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Building America Industrialized Housing Partnership II

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Executive Summary

Motivation

Following the announcement of Energy Star ® for residential hot water heaters and the continued emphasis by utilities, regulators, and industry on increasing the efficiency of water heating, several major water heater manufacturers introduced integrated electric heat pump water heaters (HPWH) in 2010. These products "upgrade" ambient enthalpy to heat water with certified Energy Factors (EF) that meet the current Energy Star ® criteria of a 2.0 or above EF. Recent energy conservation standards rulemaking by DOE will essentially require that all electric storage water heaters above 55 gallons utilize heat pump technology to meet NAECA minimum efficiency levels to be implemented in 2015.

The three integrated HPWHs tested in this study, pictured in Figure 1, represent the current domestic offerings by major manufacturers and are the only current class of electric Energy Star ® residential water heaters. At first glance, these HPWH products seem similar to one another and one might conclude that they yield the same performance and efficiency. The three units tested vary in: refrigerant used, compressor size, evaporator fan size, amount of onboard electric resistance heat, condenser design, storage tank size, number and type of appliance (control) settings, and other factors that influence performance.

Figure 1: HPWHs in this Study

Broken down by the product class category (e.g. gas-fired tankless, electric resistance storage), residential water heaters generally behave similarly across manufacturer offerings. Despite slight variations in design, one can predict the efficiency and performance across a product category with reasonable accuracy. Such an effort is currently underway in a Gas Technology Institute (GTI) led effort, sponsored by the California Energy Commission, to develop numerical modeling tools to accurately predict the efficiency and performance of gas-fired water heaters across product classes. These component level models will be integrated with a hot water distribution simulation program, to provide simulation tools for both generation and distribution of hot water at the whole-house level. This complementary HPWH evaluation of the three HPWHs pictured in Figure 1 by GTI, under the Florida Solar Energy Center (FSEC) led Building America (BA) Industrialized Housing Partnership (IHP)Team supported by the Department of Energy (DOE), will aid in the development of electric HPWH models for these and other simulation modeling tools.

Methods & Results Summary

By design, HPWHs are inherently more complex than typical gas-fired or electric resistance water heaters. The heat pump portion alone brings considerable complexity, with performance and efficiency depending on the heat content of heat reservoirs at both the evaporator (ambient conditions) and the condenser (stored hot water). As ambient temperatures are cooler or drier or as the stored water temperature is hotter, the performance and efficiency of the heat pump will decrease. In addition to factors affecting the heat pump, all three HPWHs tested are “hybrids” in that they have electric resistance heating elements in addition to the heat pump, used for either backup heat or primary heat, depending on the appliance setting (control mode). The HPWHs have numerous appliance settings, which vary by the degree of heat provided by the heat pump versus electric resistance elements. Appliance settings which allow use of both heating methods utilize proprietary control mode algorithms to decide when heat pump heating is insufficient under certain operating conditions or hot water draw patterns. Differences in physical design and operational strategies compound the difficulty in generating meaningful experimental datasets to aid the development of generic HPWH models for these whole-house modeling tools.

The three units were put through a 16-test matrix, whereby the following influences on HPWH performance and efficiency were targeted: appliance setting, hot water draw pattern (including over/undersizing relative to the standard daily hot water consumption of 64 gallons/day), ambient enthalpy, water main temperature, and thermostat setpoint. Tests both determined hourly capacity and daily efficiency, through the First Hour Rating and 24 Hour Simulated Use tests, similar to those of the current standard rating methods of test. These parameters are varied over the test matrix, utilizing an environmental chamber to maintain a hot and humid condition of 90°F/65% RH and cold condition of 50°F/70% RH for several of the tests in that matrix. Throughout testing, energy consumption is measured at the individual component level (e.g. upper resistance element). Finally extended static chamber testing with monitoring of all moisture and heat flows is performed to quantify the space cooling effect of the HPWHs. Qualitative results of this test matrix with primary insights are summarized in Table 1.

One major challenge for the manufacturers is simultaneously optimizing performance on the federal rating, the Energy Factor (EF), while producing products that give the best possible service in the field. The EF rating method was developed to compare conventional tank water heaters, and does poorly at predicting relative energy use of different technologies or realistic use patterns. For this reason, we used both the simulated draw pattern of the federal rating method and patterns representative of GTI field evaluations in our study.

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Table 1: Results Summary

Test Parameter	Efficiency Effect	Performance Effect
Appliance (Control) Setting	• Directly proportional to percentage of heat input from the heat pump. • All-resistance operation results in EFs below that of conventional electric resistance water heaters. • Two of three HPWHs rely almost exclusively on higher-efficiency heat pump heat in Hybrid mode.	• Hot water capacity increases with resistance heat usage. • Large variation in storage tank and delivered water temperatures between manufacturers.
Thermostat Setting	• The HPWH using R-410a requires increased resistance heat for setpoint temperatures above 120°F, leading to a substantially lower EF at a these higher thermostat settings.	• Two of the three HPWHs actually have a reduced First Hour Rating with a lower setpoint due to onboard controls.
Hot Water Draw Pattern	• All HPWHs performed most efficiently as undersized, with 100 gallons/day versus 64 and 30 gallons/day for “non-standard” (non-DOE) draw patterns. • In Hybrid mode, heat pump energy consumption as a relative percentage of total energy consumption is unchanged for two of three HPWHs over all draw patterns. • As ‘more realistic’ draws spread demand throughout a 24 hour period, compared to standard (DOE) draw pattern while holding the hot water load constant, heat pump run times increase by up to 69%.	• “Non-standard” (more realistic) draw patterns result in large swings in delivered water temperatures for all HPWHs tested.
Ambient Enthalpy and Water Main Temperature	• As expected, the heat pump operates most efficiently in hot & humid ambient conditions and when the stored water in the tank bottom is cooler. Efficiency improves under ‘realistic’ versus standard draw patterns for both hot & humid and cold & dry tests in 5 of six cases. This is not consistently observed at standard ambient conditions with a standard (135°F) thermostat setting. • Similar to variation of hot water draw patterns, two of three HPWHs are unchanged in the fraction of heating provided by the heat pump over varying ambient and water main conditions.	• One of the three HPWHs, with the smallest compressor and evaporator fan, requires extended operation (> 6 hours) to reach steady state heat pump operation during a sustained draw beginning at set point. • Cooling effect is between 0.25 and 0.5 tons of cooling, with latent fraction reaching 2 - 4% (R-134a) and 27% (R-410a) under the hot & humid test condition, the difference primarily due to refrigerant selection resulting in a lower evaporator-side air temperature.

Introduction

Market Transformation in Residential Water Heating

After Energy Star ® for residential water heating began in January 2009, with an increase in the minimum Energy Factor (EF) requirement for gas-fired storage water heaters in September 2010; the residential water heating market has seen a large shift in product offerings towards higher efficiency. This is illustrated by Figure 2, displaying the number of certified gas-fired water heaters by Energy Factor shifting between 2008 and 2010 (AHRI, 2010). For the most common gas-fired storage volume of 40 gallons, there are visible shifts from the minimum required EF of 0.59 in 2008 to the Energy Star ® levels of 0.62 (2009) and 0.67 (2010). Without dispute, the Energy Star ® program has been a potent market driver for residential water heating.

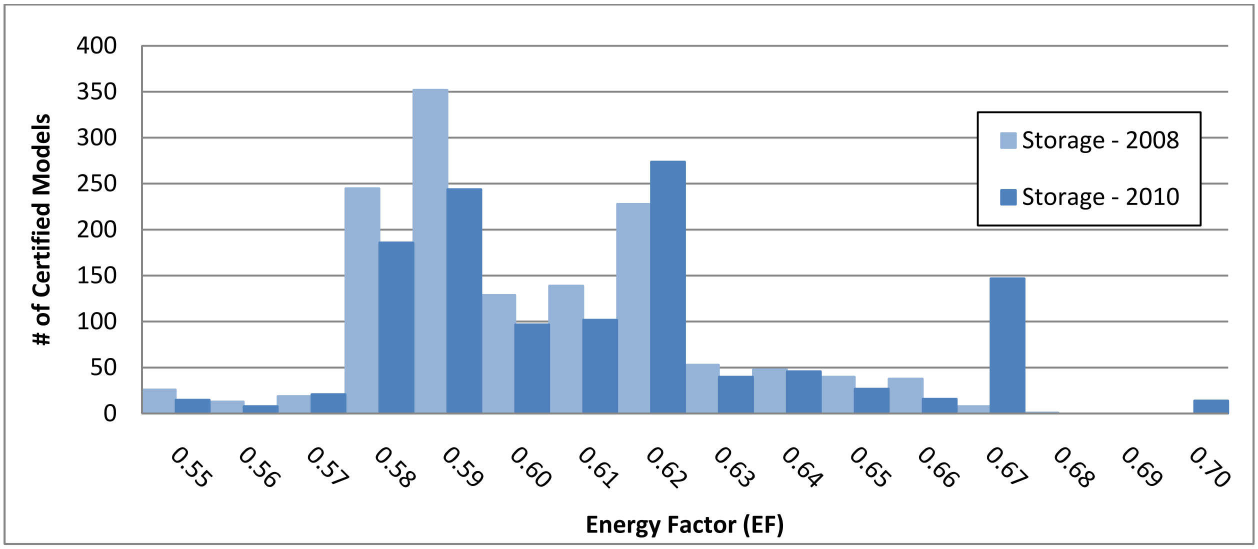

Figure 2: No. of Certified Residential Gas-Fired Water Heaters by Energy Factor (AHRI, 2010)

Acknowledging the shift in the water heating landscape, the Gas Technology Institute (GTI) initiated a residential gas-fired water heating market transformation program sponsored by the California Energy Commission (CEC). A key task of this program is the development and experimental validation of numerical models to simulate performance of these new water heating technologies under a range of operating conditions. These water heater models, grouped by technology class (e.g. tankless, gas-fired storage), will be incorporated into whole-house hot water distribution simulation tools. This integrated modeling tool looks beyond the efficiency of hot water generation equipment and includes thermal losses in the plumbing distribution and fixtures themselves while occupants wait for heated water. These emerging modeling tools are allowing the thermal losses in conventional distribution piping to be quantified. In turn, this will stimulate development and acceptance of new best plumbing practices to conserve energy and water. Additional Building America (BA) funded research at the Florida Solar Energy Center (FSEC) has shown that thermal losses also exert a very strong impact on solar water heating system efficiency where plumbing runs are longer, temperature differences are high, and water circulates for longer periods of the day (Colon 2010).

While gas-fired residential water heaters comprise three-fifths of the Energy Star ® product categories, electric heat pump water heaters (HPWH) are also emerging as a significant product class. Traditional electric resistance water heaters have been excluded from the Energy Star ® program, due to the small EF gap between mandatory minimum and commercially available maximum efficiency levels. Thus HPWHs are the only electric Energy Star ® water heaters. In response, major manufacturers have introduced residential HPWH models. This emerging product class, with EFs above 2.0, has gained the attention of utilities and regulators alike, with both offering significant financial incentives for homeowners (DSIRE, 2010).

Residential electric HPWHs, developed as *integrated* (heat pump and storage tank) and *add-on* (heat pump only) water heaters, have been sold in the U.S. for more than four decades. Reliability issues and high installed cost plagued initial product rollouts in the 1970s and 1980s, which were attributed to manufacturing issues and an overall rush to market (Hiller, 2010). Seeking to learn from mistakes and leverage new technologies and manufacturing techniques, the DOE and CEC sponsored research and development of a market-optimized residential HPWH, with substantial contributions from TIAX, LLC and Oak Ridge National Laboratory (ORNL). They achieved reliable performance and efficiencies exceeding an EF of 2.0 (TIAX, 2004). Incorporating lessons learned from this R&D and technologies developed in European and Asian markets and spurred by Energy Star ®, major manufacturers began releasing residential HPWHs in 2010. The building research community has since been concerned with characterizing the performance and reliability of these recent offerings, including large-scale field testing (EPRI, 2010) and laboratory validation of DOE certified test procedures (PG&E-ATS, 2010).

To supplement the whole-house hot water distribution model development activities under the CEC market transformation program, three of the recently available residential HPWHs were tested in the GTI Residential & Commercial Laboratory, under a range of operating conditions. The tested units are *integrated*, in that they are packaged systems as opposed to *add-on* systems, where the heat pump portion is plumbed to a separate storage tank. Like the data generated for gas-fired water heaters under the CEC program, the HPWH datasets will later be used in the development and validation of appliance models, and later integrated into the whole-house hot water distribution and other modeling tools. While these HPWH models vary in their construction and control strategies, as a product class they differ greatly from gas-fired storage, tankless, and condensing water heaters. The sensitivity of efficiency and performance to ambient conditions, user appliance setting, hot water draw pattern, and water main temperature are all explored in this study.

Heat Pump Water Heater Overview

A vapor compression refrigeration cycle is used in HPWHs to "upgrade" the ambient enthalpy to heat water. As employed in air conditioning and refrigeration but with different goals, the heat pump transfers ambient heat to the desired sink, in this case the stored water, and rejects cooled and dehumidified air to the surrounding space. Primarily through its compressor, electrical energy is consumed in the transfer of this ambient heat, not its generation, thus efficiencies (defined as energy delivered divided by energy consumed) of greater than 200% are typical. For cost, noise, air movement, and other reasons, the heat pump heating rates are relatively small at less than 10,000 Btu/hr (3 kW), relative to comparable gas-fired and electric resistance water heaters. Consequently, current *integrated* HPWHs have large storage volumes (≥ 50 gallons) and have two onboard electric resistance heating elements, which vary in size by unit. The manner in which the heat pump and/or resistance elements are utilized to meet a specific hot water demand depends not only on the demand itself, but the user appliance setting (e.g. High Efficiency mode), ambient conditions, system design, controls algorithms, and the makeup water temperature.

The designs of the three tested HPWHs vary considerably. One of the three HPWHs uses R-410a as a refrigerant, most commonly used in air conditioning as an alternative to R-22. With service ports available, the intent is that a residential HVAC technician could service the HPWH. R-134a, with a higher condensing temperature and more commonly used in refrigerators and automotive air conditioning, is used by the other two. Two condenser designs are employed by the three units tested, active and passive, which have their respective advantages and drawbacks:

- **Active (**Pumped water circulation) – water is pulled from the storage tank in a pumped circuit and heated through a co-axial heat exchanger integrated with the condenser
- **Passive (**Wrapped tank) - the single-wall condenser coil is wrapped around the storage tank[1]

Table 2: Summary of HPWH Characteristics

HPWH Tested	Storage Volume (gallons)	Compressor Power Input[1]	Resistance Element Rated Power	Refrigerant	Condenser Design
Mfr A	60 - nominal 57.6 - measured	860 W[2]	4.5 kW Upper 2.0 kW Lower	R-134a w/ service ports	Wrapped Tank
Mfr B	50 - nominal 45.6 - measured	700 W (230 VAC)	4.5 kW each Upper & Lower	R-134a w/o service ports	Wrapped Tank
Mfr C	50 - nominal 45.3 - measured	950 W (230 VAC)	2.0 kW each Upper & Lower	R-410a w/ service ports	Pumped Water Circulation

1 With 120°F water
2 As measured, nameplate output is 600 W at 230 VAC

1 If the condenser coil were submerged within the potable water tank, it would need to be double-wall construction.

The primary physical characteristics of the three HPWHs tested are summarized in Table 2. As the purpose of this study is to generate datasets for use in development of modeling tools for the complete class of residential electric HPWHs, manufacturer names are kept anonymous and the units tested are referred to throughout as Manufacturer A, B, and C (hereafter “Mfr”).

Mfr C locates the entire heat pump assembly atop the storage tank, including the condenser, and uses a pumped circulation loop to heat the water. Mfrs A and B wrap the condenser around the storage tank to heat the water it contains, while the balance of the heat pump assembly resides atop the storage tank. A fan, two in the case of the Mfr B, pulls ambient air past the compressor, expansion valve, and electronic components and then through the evaporator. Relative to the user control panel, the HPWHs move the air as follows: Mfr B draws air from the sides and rejects it through the back, Mfr A draws from the left side and rejects to the right side, and Mfr C draws from the top and rejects to the sides and back. None of HPWHs presently have ducting arrangements to the direct evaporator airstream away from the space that the unit occupies or to an area of with desired cooling. These units tested are pictured in Figure 3.

Figure 3: HPWHs Tested in this Study

Rating Residential Water Heaters

The DOE has established rating criteria to describe the performance and efficiency of residential water heaters, including HPWHs. It is with these criteria (DOE, 1998): that water heaters demonstrate compliance with minimum requirements under the National Appliance Energy Conservation Act (NAECA) and are qualified for Energy Star ®:

- **First-Hour Rating** – This is a measure of the capacity to deliver hot water. The test procedure determines the volume and average temperature of hot water delivered by a water heater during an hour of operation. A draw of 3.0 gallons per minute (gpm) is sustained until the draw temperature drops 25°F below the maximum delivered temperature for that draw. At this point, the draw ceases and the water heater recovers to its set point temperature. Subsequent draws are initiated following satisfaction of the thermostat(s) for the balance of the hour. The First-Hour Rating (FHR), reported in gallons of hot water, is the total volume of hot water delivered over the hour.
- **Energy Factor** – The Energy Factor (EF) is determined by the performance of the DOE *24 Hour Simulated Use Test*, which estimates the aggregate energy efficiency over a day long hot water draw pattern. The test sequence consists of six equal hourly hot water draws at 3.0 gpm that sum to 64.3 gallons. Following these draws in the first six hours, the water heater idles in standby for the remainder of the 24 hour period. From this test, an EF is calculated to represent the transient efficiency of the water heater under standard test conditions (outlined in the next section), following numerical adjustments for variations in ambient conditions, inlet and outlet water temperatures, and the estimated recovery efficiency. This recovery efficiency, akin to a steady state thermal efficiency, is determined between the initiation of the test to the first "cut-out", or satisfaction of the thermostat(s).

