Title

TYPICAL HOT WATER DRAW PATTERNS BASED ON FIELD DATA

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TYPICAL HOT WATER DRAW PATTERNS BASED ON FIELD DATA

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TYPICAL HOT WATER DRAW PATTERNS BASED ON FIELD DATA

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EXECUTIVE SUMMARY

There is significant variation in hot water use and draw patterns among households. This report describes typical hot water use patterns in single-family residences in North America. We found that daily hot water use is highly variable both among residences and within the same residence. We compared the results of our analysis of the field data to the conditions and draw patterns established in the current U.S. Department of Energy (DOE) test procedure for residential water heaters[1]. The results show a higher number of smaller draws at lower flow rates than used in the test procedure.

The data from which the draw patterns were developed were obtained from 12 separate field studies. This report describes the ways in which we managed, cleaned, and analyzed the data and the results of our data analysis.

After preparing the data, we used the complete data set to analyze inlet and outlet water temperatures. Then we divided the data into three clusters reflecting house configurations that demonstrated small, medium, or large median daily hot water use. We developed the three clusters partly to reflect efforts of the ASHRAE standard project committee (SPC) 118.2 to revise the test procedure for residential water heaters to incorporate a range of draw patterns. ASHRAE SPC 118.2 has identified the need to separately evaluate at least three, and perhaps as many as five, different water heater capacities. We analyzed the daily hot water use data within each cluster in terms of volume and number of hot water draws. The daily draw patterns in each cluster were characterized using distributions for volume of draws, duration of draws, time since previous draw, and flow rates.

TYPICAL HOT WATER DRAW PATTERNS BASED ON FIELD DATA

INTRODUCTION

Hot water draw patterns are a record of the timing and volume of the flow of water from a water heater. In residential buildings, people use heated water for showers, baths, and washing at sinks. Hot water also is used by dishwashers and clothes washers. Because water heating represents one of the largest energy end-uses in residential buildings, it is an important consideration in energy efficiency standards and programs for both appliances and buildings. The dearth of field research regarding the functioning of domestic hot water systems in residential buildings has meant that test procedures, standards, and guidelines have had to rely on assumptions and engineering calculations. Expanding our understanding of draw patterns will support improved test procedures, system designs, and sizing guidelines. Other beneficial effects include the ability to calculate residential hot water use in support of energy policies and standards.

The project described here aims to enrich our understanding of typical hot water draw patterns in single-family residences based on field data. The data were collected from a range of recent studies. Although none of the studies were performed solely to evaluate hot water draw patterns, the data from the studies can be used for that purpose. We collected, cleaned, and collated hot water use data from 12 independent studies. The data represent hot water flow for entire houses measured at the water heater. In some instances the data were collected from an apartment or town house unit. We used such data only if the unit had its own dedicated water heater. Because the data were collected at the water heater, we obtained no information about hot water use at fixtures or fittings.

BACKGROUND

Beginning in 2007, ASHRAE standard project committee (SPC) 118.2 has worked to revise the test procedure for residential water heaters.[2] ASHRAE SPC 118.2 seeks to make the test procedure more representative of efficiency performance in actual use and to provide for rating all technologies consistently. The committee intends to incorporate a range of draw patterns and has identified the need to separately evaluate three, and possibly as many as five, water heater capacities. SPC 118.2 will consider field data in developing the total daily volume of hot water use, total daily number of draws, flow rates, intervals between draws, and the durations of hot water draws for use in performing simulated-use tests. Inlet and outlet water temperatures observed in the field data also will be considered.

AHRI also is reviewing and amending test procedures for water heaters. The Water Heater Section of AHRI has created a working group to address the DOE test method for residential water heaters. They seek to develop and recommend to DOE a test procedure based on industry consensus. They are developing draw patterns and investigating test results for them.

DOE currently is reviewing and revising its test procedure for residential water heaters. In 2011 the Department issued a request for information regarding test procedures for residential water heaters.[3] Many of the questions posed in the request for information were the same ones being addressed by ASHRAE and the Air-Conditioning, Heating, and Refrigeration Institute (AHRI).

We hope that our analysis of field data will inform the various efforts underway to improve both the DOE water heater test procedures and the understanding of typical residential hot water draw patterns that underlies those test procedures.

DATA SOURCES

As we researched studies that could provide data for our analysis of hot water draw patterns, we encountered several issues related to using a collection of studies.

- The data were presented in inconsistent formats and used inconsistent units and/or file types.
- The studies had a variety of goals, not always related to hot water draw patterns.
- The studies used a variety of data-recording intervals, ranging from 1 second to 1 minute.
- The studies applied different data acquisition strategies, for instance as regards whether to record data at set intervals or only when water was flowing.

One criterion for selecting studies was that the data must have been collected at a recording interval of 1 minute or less. Another criterion was that the source study must have been conducted after 1995. Although our focus was on field data regarding hot water flows, some studies also recorded the temperature of the water entering and leaving the water heater. When temperature data were available, we collected those as well. The data used for this study builds on an earlier database,[4] incorporating data from two additional studies. Further quality assurance tests have been applied to data associated with draws involving extreme flow rates and minimum volume draws.

To date our database of field data on hot water use encompasses:

- 12 studies;
- 159 monitored houses;
- 250 monitored house configurations (of water heaters and/or hot water end-uses);
- 33,470 days of monitoring

- 22,902 good days (days providing acceptable data);
- 21,491 days of monitoring that included inlet water temperatures;
- 1,679,668 hot water draws; and
- 12,985,212 records of hot water flow.

The locations of the houses monitored in the 12 studies are indicated on 0.

Figure 1 Locations of Monitored House Configurations

Each circle in Figure 1 represents one monitored house configuration. The size of each circle is proportional to the number of days it was monitored. Some studies changed something in the house—perhaps the water heater or the hot water-using devices—during the monitoring period. To account for those changes, we considered that the house after the change was a different house configuration.

Table 1 summarizes the characteristics of the source studies examined to date. The studies are described further following the table.

Table 1 Characteristics of Source Studies

Researcher/Funder	Focus of Study	No. of Houses	Duration, Date	Region/ State	Record. Interval
Davis Energy Group and the Gas Technology Institute, funded by the California Energy Commission, Public Interest Energy Research program*	Field performance of advanced residential gas water heaters	18	8 mos. pre-retrofit and 4 mos. post-retrofit, April 2010–June 2011	Northern & Southern CA	4 seconds
Minnesota Center for Energy and the Environment (MNCEE), funded by the Minnesota Office of Energy Security	Field performance of natural gas storage and tankless water heaters	24 water heaters in 10 homes	December 2008–June 2010, with units alternated monthly	Minneapolis St. Paul region of MN	1 second
National Renewable Energy Laboratory (NREL) performed with Integrated Building and Construction Solutions (IBACOS)	Monitoring new energy efficient houses that include combined space and domestic water heating (solar)	2	341 days, 2008-2009; and 50 days, 2009	Boulder, CO, and Greensburg, KS	1 and 5 seconds
Natural Resources Canada	Evaluate usefulness of established regulations	40	2 to 4 weeks, October 2007–July 2008	Ottawa area	2 seconds
Gas Technologies Institute (GTI)	Field test of prototype condensing units for combined space and domestic water heating	29	Generally 2 phases, 2 to 13 mos. each, 2004-2006	Nationwide	30 seconds
Johnson Research, LLC, performed for Northeast Utilities*	Demand electric water heaters	2	3 mos., 2003–2004	CT	1 minute
Davis Energy Group*	Efficiency of hot water distribution system	1	9 mos., 2003-2004	Northern CA	2 seconds

Researcher/Funder	Focus of Study	No. of Houses	Duration, Date	Region/ State	Record. Interval
TIAX LLC, performed for California Energy Commission Public Interest Energy Research program*	Field test of prototype "market-optimized" heat pump water heater	16	From 6 to 27 mos., 2002–2003	CA	1 minute
Aquacraft, Inc., performed for East Bay Municipal Utility District and U.S. Environmental Protection Agency (EPA)	Compare pre- and post-retrofit water use by end-use	10	Typically 2 weeks pre-retrofit and 2 weeks post-retrofit, 2001-2002	East Bay Area, CA	10 seconds
Aquacraft, Inc., performed for Seattle Public Utilities and U.S. EPA	Compare pre- and post-retrofit water use by end-use	10	Typically 2 weeks pre-retrofit and 2 weeks post-retrofit, 1999–2000	Seattle, WA	10 seconds
AIL Research, Inc., performed for Northeast Utilities*	Estimate cost savings of heat pump water heaters	30 (2 phases of 15 houses each)	9 mos. each: 09/98–05/99 and 07/99–03/2000	CT and MA	1 minute
National Association of Homebuilders, performed for Geothermal Heat Pump Corporation and (NREL)*	Geothermal water heating	5	17 mos., 1997–1999	Cleveland, OH	1 minute

* Data included temperature as well as flow data.

Each of the 12 studies from which we derived data is described more fully below.

1. Davis Energy Group and the Gas Technology Institute: Water Heater Field Study[5]

The Davis Energy Group and the Gas Technology Institute (GTI) performed this field study of advanced residential gas water heaters. The study, which was funded by the California Energy Commission (CEC) Public Interest Energy Research program, monitored pre-and post-retrofit water heaters in Northern and Southern California. The existing water heaters in 18 homes were monitored for as long as 8 months, at which time an advanced gas water heater (selected from a variety of condensing and non-condensing storage and tankless units) was installed and monitored for 4 additional months.

2. Minnesota Center for Energy and Environment[6]

The Minnesota Center for Energy and Environment (MNCEE), with funding from the Minnesota Office of Energy Security, ran a 2-year field project monitoring a variety of storage and tankless gas water heaters. Ten sites were selected to reflect Minnesota's mix of household sizes for single-family detached housing in the 2000 U.S. Census in Minnesota. Homes were equipped with additional water heaters, and usage alternated monthly among two or three water heaters. Approximately a year's worth of data were collected at each home. The study concluded that the high installed cost of tankless water heaters, resulting in a simple payback period of 20 to 40 years, limits their feasibility.

3. National Renewable Energy Laboratory[7, 8]

Data were obtained for two studies performed for the Building America Program, which is sponsored by DOE through the National Renewable Energy Laboratory (NREL). One study7 involved testing and monitoring the energy consumption of various features of newly built and purportedly energy efficient row houses in Colorado (2007–2008). Features included solar hot water systems providing hot water for both space heating and domestic use. The second study8 describes efforts to coordinate and monitor the implementation and performance of new energy efficient (green) homes in Kansas.

4. Natural Resources Canada[9]

Natural Resources Canada performed field testing to determine whether current regulations and standards regarding residential hot water heaters remain appropriate for today's new technologies, in particular advanced residential gas water heaters. The study measured flow rate and number, duration, and volume of hot water draws at 40 sites. Each site was monitored for 2 to 4 weeks.

5. The Gas Technologies Institute Condensing Water Heater Field Study

The Gas Technologies Institute performed this field study to evaluate a prototype condensing gas water heater designed for combination space and water heating applications in residences. The product was tested in various types of homes throughout the United States during 2004–2006. The project involved metering water flow at 29 houses at 30-second intervals. Although no report of this study has been released, the researchers provided the data on domestic hot water use to us.

6. Johnson Research LLC Demand Electric Water Heater Study[10]

In this study, performed for Northeast Utilities, two whole-house demand (also known as tankless or instantaneous) electric water heaters were monitored and their performance compared to customers' existing gas or electric storage water heaters. The goal was to help Connecticut Light and Power, an operating company of Northeast Utilities, increase understanding of demand water heaters and evaluate their savings potential. Each week the source of household hot water was alternated between the demand heater and the storage heater. Data were collected every week throughout a 3-month test period during 2003–2004. Flow and temperature data from the two monitored houses were provided to our study.

7. *Davis Energy Group Water Heater Field Study*6[11]
In this study, hot water usage was monitored for one house in Northern California to better understand factors that affect the energy efficiency of hot water distribution systems. Data were collected at 2-second intervals for 9 months in 2003 and 2004.

8. TIAX LLC Heat Pump Water Heater Study[12]
With funding from the CEC's Public Interest Energy Research program, TIAX LLC field-tested a new "market-optimized" prototype heat pump water heater. The goal was to refine the design of the prototype product through both laboratory and field testing. The study provided supplemental information for a previous project in which two generations of prototype market-optimized heat pump water heaters were developed and tested. To evaluate this third-generation prototype, data were recorded every minute in 20 California homes. Monitoring periods ranged from 6 to 27 months. Flow and temperature data for 16 residential sites were made available to our study.

9. Aquacraft, Inc., *Indoor Residential Water Conservation Study*[13]
This study evaluated the impacts and acceptance of high-quality water conservation fixtures and appliances in single-family homes in the East Bay Area of California. The East Bay Municipal Utility District and the U.S. EPA funded the study, performed by Aquacraft, Inc. The study involved a before-and-after comparison of water use patterns from 33 single-family homes in the district's service area. Hot water use was recorded at 10 of the 33 houses for 6 to 8 weeks. Flow data from all 10 houses were made available for our study.

