DERIVING SIMULATION PARAMETERS FOR STORAGE-TYPE WATER HEATERS USING RATINGS DATA PRODUCED FROM THE UNIFORM ENERGY FACTOR TEST PROCEDURE

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ABSTRACT

Building energy modeling (BEM) is commonly used to estimate the energy usage of residential buildings. Uses for BEM include evaluating design options, calculating home energy ratings, demonstrating compliance with performance-based energy codes, and establishing whether designs meet voluntary program requirements, such as ENERGY STAR® qualified homes. BEM requires simulating subsystems within the building, including storage-type water heaters. Simulating the in-situ performance of residential storage water heaters requires values for key water heater parameters (including the overall heat loss coefficient (UA) and conversion efficiency (η_c) of the water heater) which can be derived from water heater rating data. The testing procedure and rating standard for residential water heaters have recently changed: the new rating standard provides a Uniform Energy Factor (UEF) rather than the Energy Factor (EF) used previously. This paper discusses how to derive the necessary model parameters from the ratings data produced from the latest test procedure.

INTRODUCTION

Federal efficiency standards for appliances and equipment have existed in the United States since 1975, originally created as part of the Energy Policy and Conservation Act (U.S. Department of Energy, 2018). Over the years, the original act has been amended and expanded to cover a wide variety of products and it mandates regular reviews and updates of the standards. The standards generally specify both a testing procedure and minimum efficiency levels for each type of product. Currently, more than 60 different products are covered by an energy standard; these covered products account for more than 90% of residential sector energy consumption (Armstrong, 2017).

One of the more recently updated standards covers residential water heaters. The minimum efficiency levels for residential water heaters were updated in 2010 (U.S. Department of Energy, 2014). This update increased the rated efficiency, called the Energy Factor (EF), of all residential water heaters, with larger increases for gas-fired storage water heaters with a tank volume of more than 55 gallons (208 L) and electric storage water heaters with a tank volume of more than 50 gallons (189 L). To comply with these higher efficiency requirements, condensing water heaters and heat pump water heaters (HPWHs) are typically required, although an exception was later added by Congress to allow grid-enabled electric resistance water heaters with a volume of more than 50 gallons (U.S. Congress, 2015). The test procedure for residential water heaters was subsequently updated in 2014, resulting in a new rated efficiency metric, called the Uniform Energy Factor (UEF) (U.S. Department of Energy, 2014). The rated efficiencies under the new test procedure cannot be directly compared to the EF because of the differences in the test procedures. The new test procedure uses different hot water draw profiles and a different water heater setpoint temperature.

The rated efficiency provides a basis for comparing the performance of different products under a standard set of conditions that represents typical usage; however, differences between test conditions and conditions under which a water heater is installed and operated impact the performance of a product. The supply water temperature, tank setpoint temperature, hot water usage patterns, and surrounding air temperature (and humidity for HPWHs) can have a significant impact on a water heater's performance. As a result, the performance of any specific water heater can vary significantly across households. Storage-type water heater simulation models have been developed that can account for specific usage and environmental conditions, and these are commonly incorporated into building energy modeling (BEM); however, to use these water heater simulation models in BEM, model parameter values physically representing the water heater are needed. One approach is to derive these parameter values from water heater rating data.

For residential storage-type water heaters, the necessary model parameters to be derived are overall heat loss coefficient (UA) and conversion efficiency (η_c). The overall heat loss coefficient accounts for the heat loss from the storage tank to the surrounding air. Heat loss occurs both through the insulated tank surface and through thermal shorts. In addition, for gas-fired water

heaters a significant amount of the heat loss from the tank occurs through the central flue. The conversion efficiency describes the efficiency of the heat source (either a burner or electric resistance element). For electric resistance water heaters, the conversion efficiency is always 1.0. For gas water heaters, the conversion efficiency varies depending on the design of the burner. The method proposed here is intended to be used with noncondensing gas-fired and electric resistance storage water heaters. This method does not apply to instantaneous water heaters, condensing gas-fired water heaters, or HPWHs.