Performance and efficiency, represented by the FHR and EF respectively, are generally at odds for the hybrid HPWHs testing. The heat pump component has long recovery time due to its lower heat input, thus use of the lower efficiency electric resistance elements is required for higher demand hot water draws. To both satisfy the rating requirements and meet diverse user needs that vary from rapid recovery to efficient operation, the HPWHs tested have several operating modes. While differing in name and specific management of heat pump and/or electric resistance element operation, the three units effectively can operate in three regimes:

- *High-Efficiency* – This mode is exclusively (Mfrs A and B) or heavily (Mfr C) reliant upon the heat pump. Mfr C qualifies for Energy Star ® in this mode.
- *Hybrid* – This mode employs some combination of heat pump and electric resistance heat to satisfy higher demands through shorter recovery times and is the default "out-of-the-box" setting for all products tested. Mfr B can operate in two such hybrid modes that differ by magnitude of anticipated demand, the more efficient of which is the default factory setting for Energy Star® qualification. Mfr A and B qualify for Energy Star ® in this mode.
- *All Resistance* – The heat pump portion can be disabled and the HPWH can operate as an electric resistance heat only water heater.

Published EF and FHR ratings for the various operating modes are summarized in Table 3 below.

Table 3: Certified FHR and EF Ratings

HPWH Tested	Operating Mode[1]	Energy Factor	First-Hour Rating (gallons)
Mfr A	Hybrid	2.33	68
	Efficiency	2.40	51
	All Resistance	0.88	66
Mfr B	Hybrid	2.35	63
Mfr C	Hybrid	1.50	67

1 Modes without published information are not listed

Test Methodology

To provide meaningful datasets to develop and validate equipment models, the three HPWHs are tested at a range of standard and non-standard conditions representative of actual use. Manufacturers and others have published results from testing at standard conditions and the test battery begins at these conditions both to baseline and validate testing within the GTI Residential/Commercial Laboratory.

Test Parameters

The following parameters are varied over the sixteen test matrix applied to each HPWH:

- **Appliance Setting –** As evidenced by the range of certified FHR and EF ratings for each setting in Table 3, the appliance setting dictating the utilization of heat pump and/or electric resistance heat is an important parameter. Five out of ten settings over all three HPWHs employ some combination of heat pump and electric resistance heat, differentiated by proprietary algorithms are not available for model developers. In general, the control algorithms shift between the two heat sources depending on ambient temperatures, water temperatures, and sensed draw events; employing time delay and modulation. Due to their inherent complexity and the likelihood of modified algorithms appearing in subsequent HPWH generations, inferring these control algorithms is outside of the project scope. The majority of tests are performed in the default factory setting, however this dependency is explored on a limited basis in testing.
- **Hot water draw pattern –** The effect of a hot water draw pattern on the performance and resulting efficiency of residential water heaters has been an area of research and debate since the development of the current DOE certification procedures. ASHRAE Standard Project Committee, SPC 118.2 and an AHRI working group are tackling this very issue with respect to modifying the current test procedures. While all classes of residential water heaters have shown variations in performance and efficiency when put through DOE certification versus hot water draw patterns more representative of actual use in homes, the HPWH may have large variations. This is largely a result of onboard control response to the varying frequency, number, and magnitude of hot water draws over a 24 hour period. This may result in a range of net energy inputs required for a given output over 24 hours.

  In addition to the DOE standard 64.3 gallons/day profile described on page 7, GTI tested the three HPWHs with three more typical draw patterns for low, medium, and high use in homes. These are shown in detail in Figure 28 through Figure 30, with the 64 gallons/day medium draw pattern comparable to the DOE certified draw pattern daily total for hot water volume. These patterns were generated from field-sampled daily hot water draws, averaged over a week and reduced to 10 minute bins (Kalensky 2006). The draw rates for each pattern were averaged into “high” and “low” draw rates, shown in both Table 4 and in Figure 28 through Figure 30.

Table 4: Draw Rates for GTI Hot Water Draw Patterns

GTI Draw Pattern (gal/day)	"High" Draw Rate (gpm)	"Low" Draw Rate (gpm)
Low (30)	1.0	0.5
Medium (64)	**3.0***	1.0
High (100)	2.0	1.0

* Corresponds to DOE test protocol

- **Ambient Enthalpy –** As an air-source heat pump, the efficiency of the HPWH is dependent on the ambient enthalpy, or the wet bulb temperature as more practically represented in testing and modeling. During winter when room temperature and water main temperatures are at their lowest system efficiency and recovery rates will suffer. Four of the sixteen tests are performed inside an environmental chamber, controlling temperature and humidity to cold/dry and hot/humid conditions consistent with extreme winter and summer wet bulb design conditions for a Southeastern climate at: 50°F dry bulb/70% RH and 90°F dry bulb/65% RH, respectively.

  Noting the interaction between HPWH operation and space heating during the winter months, the Northwest Energy Efficiency Alliance (NEEA) has developed the *Specification for Residential Heat Pump Water Heaters Installed in Northern Climates*. This specification recommends that HPWHs installed in unconditioned spaces have direct venting of cold evaporator exhaust air exterior to the residence and be rated by an annual efficiency metric, demonstrating an annual equivalent of a 2.0 EF. Those HPWHs installed in conditioned spaces are required to minimize the adverse effect on space heating through direct venting of evaporator exhaust air or other means.

- **Water Main Temperature –** The water main temperature can vary greatly annually, ranging from approximately 64°F to 83°F in Jacksonville, FL for instance. This impact is not unique to HPWHs, as colder water temperatures improve heat transfer but reduce the capacity to deliver hot water. This reduced hot water capacity due to cooler water temperatures will have an enhanced impact on the Mfr C HPWH, which draws water from the tank bottom to the condenser. While temperatures lower than the DOE prescribed 58°F are not likely in the hot and humid climates, for those tests within the environmental chamber simulating summer temperatures, the water main temperatures correspond to average summer temperatures per datasets provided by FSEC at 83°F. During the winter condition, water main temperatures are maintained at the DOE test point water temperature of 58°F.

- **Thermostat setpoint** – The DOE certification test procedures require a setpoint of 135°F and the factory default setting on the three tested HPWHs is 120°F. Previous studies have shown an impact on efficiency by a small change in thermostat setpoint. For example, a reduction from a 133°F to 129°F on Mfr C increased its EF by up to 0.41 points in the *Efficiency* mode (PG&E-ATS, 2010). As the hot water temperatures begin to approach the condensing temperature of R-410a, the Mfr C HPWH shifts to electric resistance heat. Tests intended for direct comparison with certified results have a 135°F setting, with one test at the factory default setting of 120°F and the environmental chamber tests at the average user setting of approximately 125°F, per manufacturers based on their limited HPWH user feedback to date.

The sixteen test parameter matrix applied to each HPWH is shown in Table 6, with variations discussed above.

- The first four tests are the DOE standard First-Hour Rating test, with one test at each of three appliance settings outlined previously (including Mfr B "High-Demand" mode) and a final test at a factory default setpoint temperature and appliance setting.
- Tests 5 through 12 are 24 Hour Simulated Use Tests at standard ambient conditions (see Table 5). These tests vary the hot water draw pattern and both reduce the setpoint temperature and vary the appliance setting while using the DOE draw pattern.
- The final four tests are inside the environmental chamber at hot and cold conditions. Both the GTI and DOE 64 gallons/day draw patterns are used at each condition.

For the twelve tests not in the environmental chamber and using the DOE hot water draw pattern, conditions are maintained at the specified conditions shown in Table 5. Departures in ambient humidity and temperature are observed from specifications, with the average temperature and relative humidity shown in Figure 72 and Figure 73.

Table 5: DOE 24 Hour Simulated Use Test Control Specifications

Controlled Condition	DOE Specification
Ambient Dry Bulb Temperature	67.5 ± 1°F
Ambient Relative Humidity	50 ± 1%
Water Main Pressure	40 psig up to mfr. spec.
Water Main Temperature	58 ± 2°F
Water Draw Rate	3.0 ± 0.25 gpm
Water Heater Set Point Temperature	135 ± 5°F
Supply Voltage	Within 1% of mfr. spec.

Experimental Setup & Instrumentation

Two test bays were constructed for this project, one in the greater Residential Commercial Laboratory (pictured in Figure 4) and one within the environmental chamber. In terms of piping and accuracy of instrumentation, these bays conform to DOE requirements of the First-Hour Rating and the 24 Hour Simulated Use Test (DOE, 1998). The complete list of measured quantities, instrument make, model, and accuracy are summarized in Table 10 and Table 11. Despite construction per DOE specifications, GTI's laboratories are not certified per GAMA requirements. Departures from ambient conditions outside of the specifications in Table 5 are recorded and acknowledged. In addition to brief departures from required ambient conditions, it was found during testing that the supplied voltage was lower than manufacturer recommendations, at approximately 210 VAC versus the requirement of up to 240 VAC. Other laboratories have reported voltage shortfalls in their HPWH testing as well (PG&E - ATS, 2010). Future testing will require investment in voltage regulating hardware, which was beyond this project budget. **Therefore, while some reported results are from the execution of DOE test**

procedures, they are only relevant in relative comparison to experimental data from this project and are not directly comparable to First Hour Ratings (FHR) nor Energy Factors (EF) published elsewhere.

Figure 4: Photo of Laboratory Test Stand

To ensure repeatability and applicability of test results requiring specific water main temperatures, water preheating and precooling loops were modified using a modulating tankless water heater and a 1.5 ton portable chiller respectively. Over the course of the testing the groundwater temperatures in the Chicago area ranged from approximately 56 °F up to 70 °F between May and October, requiring heating and cooling (collectively referred to as preconditioning) of this inlet water. Additionally, water pressure available to GTI's laboratory facilities is fairly low, typically less than 40 psi. To maintain required water pressures during simultaneous HPWH tests, a booster pump is used to maintain pressure at approximately 45 psig.

Temperature measurements within the tanks were made with a so-called "thermocouple tree", which is common in residential water heater testing. Six thermocouples of varying lengths are immersed and spaced vertically within the tank such that they are located at the midpoint of six equal volume fluid elements. One tree was constructed for each HPWH, due to their variation in internal dimensions. A typical thermocouple tree is shown in Figure 5. When temperatures are reported, they are labeled by the distance from the top of the storage tank interior.

Figure 5: Typical Thermocouple Tree for Storage Tank Temperature Measurement

Table 6: Test Parameter Matrix for each HPWH

Test Number	Appliance Setting	Ambient Temperature (F)*	Ambient RH*	Groundwater Temperature (F)	Water Heater Set Point (F)	Draw Pattern Used	Notes	In Env. Chamber?*
1	Energy Saver (EF)	67.5	50%	58	135	FHR	First-Hour Rating test	No
2	Hybrid (FHR)	67.5	50%	58	135	FHR	"	No
3	All-Resistance	67.5	50%	58	135	FHR	"	No
4	Factory Default	67.5	50%	58	120	FHR	"	No
5	Factory Default	67.5	50%	58	135	DOE - 64		No
6	Factory Default	67.5	50%	58	135	GTI - 100		No
7	Factory Default	67.5	50%	58	135	GTI - 64		No
8	Factory Default	67.5	50%	58	135	GTI - 30		No
9	Energy Saver (EF)	67.5	50%	58	135	DOE - 64	Eliminate if repeating 5	No
10	Hybrid (FHR)	67.5	50%	58	135	DOE - 64	"	No
11	All-Resistance	67.5	50%	58	135	DOE - 64	"	No
12	Factory Default	67.5	50%	58	120	DOE - 64		No
13	Factory Default	90	65%	83	125	DOE - 64	Hot & Humid /Garage	Yes
14	Factory Default	90	65%	83	125	GTI - 64	"	Yes
15	Factory Default	50	70%	60	125	DOE - 64	Winter /Garage	Yes
16	Factory Default	50	70%	60	125	GTI - 64	"	Yes

* During HPWH tests number 1 through 12, that were not conducted in the environmental chamber, best efforts were made to control the Residential/Commercial Laboratory within the DOE test procedure specifications in Table 5. However, excursions in ambient humidity and temperature were observed from specifications as documented in Figure 72 and Figure 73.

Each test bay is independently controlled, allowing for simultaneous testing under different conditions. Data acquisition and control are executed through a combination of National Instruments *Field Point* hardware and *LabView* software and custom programs written in C++. Data is sampled in 5 second intervals unless otherwise specified. Hot water draw patterns are automated through use of a previously developed custom program, with the Graphical User Interface (GUI) shown in Figure 6. For 24 Hour Simulated Use Tests, the program initiates draws of a desired volume at user-defined intervals through activation of a “high” or “low” flow solenoid valve downstream of the HPWH, which closes once the desired draw volume is recorded by the flow meter.

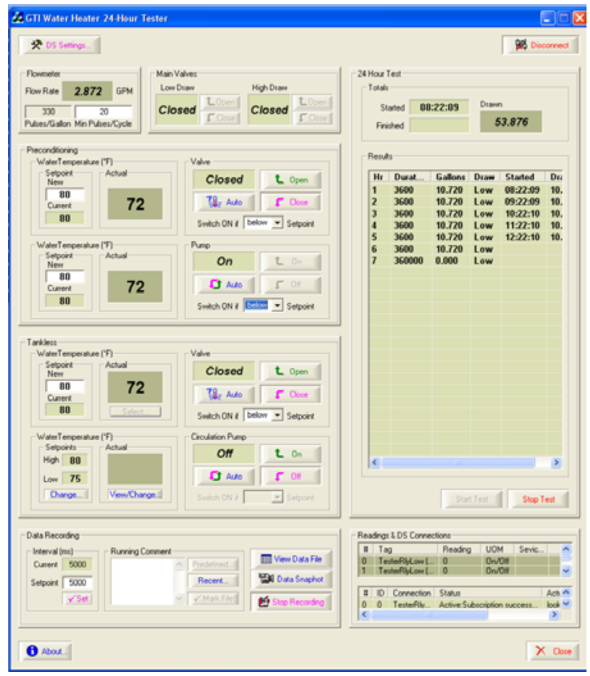

Figure 6: Water Heater Test Software GUI

While operating in the environmental chamber at the summer wet bulb condition equivalent to 90°F dry bulb/65% RH, the space conditioning effect provided by the HPWHs is quantified. As the chamber was modified to accommodate the measurement and controls necessary for HPWH testing, the overall heat loss (so-called *UA* value) and the leakage rate were quantified through separate tests. Those separate test procedures, results, and analysis are discussed in Appendix A – Test Methodology. The UA value is determined through maintaining the chamber at the 90°F dry bulb condition for a period of 12 hours and measuring the heat input necessary to maintain this condition inside the 70°F dry bulb laboratory space. The leakage rate of the chamber is determined through creation of an oxygen depleted environment within the chamber by displacement with nitrogen, to 18% O_2 by volume, and allowing the chamber to recover to 20.9% O_2 by volume while continuously sampling the chamber atmosphere. Through the two tests, the approximately 900 ft^3 chamber was found to have the following characteristics:

Table 7: Environmental Chamber UA and Leakage Rate

Chamber Quantity	Calculated Value
UA	24 Btu/hr-°F
Leakage Rate	13 CFH (0.02 ACH)

Test Results & Analysis – First Hour Rating

As discussed in "Rating Residential Water Heaters", the First-Hour Rating (FHR) is a measure of the hourly hot water capacity of a residential water heater. Each HPWH is run through the FHR test in each of its three primary appliance settings: *High-Efficiency, Hybrid,* and *All-Resistance*. Mfr B has an additional mode intended to meet a larger demand, the so-called *High-Demand* mode, which is also tested for a FHR. The results are shown in Figure 7 and quantified in the appendices, in Table 12.