10. Aquacraft, Inc., Home Water Conservation Study[14]
This study was a before-and-after comparison of water use patterns in 10 single-family homes in the Seattle area. Aquacraft, Inc., performed the study to measure the impacts of various indoor water conservation fixtures and appliances on both aggregate and individual water use patterns. Acceptance of the water conservation fixtures and appliances also was evaluated. The 10 houses were monitored for periods ranging from 2 to 8 weeks in 1999–2000. Data were recorded every 10 seconds. Flow data from all 10 houses were made available for our study. The study was funded with a grant from the U.S. EPA and by the Seattle Public Utilities.

11. AIL Research Heat Pump Study[15]
This field study was performed for Northeast Utilities to determine the efficiency and cost savings of newly installed heat pump water heaters in 30 houses. Two sets of field measurements were collected during 9-month intervals from 1998 to 2000. The goal was to predict the operating cost savings of heat pump water heaters.

12. National Association of Homebuilders Research Center Geothermal Water Heating Study[16]
This study was intended to provide potential users of geothermal water heating systems with information that would increase confidence in sizing methods and system performance. Data collection and analysis were performed on five newly built homes in the greater Cleveland, Ohio, area. The houses were monitored at 1-minute intervals for approximately 17 months in 1997–1999. Flow and temperature data for three houses were made available for our project. The study was performed for NREL and the Geothermal Heat Pump Consortium.

Some of the projects described above studied individual houses; in others different configurations or modes of operation of hot water systems were evaluated. In the MNCEE study, for instance, homes were equipped with multiple water heaters, and usage changed monthly. In Johnson Research's study for Northeast Utilities, the source of household hot water was alternated weekly between a demand and a storage water heater. For each case of multiple configurations in our database, we assigned a separate identification numbers to each house configuration. Our database thus contains more house configurations than houses, and the following discussion generally refers to house configurations. The database contains 159 monitored houses and 250 monitored house configurations.

APPROACH

We obtained the data from each study in their original structure and format. The 12 studies provided huge quantities of data that were impossible to analyze by hand or with spreadsheets. We used software scripts to automate the process, reduce errors, and provide for a consistent analysis. The scripts also enabled us to re-run computations easily to include refinements and corrections. Figure 2 illustrates the method we applied to process the data.

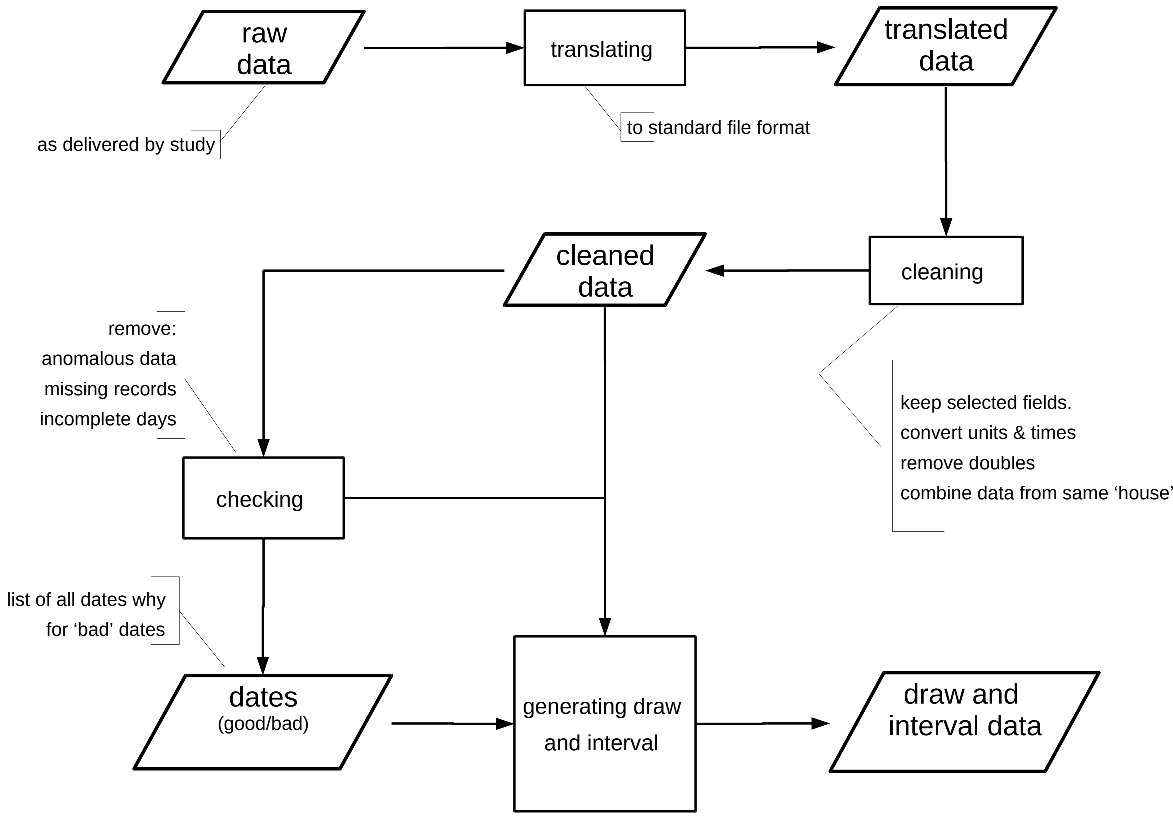

Figure 2 Flowchart of Data and Programs

Data Preparation

The following sections describe the steps we took to begin preparing the vast quantity of data for analysis.

Translating

Data from the 12 studies were supplied in a range of file formats—spreadsheets, databases, proprietary binary files, ASCII text files, and so on. Our first step was to translate the data from all studies into a consistent format of comma-separated values.

Cleaning
Cleaning scripts were used to clean the translated data files for each study. Cleaning meant retaining only selected fields, changing the date and time formats, converting units (if needed), combining all the data from the same house into one file, and removing duplicate records.

Checking
After completing the translating and cleaning steps, we performed an automated quality assurance check on the data. We had records for 33,470 days of monitoring for all houses in the database. Of those, 22,902 days passed the checking criteria. We had two broad criteria for checking the quality of data for a day: whether the data were complete and whether they were good.

We applied the completeness criterion to avoid using data from incomplete days. Because hot water use shows daily cycles, we included a day only if we had a complete set of good data for that day. Otherwise, it was classified as a "bad" day and excluded. We did not want, however to exclude days when the occupants used no hot water but the data were complete. We applied the completeness criterion to studies that recorded data continuously. For those data sets, no more than 30 minutes total and no more than 10 continuous minutes of data could be missing during a day.

Two studies recorded data both when hot water was flowing and once every 15 minutes even if water was not flowing. If more than two 15-minute "heartbeat" records were missing, equivalent to missing 30 minutes of data, we excluded that day. For the studies that recorded data only when water was flowing, we excluded both the first and last day of the monitoring period if data recording started after noon.

Regarding the second broad criterion (whether the data were good), if some of the data for a day were implausible, we excluded the entire day's worth of data on the assumption that something was wrong with the data collection system that day. For studies in which water temperatures were recorded, inlet and outlet water temperatures had to be between freezing and boiling. In addition, the highest incoming cold water temperature for any day had to be less than the highest outgoing hot water temperature for the same day.

We visually examined some data sets for which the summary data exhibited suspicious patterns. Based on that examination, we manually removed certain days for certain house configurations from the data set. For example, we removed data for one house for which the highest and lowest inlet temperatures were 10 to 20 degrees above those for all the other days for that house. We also removed data for a day when a single draw of about 2,000 gallons was recorded. Eventually, we used data only from good days.

Generating Draw and Interval Data

The resulting data set contains the measured volume of hot water for each time interval when water flow was detected for every household in every study that provided useable data. We also included the cold (inlet) and hot (outlet) water temperatures when available. After checking all the data, we generated draw and interval data for good days only. To calculate individual draws, we examined the measured volume of hot water for each time interval. For the analysis we considered a draw to be a period of uninterrupted flow of water through the water heater. When the flow stopped for at least one data-recording interval, we considered that draw to have ended. Our definition means that overlapping draws made for different uses were counted as one draw. It also means that if two draws were separated by an interval shorter than the data-recording interval, they were treated as one draw.

We recorded the start time and duration of each draw. We did not correct the start time and duration for flows that occurred for only part of a monitoring interval, because the data could not tell us when during the interval the flow had occurred. From those data we calculated the time elapsed since the previous draw. We also calculated and recorded the total volume of hot water for each draw.

Additional Cleaning

Even after we performed the cleaning and checking steps, the field data contained a few extraneous or unusual data. Although we could not identify the reasons for the unusual data, any days having anomalous data were removed from the data set.

One reason for excluding days was the presence of extremely high flow rates, which we defined as flow rates that exceeded 12 gallons per minute. Any day on which any recorded hot water flow rate exceeded 12 gallons per minute was excluded from the analysis. The other reason for excluding data was draws having unbelievably low-volumes. Some studies recorded draws having very small volumes. Those small draws probably do not represent actual use of hot water. They may be the result of pressure fluctuations in the house's plumbing system that trigger a reading by the flow meter. Or the draws may reflect small leaks. It seemed prudent to exclude such draws from the analysis, because they likely do not represent intentional hot water uses. We excluded from the analysis any days on which more than 2 percent of the total volume of hot water use was from such very small draws.

To complicate matters, different studies used different flowmeters; sometimes two different types were used in one study. The flowmeters might require different minimum flow rates for recording or might incorporate different recording intervals. We assigned a minimum volume of flow for the recording interval in each study. We dropped from the data set any short draws having the minimum flow, believing the data did not reflect an actual intentional use. Table 2 lists the minimum recorded volumes and recording intervals of the 12 studies.

Table 2 Minimum Volumes and Recording Intervals by Study

Study	Minimum Recorded Volume (gallons)	Recording Interval (seconds)
Davis Energy Group/GTI for California Energy Commission	0.002	4
Minnesota Center for Energy and Environment	0.0050	1
National Renewable Energy Laboratory	0.003 0.013	5 1
Natural Resources Canada	0.0066 0.0132	2
Gas Technologies Institute (GTI)	0.1	30
Johnson Research for Northeast Utilities	0.00660 0.00661	60
Davis Energy Group	0.0019	2
TIAX LLC for CEC	0.0044 0.0079 0.0084 0.0092 0.01	60
Aquacraft for East Bay Municipal Utility District	0.002	10
Aquacraft for Seattle Public Utilities	0.002 0.008	10
AIL Research for Northeast Utilities	0.007	60
National Association of Homebuilders for Geothermal Heat Pump Corporation and NREL	0.003 0.02	60

If the total volume of minimum draws in one day was more that 2% of the total volume of hot water used in that day, we excluded that entire day. This is shown in Figure 3. Figure 4 shows the cumulative number of days by fraction of total hot water use by minimum draws.