One of the first methods developed to derive the model parameters from the test data is the Water Heater Analysis Model (WHAM) (Lutz et al., 1998). The WHAM approach is based on a simple energy balance of the water heater over the entire ratings test. The WHAM approach makes several assumptions, most significantly that the rated Recovery Efficiency (RE) equals the conversion efficiency. Burch and Erickson (Burch and Erickson, 2004) developed a methodology that is based on the same energy balance as WHAM, but it also accounts for standby losses during the period of the test to calculate a conversion efficiency. Taking these losses into account increases the calculated conversion efficiency of the burner for gas-fired water heaters by 0.01–0.02. This methodology was later refined to account for stratification that can occur in electric resistance water heaters (Burch, 2011). In electric resistance water heaters, the volume of water below the lower electric resistance element often remains unheated, which effectively reduces both the volume of available hot water in the tank and the standby losses. This is accounted for by assuming that there are two isothermal nodes in the tank, one above the lower element and one below.

WATER HEATER TEST PROCEDURE

The previous (prior to 2014) version of the water heater testing standard for residential water heaters is defined in 10 CFR 430, Subpart B, Appendix E of the Federal Register and commonly referred to as the Energy Factor test (U.S. Department of Energy, 2010). The EF test is a 24-hour use test designed to capture the performance of the water heater under a typical draw profile. It consists of 6 draws, 1 per hour for the first 6 hours, followed by an 18-hour period of standby. Each draw is done at a flow rate of 3 gal/min (11.3 L/min), and the total draw volume is 64.3 gal/day (243 L/day).

Since the EF test was developed, new technologies, including instantaneous and HPWHs, have gained measurable market share. The performance of these units has been shown to be sensitive to the timing and flow rate of draws (Davis Energy Group, 2007) (Sparn et al., 2014). New research has also shown that the average installed water heater setpoint is approximately 125°F (51.7°C), lower than the value of 135°F (57.2°C) specified in the EF test (Lutz and Melody, 2012). In the same study, hot water usage patterns were found to vary widely across households.

The new UEF test specifies a hot water setpoint temperature of 125°F (51.7°C) and four different hot water draw profiles. The UEF test procedure specifies the draw profile under which a water heater must be tested, depending on the first hour rating (FHR) of the water heater. The FHR is derived from a separate ratings test, also specified as part of the UEF test standard. It denotes the number of gallons of hot water that can be delivered in 1 hour when starting from a fully heated tank. FHR is useful when determining what size water heater might be needed for a given household based on the number of occupants and their hot water usage. The UEF test procedure specifies that units with larger FHRs be tested with larger draw volumes. Table 1 indicates the draw profiles to be used as specified by the UEF test procedure. Figure 1 summarizes the draw profiles used in the EF test and the new UEF test, and Figure 2 (located at the end of this paper) shows the draw profiles for each of the tests.

Table 1 UEF draw profile based on FHR

First Hour Rating	UEF Draw Pattern
0–18 gal	Very Small Usage
18–51 gal	Low usage
51-75 gal	Medium Usage
>75 gal	High Usage

APPROACH

The approach outlined here extends previous analysis (Burch 2010) to deriving the simulation parameters based on UEF ratings data. An energy balance of the tank over the entire UEF test period is calculated with three key assumptions. First, the tank temperature is assumed to be constant during the entire test period. For gas-fired storage tanks, the water in the tank is assumed to be well mixed and entirely at the setpoint temperature. For electric resistance storage tanks, the volume of water above the bottom element is assumed to be at the setpoint temperature, and the volume of water below the bottom element is assumed to be halfway between T_{env} and T_{set}, or 96°F (Burch 2010). Second, all draws are assumed to occur at the tank setpoint temperature. Third, the tank temperature is assumed to start and end the 24-hour period at the same temperature. This assumption means that the energy stored in the tank at the end of the test