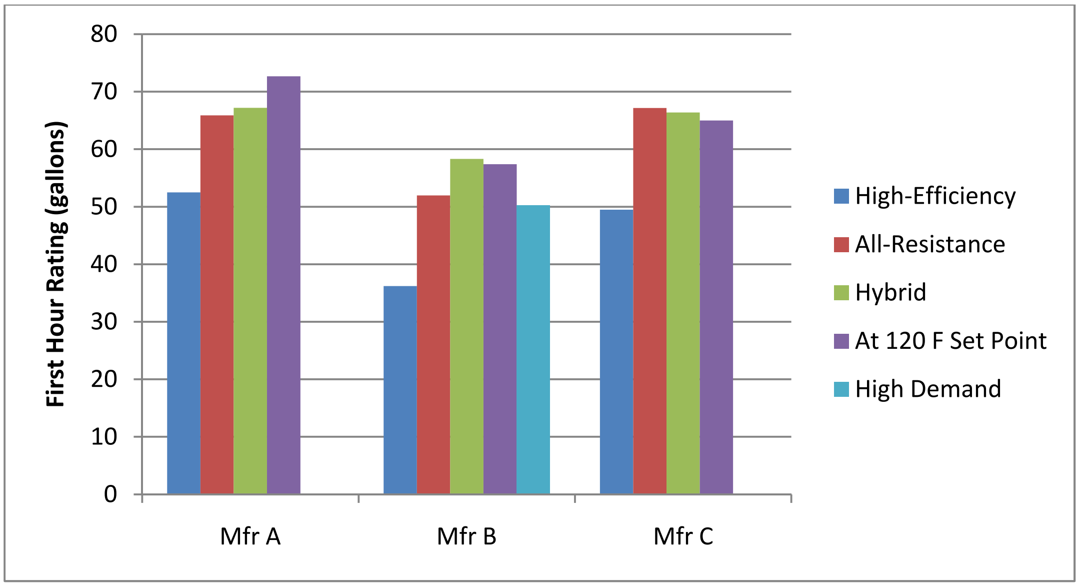

Figure 7: First-Hour Ratings by Appliance Mode

As the HPWHs have longer recovery times than other residential water heating classes due to their reduced heat inputs from the heat pump, the majority of HPWHs in their different appliance modes do not satisfy their thermostats in the first hour following the draws as specified in the EF test. Per the DOE standard test procedure, the second draw is imposed at the end of the hour until the delivered temperature drops 25°F below the highest temperature recorded during the first draw. In a few cases, the initial delivered temperature in the second imposed draw is below this draw termination temperature initially, negating this second draw volume. Charts displaying the inlet, outlet, and stored water temperatures are shown in Appendix B: Detailed Test Results, in Figure 36 through Figure 48.

In two of the three cases, the reduced thermostat setting of 120°F decreases the FHR relative to the higher thermostat setting of 135°F in the *Hybrid* mode. In the case of Mfr B, the lower overall average tank temperatures following the first draw from starting at a lower set point, causes the unit to rely more on its lower rather than upper resistance element, which while with the same rated input as the higher element, does not immediately result in increased outlet temperatures. In the case of Mfr C, its *Hybrid* mode is more biased towards utilization of the upper resistance element. However, with the DOE standard thermostat setting of 135°F, the element is energized during the first draw with a lower thermostat setting and the control algorithm delays energizing of this element until 20 minutes after the completion of the first draw. Conversely, the Mfr A unit, with a larger overall nominal tank size of 60 versus 50 gallons, yields the anticipated result of an enhanced FHR with a reduced thermostat setting. As the gap between water main and thermostat set point temperature is decreased, recovery times are subsequently shortened, yielding a higher FHR.

Those HPWHs that do recover within the first hour, initiating a second draw before the 60th minute are Mfr B in two modes (*High-Demand & All-Resistance*) and Mfr A in two modes (*Hybrid & All-Resistance*). The test procedure specifically denotes that the second draw be initiated when the thermostat controlling the upper resistive element is satisfied. Closer inspection of the stored water thermocouple tree readings, the example of Mfr A in *Hybrid Mode* shown in Figure 8, highlights the achievement of this goal in its operation of the heat pump, upper, and lower resistive elements. Note that following the first draw after the 16th minute, the two upper-most thermocouples in the vicinity of the upper resistive element show targeted heating up to the point of thermostat satisfaction, at approximately the 55th minute. While the upper element is heating the top of the tank, the bottom half of the tank remains cold through the remainder of the test. The HPWH begins the second draw with an average tank temperature of 93°F.

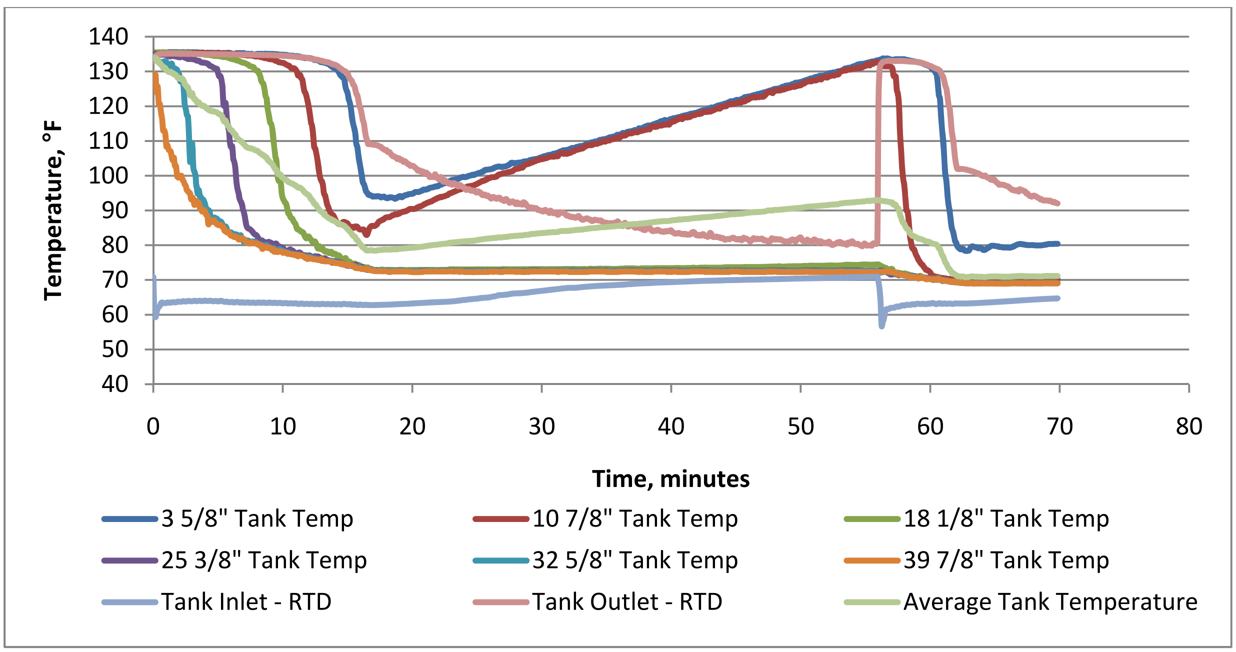

Figure 8: Mfr A First-Hour Rating in Hybrid Mode – Temperatures

This targeted heating of the upper tank during this test is the strategy employed by those HPWH modes recovering within this hour. The energy consumption monitored during the same test confirms this strategy of relying upon the upper resistive element, as shown in Figure 9. Figure 9 shows the cumulative energy over the course of the hour, separately for the upper resistive element and compressor and normalized to their respective total energy at the end of the hour. The figure is scaled in this manner since the total energy consumption of the upper element over the test is much greater than the compressor, which is 2300 Wh versus 92 Wh. At the 14 minute mark of the test, the compressor has effectively ceased operation while the upper resistive element operates for most of the balance of the hour. The upper resistive element thermostat is satisfied just before the end of the hour, thus initiating the second draw. The lower element is not energized throughout this test.

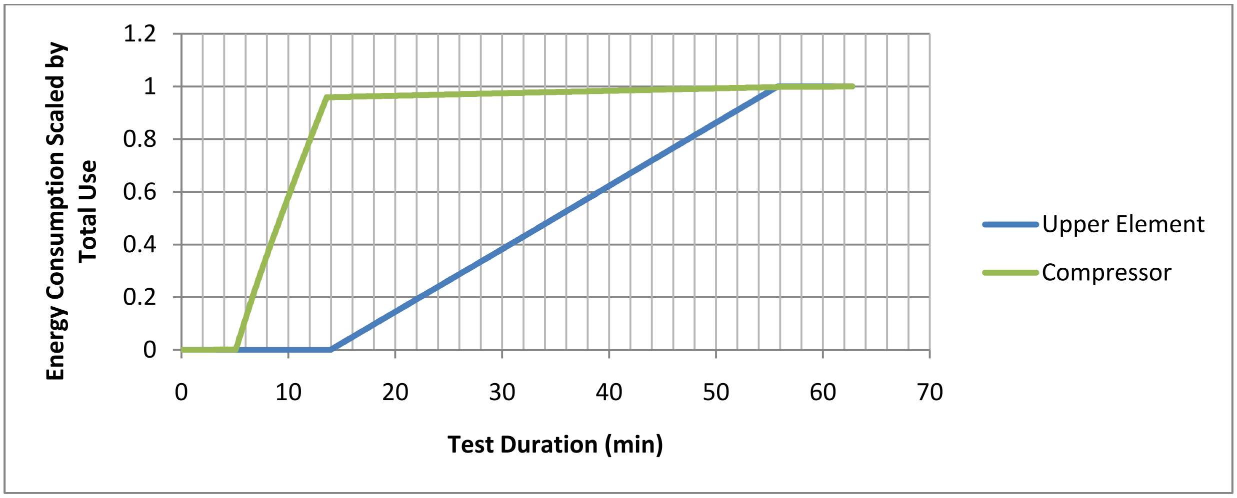

Figure 9: Mfr A First-Hour Rating in Hybrid Mode – Scaled Energy Consumption

In general as shown in Figure 7, the FHR results follow trends that one would expect. The greater storage volume of the 60 gallon Mfr A model has higher overall FHRs than the 50 gallon Mfr B and Mfr C units. FHRs tend to increase as appliance settings (control modes) progress from *High Efficiency* (predominately or exclusively heat pump operation), to *All Resistance*, and finally to *Hybrid* operation. Mfr C is the exception with a slight loss in FHR in *Hybrid* operation probably due to its heat pump operation using pumped water circulation which disturbs thermal stratification in the storage tank.

Mfr B has an additional *High-Demand* mode, which counterintuitively resulted in less hot water delivered than in the *High Efficiency, All Resistance* or *Hybrid* modes. *High-Demand* mode delivered approximately 8 gallons less than the peak FHR achieved in *Hybrid* mode. In the two modes, approximately the same energy inputs were observed, 3.2 kWh versus 3.1 kWh total and 2.6 kWh versus 2.5 kWh to the upper resistive element for the *High Demand* and *Hybrid* modes respectively. Examining the graph in Figure 10, the delivered temperatures are identical for the first and second draws. The difference lies in the manner in which the upper element thermostat is satisfied prior to the test, during the predraw, impacting the average tank temperature. In *High Demand* mode, the HPWH favors use of the resistance heating elements, leaving the bottom portions of the tank relatively cool. In *Hybrid* mode the heat pump is used more frequently, and following the predraw either the heat pump or upper element is utilized, favoring the heat pump, thus heating the stored water more evenly. This results in a higher average tank temperature, decreasing the time required to recover following the first draw.

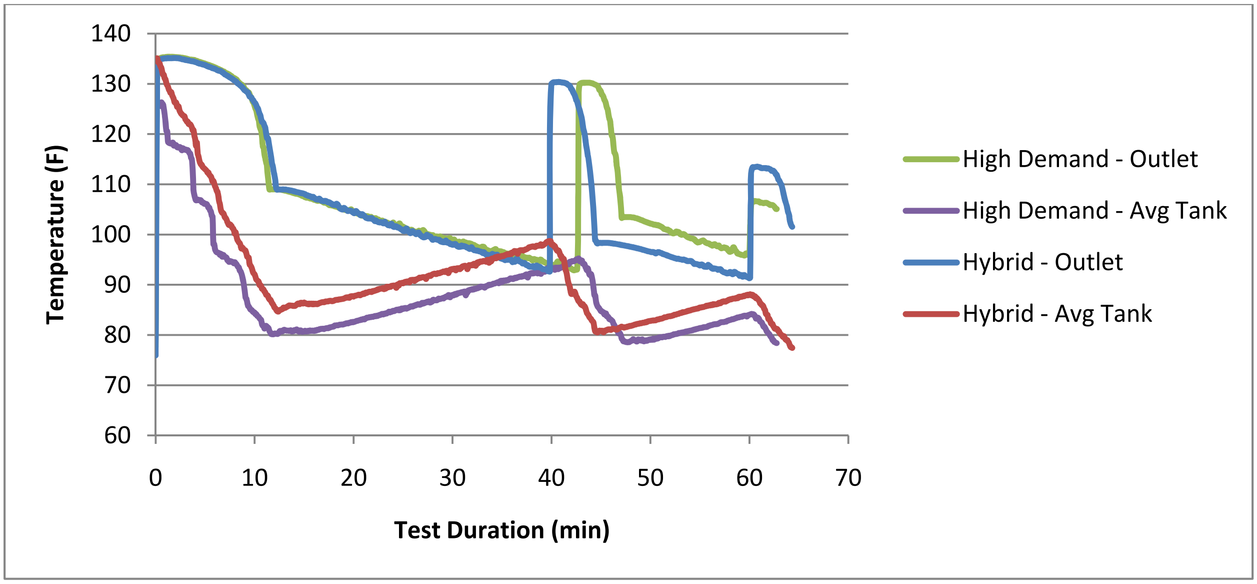

Figure 10: Mfr B First Hour Rating - Comparing Outlet and Tank Temperatures

Test Results & Analysis - 24 Hour Simulated Use Tests

Deviations from Standardized Testing

The official metric for the energy efficiency of residential water heaters is the Energy Factor (EF), which imposes six regularly spaced equal magnitude draws in the first five hours, followed by an extended standby period (visualized in Figure 11). It is widely recognized by most in the industry that this pattern does not treat different water heater types equally. Acknowledging these and other issues, manufacturers, efficiency advocates, end users, and regulators are meeting through ASHRAE, AHRI, and other organizations to potentially revise this test procedure.

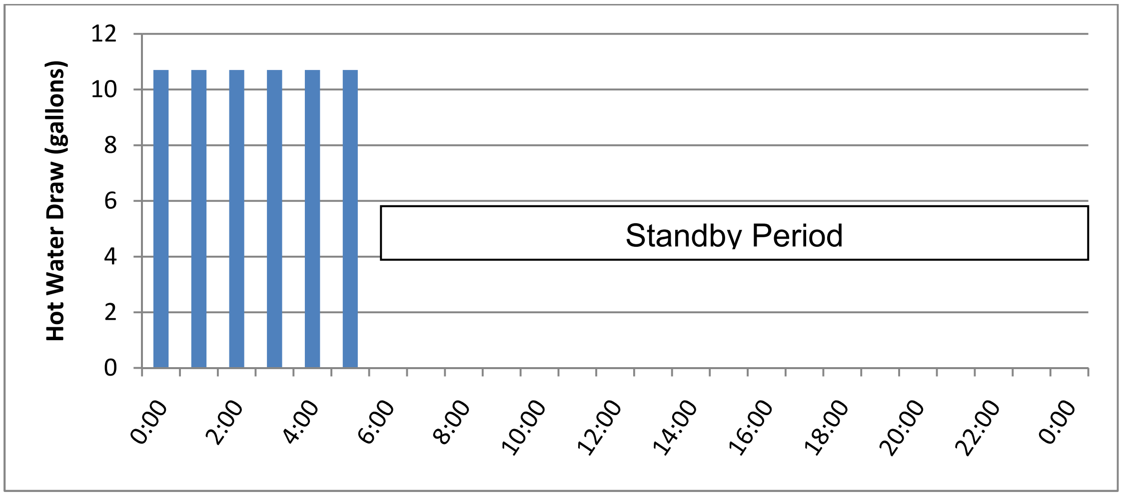

Figure 11: Visualization of DOE *24 Simulated Use Test* Hot Water Draw Pattern

For the foreseeable future the current DOE test procedure will be in place for rating residential water heaters. Manufacturers design and optimize products specifically to maximize efficiency estimated by these test procedures. This and the potential shortcomings of certified test procedures in predicting actual performance and efficiency continue to prompt researchers to perform field and laboratory studies like those described in this report. Manufacturers are motivated by Energy Star ® certification and enabled by the regularity of the hot water draw pattern shown in Figure 11, to make "designing to the test" a common practice with residential water heaters. With non-condensing gas-fired storage and electric resistance storage water heaters, representing the majority of water heaters sold, this is managed by balancing the tradeoff between capacity (FHR), reduced standby losses (EF), and enhanced recovery efficiency (EF). With onboard electronic control, multiple immersed thermistors, and independent control of three heat sources: two resistive heating elements and a heat pump, the HPWHs are particularly well-suited to both detect and perform to a specified hot water draw pattern. Designing to a test is not necessarily a negative practice, so long as performance as certified and during actual end use does not differ too greatly. Application of non-standard draw patterns in tests 6 – 8, 14, and 16 was designed to assess the magnitude of the expected performance difference between actual and certification results.

The EF basically quantifies a delivered efficiency (i.e. ratio of energy output to input), with standardized calculations adjusting throughout the hot water draws for deviations in:

1. Inlet and outlet water temperatures
2. Ambient conditions
3. A calculated recovery efficiency, based upon the first satisfaction of the thermostat(s),
4. Changes in stored thermal energy departures from start to finish of the 24 hour period.

To assure repeatability and facilitate comparisons across products and product classes (e.g. gas-fired tankless versus electric resistance storage), this certification test is performed at standard conditions as outlined in Table 5. As the HPWH may be particularly sensitive to deviations from these standard ambient and water temperature conditions, these impacts on EF is explored in tests 13 and 15.