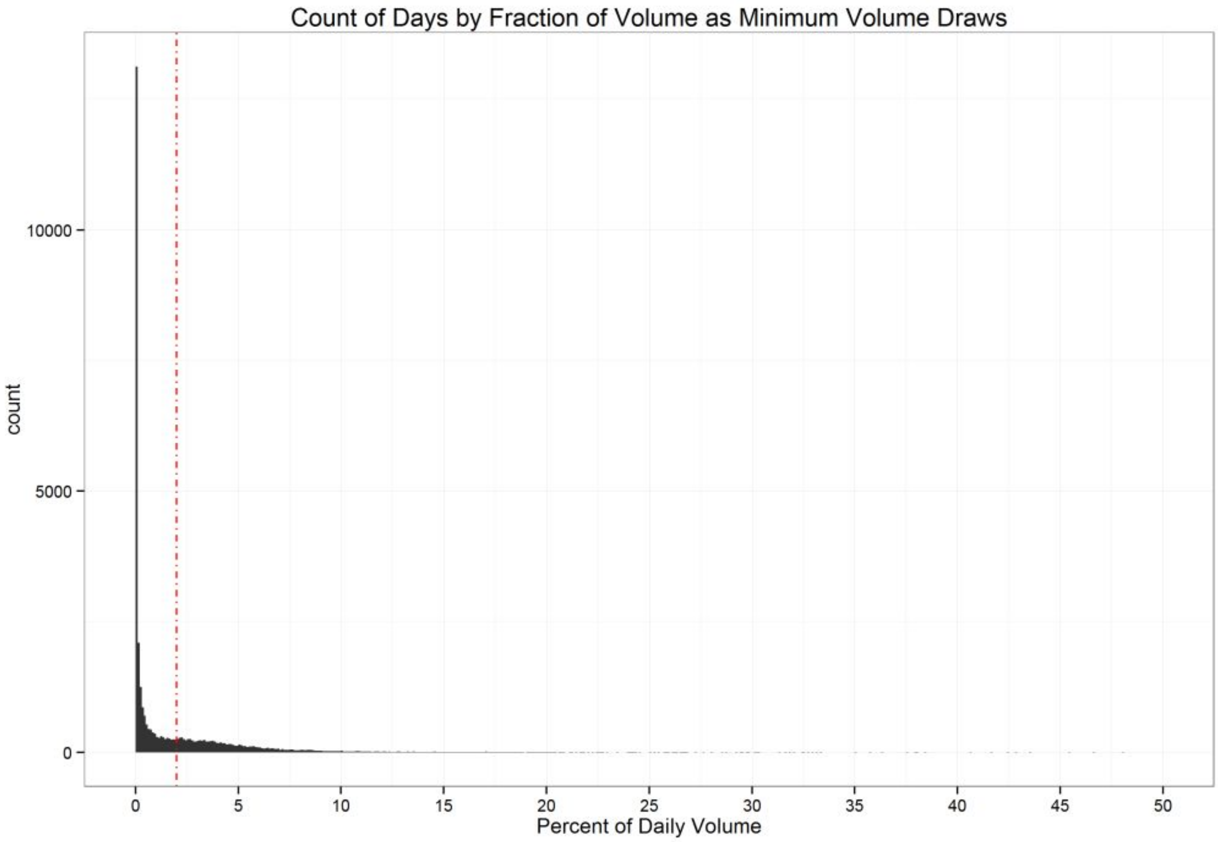

Figure 3 **Number of Days by Fraction of Volume as Minimum-Volume Draws**

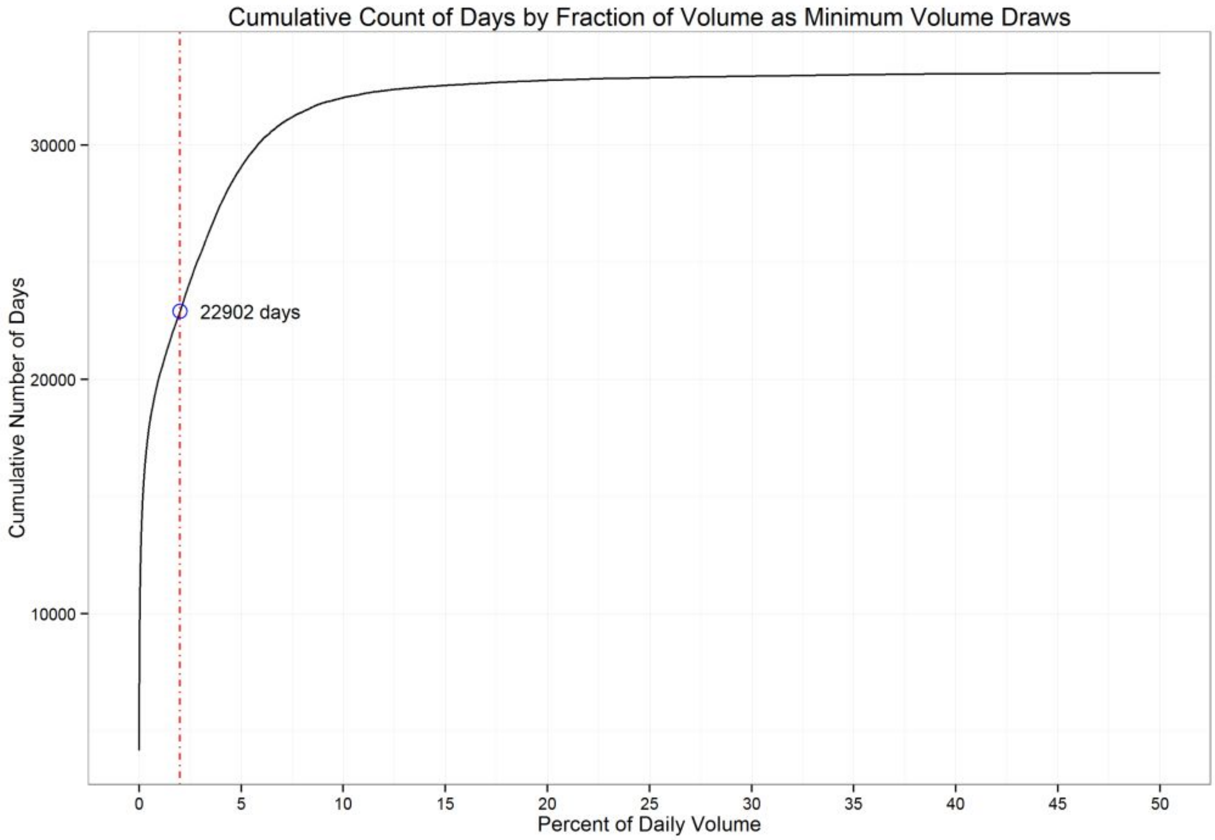

Figure 4 Cumulative Number of Days by Fraction of Volume as Minimum-Volume Draws

DATABASE

The processed and aggregated data from the 12 studies were collected in two tables, *Intervals* and *Draws,* as described below.

Intervals

The Intervals table contains the data related to water flow. When available, water temperature for every recorded interval on good days only is included for each interval. The Intervals table contains 12,985,212 records of hot water flow and 8 fields. The fields, type of variable, and description of variable for each field are listed in Table 3.

Table 3 Description of Fields in Intervals Table

Field Number	Field Name	Description
1	house_id	Unique identifier for each house configuration
2	draw_id	Unique identifier for each draw
3	date	Date of beginning of the draw
4	time	Time of beginning of the draw
5	vol	Gallons of hot water drawn in the interval
6	flow_rate	Measured rate of water flow for the interval
7	Tin	Inlet water temperature during the interval
8	Tout	Outlet water temperature during the interval

Draws

The Draws table contains the data for every draw that occurred on every good day. Each draw comprises one or more intervals. The database contains 1,679,668 draws and 7 fields. The fields and variable type for each field are listed in Table 4.

Table 4 Description of Fields in Draws Table

Field Number	Field Name	Description
2	house_id	Unique identifier for each house configuration
1	draw_id	Unique identifier for each draw
3	date	Date of the beginning of the draw
4	time	Time of the beginning of the draw
5	duration	Duration of the draw in intervals
6	total_vol	Total volume, in gallons, of the draw
7	time_since_previous_draw	Time, in seconds, from the end of the previous draw to the beginning of the current draw

RESULTS

We used the data to determine the volume of hot water used and the number of draws each day. One feature of daily hot water use is its variability. A simple, unweighted calculation of the average hot water use for all households and all days in our database results in 54.5 gallons per day (gpd), with a standard deviation of 36.1 gpd. There is a large variation in use from day to day within one house. Figure 5 illustrates the variation in daily hot water use among houses. Each circle represents the total volume and number of draws of hot water at one house for one day. For comparison, the daily hot water use assumed in DOE's test procedure water heater efficiency is indicated by the purple cross.

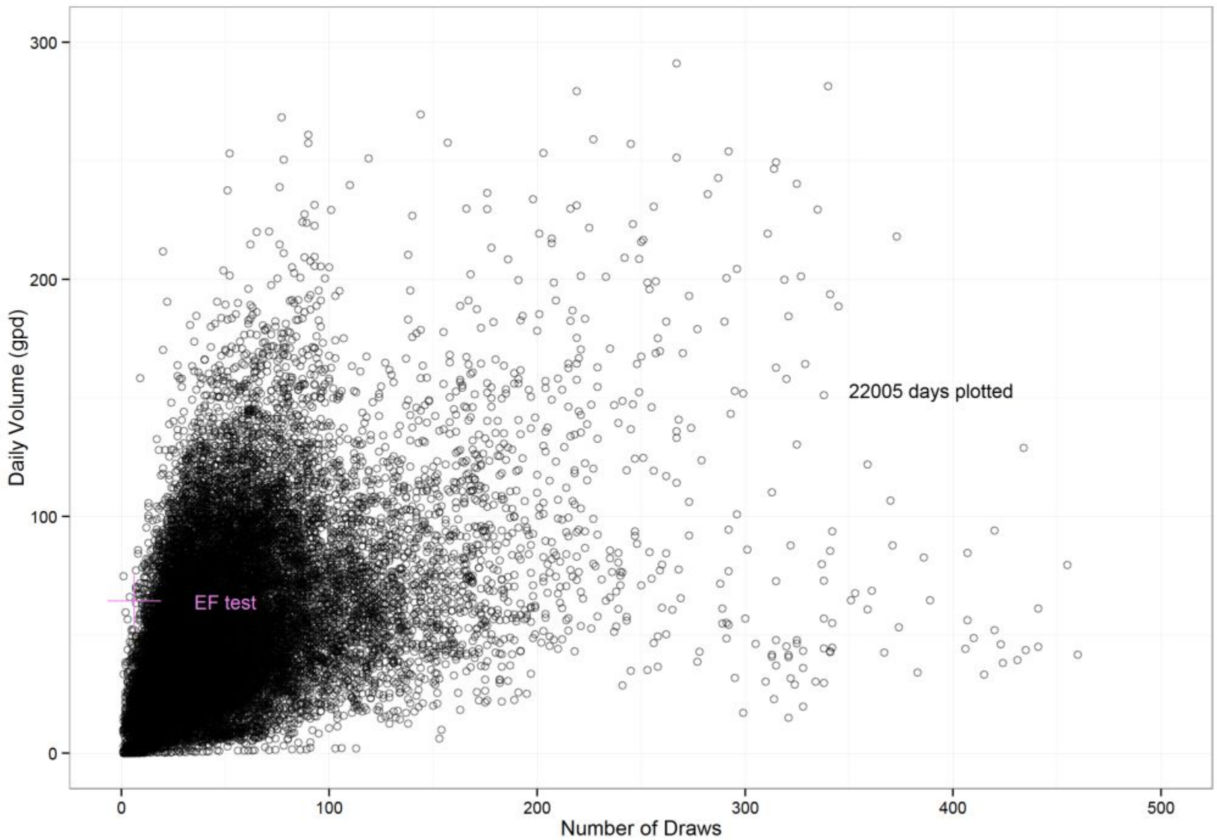

Figure 5 Daily Hot Water Use

Water Temperature

Based on data that included water temperature measurements, we estimated average inlet water temperature and water heater setpoint.

Inlet Water Temperature

We selected the minimum, rather than average, inlet temperature for each day from the field studies that recorded water temperatures when water was flowing. In many field installations, the temperature of the water in the pipe entering the water heater is increased by heat lost from the water heater when water is not being drawn. An average inlet water temperature would not reflect the actual temperature of water delivered to the house. Minimum inlet water temperatures are plotted in Figure 6. For comparison, the inlet temperature specified in the 24-hour DOE test of water heater energy efficiency (EF) is shown as a red line. The inlet water temperature for the test, 58 °F, is similar to the minimum inlet water temperature, 57.6 °F, from all days in the data.

