volume, duration, and average flow rate presented here should be useful in design of hot water systems. The confidence intervals around these values indicate a high probability that the values are representative of actual values for the population as a whole. The data on hourly breakdown of each end-use show that with the exception of clothes washers, which peak in late morning, the other uses all tend to peak fairly simultaneously, from early to mid morning and again in the early evening. This makes it harder to use the start time of events as a reliable parameter for disaggregation. On the other hand, use of event peak flow, volume, duration and mode flow in combination with the expert systems analysis has been found to provide reliable results with relatively little effort.

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