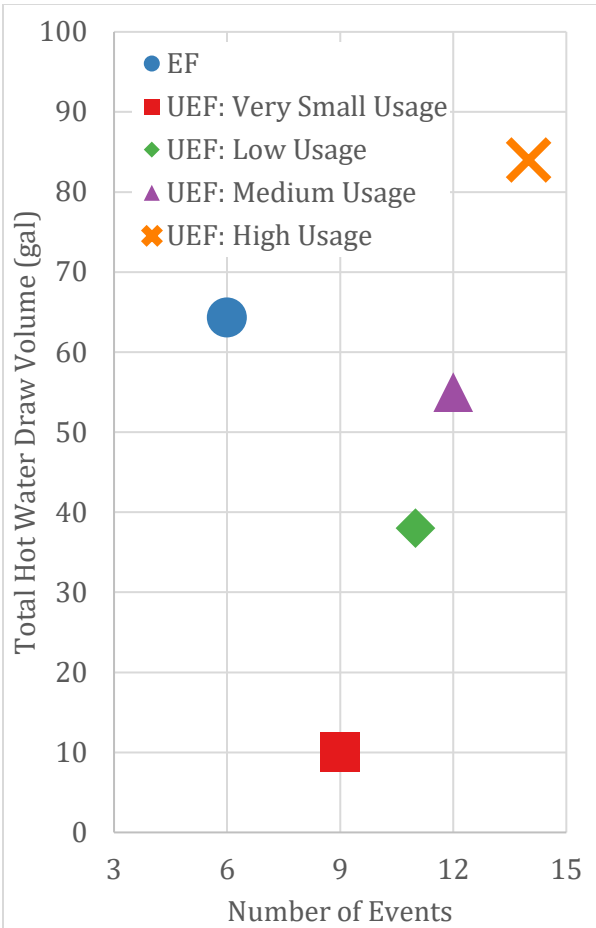

Figure 1. Comparison of Energy Factor and Uniform Energy Factor draw profiles

equals the energy stored in the tank at the start of the test. The UEF test procedure includes a preconditioning period designed to bring the tank temperature at the start of the test close to the final temperature, but it is possible for the stored energy to be slightly different at the start and end of the test.

Given these three assumptions, the UEF can be expressed as:

$$UEF = \frac{Q_{load}}{Q_{cons}} \tag{1}$$

Q_{load} is the net energy withdrawn from the water heater during the period of the test procedure, and Q_{cons} is the net energy consumed during the period of the test procedure. Q_{load} varies depending on which draw profile is used during the test. The draw volume and associated Q_{load} for each draw pattern are given in Table 2.

Table 2: Draw volume and delivered energy from the UEF test for all draw patterns. The old EF is shown for reference

	UEF Test				***EF Test***
	Very Small Usage	**Low Usage**	**Medium Usage**	**High Usage**	***All Usage***
Draw volume (gal)	10	38	55	84	*64.3*
Q_{load}* (Btu)	5,561	21,131	30,584	46,710	*41,092*

The RE of the unit is calculated as:

$$RE = \frac{Q_{load,draw}}{Q_{cons,draw}} \tag{2}$$

The RE is calculated for the first recovery period during the test. $Q_{load,draw}$ and $Q_{cons,draw}$ include all energy delivered and consumed during this recovery period. Depending on the test draw pattern and the output of the burner or element, the length of time for recovery might vary. There are tank losses during this entire recovery period, and some of the energy consumed during this period goes to offsetting them. As a result, the RE is less than the η_c, which is a physical property of the burner or element that has no dependence on the tank losses. For electric storage tanks, the allowable measurement error of the sensors used during the test is large enough that the calculated recovery efficiency provides no useful information (Healey, Lutz and Lekov, 2003). As a result, all electric water heaters have a reported RE of 0.98; however, the efficiency of the electric resistance elements is approximately 1, and η_c should be set to 1 when modeling electric storage tanks.

Detailed derivations of the calculations for UA_{gas}, $\eta_{c,gas}$, and UA_{elec} are provided in (Burch 2010). For gas-fired storage-type water heaters treated as one isothermal node, UA and η_c are calculated as:

$$UA_{gas} = \frac{\frac{RE}{UEF} - 1}{(T_{set} - T_{amb})\frac{t_d}{Q_{load}} - \frac{T_{set} - T_{amb}}{P_{in} * UEF}} \tag{3}$$

$$\eta_{c,gas} = RE + \frac{UA(T_{set} - T_{amb})}{P_{in}} \tag{4}$$

For an electric water heater treated as two separate isothermal nodes above and below the lower element, UA can be calculated as:

$$UA_{elec} = \frac{Q_{load}\left(\frac{1}{UEF} - 1\right)}{t_d(T_{set} - T_{amb})\left(f_{high} + f_{low}\left(\frac{T_{inlet} - T_{amb}}{T_{set} - T_{amb}}\right)\right)} \quad (5)$$

f_{low} and f_{high} are the fraction of the tank area below and above the lower element, respectively. Note that the area and volume above and below the lower element are different as the area of the tank top and bottom need to be accounted for. Actual values will depend on the geometry of the electric tank. Typical values for f_{low} range between 0.15–0.25 (Burch, 2010), and f_{high} = 1-f_{low}. The exact height of the element and tank geometry can vary significantly between units, as shown in Figure 3, so it is recommended to try to determine the height of the lower element in the tank when modeling a specific electric water heater.