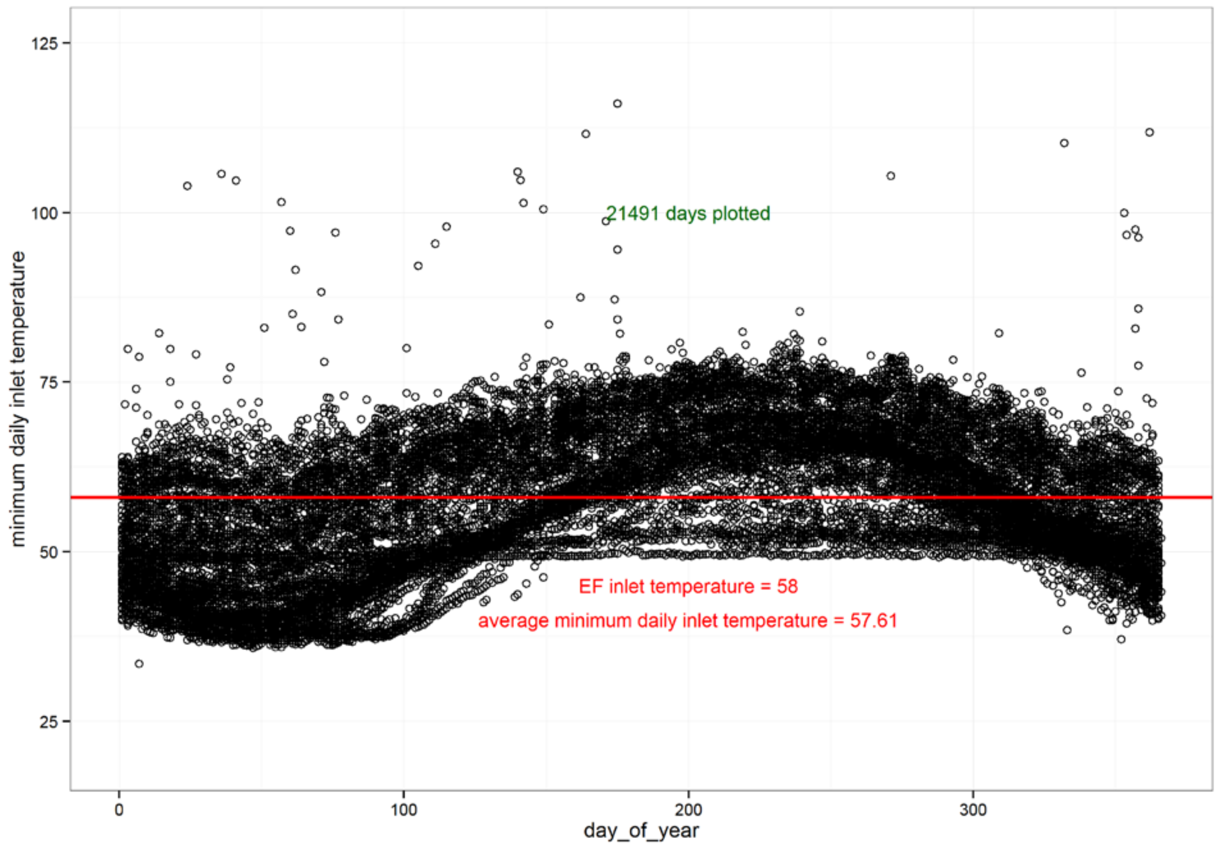

Figure 6 Minimum Inlet Water Temperatures

Outlet Water Temperature

A setpoint is the temperature of the water at which the water heater's thermostat initiates heating. Measuring the setpoint of water heaters in the field is difficult, however, because water heater thermostats rarely are labeled with the temperatures. In addition, water heater thermostats tend to be inaccurate, and outlet temperature may not be the same as the setpoint temperature.

Maximum daily water heater outlet temperatures vary from day to day depending on use patterns. If hot water is not used for some time after the water heater has fired, the delivered hot water will be cooler than the setpoint. If there are multiple short firings, the temperature at the top of the water heater near the outlet may be higher than the setpoint. Other factors also affect outlet water temperature.

We estimated the thermostat setpoint for water heaters in the field based on monitored outlet temperatures. The setpoint was estimated as the median daily hot water temperature. Median daily hot water temperatures were available for 19,587 days from 105 house configurations in 8 studies. Figure 7 shows the median outlet water temperature for each day for every house configuration in all studies that recorded outlet temperatures. Each vertical line represents the data from one house configuration. The solid dot on each vertical line is the median daily outlet temperature. The vertical line extends one standard deviation above and below the average. The hollow diamonds indicate the median outlet temperature. The size of the hollow square is proportional to the number of monitored days.

The average of the median daily outlet temperatures for all house configurations is 122.7 °F. This average was weighted by the number of days each house configuration was monitored. The black dashed line on the plot shows the average median daily outlet temperature. The dotted lines are one standard deviation (9.7 °F) above and below that average. The red dashed line represents 135 °F, the mean tank temperature specified by the DOE EF test procedure for water heaters.

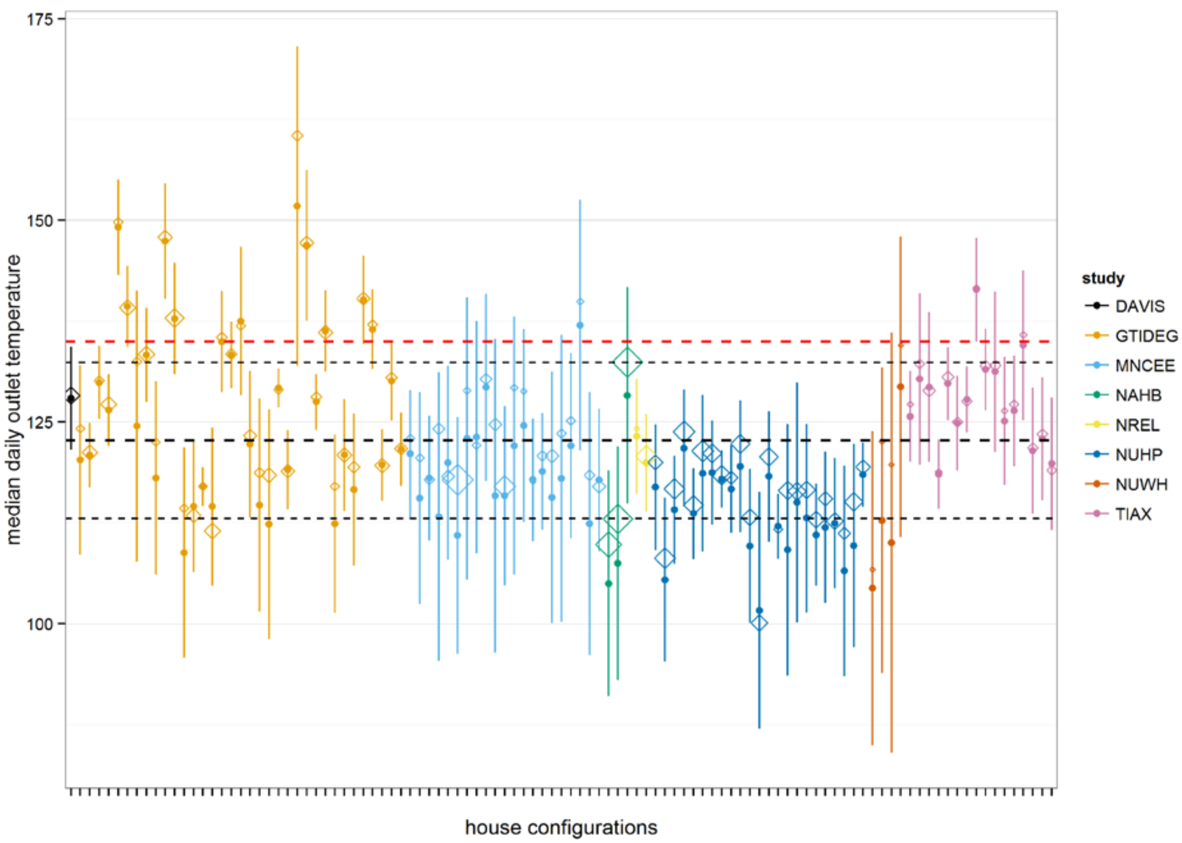

Figure 7 Median Daily Outlet Water Temperatures

The GTI study of condensing gas water heating systems recorded outlet temperatures from water heaters used for combined space and domestic water heating. The study did not measure the temperature of the delivered domestic hot water, which was reduced to a lower temperature using a mixing valve. Data from that study were not used in the analysis of outlet water temperatures.

Daily Hot Water Use

Figure 8 plots the median number of draws per day and median volume of hot water used per day for each house configuration considered in this analysis. Each circle represents one house configuration. The size of a circle is proportional to the number of days that house configuration was monitored.

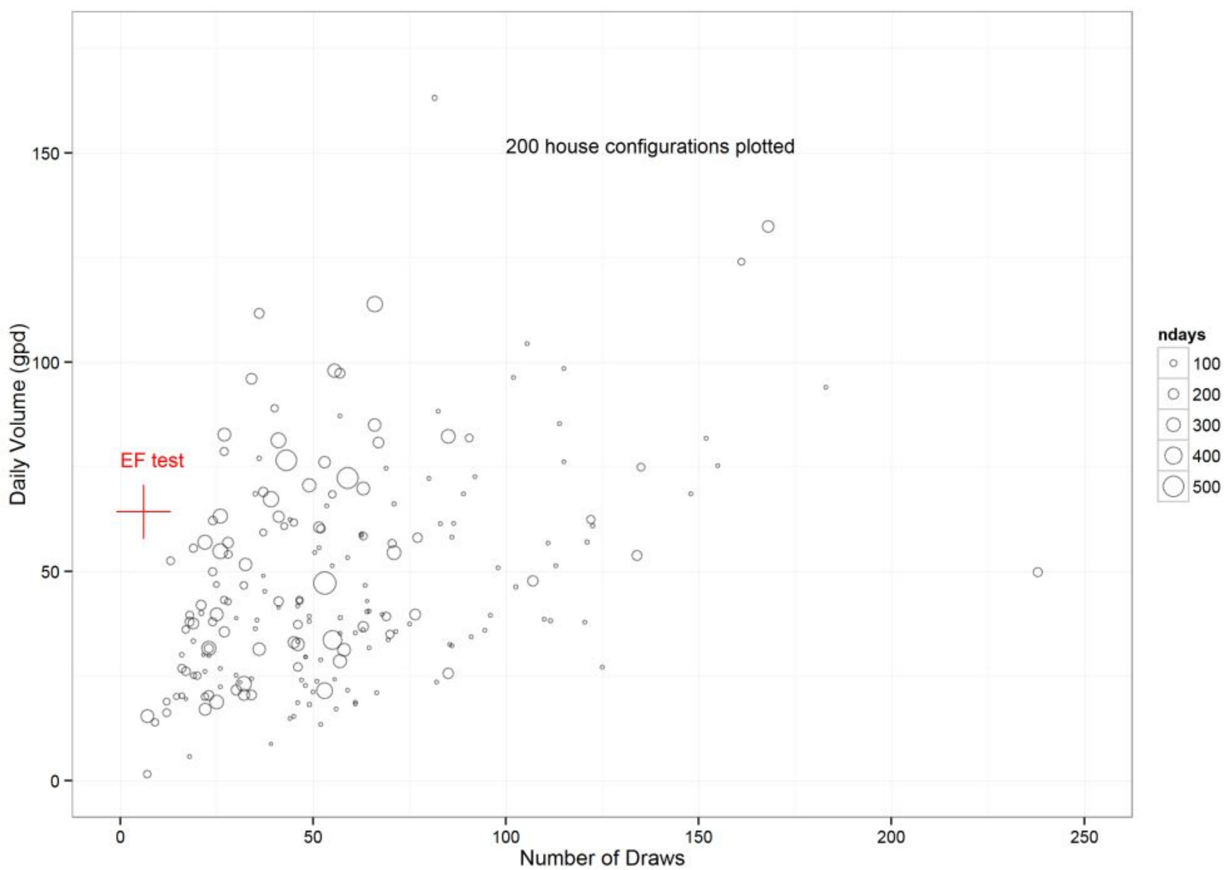

Figure 8 Median Daily Hot Water Use

Cluster Analysis

Although we analyzed inlet and outlet temperatures from all house configurations for which we had temperature data, we analyzed the data for other parameters and relationships by clusters of house configurations. We identified the clusters of house configurations based on median daily hot water uses. We grouped the house configurations into small, medium, and large hot water users based on median daily hot water users. Subsequent analyses were performed separately for each cluster. We developed the three clusters partly to reflect the intentions of the ASHRAE SPC 118.2 to revise the test procedure for residential water heaters to incorporate a range of draw patterns that better represent those found in the field. The ASHRAE SPC 118.2 has identified the need to separately evaluate at least three, and perhaps as many as five, different capacities of water heaters.

A standard method of grouping data into clusters is to use the k-means clustering algorithm. The k-means method partitions the data points into k groups such that the sum of squares of the distance from the points to the assigned cluster center is minimized.[17] Because the k-means algorithm does not provide a closed-form solution, we repeated the cluster analysis 1,000 times and used the most common result.

The average median daily volume of hot water use among all the house configurations is 49.6 gallons. Data from the GTI study were not used in the cluster analysis or subsequent distributional analyses because the volume of hot water used for domestic purposes was not measured directly in that study. For most house configurations the median use of hot water falls within a broad range of between 20 and 80 gpd. The results of our cluster analysis on median daily hot water use are shown on Figure 9. The different clusters are coded with different colors. Each bar in the histogram represents the number of house configurations having a median daily hot water use that falls within that bin. The bins for median daily hot water use are one gpd wide. The ranges in median daily hot water use for the three clusters were less than 44 gpd, more than 44 but less than 80 gpd, and more than 80 gpd.