Test Results

Appliance Setting

The test results using the DOE hot water draw pattern and test procedure are summarized in Figure 12 by appliance setting, from tests 9 – 12, with numerical results shown in Table 13. For those appliance settings that manufacturers have reported certified EFs, there is generally good agreement with test results. The exception is the Mfr C High-Efficiency test results, with a 18% variance from certified results. Following discussions with their technical staff, this is caused by the recovery cycle occurring during the extended standby period observed in the GTI lab but not during certified testing. If the energy input during said recovery cycle was numerically removed from the calculation, the resulting EF is 1.98, consistent with the certified value. The cause for the discrepancy has been identified as slight (< 2°F) departures below standard ambient conditions during testing in the GTI laboratory. In certified testing, this particular HPWH reaches the point at which the thermostat calls for heat just following the completion of the standby period after the end of the 24 hour test.

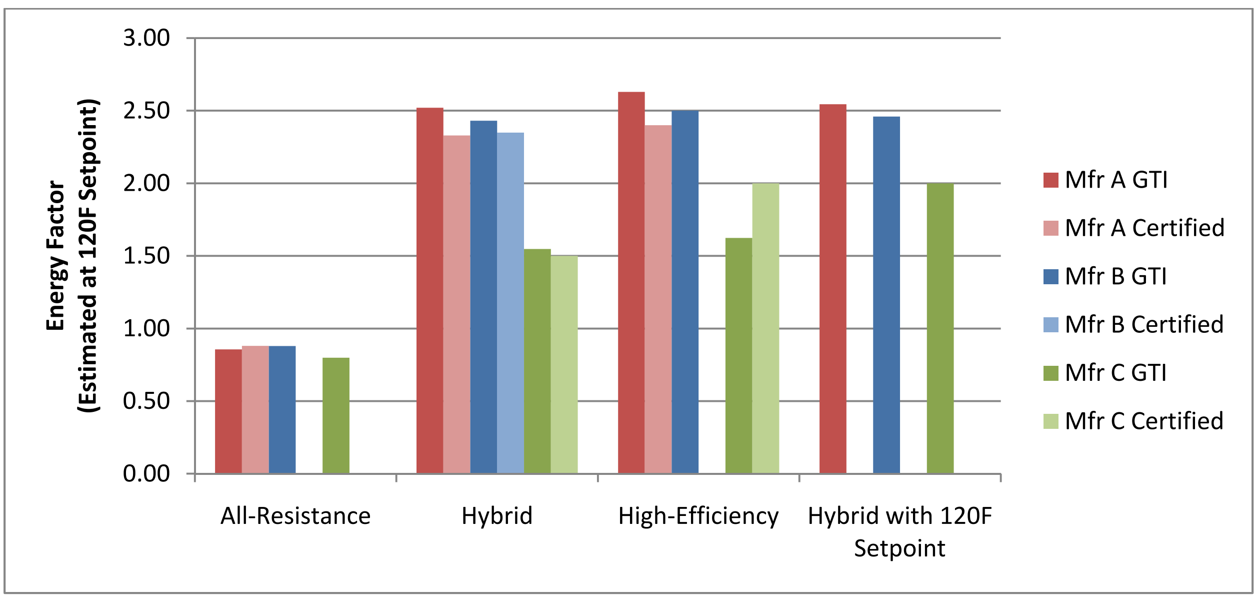

Figure 12: DOE EF Results at Standard Conditions

Table 8: Measured EFs from DOE Hot Water Draw Pattern by Appliance Setting

HPWH	Energy Factor by Appliance Setting (Certified Value[1])			
	All-Resistance	Hybrid	High-Efficiency	Hybrid with 120°F Setpoint[2]
Mfr A	0.86 (0.88)	2.52 (2.33)	2.63 (2.40)	2.55
Mfr B	0.88	2.43 (2.35)	2.50	2.46
Mfr C	0.80	1.55 (1.50)	1.62 (2.0)	2.00

1 Those setting without certified values are not reported by the manufacturer

2 Estimated EF

In addition to differences brought about by fundamental physical differences amongst the HPWHs (e.g. tank size, condenser design, compressor size, refrigerant choice), the differences in thermal management via design decisions and control algorithms are wide ranging. Figure 13 displays the average tank temperature throughout the first six hot water draws of the DOE 24 Hour Simulated Use Test in *Hybrid* mode. It is evident that Mfr C controls emphasize recovery within each of the six hours, with the initial oscillation resulting from an artifact of sizing the compressor, Mfr B does not fully recover to the thermostat goal following the first hot water draw until well after the six draws are complete. In between the two, Mfr A recovers over 2 to 3 hot water draws, with no call for heat following the third draw. These reflect the differences in approach to system design, balancing recovery time, delivered water temperature, and efficiency.

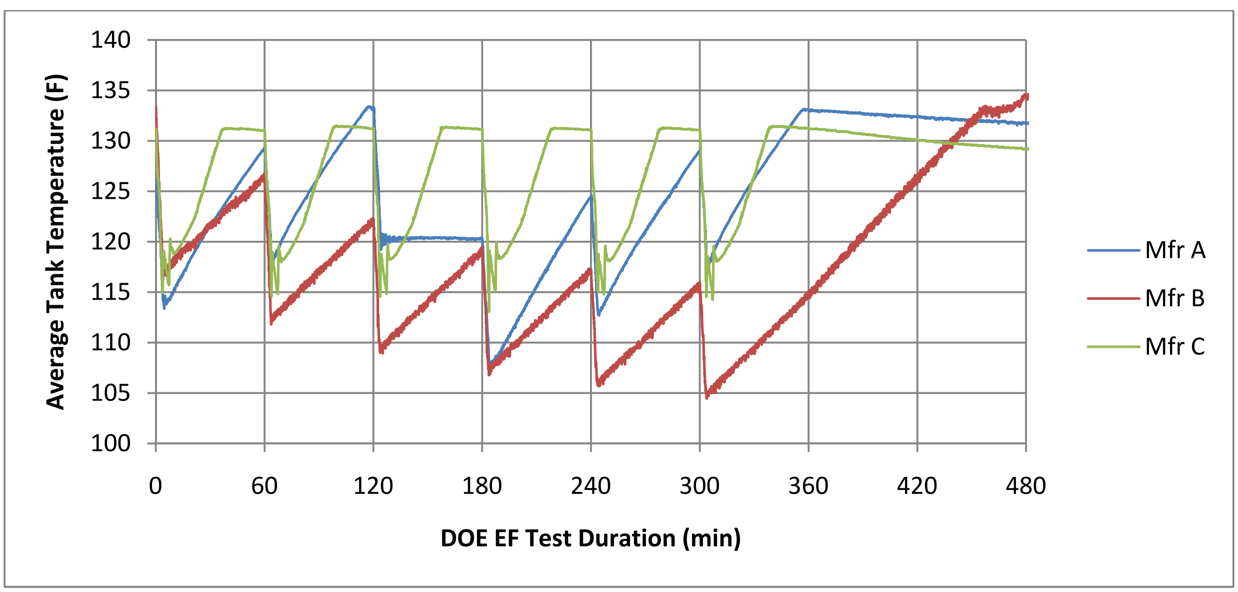

Figure 13: Average Tank Temperature during DOE EF Test in Hybrid Mode

Tank stratification may prevent direct correlation between average tank temperatures and average delivered temperature, what the end user ultimately sees, especially for Mfrs A and B with a wrapped condenser design, as only Mfr C suppresses tank stratification by virtue of its water circulation pump. Examining Figure 14 this appears not to be the case, charting the average delivered water temperature for each of six draws for the same test as in Figure 13. Consistent with the average tank temperatures, the relatively quick-recovering Mfr C provides steady outlet temperatures, variations in Mfr A tank temperatures are translated to outlet temperatures and the reduced recovery rate of Mfr B translate to a steady decline in delivered water temperature. Assuring common tank preconditioning prior to test initiation between HPWH units, this steady drop in outlet temperature appears to be an intentional decision on the part of Mfr B executed through controls. The *recovery efficiency*, calculated per the DOE test procedure over the first complete draw/recovery cycle, is used to adjust the EF in the event that the stored hot water has a net energy loss over the 24 hour test period. With the recovery cycle stretching over all six hot water draws exclusively using high-efficiency heat pump heating, this *recovery efficiency* is averaged over that period. The tendency of Mfr B to fall off during high load situations may result in appliance setpoint or appliance setting changes in the field.

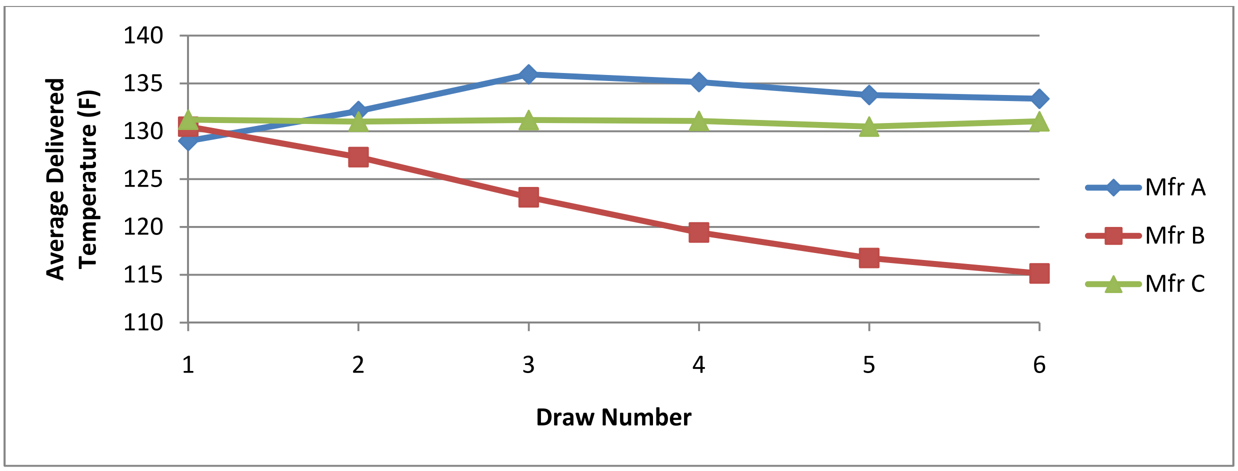

Figure 14: Average Delivered Water Temperature by Draw during DOE EF Test in Hybrid Mode

As the integrated HPWHs are designed as hybrid systems, they are not optimized for electric-resistance only operation. As such, the EFs observed in All-Resistance mode and similar results in the literature are less than 0.90, compared to conventional electric resistance only water heaters with an EF greater than 0.92 (PG&E- ATS, 2010). For the HPWH with a pumped water circulation loop, reduced EFs are the result of continued operation of the circulation pump, which extracts, then exposes hot water to the tank exterior and suppresses beneficial stratification throughout the hot water draw pattern. As tank temperatures approach uniformity, hot water capacity is reduced during extended duration draws, something observed with all storage water heaters, and warmer bottom tank temperatures reduce the efficiency of the heat pump. Those HPWHs with a condenser wrapped tank do not have direct insulation of the storage tank, losing heat in standby to the inactive condenser, which as determined through the DOE standard calculations have standby heat losses of between 185 and 275 Btu/hr.

Thermostat Setting

The factory default thermostat setting of the three HPWHs tested is 120°F, in contrast to the 135°F setpoint required by DOE test procedures. Anecdotally, manufacturers have noted that customers typically do not leave their HPWH with this reduced thermostat setpoint, nonetheless the impact of this non-standard thermostat is quantified in tests 4 and 12. In test 4, the FHR was not generally enhanced by the reduced thermostat setting, as HPWHs with a 135°F thermostat setting and the same appliance setting had a slightly increased FHR. For two of the three HPWHs, this counterintuitive reduction in FHR with a reduced thermostat is due strictly to the control algorithms, which in one case preferred the lower over the upper resistance element at cost of upper tank (thus outlet) temperatures and in the other case delayed usage of the elements all together.

Test 12, referred to in Figure 12, examines the impact of a reduced thermostat setpoint on the energy efficiency, as determined by the DOE 24 Hour Simulated Use Test. A slight improvement in estimated EF by 0.03 points is observed for both Mfr A and Mfr B. Mfr C enjoys a marked increase by 0.45 points in estimated EF, due to greater reliance on the heat pump versus resistance elements. Using R-410a, Mfr C has a lower condensing temperature, and requires electric resistance heat to reach a 135°F setpoint. Typically, following a call for heat and after the heat pump initiates operation, at an average tank temperature of 121°F the upper resistance element is energized and above an average tank temperature of 131°F the heat pump is turned off[2]. As both of these trigger temperatures are above the setpoint of 120°F, resistance heat is not used during this test and the estimated EF is subsequently much higher, versus the 135°F test where total energy consumption is 40% upper resistance element heat. Lastly, all units show an improvement in EF with a lower setpoint, due to a slightly reduced standby heat loss rate and increased heat pump efficiency, due to an overall lower temperature heat sink.

Draw Pattern

To investigate performance during more realistic simulated use, three hot water draw patterns generated from prior GTI field testing are applied to the HPWHs. These patterns are shown in Figure 28 through Figure 30, which are weeklong averages of 30 gallon/day, 64 gallon/day, and 100 gallon/day households, referred to as “Low”, “Mid”, and “High” respectively. These patterns are sampled from homes during a 2005 GTI 30-unit field study (Kalensky, 2006). Tests with these draw patterns versus those with the DOE draw pattern shown in Figure 11 highlight any variations in performance due to (a) the HPWH being designed to maximize efficiency when a DOE pattern is applied versus a non-standard draw pattern and by consequence (b)the DOE profile not accurately capturing efficiency and performance in actual use. The former primarily applies to hybrid appliance settings, whereby resistance heating may be favored over heat pump heating under certain draw patterns, however settings with all resistance or all heat pump heating can also vary due to enhanced or diminished capacity brought out by non-standard draw patterns.

Many recent studies have quantified the changes in system efficiency resulting from variations in hot water draw patterns, primarily from the point of view of revising the current DOE test method (Butcher, 2010 and Glanville, 2010). As with any standardized test replicating anticipated energy use, discrepancies exist between certified test results and performance observed during actual use. Hot water draw patterns can be broken down into individual “cycles”, as defined in the diagram in Figure 15. Each individual “cycle” varies in its draw flow

2 Note that due to the use of a water circulation pump, the Mfr C tank will typically have a vertical temperature distribution of no greater than 2°F.

rate and the duration of the draw and standby/recovery period respectively. In other words, these "cycles" vary in their draw magnitude, draw rate, and degree of intermittency. Thus daily draw patterns, comprised of many "cycles", can be characterized by these three descriptors. Over the range of water heater technology classes (electric resistance technologies and the five distinct classes identified by Energy Star®), different kinds of draw patterns produce very different results. For example, draw patterns composed of short duration, small magnitude, and intermittent hot water draws substantially reduce the efficiency of gas-fired tankless water heaters, reducing the EF by more than 9% (Davis Energy Group, 2006 and Colon et al. 2010). By comparison, the efficiency of non-condensing gas-fired storage water heating is relatively unaffected by such patterns. With decreased recovery rates, variable control strategies, and specific sensitivity to tank temperatures observed in standard testing, the effect of draw patterns on HPWHs is of great interest.

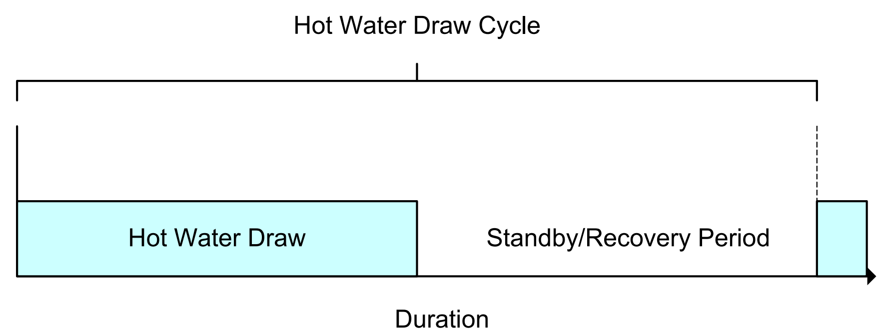

Figure 15: Diagram of Hot Water Draw "Cycle"

The Low, Mid, and High Use draw patterns, as shown in Figure 28 through Figure 30, are field measured draw patterns averaged into 10 minute "cycles" with a specific draw volume and flow rate specified. In subsequent data analysis, an energy balance is calculated for each individual cycle *i* as shown below. The average EF over the test, EF_{avg}, is calculated as a simple delivered energy efficiency over the whole draw pattern. To account for difference in storage energy in the hot water tank at the beginning and end of the 24 hour draw pattern, $\Delta Q_{storage}$, there is a credit or debit applied to derive the estimated EF, or EF_{est}[3]. If an energy surplus is observed, it is credited as additional output, and if a deficit is observed, the necessary input is increased by the deficit amount adjusted by the average efficiency, EF_{avg}. As it is desirable to minimize $\Delta Q_{storage}$ to reduce its bias over the estimated EF, in some cases profiles are run back-to-back and the 24 period is shifted to begin and end with approximately the same storage tank thermal state. This is required for the High Use draw pattern for both Mfr A and Mfr B HPWHs, as the concentration of draws at the day's end require these systems to recover past "midnight."