EXAMPLE CALCULATION

For a 40-gallon (151 L) nominal capacity gas-fired storage-type water heater with a UEF of 0.64, a RE of 0.79, a burner capacity of 40,000 Btu/h (11.7 kW), and an FHR of 70 gallons (265 L), the UA value is:

$$UA_{gas} = \frac{\frac{0.79}{0.64} - 1}{(125 - 67.5)\frac{24}{30584} - \frac{125 - 67.5}{40000 * 0.64}} \quad (6)$$

$$UA_{gas} = 5.47\ \frac{Btu}{hr - F}$$

The conversion efficiency of this unit would be:

$$\eta_{c,gas} = 0.79 + \frac{5.47(125 - 67.5)}{40000} = 0.80 \quad (7)$$

For a 50-gallon (189 L) nominal capacity electric resistance water heater with an UEF of 0.95, element capacity of 5.5 kW (18,800 Btu/h), and FHR of 75 gallons (284 L), and f_{low} = 0.2 the UA value is:

$$UA_{elec} = \frac{30584\left(\frac{1}{0.95} - 1\right)}{24(125 - 67.5)\left(0.8 + 0.2\left(\frac{58 - 67.5}{125 - 67.5}\right)\right)} \quad (8)$$

$$UA_{elec} = 1.52\ \frac{Btu}{hr - F}$$

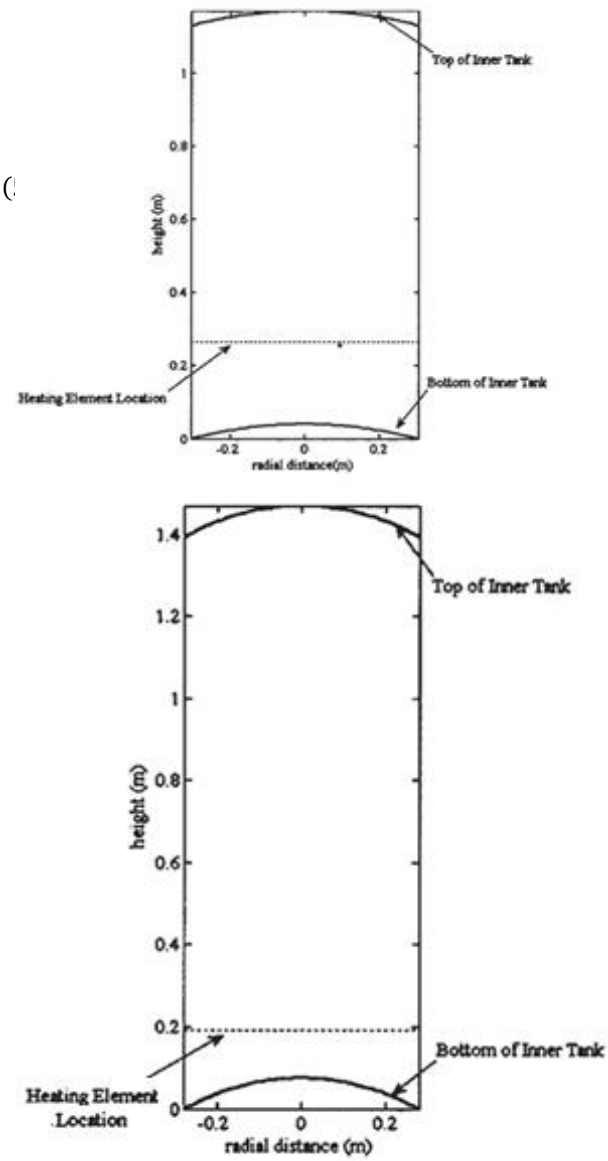

Figure 3 Geometry of two different electric resistance tanks. Adapted from (Healey, 2008)

EXAMPLE USAGE

To demonstrate this approach in a simulation engine, the example gas and electric water heaters described here were simulated using the UEF test conditions. The simulations were performed with EnergyPlus using a mixed tank model for the gas water heater and a stratified tank model for the electric water heater. The stratified tank model was used for the electric water heater to properly account for the impact of the volume of unheated water below the lower element. Twelve nodes were used to appropriately characterize the stratification that occurs in electrically heated tanks (Maguire, 2012).