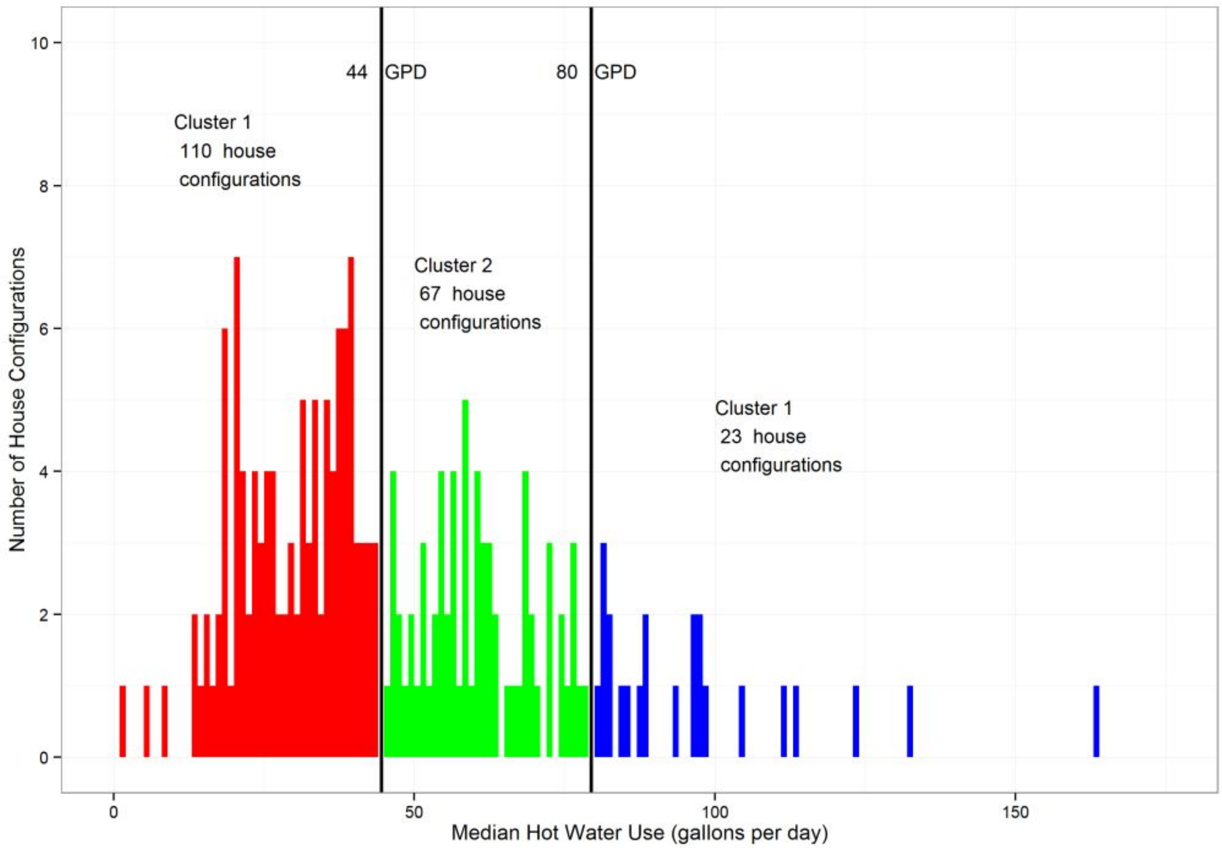

Figure 9 Clustered Data for Median Daily Hot Water Use

Table 5 presents the results of using cluster analysis to divide the data set of 200 house configurations into three clusters. The table presents the minimum, average, and maximum median daily hot water use for the house configurations in each cluster.

Table 5 Results of Cluster Analysis

Cluster	House Configurations	Median Daily Volume (gallons)			Average Daily Draws
		Minimum	Average	Maximum	
1	110	1.52	29.38	43.23	45.22
2	67	45.25	60.52	78.66	66.48
3	23	80.74	98.04	163.21	86.37

Distributional Parameters

We analyzed other parameters related to draw patterns: draw volumes, duration of draws, times since previous draw, and flow rates based on a distributional analysis for each parameter. For each of the three data clusters we developed cumulative distribution charts related to draw patterns derived from the field data. The distributional parameters include volume per draw, time since previous draw, duration of each draw, and flow rate recorded during monitored intervals. Each parameter is displayed as a cumulative distribution of all the draws or all the intervals. This type of plot orders the value of the parameter for each event, *e.g.*, volume of hot water use for each draw, in ascending order. The plot then shows the cumulative fraction of total events that are less than a given value. The dissimilarity between two patterns can be summarized as the maximum difference between the cumulative distribution plots of the two sets of events.

Draw Volumes

Draw Volumes

On Figures 10, 11, and 12, each black line represents the cumulative distribution of volumes of all draws for a given water heater, from smallest to largest, recorded for small, medium, and large water-using house configurations, respectively. Each house configuration is assigned one entire line. The green line in each figure is the cumulative distribution of the volumes of all monitored draws from all monitored house configurations in that cluster. The red line in each figure shows the cumulative distribution of the volume of draws in the DOE EF test procedure. The vertical axis shows the volume of draws on a logarithmic scale, used because the range of draw volumes is so large. The horizontal axis is the cumulative fraction of draws.

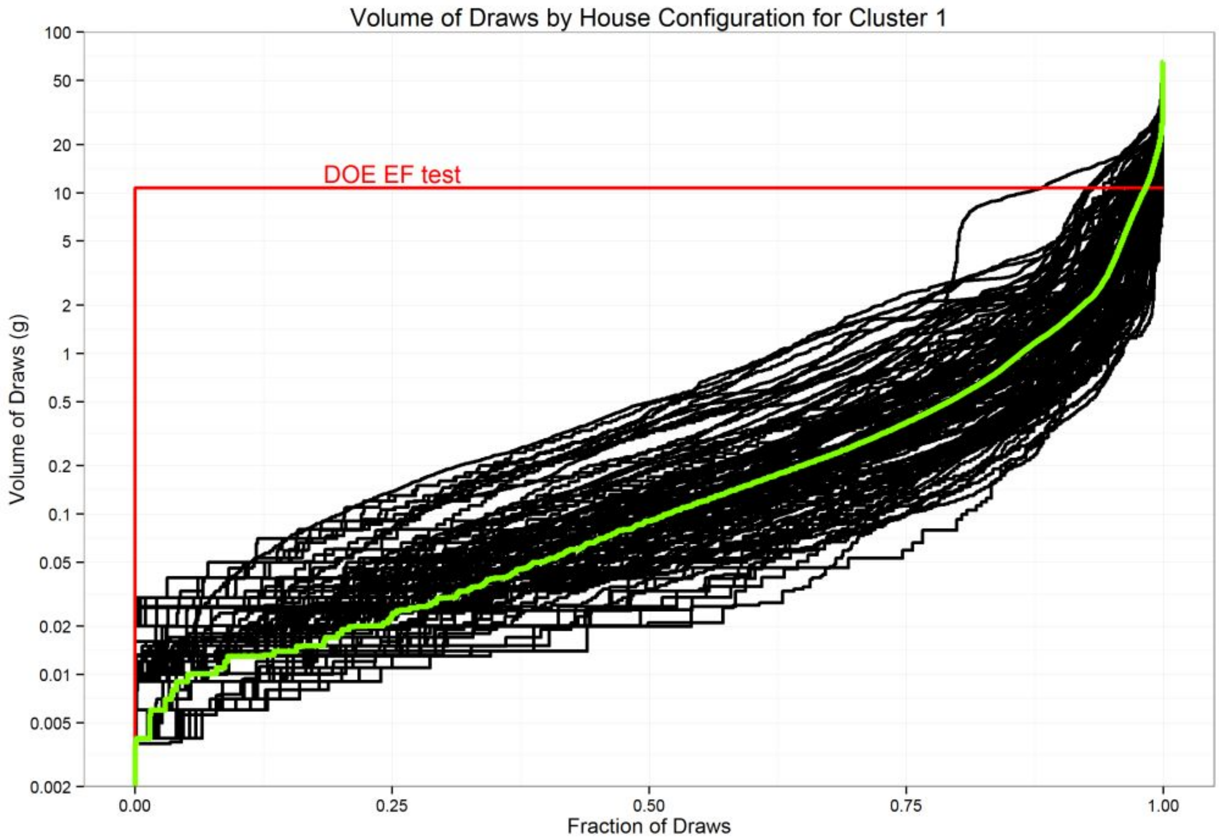

Figure 10 Cumulative Distribution of Draws by Volume for House Configurations in Cluster 1

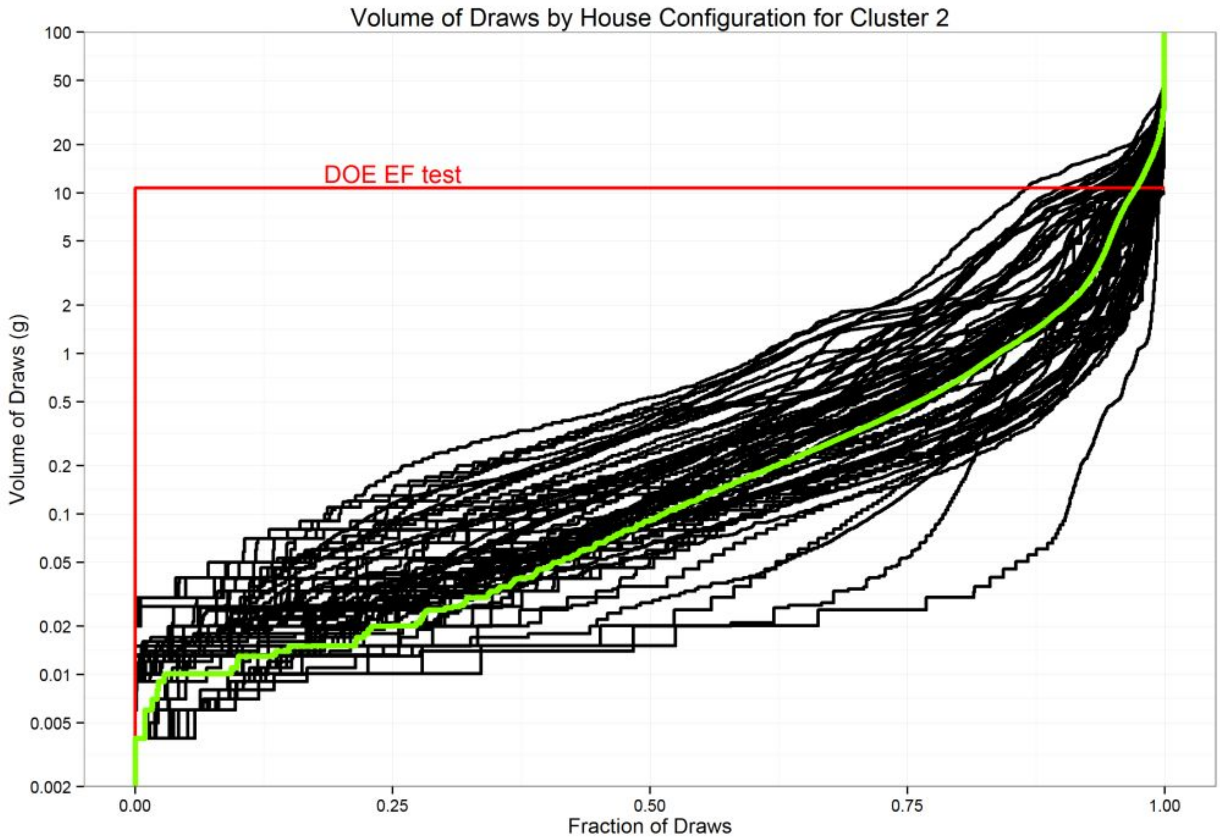

Figure 11 Cumulative Distribution of Draws by Volume for House Configurations in Cluster 2