3 Note that for the purposes of discussion, the terms "EF" and "Estimated EF" differentiate between calculation methods, the former from the DOE *24 Hour Simulated Use Test* and the latter as outlined in this section. This applies specifically to the use of non-DOE draw patterns, whereby a recovery efficiency based the first draw/recovery cycle (with six identical draws) cannot be feasibly calculated, and the use of non-DOE standard temperatures (ambient, thermostat, etc.).

$$EF_{avg} = \frac{\sum_i \rho_i C_p V_i \left(T_{del,i} - T_{in,i}\right)}{W_{in,total}}$$

if $\Delta Q_{storage} > 0$;
$$EF_{est} = \frac{\left(\sum_i \rho_i C_p V_i \left(T_{del,i} - T_{in,i}\right)\right) + \Delta Q_{storage}}{W_{in,total}}$$

if $\Delta Q_{storage} < 0$;
$$EF_{est} = \frac{\sum_i \rho_i C_p V_i \left(T_{del,i} - T_{in,i}\right)}{W_{in,total} + \Delta Q_{storage} / EF_{avg}}$$

Figure 16 summarizes the estimated EFs for the three HPWHs in their "out of the box" appliance setting (*Hybrid* in all cases), with the DOE standard, and GTI Low, Mid, and High use draw patterns. Due to their large volumes and lower heat inputs, compared to standard electric and gas storage water heaters, these systems appear to be most efficient when they are undersized as the highest EFs estimated for all HPWHs were during the High use 100 gal/day test.

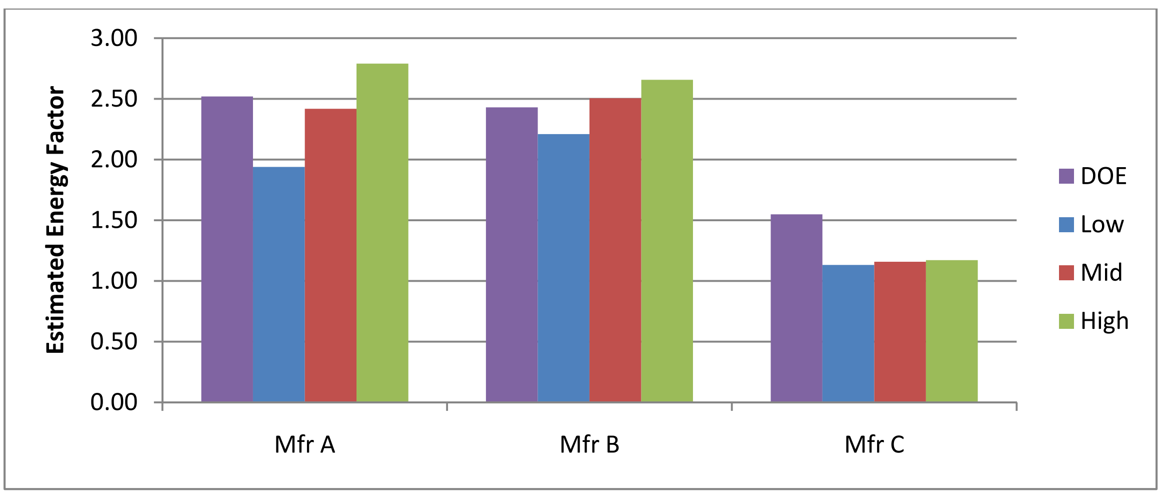

Figure 16: Energy Factor Sensitivity to Hot Water Draw Pattern

Additionally, the fraction of heat pump operation, defined as percentage of total energy consumed, is relatively constant for Mfr A and Mfr B HPWHs as shown in Figure 17. This is an important result, as these two units operate with near to or above the Energy Star ® efficiencies with non-standard draw patterns and as an undersized or oversized system (relative to DOE daily hot water draw volumes), with little or no resistance heat operation in the "out-of-the-box" appliance setting. Mfr A consistently has over 80% of its total energy devoted to heat pump operation, with approximately 10% applied to the evaporator fan while the remainder is for onboard controls and limited or no resistance element operation. Mfr B exceeds over 90% of its total energy for heat pump operation, with two small variable speed fans that total less than 2% of total energy consumption while the remainder is for onboard controls and very limited or no resistance element operation.

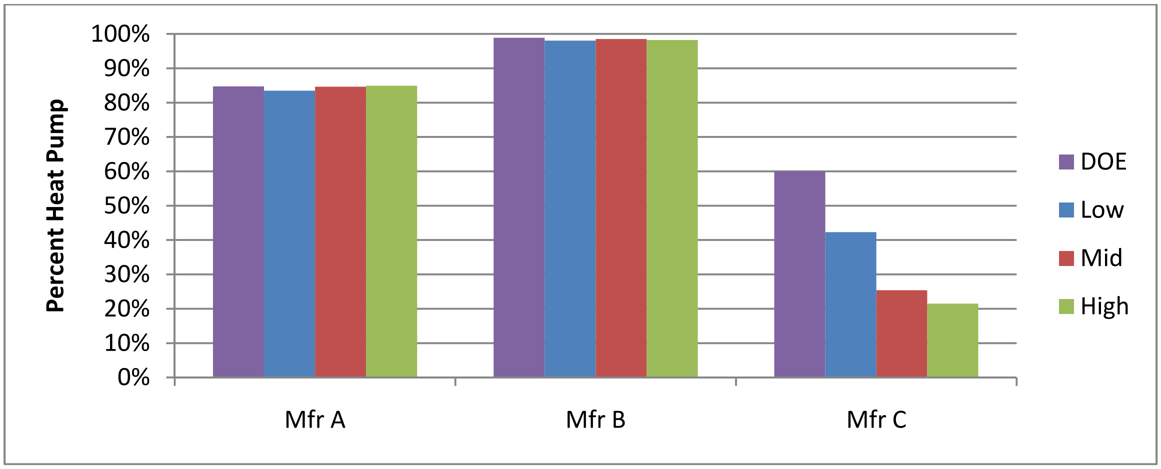

Figure 17: Fraction of Heat Pump Energy Consumed by Hot Water Draw Pattern

Conversely, Mfr C unit relies more heavily on resistance heat with the non-standard draw patterns, with heat pump operation consuming between 42% and 22% of total energy consumption ranging from the Low to High use draw patterns. It is worth noting that, for the sake of comparison with the standard DOE draw pattern tests, these non-standard draw patterns were tested with a 135°F thermostat setpoint. **As was observed with comparing the DOE standard draw pattern with a 135°F and a 120°F setpoint, this reduction in efficiency of Mfr C is largely due to the requirement of resistance heat at average tank temperatures above 131°F (initially utilized at temperatures above 121°F)**. Two diagrams highlighting the energy consumption by source and water flows are shown in Figure 58 and Figure 59 in Appendix C: Detailed Test Results – 24 Hour Simulated Use Test for Mfr A and Mfr C units during the Mid Use draw pattern, highlighting this difference in resistance heat usage.

The average delivered water temperatures by hot water draw pattern are shown in Figure 18, which follow a consistent pattern, with the exception of the average delivered temperature of Mfr B during the DOE standard hot water draw pattern test. This anomaly in delivered temperature in the standard DOE Mfr B test is likely an artifact of the onboard control algorithms, which recognize and control operation for this standardized pattern specifically. Perhaps not intuitive, the Low hot water draw pattern consistently has reduced average delivered temperatures versus the Mid and High patterns. This is due to the fact that almost 80% of the water volume drawn occurs in two long duration draws (showers) that are within 30 minutes of each other. It is the second draw, which occurs during recovery from a partially depleted tank, which pulls this average delivered temperature down. Detailed charts of outlet temperatures as averaged over each draw cycle are shown in Figure 53 through Figure 55.

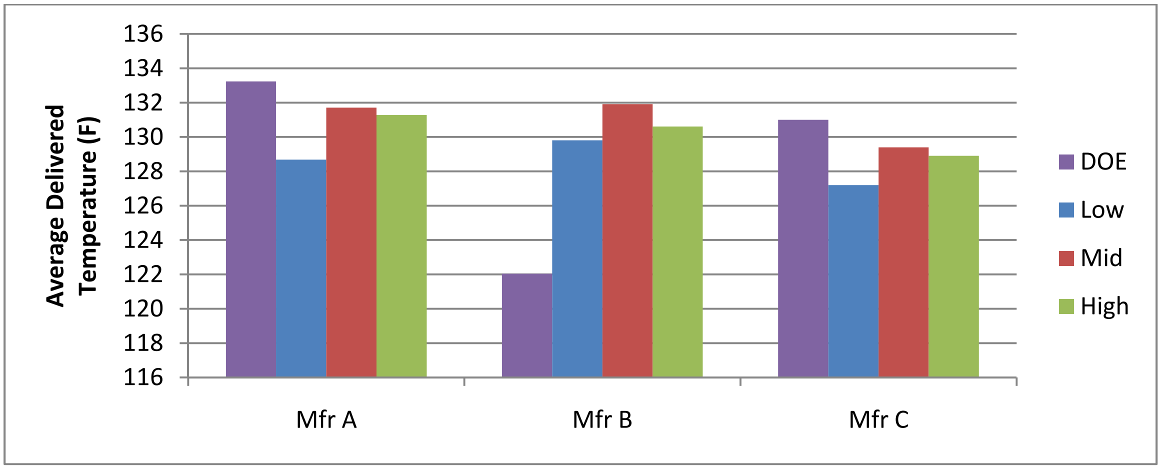

Figure 18: Average Delivered Temperature by Hot Water Draw Pattern

While secondary to the performance and efficiency impacts, non-standard profiles do greatly increase heat pump run times. Figure 19 compares the relative percentages of the 24 hour period during a draw, recovery (heat pump and/or resistance element operation), and standby for the standard DOE 64 gallons/day versus the Mid Use 64 gallons/day draw patterns in *Hybrid* mode. For a daily hot water draw of equal magnitude, Mfrs A, B, and C recover for 13%, 42%, and 69% longer, respectively, during the Mid Use draw pattern. Not surprisingly, the percentage of time in recovery is larger for the High Use and lower for the Low Use draw patterns.

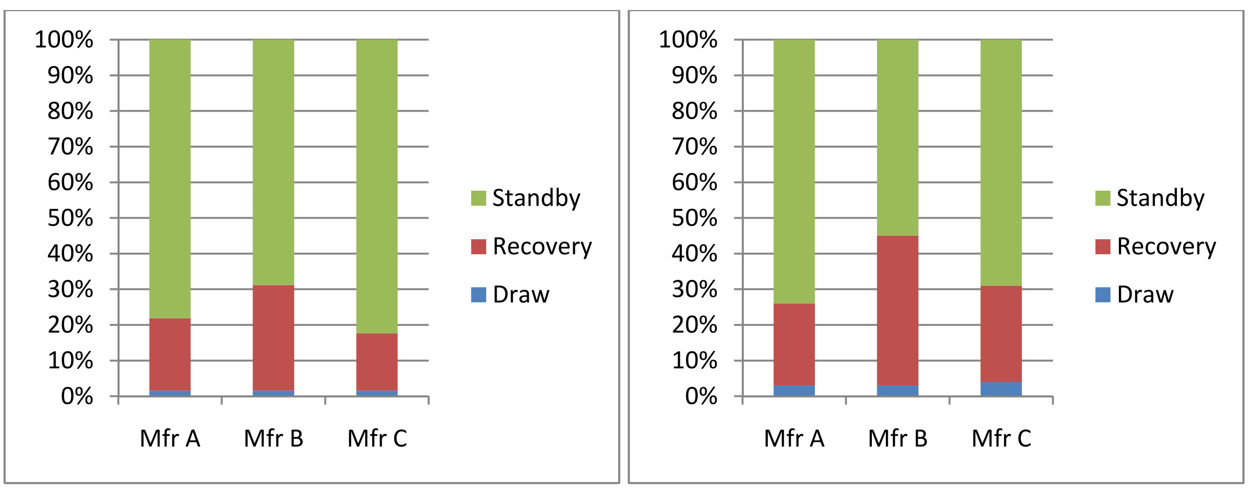

Figure 19: Percentage of Time in Standby, Recovery, and Draw during DOE (left) and Mid Use (right) Tests

Ambient Conditions and Water Main Temperature

As the heat pump water heating expert Dr. Carl Hiller once stated, with heat pump water heating you "*only pay for the energy to move the heat, not the moved heat*", and as such, the heating rate and efficiency of HPWHs is inherently tied to the ambient enthalpy. Additionally, unlike most typical vapor compression systems (e.g. residential air conditioning) that have approximately constant temperature heat reservoirs (ambient air) at both the evaporator and condenser; HPWHs have a variable temperature heat sink on both the evaporator and condenser side over an operational cycle. In other words, the heat pump efficiency is inversely proportional to the stored water temperature. This is especially meaningful for the Mfr C HPWH, which approaches the condensing temperature of R-410a during normal operation.

Issues concerning the impact of ambient conditions on HPWH operation and vice versa have long been a concern of industry, regulators, and efficiency advocates. For example, the Northwest Energy Efficiency Alliance (NEEA) has worked with regional partners to develop a *Northern Climate Specification for Heat Pump Water Heaters* to outline HPWH designs and installation practices that address issues surrounding HPWH/ambient interactions. Such issues identified in this specification are (1) reduced HPWH efficiency during the heating season and (2) management of cold evaporator exhaust air and impact of HPWH operation on space heating (if installed in conditioned space). Suggestions range from direct venting the HPWH evaporator air intake from outside and then exhausting back outside, to exhaust only ducting, such as from a bathroom for example, to usage of an outdoor temperature sensor and/or heating system monitor to limit or cease operation of the heat pump component.

The impact of ambient enthalpy and water main temperatures are explored in tests 13 through 16, beyond the standard conditions outlined in Table 5. Conditions are selected as representative of a hot/humid condition and a cold/dry condition consistent with a HPWH installed in a garage, which are 90°F dry bulb/65% RH with 83°F inlet water and 50°F/70% RH with 60°F inlet water respectively, approximating summer and winter operating conditions for a Southeastern climate. Note that the thermostat setpoint is also changed, to a lower value of 125°F. An environmental chamber was used to monitor and maintain ambient conditions, controlling for ambient dry bulb and dew point temperatures. The chamber is pictured in Figure 20, with ambient conditions plotted from test 16 for the Mfr A HPWH. This level of dry bulb and dew point temperature control is typical of tests 13 through 16, with tight control within +/- 1°F dry bulb and +/- 1°F dew point, with two to three brief departures of up to 5°F (approximately 20 minutes). These infrequent and brief departures occur for one of two reasons: (1) the in-duct humidifier proceeds through an automatic flush cycle once every 8 hours, during which it does not humidify leading to departures in dew point if the heat pump is operating, and (2) for tests 15 and 16 only, the cooling fan coil proceeds through an automatic defrost cycle once every 24 hours, which results in a brief interruption of chamber cooling. Necessary in later tests that quantify the space conditioning effect of the HPWHs, requiring a full energy and moisture balance on the environmental chamber, the heat loss (via a UA) and leakage rate are quantified in Table 7.

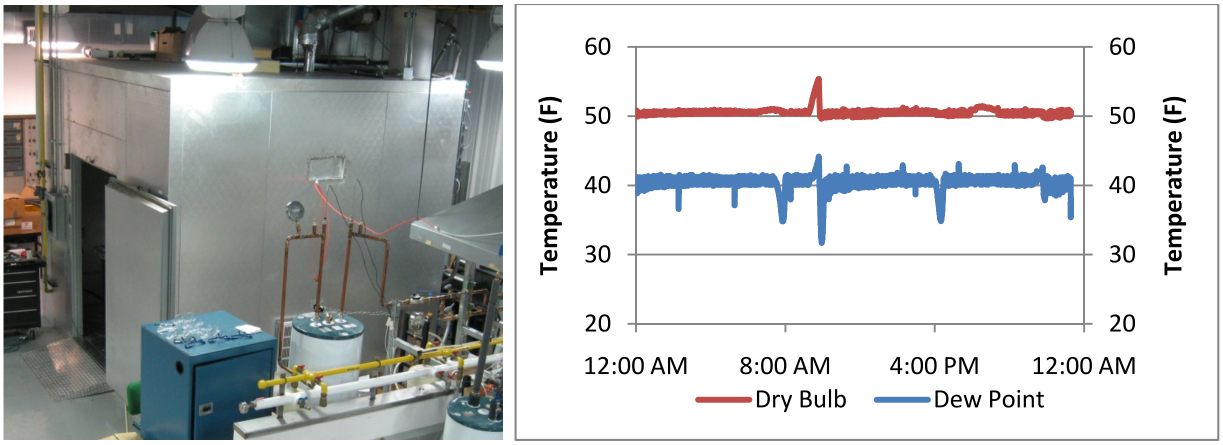

Figure 20: Photo of Environmental Chamber and Ambient Conditions Control during Typical Test

Figure 21 shows, from left to right, the range of estimated EFs observed for comparing tests in the *Hybrid* mode and standard DOE draw pattern with hot/humid and cold conditions, tests 13 and 15 respectively. Predictably, higher ambient enthalpies, incoming water temperatures, and reduced thermostat settings enhance HPWH efficiency and lower ambient enthalpies reduce efficiency. Note that in the standard EF calculations employed, necessary adjustments are made to reflect changed target inlet water temperature, thermostat setpoint, and ambient temperature[4].