Simulations were performed using the associated test draw pattern during a 2-day period to include the preconditioning period. The results of the simulations are presented in Table 3.

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Table 3: Results from simulated UEF test

	Gas Water Heater	Electric Water Heater
Rated UEF	0.64	0.95
Simulated UEF	0.64	0.95
Delivered energy (kBtu)	29.5	45.4
Consumed energy (kBtu)	46.3	47.7

The simulation results indicate that the method outlined here produces UEF values that agree well with the rated UEF. The simulated delivered energy is lower than the assumed delivered energy by less than 5% because of some sag in the outlet temperature, but this results in correspondingly lower consumed energy and ultimately good agreement between the rated and simulated EFs.

CONCLUSIONS

A method for determining model parameters for simulating gas and electric resistance storage water heaters has been outlined and demonstrated. The procedure only requires the rated data for water heaters, including the nominal volume, FHR, UEF, RE, input capacity, and conditions under which the tests are performed. For electric water heaters, it is also necessary to estimate the height of the lower element in the tank to get an accurate estimate of the unheated volume of water below the lower element, which impacts the tank losses. An example calculation is shown for deriving the parameters of both types of water heaters. The methodology developed here was tested by simulating both gas and electric resistance water heaters under the UEF test conditions. Simulation results showed that the rated UEF can be extracted from models using the parameters derived in the example calculations

NOMENCLATURE

f: Fraction of total surface area
EF: Energy Factor
FHR: First Hour Rating
P: Power into tank
Q: Quantity of energy
RE: Recovery Efficiency
t: Time
T: Temperature
UA: Overall loss coefficient of the storage tank
UEF: Uniform Energy Factor

Subscripts:

amb: Ambient air temperature
day: One day; 24 hours
elec: Electric water heater
gas: Natural gas (or other fossil fuel)
high: Area above the upper electric element
in: Input power
inlet: Incoming water temperature
load: Water heating load
low: Area below the lower electric element
set: Water heater setpoint temperature

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REFERENCES

Armstrong, A., "Appliance and Equipment Standards: Water Heating," in *ACEEE Hot Water Forum*, Portland, OR, 2017.

Burch, J. "Deriving Simulation Parameters from Rating Data For Stratified Storage Tank Water Heaters," in *ASES Annual Conference*, Raleigh, NC, 2011.

Burch, J and Erickson, P. "Using Ratings Data to Derive Simulation-Model Inputs for Storage-Tank Water Heaters," in *ASES Annual Conference*, Portland, OR, 2004.

Davis Energy Group, "Residential Feasibility Assessment of Gas Tankless Water Heaters in PG&E Service Territory," Davis Energy Group, Davis, CA, 2007.

Healey, W. "Effect of Temperature Stratification Near Heating Elements on the Measured Energy Factor of Electric Water Heaters," *ASHRAE Transactions,* pp. 85-95, 2008.

Healey, W., Lutz, J, and Lekov, "Variability in Energy Factor Test Results for Residential Electric Water Heaters," *HVAC & R Research,* p. 435, 2003.

Lutz, J and Melody, M. "Typical Hot Water Draw Patterns Based on Field Data," Lawrence Berkeley National Laboratory, Berkeley, CA, 2012.

Lutz, J., Whitehead, C. D., Lekov, A. and Winiarski D., "WHAM: A Simplified Energy Consumption Equation for Water Heaters," in *ACEEE Summer Study*, Pacific Grove, CA, 1998.

Maguire, J. "A Parametric Analysis of Residential Water Heaters," CU Boulder, Boulder, CO, 2012.

Sparn, B., Hudon, K., and Christensen, D. "Laboratory Performance," National Renewable Energy Laboratory, Golden, CO, 2014.

U.S. Congress, "Energy Efficiency Improvement Act of 2015," 114th U.S. Congress, Washington DC, 2015.

U.S. Department of Energy, "Appliance & Equipment Standards: History and Impacts," 26 January 2018. [Online].