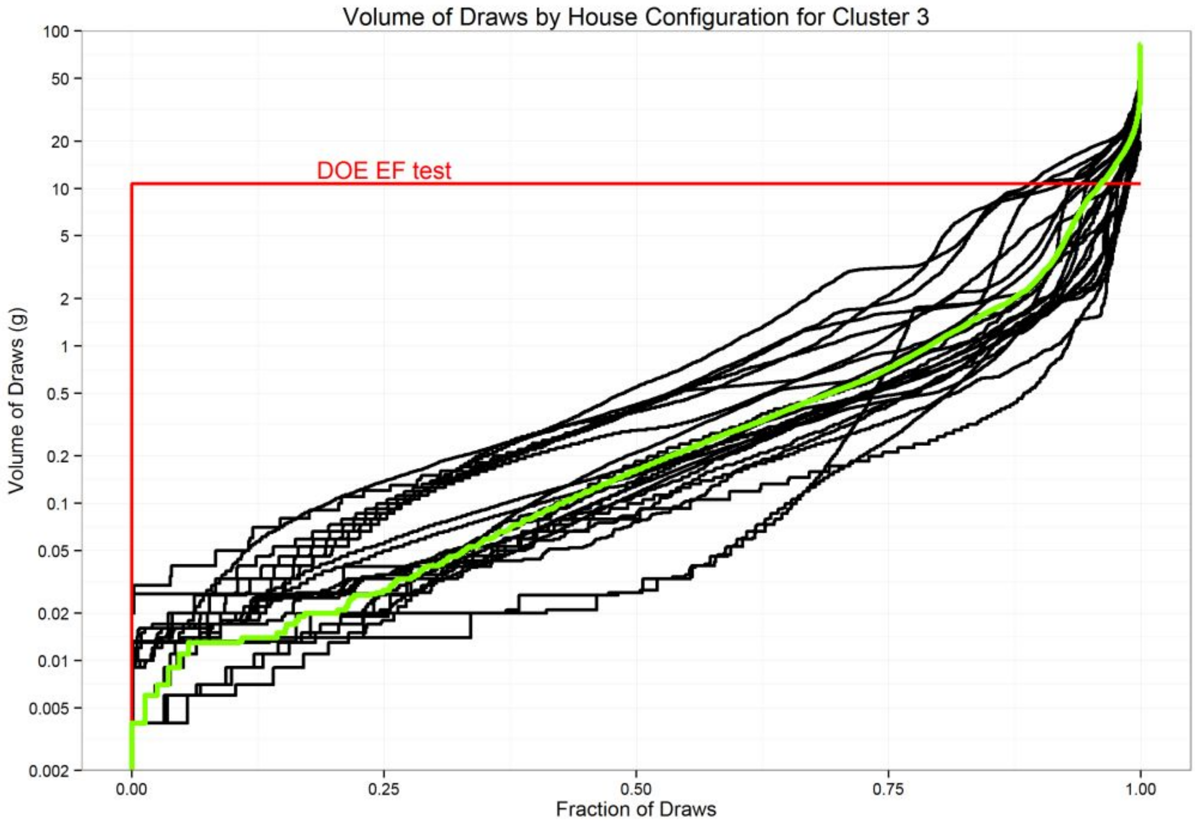

Figure 12 Cumulative Distribution of Draws by Volume for House Configurations in Cluster 3

Figures 10 through 12 show that the volume of all the draws used in the DOE test procedure are larger than about 95 percent of the draws for all three clusters of house configurations. Table 6 presents the draws by volume for the three clusters of house configurations in the data set. Most draws are less than 0.5 gallon for all house configurations. For clusters 1 and 2, half the draws are less than a tenth of gallon in volume. For the larger hot water-using house configurations of cluster 3, 90 percent of draws have a volume less than 2 3/4 gallons.

Table 6 Distribution of Draws by Volume (gallons)

Percentile	Cluster 1	Cluster 2	Cluster 3
98%	9.85	13.08	15.73
90%	1.50	1.89	2.76
75%	0.37	0.46	0.72
50%	0.09	0.09	0.16
25%	0.02	0.02	0.03
10%	0.013	0.013	0.013
2%	0.006	0.007	0.006

Duration of Draws

Figures 13, 14, and 15 present plots of the cumulative distribution of draws by duration for small, medium, and large hot water-using house configurations, respectively. Each house configuration is assigned one black line. The green line in each figure is the cumulative distribution of the durations of all monitored draws for the given house size. The red line in each figure shows the cumulative distribution of draws by duration in the DOE EF test procedure. The vertical axis shows the duration of draws on a logarithmic scale, used because the range of durations is so large. The horizontal axis is the cumulative fraction of draws by duration. The smallest possible duration of any draw is the length of the recording interval used by the associated data acquisition system. The flat section of the green line at a duration of 1 minute is because several studes had a 1-minute recording interval. No draws of shorter duration were recorded in those studies.

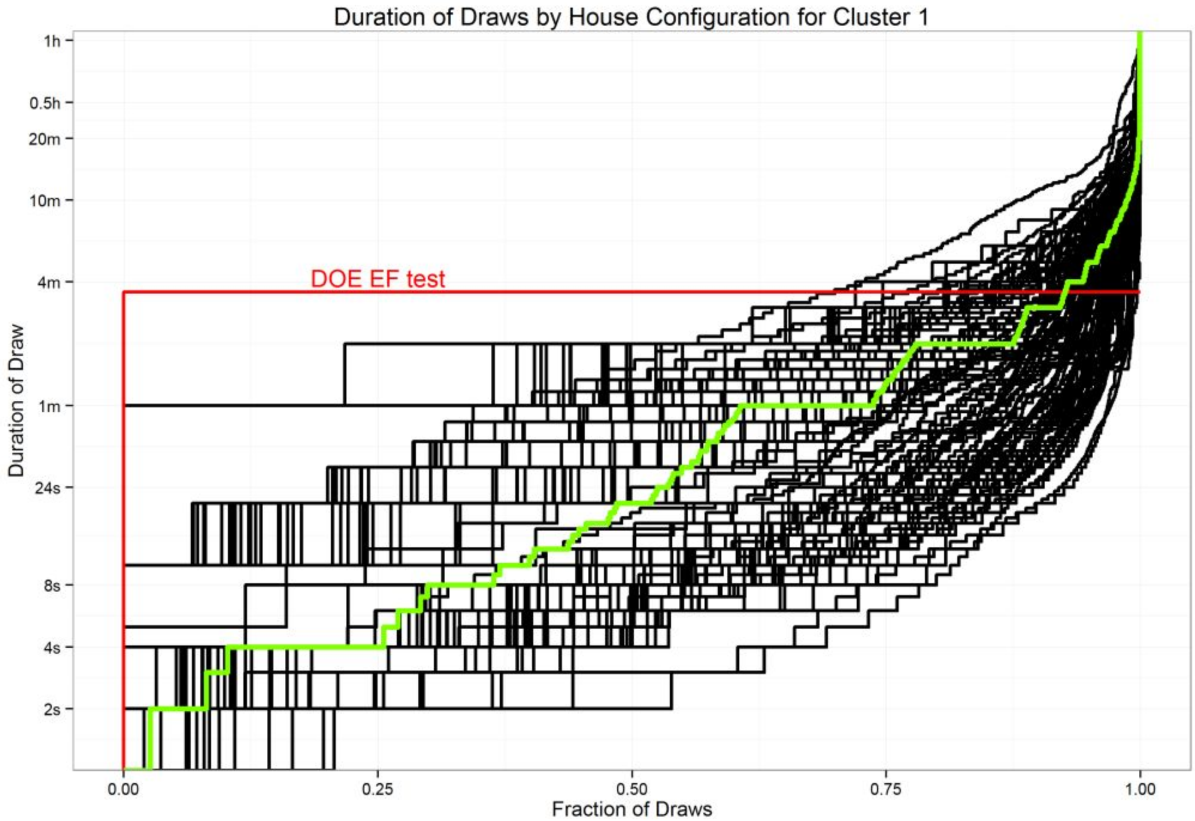

Figure 13 **Cumulative Distribution of Draws by Duration for House Configurations in Cluster 1**

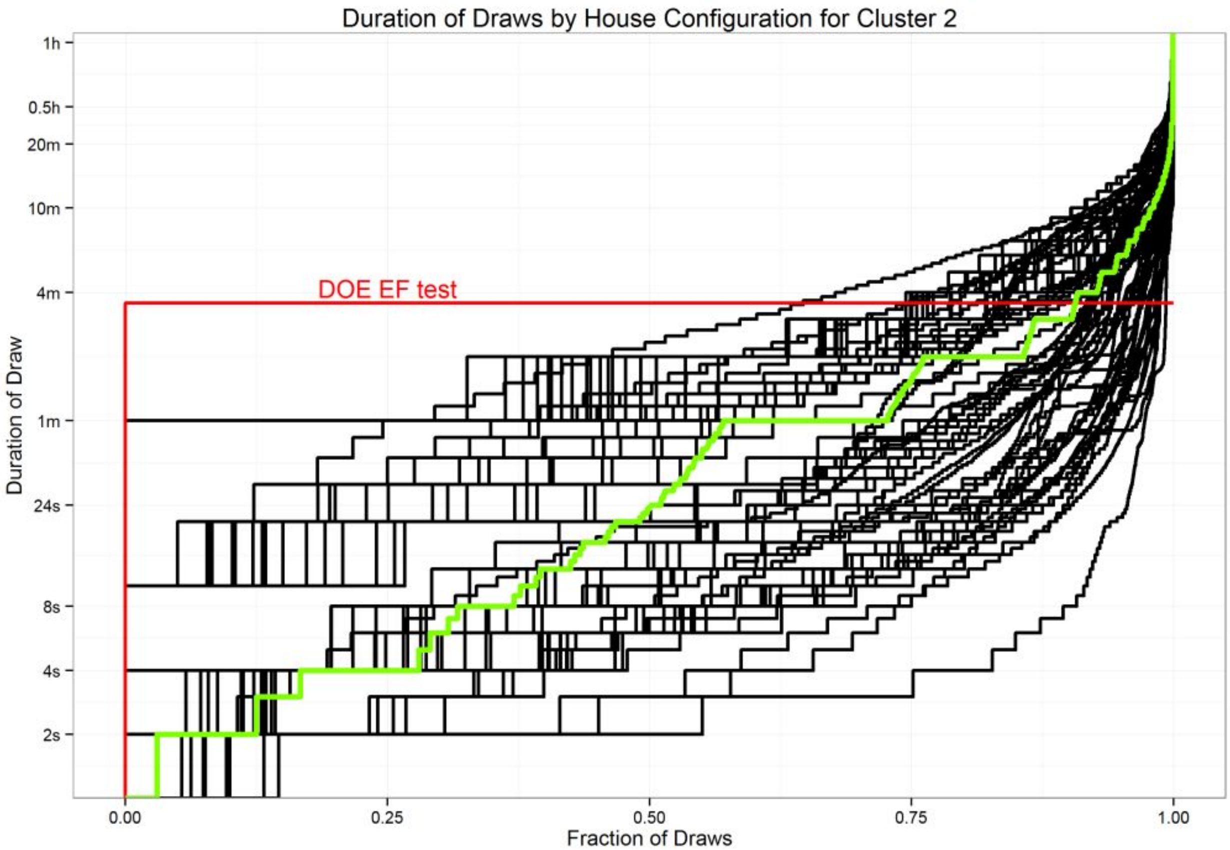

Figure 14 **Cumulative Distribution of Draws by Duration for House Configurations in Cluster 2**

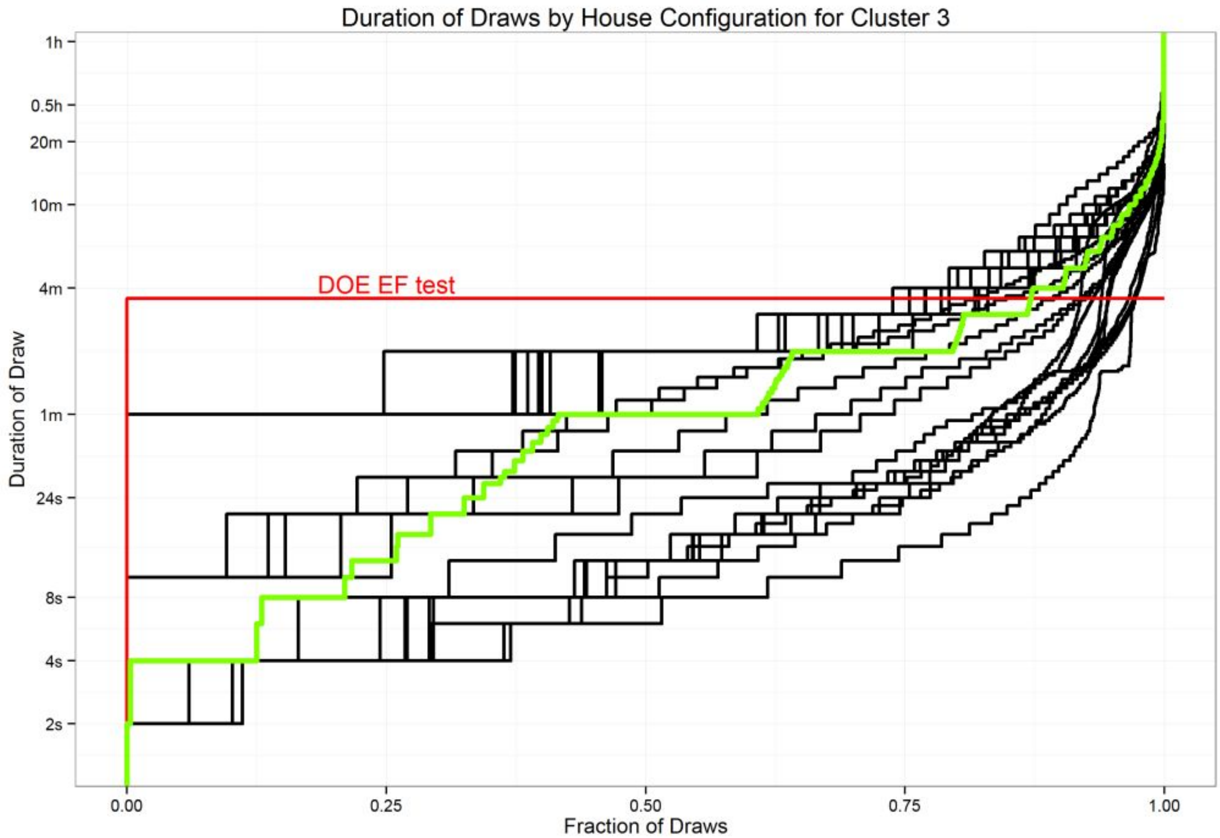

Figure 15 Cumulative Distribution of Draws by Duration for House Configurations in Cluster 3

Table 7 presents the draws by duration of draw for the three clusters of house configurations in the data set. Fifty percent of draws last 1 minute or less for all clusters. Ninety percent of draws last 3 minutes or less for clusters 1 and 2, and 4 minutes or less for the larger hot water-using house configurations of cluster 3. The DOE EF test procedure sets the draw duration uniformly at just under 4 minutes.