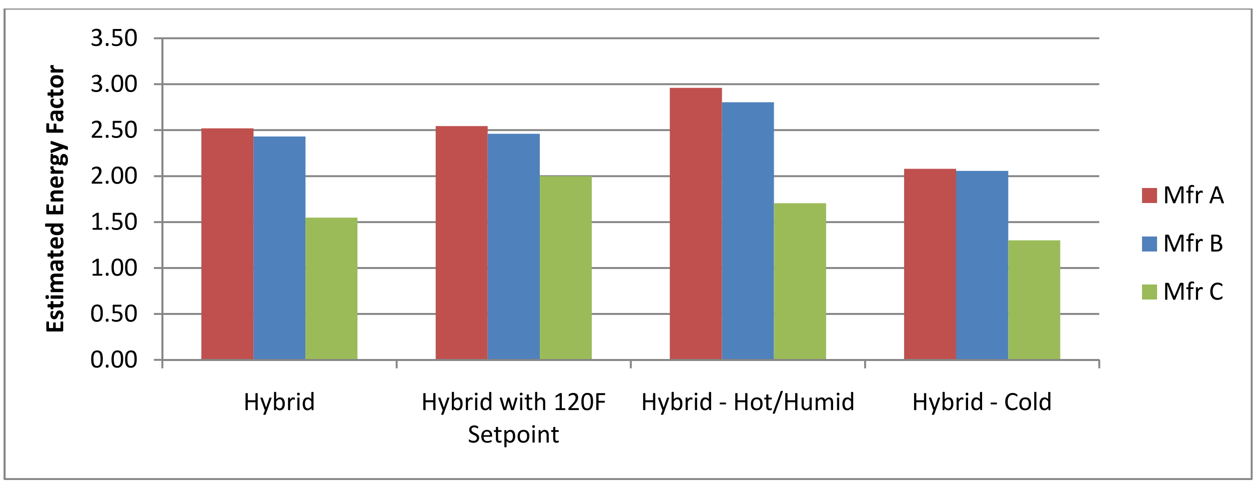

Figure 21: Estimated Energy Factor in Hybrid Mode during DOE EF Test by Ambient Condition

Average delivered water temperatures, shown in Figure 22 and Figure 23, do not completely follow the trends seen previously in Figure 14 at laboratory conditions. First of all, note that

4 Specifically, the calculation of Q_{da} is modified to reflect actual setpoint and ambient targets (125°F and 90°F or 50°F) and the calculation of both $Q_{HW,\ 77°F}$ and E_f are modified to reflect actual setpoint and inlet water temperature targets (125°F and 83°F or 60°F).

unlike the Mfr A and Mfr B HPWHs, Mfr C does not have a specific temperature setting, and as such the setting at level above "normal", out of the box, is used. This results in tank temperatures that are consistently above 120°F. At hot and humid ambient conditions, note that Mfr B satisfies its internal tank thermostat between draws 3 and 4, similar to Mfr A in this and the previous test at laboratory conditions, due both to the shorter recovery time and lower initial tank temperature. At cold ambient conditions however, Mfr B exhibits similar behavior as at laboratory conditions. In both cases, Mfr A and Mfr C do exhibit similar behavior as seen in Figure 14. Detailed charts of outlet temperatures as averaged over each draw cycle are shown in Figure 64 and Figure 65.

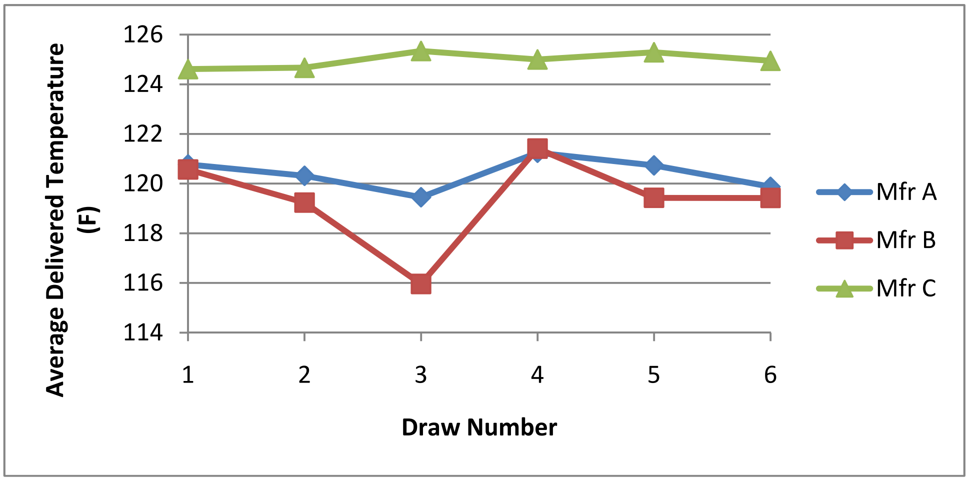

Figure 22: Average Delivered Water Temperature by Draw during DOE EF Test in Hybrid Mode at Hot/Humid Ambient Condition

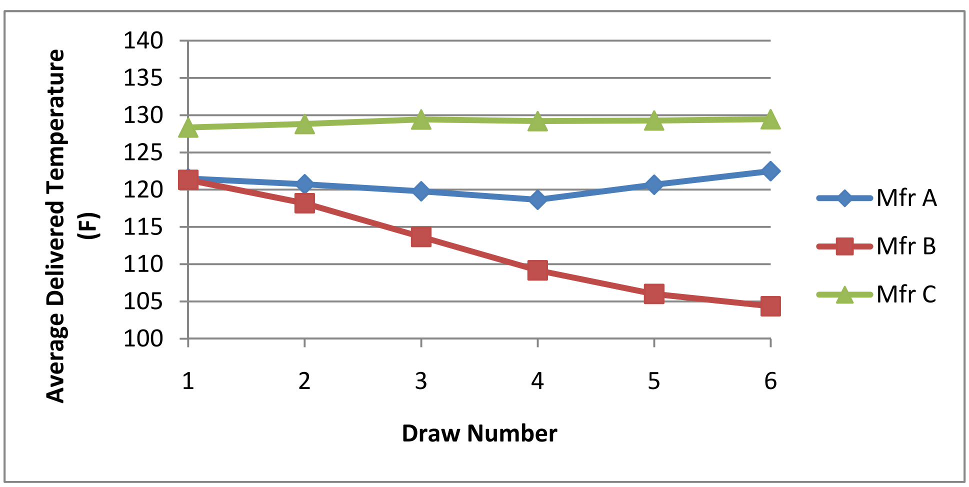

Figure 23: Average Delivered Water Temperature by Draw during DOE EF Test in Hybrid Mode at Cold Ambient Condition

Similar trends arise from tests 14 and 16, examining the impact of ambient condition and water main temperature on the Mid Use non-standard draw pattern. Overall as shown in Figure 24, at hot and humid ambient conditions, the estimated EF improves versus laboratory conditions *more* when faced with the Mid Use draw pattern than the standard DOE draw pattern, ranging from 5 to 35 percentage points *greater* improvement. Similarly, at cold ambient conditions the estimated EF versus laboratory conditions is reduced *less* during the Mid Use draw pattern than the standard DOE draw pattern by 2 to 11 *fewer* percentage points. Interestingly, Mfr C shows an improvement from laboratory to cold ambient conditions, due primarily to the reduced thermostat setpoint from 135°F to 125°F, resulting in an increase of heat pump operation from 25.4% to 46.8% of total energy consumed. In terms of reliance on the higher efficiency heat pump over electric resistance heat, Mfr A and Mfr B remain unchanged with respect to both draw pattern, as shown earlier in Figure 17, but also to variations in ambient conditions, water main temperature, and thermostat set point, as shown in Figure 25. Similar trends are observed in percentage of time as recovery with detailed charts shown in Figure 63. Additionally, to better visualize the interaction of the water draw pattern on energy consumption breakdown, charts tracking energy and water flows are shown in Figure 66 through Figure 71.

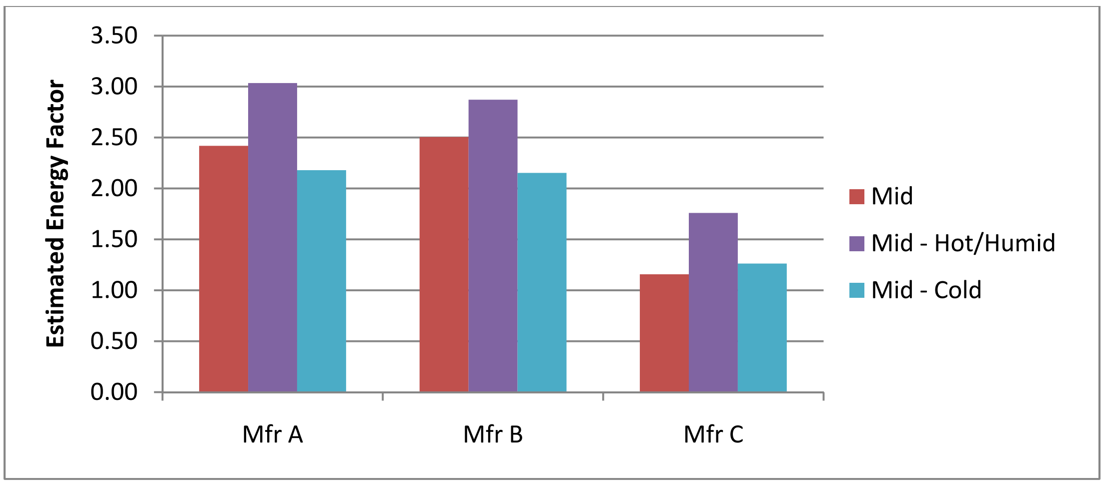

Figure 24: Estimated Energy Factor in Hybrid Mode for Mid Use Draw Pattern by Ambient Condition

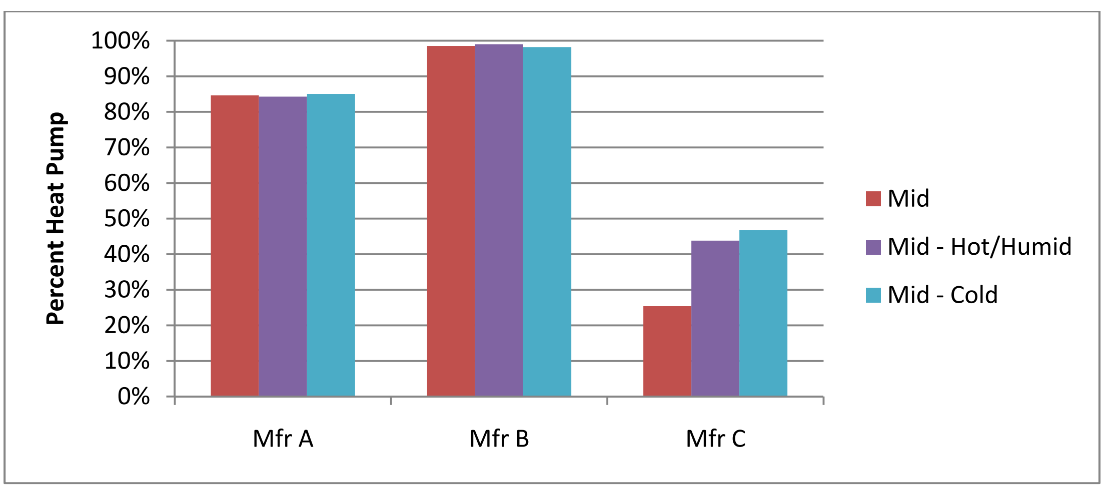

Figure 25: Fraction of Heat Pump Operation by Ambient Condition

Of particular interest to the development of performance maps, the instantaneous Coefficient of Performance (COP) was calculated and averaged with the datasets from tests 10, 13, and 15, using the standard DOE draw pattern in *Hybrid* mode at various ambient conditions. The COP is averaged over the 24 hour test period for datapoints with the compressor running that do not have (1) a hot water draw occurring and (2) simultaneous operation of resistance elements, which for the three units is the majority of the compressor run-time. The average COPs are summarized in Figure 26, with brackets indicating the range of COP for a bottom tank temperature of 95°F < $T_{tank,bottom}$ < 125°F. Note that these are not true steady state COPs, as they are calculated from normal transient operation, albeit from extended recovery cycles. Overall, Mfr B shows COPs that are in closer proximity to the EF of the corresponding 24 hour test. Discussed in greater detail during the quantification of the space conditioning effect of the HPWHs, the extended steady state COP of Mfr B at 70°F and 50% RH ends up much closer to the other two HPWHs. This is primarily a function of the reduced compressor and fan size of the Mfr B HPWH, which takes much longer to exhibit steady state operation than the other two HPWHs. For example, under a steady state load and controlled ambient conditions, Mfr B did not show measureable condensate for over 6 hours versus Mfr A, which despite having a similar compressor size and steady state evaporator air-side temperatures of 44 - 45°F, showed measureable condensate within 30 minutes of operation.

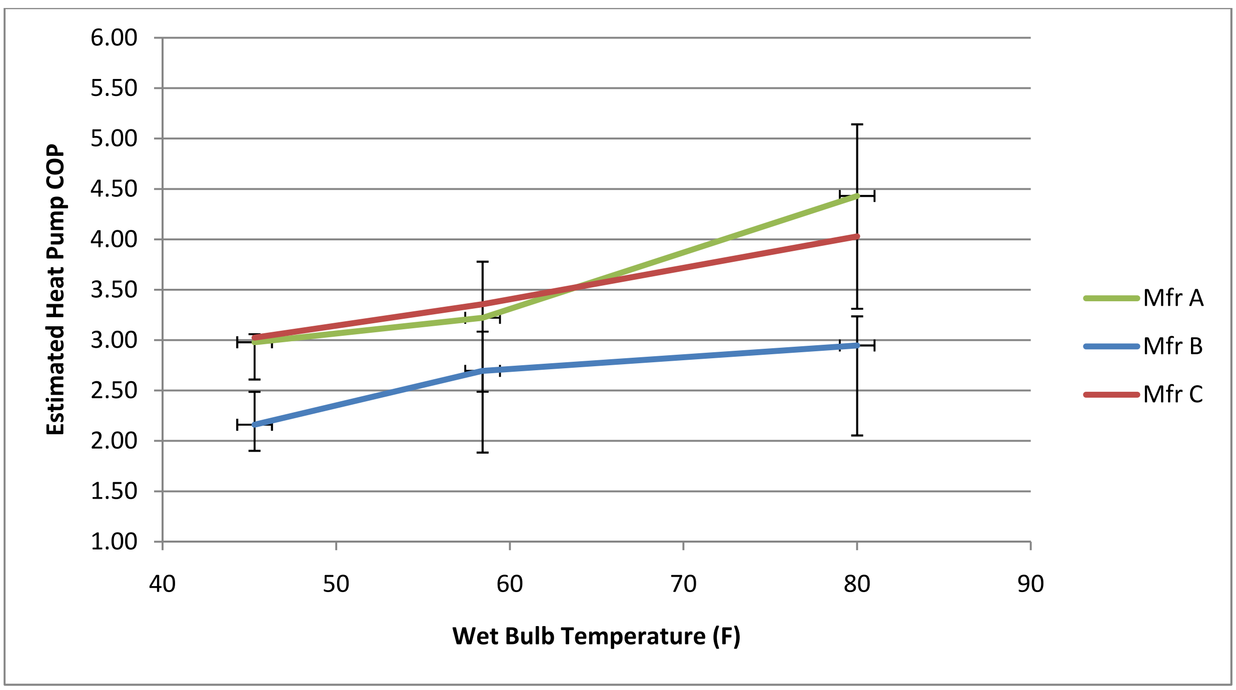

Figure 26: Average Heat Pump COP as Function of Ambient Wet Bulb Temperature[5]

Note that brackets are not shown for the Mfr C HPWH in Figure 26, which due to its pumped circulation loop does not offer a direct measurement between bottom tank water temperatures

5 Bars indicate range of average COP from 95°F < $T_{tank,bottom}$ < 125°F

and heat pump efficiency. To illustrate this, the bottom tank temperature is shown (average of lower two thermocouples) for a typical Mfr C HPWH recovery is shown in Figure 27. Other than the jump in temperatures due to the time lag of heating from the pumped circulation loop return, temperature changes are nowhere near as linear as the tank-wrapped condenser HPWHs, as illustrated for a typical Mfr A HPWH recovery that is overlaid (and scaled for sake of comparison) in Figure 27.