U.S. Department of Energy, "Energy Conservation Program: Energy Conservation Standards for Residential Water Heaters, Direct Heating Equipment, and Pool Heaters," U.S. Department of Energy, Washington, DC, 2010.

U.S. Department of Energy, "Energy Conservation Program for Consumer Products and Certain Commercial and Industrial Equipment: Test Procedures for Residential and Commercial Water Heaters; Final Rule," U.S. Department of Energy, Washington, DC, 2014.

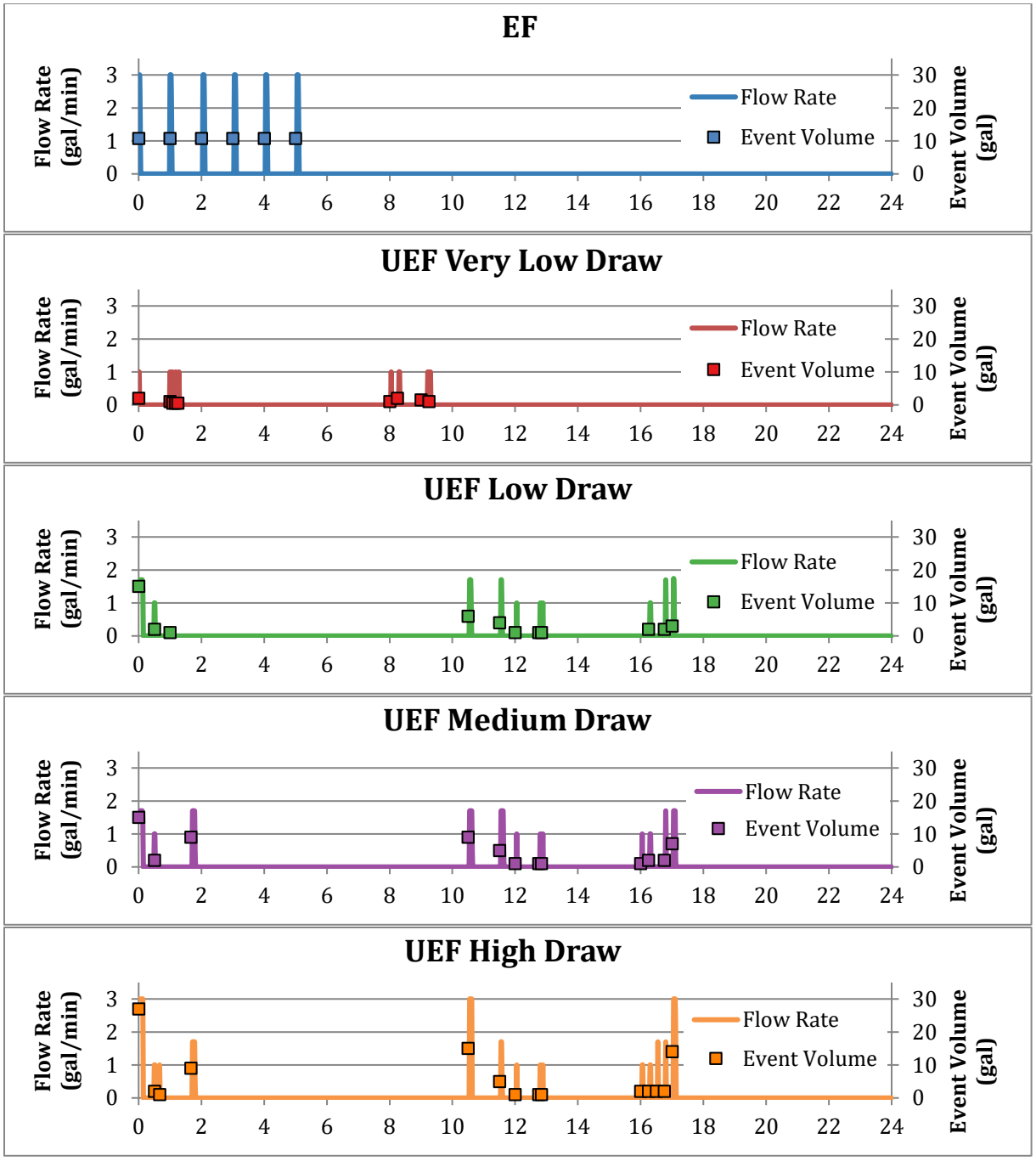

Figure 2. Water heater testing draw profiles