Table 7 Distribution of Draws by Duration (mm:ss)

Percentile	Cluster 1	Cluster 2	Cluster 3
98%	8:04	10:00	12:00
90%	3:00	3:00	4:00
75%	1:16	1:32	2:00
50%	0:20	0:24	1:00
25%	0:04	0:04	0:12
10%	0:03	0:02	0:04
2%	0:01	0:01	0:04

Just as draw volumes in the field generally were smaller than those stipulated for the DOE laboratory test, the durations of almost all draws recorded in the field for all house configurations were much shorter than the duration of the draw used in the test. Nearly half the monitored draws lasted less than 12 seconds, compared to the nearly 4-minute draws in the test procedure. The duration of draws is especially important when measuring the efficiency of tankless water heaters. The amount of residual heat left in a tankless water heater after a draw is relatively independent of draw length. Thus a tankless water heater is less efficient for shorter draws.

Time Since Previous Draw

The distributions for the time gaps between draws are shown on Figures 16, 17, and 18 for small, medium, and large hot water-using house configurations, respectively. Each house configuration is assigned one black line. The green line in each figure is the cumulative distribution of the time since previous draw for all monitored draws for all house configurations in each cluster. The red line in each figure shows the cumulative distribution of the times since previous draw in the DOE EF test procedure. The step on the right side of the DOE EF test line shows the 19-hour standby period at the end of the test. The vertical axis shows the time since previous draw on a logarithmic scale, used because the range of time intervals is so large. The horizontal axis is the cumulative fraction of draws by time since previous draw.

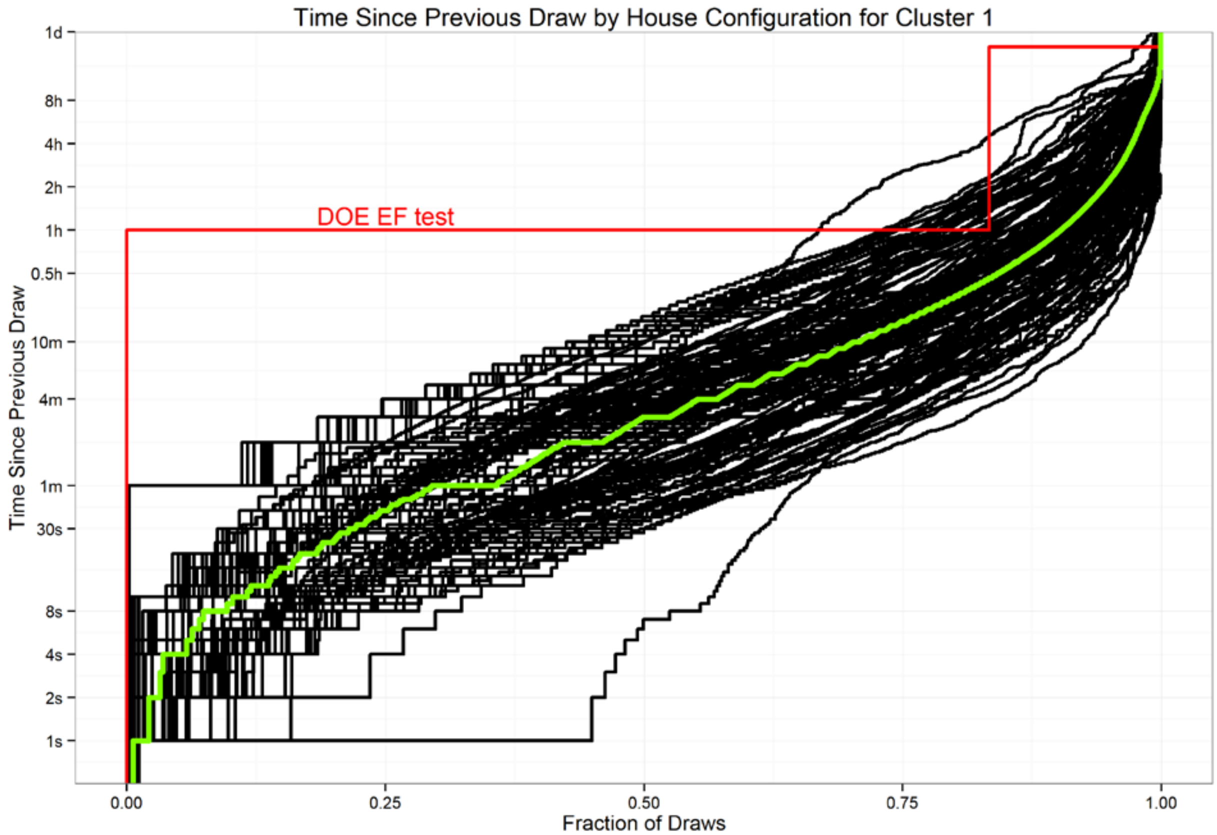

Figure 16 Cumulative Distribution of Draws by Time Since Previous Draw for House Configurations in Cluster 1

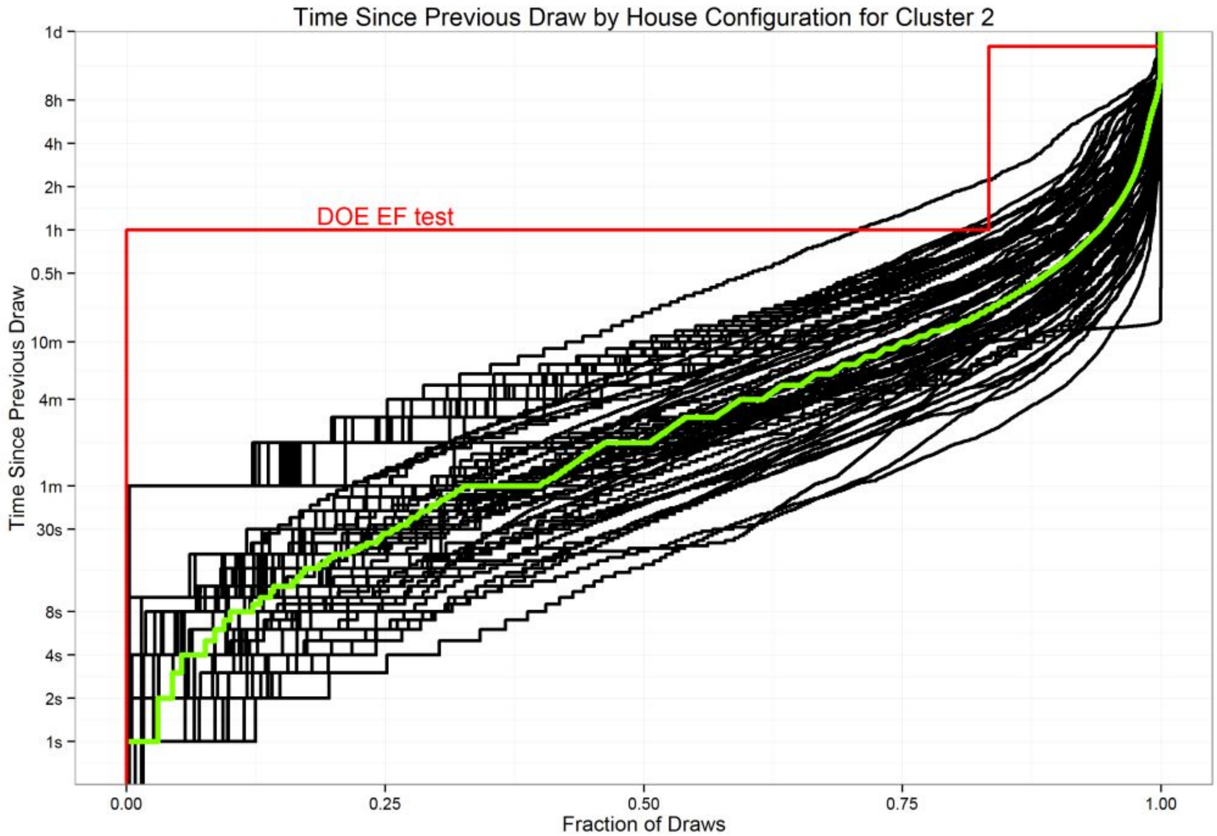

Figure 17 Cumulative Distribution of Draws by Time Since Previous Draw for House Configurations in Cluster 2

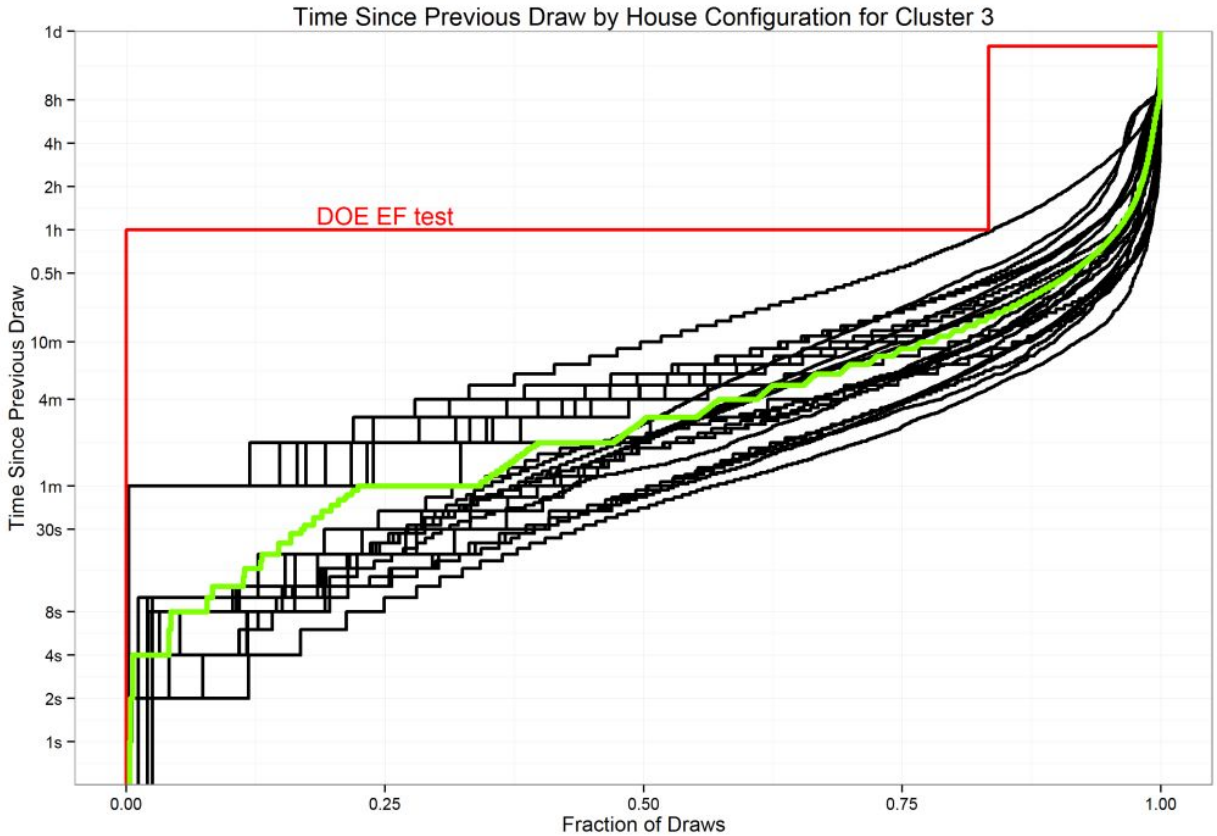

Figure 18 **Cumulative Distribution of Draws by Time Since Previous Draw for House Configurations in Cluster 3**

Table 8 shows the draws by time since previous draw for the three clusters of house configurations in the data set. For all three clusters, 75 percent of monitored draws occurred within less than 15 minutes of the previous draw. For 50 percent of draws, the time since the previous draw is less than three minutes, more than an order of magnitude less than the 1 hour stipulated in the DOE EF test procedure.