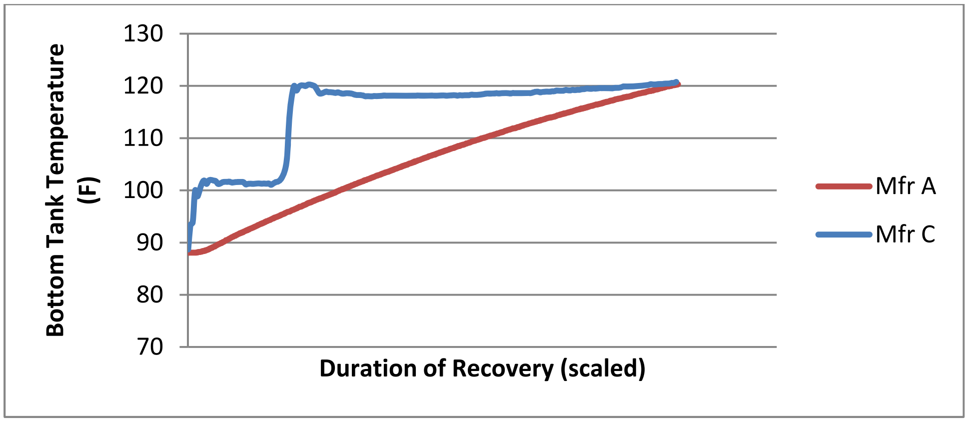

Figure 27: Bottom Tank Water Temperatures during Typical Mfr A and Mfr C Recovery

Space Conditioning Effect

As emphasized by the NEEA specifications and discussed by industry groups as both a positive and negative aspect of HPWH operation, the space conditioning effect of this emerging class of residential water heaters is undoubtedly of interest. As such, this space conditioning effect was quantified through an extended steady state test, whereby the environmental chamber is held at 70°F dry bulb and 50% RH, the HPWH is put into a mode that most closely resembles 100% heat pump heating, and a small continuous draw is imposed to assure the average tank temperature remains at approximately 105°F – 115°F and cycling of the heat pump does not occur. In addition to monitoring and recording of measured quantities throughout prior testing (e.g. tank temperatures), additional energy and moisture flows are measured, including: energy and moisture inputs for chamber space heating and humidification; and the mass of condensate leaving the HPWH. Complete moisture and energy balances are defined at the chamber and HPWH level, from which the space cooling effect is determined. Due to the influence of previously discussed humidifier flush cycle that occurs every 8 hours on maintenance of the prescribed ambient dew point temperature, the sampling period for calculation is defined between flush cycles. Heat loss and moisture loss, determined through the previously determined UA and leakage rate in Table 7, is also taken into account. The space cooling effect is first calculated via a balance of the entire chamber and then it is compared to an energy balance on the HPWH itself.

With results summarized in Table 8, the three HPWHs show substantial differences in steady state performance. Despite having R-134a in common, comparably sized compressors by output, and similar steady state COPs, the Mfr A heat pump drives a higher rate of heat transfer, due to its larger evaporator fan and higher refrigerant pressures. Both R-134a HPWHs have a small fraction of total space cooling as latent, whereas Mfr C has a much larger fraction of cooling as latent, due to use of R-410a and a larger compressor. Note that Mfr B has a higher COP following almost 18 hours of steady operation than was estimated from transient operation in Figure 26.

Table 9: Results of Space Conditioning Test

Manufacturer	Condenser Heating Effect (Btu/hr)	Evaporator Cooling Effect (Btu/hr)	Percent Latent Cooling	Percent Sensible Cooling	Steady State Air-Side Evaporator Temperature (°F)	Steady State COP
Mfr A	9,230	6,620	2.1%	97.9%	45	3.15
Mfr B	5,060	3,390	3.9%	96.1%	50	3.28
Mfr C*	9,910	6,390	26.7%	73.3%	44	3.04

*Unit had continuous operation of upper resistance element, which was compensated for; reported results are for heat pump only.

Table 9 indicates the control of ambient conditions during the calculation period of results in Table 8, the error in moisture balance, and the error between the total chamber energy balance and the HPWH energy balance. During the execution of the Mfr B space conditioning tests, an unresolvable issue with the tracking and recording of the chamber heater relay positions with the data acquisition system, prevented the completion of the total chamber energy balance. As such, the reported results in Table 8 for evaporator cooling effect reflect only the HPWH energy balance, and there the error in comparing energy balances is not applicable.

Table 10: Chamber Control and Errors in Moisture Balance and Differential in Chamber & HPWH Energy Balance

Manufacturer	Dry Bulb Temperature Control	Dew Point Temperature Control	Moisture Balance Error*	Energy Balance Error Chamber vs. HPWH
Mfr A	1.3%	2.3%	-0.7%	-1.9%
Mfr B	0.4%	1.6%	2.2%	n/a
Mfr C	0.9%	2.4%	1.1%	0.2%

*Values for moisture balance error are approximately+/- 18% accounting for measurement accuracy, based upon the "root sum of squares" method.

Concluding Summary & Discussion

While end user control of residential water heaters primarily takes the form of a thermostat setting, HPWHs allow additional control of the system efficiency versus capacity through the choice of appliance settings. Depending on end user setting, the HPWH will use all, more, less, or no electric resistance heat, which has a higher heat input but lower delivered efficiency than the heat pump component. This presents a unique challenge to development of HPWH performance maps needed for simulation of HPWH performance. Under "hybrid" appliance settings, resistance and heat pump components are used simultaneously to varying degrees depending on:

- Appliance setting
- Manufacturer control architecture
- Thermostat setting
- Draw pattern
- Ambient conditions.

For example, when in the hybrid appliance setting, a high flow, long duration hot water draw (e.g. shower) may initially trigger heat pump recovery, but eventually shift to primarily resistance heat partway through the draw event. While primarily concerned with capacity, the end user may or may not change usage behaviors based upon increased reliance on resistance heat, as historically end-user interaction with residential water heaters is limited (Note that the HPWH units tested do not have external indication of heat pump versus electric resistance heating). Thus, there is a potential for efficiency degradation in hybrid appliance modes, via increased reliance on resistive heat, in cases of under-sizing the HPWH, or disabling of the heat pump due to unfavorable ambient conditions. For example, when improperly installed in spaces subjected to frosting conditions, HPWHs will operate under a frost-protection cycle and disable heat pump operation. The impacts of appliance setting and ambient conditions are investigated in tests 9 – 11 and 13 – 16.

As the HPWH management of heat pump versus resistance heat is key to installed system efficiency and performance, issues concerning the disabling of heat pump operations due to heat pump faults are also important. By their nature, HPWHs may over their life require attention from disparate service industries, namely plumbers, HVAC technicians, and electricians. Concerning this issue, the HPWHs tested in this study vary in the level of access they provide for refrigerant loop service. Some HPWH models are unserviceable, similar to many residential refrigerators, and others are serviceable, like many residential A/C units. Potential issues on the refrigerant loop-side affecting HPWH performance include leaks, low factory charge, and compressor failure. An example of such an issue occurred during laboratory testing in this study. Partway through testing and data analysis, it was found that one of the HPWHs had much lower EFs than was expected by the manufacturer's technical staff. Examination of datasets showed that while in a hybrid appliance setting, the compressor would shut down after several minutes of operation and both resistance elements were activated. The consistency of this operation sequence and onboard diagnostics were consistent with a low-refrigerant charge fault. Believing it to be a low factory charge, the system was recharged on-site by a manufacturer representative and testing continued. The issue returned after several weeks of testing, indicating the presence of a small refrigerant leak. While the unit was promptly replaced and testing continued without issue, this level of homeowner awareness is unlikely. Following the compressor fault, the HPWH shifted automatically to all-resistance heat, continuing to meet hot water demands. Not directly measuring performance, the end user is unlikely to notice a difference in hot water output and will continue use of the efficiency-degraded HPWH operating with all-resistance heat. While this scenario is not anticipated to be prevalent enough to warrant specific inclusion in HPWH performance maps, it is worth noting as this emerging class of residential water heaters continue to gain market share.

Summary of Results

Throughout the execution of the test matrix outlined in Table 6, the following results of note were observed broken down by the parameter varied:

- **Appliance Setting**

  Variation of appliance (control) setting was the focus of hourly capacity testing, via the First Hour Rating (FHR) test. Overall, the FHR results follow what one would expect, with the larger values resulting from a higher heating input (primarily delivered by resistance elements) and larger storage volumes with the 60 gallon Mfr A model having higher overall FHRs over the 50 gallon Mfr B and Mfr C units. The exception is the Mfr B unit which counterintuitively delivered more hot water while in *Hybrid* mode as opposed to *High-Demand* mode by approximately 8 gallons. This was due to a higher reliance on the upper electric resistance element and less on the heat pump during operation in *High-Demand* mode, which left bottom tank temperatures colder, thus reducing total capacity (FHR).

  Similar to testing for the FHR, 24 Hour Simulated Use test results from varying the appliance setting showed the degree of resistance heat use as having the greatest correlation to the resulting Energy Factor (EF). As the heat pump portion of the three HPWHs tested have similar steady state COPs, shown in Table 8, this is also not surprising. Operating in an All-Resistance heat mode resulted in EFs below 0.90, slightly lower than that of conventional electric resistance water heaters, due to heat loss via condenser design, either heat loss and stratification destruction via a pumped water circulation loop or jacket losses of the condenser-wrapped tank. Operating at or near 100% heat pump heating generated the highest EFs, with wide variation in delivered temperatures among the three HPWHs due to physical design decisions and control architecture. Hybrid modes, operating with both heating methods, resulted in EFs in the middle. The two HPWHs with condenser-wrapped tank designs still operated with near 100% heat pump heating, and as such the EFs of Hybrid and High-Efficiency modes were within 4% of one another. As certified, the HPWH with a pumped circulation loop condenser design relies more on resistance heat in Hybrid mode, resulting in a 25% difference in EF from High Efficiency to Hybrid modes. Test results showed a smaller discrepancy, due to a lower than certified EF in High Efficiency mode from a recovery cycle in the extended standby period. Compared to the other HPWHs, this is primarily due to the use of R-410a, which with a lower condensing temperature the Mfr C HPWH uses resistance heat to reach the DOE standard setpoint of 135°F.

- **Thermostat Setting**

For two of the three HPWHs, the reduced thermostat setting of 120°F decreases the FHR relative to the higher thermostat setting of 135°F in the *Hybrid* mode. In the case of Mfr B, with a lower setpoint and thus a lower overall average tank temperature following the first draw, the unit relies more on its lower rather than upper resistance element. Despite the fact that the lower element has the same rated input as the upper element, it does not immediately increase outlet temperatures. Even though Mfr C must rely on resistance heating to reach the 135°F DOE setpoint, the lower resistance element is not energized until 20 minutes after completion of the first draw. Conversely, the Mfr A unit, with a larger overall nominal tank size of 60 versus 50 gallons, yields the anticipated result of an enhanced FHR with a reduced thermostat setting. As the gap between water main and thermostat set point temperature is decreased, recovery times are subsequently shortened, yielding a larger capacity.

During 24 Hour Simulated Use tests, a slight improvement in estimated EF by 0.03 points is observed for both Mfr A and Mfr B. . Mfr C enjoys a marked increase in estimated EF, due to greater reliance on the heat pump versus resistance elements. Using R-410a, Mfr C has a lower condensing temperature, and requires electric resistance heat to reach a 135°F setpoint, typically initiated at an average tank temperature of 121°F and used exclusively above an average tank temperature of 131°F. Lastly, all units show an improvement in EF with a lower setpoint, due to a slightly reduced standby heat loss rate and increased heat pump efficiency, due to an overall lower temperature heat sink.

- **Hot Water Draw Pattern**

Three draw patterns derived from prior GTI field testing, at usage levels of 30, 64, and 100 gallons per day, were used to determine the impact of non-standard and more realistic hot water draw patterns on the performance and efficiency of the HPWHs tested. Due to their larger tank volumes and lower heat input capacities, compared to standard electric and gas storage water heaters, these systems are most efficient when they are undersized, as the highest EFs estimated for all HPWHs were during the High use 100 gal/day test. This trend was more visible with the Mfr A and Mfr B HPWHs, with High Use EFs greater than certified levels, as they used little or no resistance heat for all three non-standard draw patterns. As such, the recovery periods were increased, with heat pump operation up over half of the 24 hour period. The fraction of electric resistance heating of total energy consumption increased with the daily hot water consumption for Mfr C, resulting in little EF improvement with undersizing (note that tests were performed with a 135°F thermostat setpoint). For each draw, delivered water temperatures varied significantly for all HPWHs for each non-standard draw pattern, by ±6.3°F.

- **Ambient Enthalpy & Water Main Temperature**

The units were tested with standard and non-standard 64 gallon/day draw patterns under hot/humid and cold/dry conditions and a more typical thermostat setpoint of 125°F. Overall, at hot and humid ambient conditions the estimated EF improves versus laboratory conditions more when faced with the non-standard Mid Use draw pattern than the standard DOE draw pattern, ranging from a 5 to 35 percentage point improvement. Similarly, at cold ambient conditions the estimated EF versus laboratory conditions is reduced less during the non-standard Mid Use draw pattern than the standard DOE draw pattern by 2 to 11 fewer percentage points. Interestingly, Mfr C shows an improvement from laboratory to cold ambient conditions, due primarily to the reduced thermostat setpoint from 135°F to 125°F, resulting in a significant increase of heat pump operation from 25.4% to 46.8% of total energy consumed. A key result from this study, Mfr A and Mfr B HPWHs not only remain unchanged in their reliance on heat pump heating over less-efficient resistance heating for both draw patterns, but also for variations in ambient conditions, water main temperature, and thermostat set point. This suggests that for the HPWHs with the tank-wrapped condenser design, only extreme events (e.g. tub filling) or operational conditions induce the usage of lower-efficiency resistance heat.

Heat pump operation was isolated to define an average heat pump COP during steady state operation as a function of both the ambient enthalpy and lower tank water temperature. Mfr A and Mfr C had comparable heat pump COPs with Mfr B showing reduced average COP, due to a smaller evaporator fan requiring longer operating times to reach true steady state operation. Later extended operation tests to define the space condition effect of HPWH operation showed steady state heat pump COPs for Mfr B closing this gap, with all HPWHs having similar COPs between 3.0 and 3.3 at 70°F dry bulb and 50% RH. Space cooling effects from these extended steady state operating tests were approximately 0.5 tons cooling for the Mfr A and Mfr C units and 0.25 tons cooling for the Mfr B unit. At 70°F and 50% RH, the Mfr A and Mfr B cooling effects were predominantly sensible, whereas Mfr C, with R-410a instead of R-134a as the refrigerant, had approximately 25% latent cooling.

Recommendations

In addition to this reporting, the full datasets will be utilized and analyzed further as needed in the development of predictive models. Considering the aforementioned nuances in performance and efficiency resulting from physical design differences, operating conditions, appliance settings (control modes), and end user interaction, this is certainly a greater task than similar models for conventional gas or electric water heaters. Much of this concerns controls in Hybrid modes, where the active switching between heat pump and electric resistance heat has a great effect on performance and efficiency. Despite its great influence in Hybrid modes, control algorithms cannot be used in this development effort, as they are proprietary and likely will be continually updated with each HPWH model generation. Using datasets like those generated in this study to determine the relative usage of heat pump and electric resistance heat, model development will instead have to rely on traditional performance maps, the combination of known trigger points (e.g. Mfr C switching to all resistance heat at tank temperatures above 131°F), and model user inputs where such a trigger point is defined.

In support of this HPWH model development, future testing should focus on the following:

- Testing of so-called “add-on” HPWH systems.
- Filling in the performance map of Figure 26 with additional ambient psychrometric conditions, including a hot and dry condition.
- Continued testing in standard and non-standard ambient conditions with other hot water draw patterns.
- Isolating the effect of stored water temperatures on heat pump efficiency through similar extended operating tests.
- A greater focus on the heat pump components, with direct measurement of both air and refrigerant-side temperatures.

- Validation testing of trigger point based models to represent the more complex algorithms used for control of heat pump and electric resistance components in actual HPWHs

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List of Acronyms

Acronym	Description
ACH	Air Changes per Hour
ASHRAE	American Society of Heating Refrigeration and Air-Conditioning Engineers
CFH	Cubic Feet per Hour
DOE	Department of Energy
EF	Energy Factor
FHR	First Hour Rating
FSEC	Florida Solar Energy Center
GPM	Gallons per minute
GTI	Gas Technology Institute
HPWH	Heat Pump Water Heater
FSEC	Florida Solar Energy Center
NAECA	National Appliance Energy Conservation Act
NEEA	Northwest Energy Efficiency Alliance
ORNL	Oak Ridge National Laboratory
SCFH	Standard Cubic Feet per Hour

Appendix A: Test Methodology

The following figures, tables, and discussions are detailed descriptions of the testing methodology, which are referenced throughout the main body of the report.