Table 8 Distribution of Draws by Time Since Previous Draw (hh:mm:ss)

Percentile	Cluster 1	Cluster 2	Cluster 3
98%	5:25:08	3:08:00	1:56:00
90%	57:48	33:40	26:00
75%	14:00	10:00	9:00
50%	3:00	2:00	2:52
25%	0:40	0:28	1:00
10%	0:09	0:08	0:12
2%	0:01	0:01	0:04

Flow Rates

Figures 19, 20, and 21 show the cumulative distributions of every recording interval by flow rate for small, medium, and large hot water-using house configurations, respectively. Each house configuration is assigned one black line. The green line in each figure is the cumulative distribution of recording intervals by flow rate of all intervals for all house configurations in a given cluster. The red line in each figure shows the cumulative distribution of recording intervals by flow rate of draws in the DOE EF test procedure. The vertical axis shows the flow rate in gallons per minute (gpm). The horizontal axis is the cumulative fraction of recorded intervals by flow rate. Almost all flow rates recorded during the field studies are significantly lower than the flow rates specified in the DOE EF test. Flow rates will appear lower than they actually are in studies that use long recording intervals. For a data acquisition system that uses 1-minute recording intervals, a 15-second draw at 4 gpm will appear as a 1-minute draw at 1 gpm.

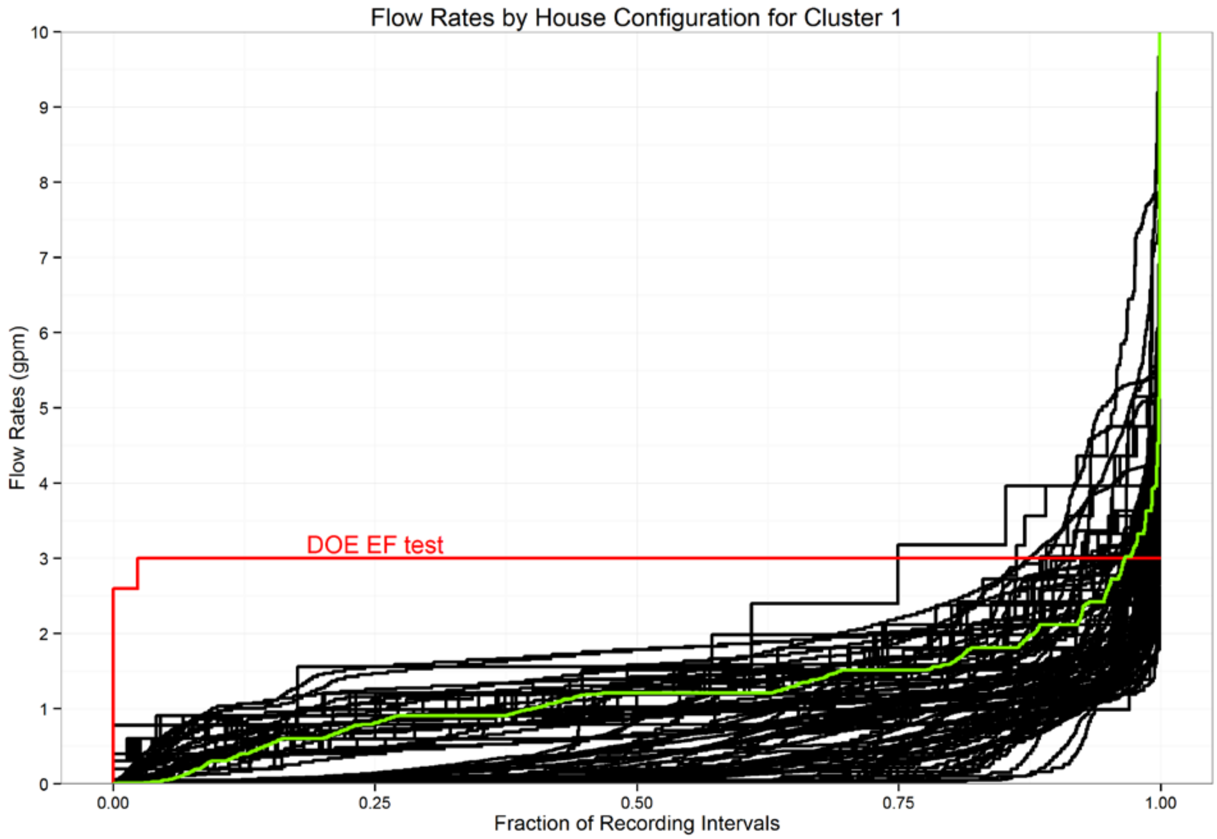

Figure 19 Cumulative Distribution of Intervals by Flow Rate for House Configurations in Cluster 1

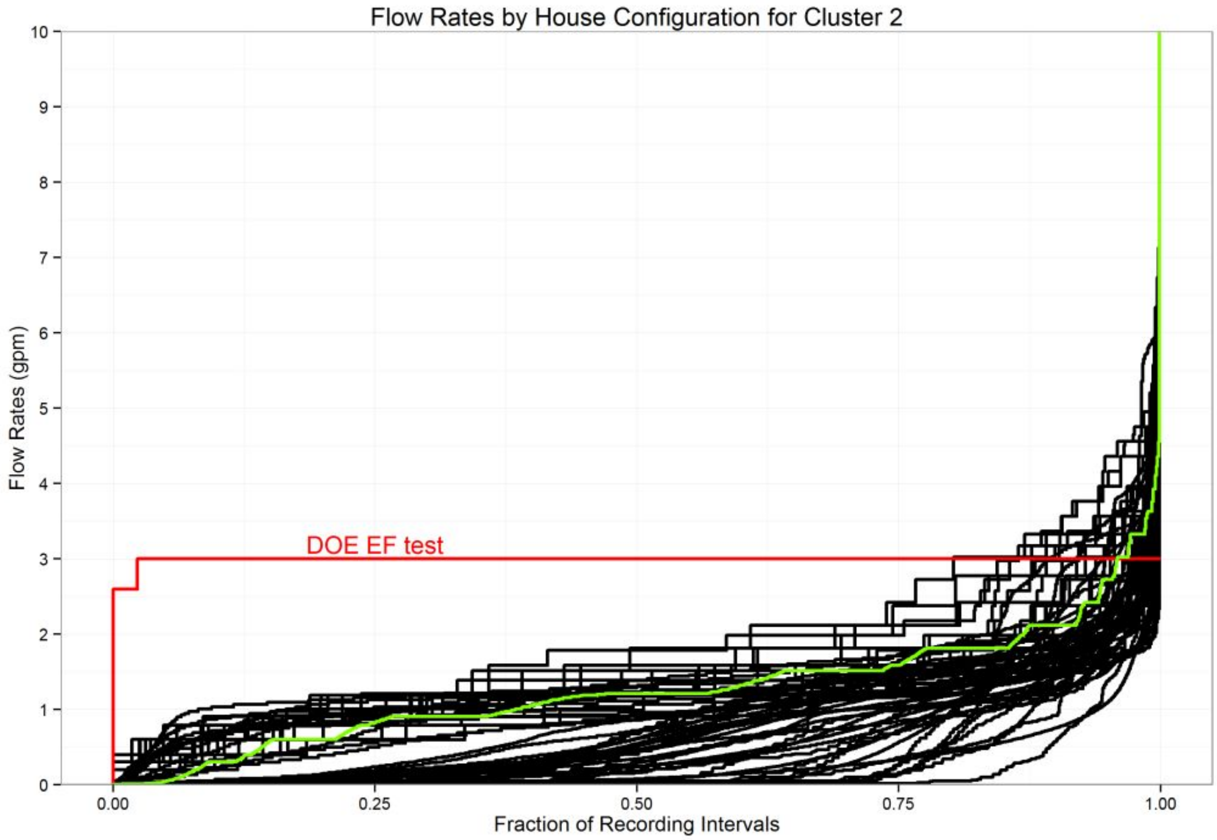

Figure 20 Cumulative Distribution of Intervals by Flow Rate for House Configurations in Cluster 2

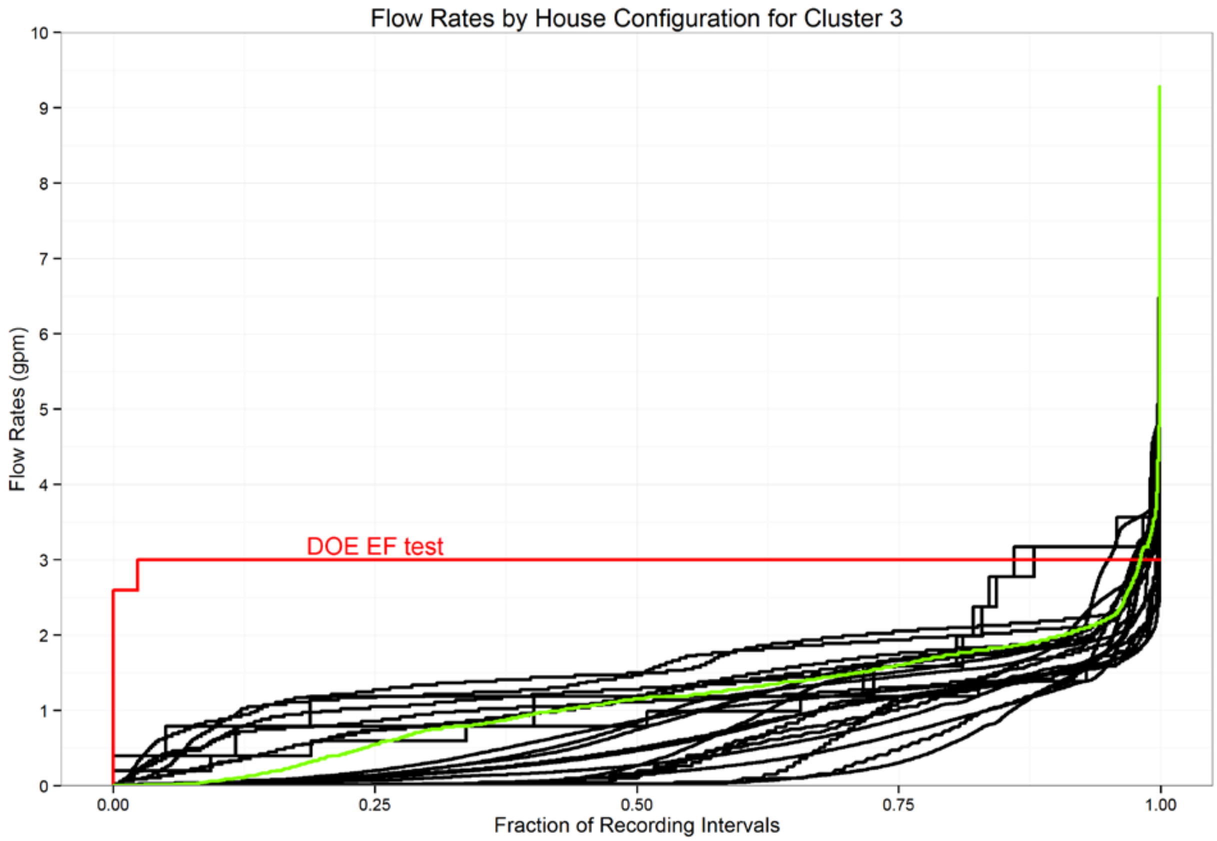

Figure 21 Cumulative Distribution of Intervals by Flow Rate for House Configurations in Cluster 3

Table 9 lists the draws by flow rate of draw for the three clusters of house configurations in the data set. For all three clusters, 90 percent of recorded flows are lower than the 3-gpm flow rate used in the DOE EF test procedure; 50 percent are less than half the flow rate.

Table 9 Distribution of Draws by Flow Rate (gallons per minute)

Percentile	Cluster 1	Cluster 2	Cluster 3
98%	3.33	3.33	2.95
90%	2.12	2.12	1.97
75%	1.51	1.59	1.61
50%	1.21	1.21	1.16
25%	0.81	0.83	0.56
10%	0.30	0.30	0.07
2%	0.01	0.01	0.01

CONCLUSIONS

There is significant variation in hot water use and draw patterns among households. The field data show more, shorter, smaller draws at lower flow rates clustered closer together in time than the current DOE test procedure. Using at least three different draw patterns for water heaters having different capacities, rated volume and/or rate maximum flow rate, could better reflect the wide range of hot water use seen in field data.

Our study found a higher-than-expected number of draws per day. This result indicates a need to reconsider the start-up losses for tankless water heaters and the losses in hot water distribution systems caused by numerous short draws. This topic warrants more investigation.

The studies from which we derived our data did not identify the configuration of the distribution systems in the monitored houses. Thus the database does not support an analysis of whether the configuration of the distribution system leads to different hot water use patterns. This topic also warrants further consideration.

Clearly, more work is necessary to understand residential hot water draw patterns. We hope this analysis provides a way to begin developing such an understanding. We expect to continue expanding and refining both the data and the analyses.

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