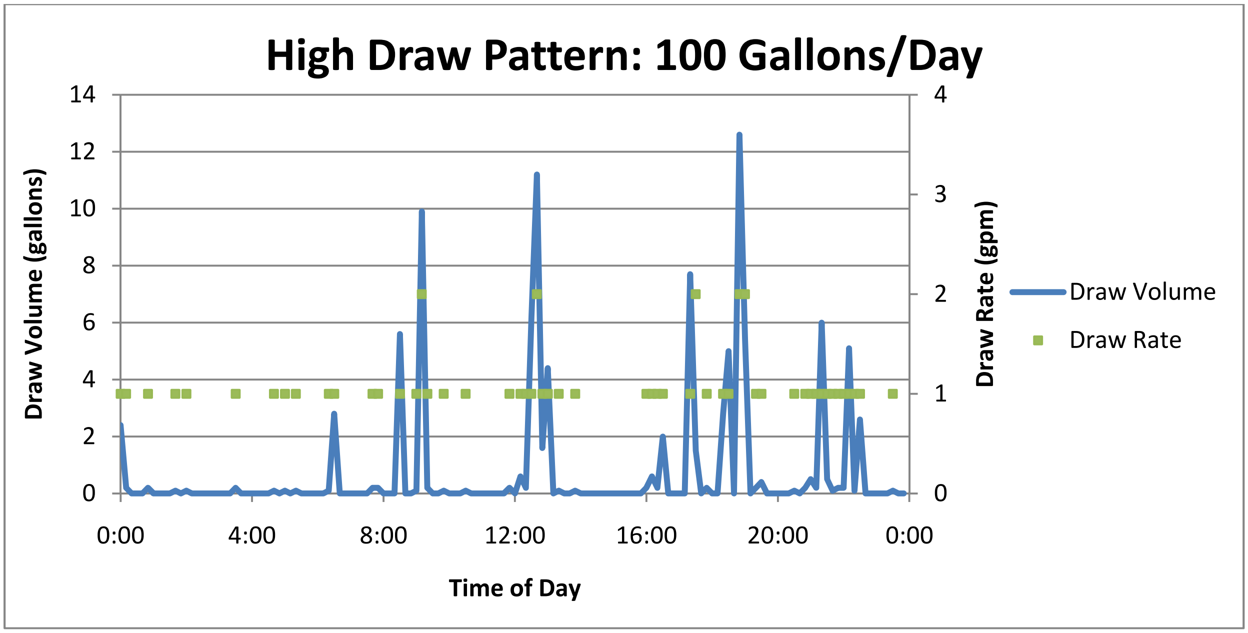


Figure 28: GTI High Use Hot Water Draw Pattern

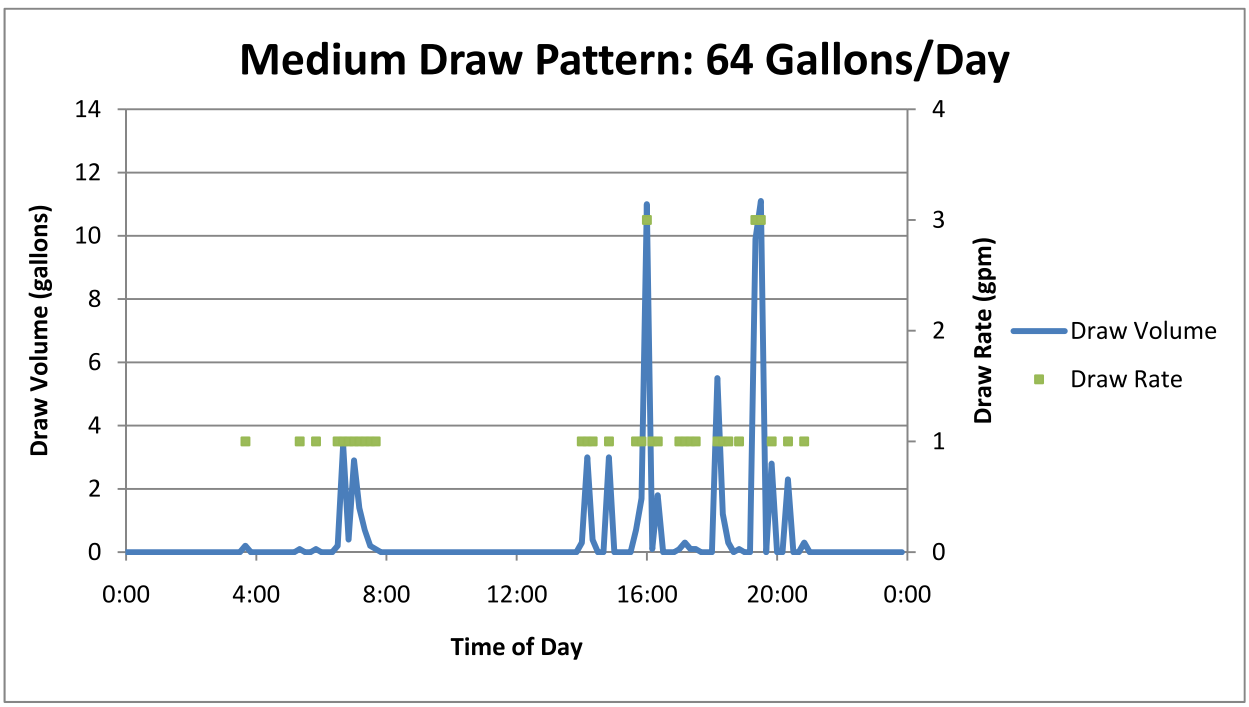


Figure 29: GTI Mid Use Hot Water Draw Pattern

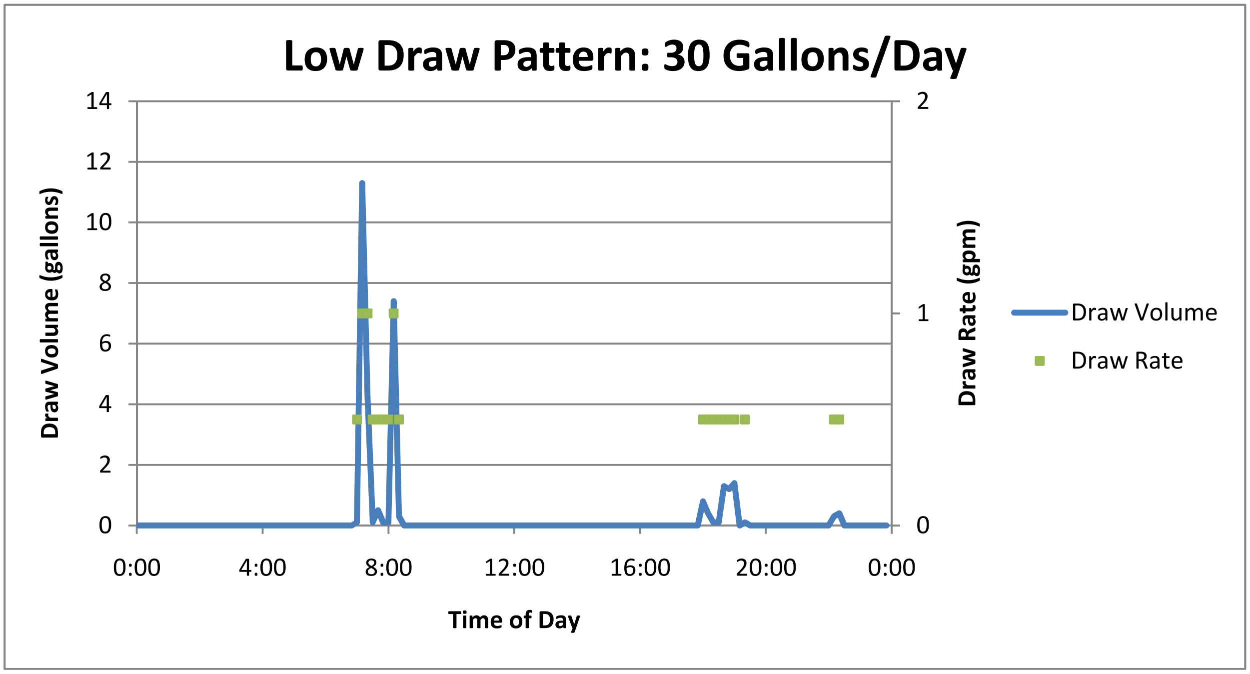


Figure 30: GTI Low Use Hot Water Draw Pattern

Table 11: Summary of Measured Quantities and Methods

Measured Media	Quantity/Units	Measurement Point	Instrument Type
Water	Temperature, °F	HPWH Inlet and Outlet	RTD
		Storage Tank Temperature @ 6 points	Thermocouple
		Precooling & Preheating Water	
	Pressure, psi	Water Main Pressure	Mechanical Differential Pressure Gauge
		Storage Tank Pressure	
	Flow, gpm	HPWH Outlet	In-line Turbine Flow Meter
		Environmental Chamber Humidifier Fill	
	Volume, gallons	HPWH	Mechanical Scale
Air	Temperature, °F	Ambient, Laboratory @ HPWH	Thermocouple
		Ambient, Laboratory @ RH measurement	
		Ambient, Environmental Chamber @ 12 points	
	Relative Humidity, %RH	Ambient, Laboratory	Thin-film capacitance probe
		Ambient, Environmental Chamber	
	Dew Point, °F	Ambient, Environmental Chamber @ 2 points	Chilled-mirror hygrometer
	Oxygen, % dry by volume	Ambient, Environmental Chamber (during leakage test only)	Paramagnetic Analyzer
	Pressure, hPa	Ambient, Laboratory	Electronic Barometric Pressure Transducer
	Pressure, " W.C.	Differential, Laboratory to Environmental Chamber	Electronic Differential Pressure Transducer
Electric Power	Energy, kWh	HPWH at: Total Power, Compressor, Upper Element, Lower Element, Blower, and Water Circulation Pump (Mfr C only)	kWh Transducer
		Environmental Chamber: Humidifier and Heating Elements	

Table 12: Summary of Instrumentation and Control Devices

<table>
<tr><th colspan="2">Measured Quantity/Control Device</th><th>Instrument/Device</th><th>Manufacturer</th><th>Accuracy</th></tr>
<tr><td rowspan="2">Water Temperature</td><td>Cold Inlet & Hot Outlet</td><td>Ultra Precise Fast Response RTD – 1/8” dia</td><td>Omega</td><td>±0.18 °F</td></tr>
<tr><td>Other</td><td>T-Type Thermocouple</td><td>Omega</td><td>±1.8 °F</td></tr>
<tr><td colspan="2">Water Flow Rate</td><td>In-line turbine low flow meter</td><td>Seametrics</td><td>330 pulses/gallon</td></tr>
<tr><td colspan="2">Water Pressure</td><td>Mechanical Differential Pressure Gauge</td><td>Miljoco</td><td>± 1%</td></tr>
<tr><td colspan="2" rowspan="2">Water Preheating/Precooling</td><td>Portable Chiller</td><td>AEC, Inc.</td><td rowspan="2">n/a</td></tr>
<tr><td>Tankless Water Heater</td><td>Rinnai</td></tr>
<tr><td colspan="2">Control Valve</td><td>Normally Closed Solenoid</td><td>ASCO RedHat</td><td>n/a</td></tr>
<tr><td rowspan="4">Ambient RH & Temperature</td><td rowspan="2">Laboratory</td><td rowspan="2">Humidity & Temperature Transmitter – HMT100</td><td rowspan="2">Vaisala</td><td>±1.7 %RH</td></tr>
<tr><td rowspan="2">±0.2 °F dry bulb</td></tr>
<tr><td rowspan="2">Environmental Chamber</td><td rowspan="2">Dew Point Hygrometer - HYGRO-M1</td><td rowspan="2">General Eastern</td></tr>
<tr><td>±0.36°F dew point</td></tr>
<tr><td colspan="2">Barometric Pressure</td><td>Barometric Pressure Transducer</td><td>Cole Parmer</td><td>±0.3 hPa</td></tr>
<tr><td colspan="2">Differential Pressure - Air</td><td>Differential Pressure Transmitter – DM2000</td><td>Dwyer</td><td>±1.0%</td></tr>
<tr><td colspan="2">Oxygen Concentration</td><td>Infrared Gas Analyzer</td><td>Rosemount</td><td>±0.01% O_2</td></tr>
<tr><td colspan="2" rowspan="2">Electrical Power Consumption</td><td>Wattnode™ kWh Transducer</td><td rowspan="2">Continental Control Systems</td><td>±0.5%</td></tr>
<tr><td>Current Transformers (5A – 30A)</td><td>±1.0%</td></tr>
<tr><td colspan="2">Data Acquisition Hardware/Software</td><td>FieldPoint™ hardware and LabView Software™</td><td>National Instruments</td><td>n/a</td></tr>
</table>

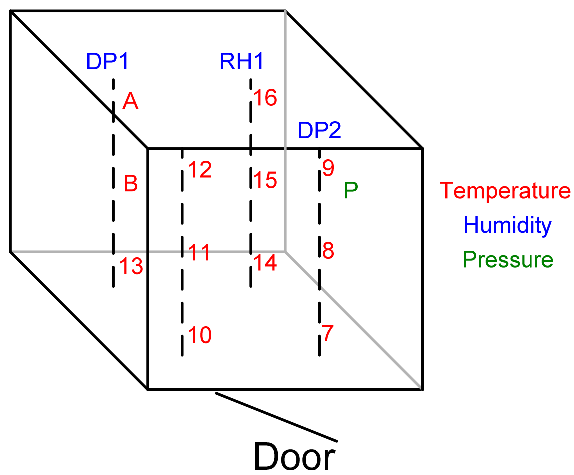
Environmental Chamber: UA and Leakage Tests

Summary of Results:

UA Test: At a steady 90 °F condition maintained with electric resistance heating over 12 hours, the UA is estimated at **24 Btu/hr-°F**.

Leakage Test: Using both analytical and empirical techniques, the leakage rate is estimated at **0.015 ACH or 13.3 ACFH**.

Leading up to the quantification of the space conditioning effect from Heat Pump Water Heater (HPWH) operation, the following tests are used to characterize the background heat loss and leakage rates of the environmental chamber, to better characterize this effect. The chamber is equipped with a thermocouple array of 12 sensors surrounding the HPWH placed the center, dewpoint and RH measurement, and differential pressure measurement between the chamber interior and the outer laboratory. These instruments are arranged per the diagram below.



Subscripts: RH – Relative Humidity and DP – dew point

Figure 31: Diagram of Environmental Chamber Sensor Positions

UA Test

Test Procedure: Maintaining an average 90 °F condition within the EC without increasing or decreasing humidity, the heat input necessary through electric resistance heat is monitored over a 12 hour period. Using a simple balance, the UA is estimated over 30 minute increments and plotted against the average temperature difference.

$$\dot{Q}_{input} = (UA)\left(T_{chamber}(t_i) - T_{laboratory}(t_i)\right)$$

The resulting steady state UA is approximated at 24 Btu/hr-°F.

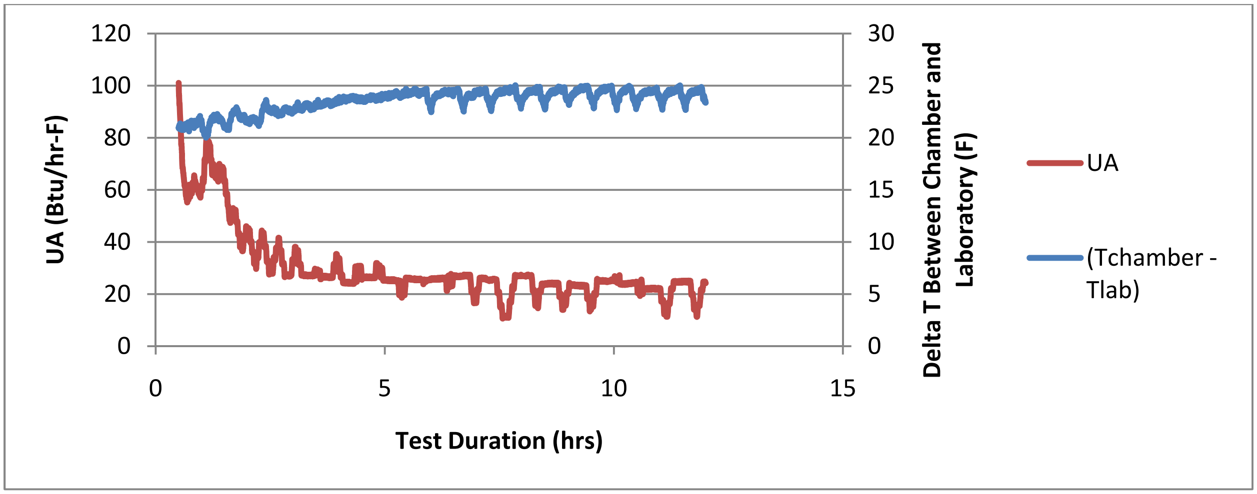


Figure 32: Chamber to Laboratory ΔT versus Calculated UA

Leakage Test

To accurately quantify the background heat and moisture loss of the chamber, a leakage test is needed to quantify the leakage rate, in air changes per hour (ACH), during typical operation. Testing will be performed with an unconditioned chamber, with leakage rate determined through the creation of an oxygen depleted environment as follows, occurring over approximately 13 hours:

1. Close the chamber door and apply the necessary safety warning tag/lockout to the chamber door handle. Adjust the N_2 regulator to confirm that the pressure entering the chamber is no greater than 10" water column, gage. Close the N_2 valve (at chamber and source).
2. Using chamber thermocouple trees, assure the average chamber temperature is within ± 2 °F of the laboratory.
3. Begin data acquisition of chamber conditions, including O_2 sampling and measurement at a rate of no greater than 5 cfh (2.3 L/min), record the sampling rate. Activate the laboratory exhaust fan and chamber fans.
4. Open the N_2 valve, metering in approximately 40 cfh (18.4 L/min) of N_2 into the chamber. Record actual N_2 flow rate. Continue until the chamber O_2 reading is at 17% (by volume, dry). This should take approximately 3 hours.
5. Close the N_2 valve at the chamber and at the source and continue to run data acquisition and O_2 sampling until the chamber reaches ambient conditions. Make note of O_2 sampling rate. This should take between 8 and 10 hours.
6. Confirm chamber conditions exceed 20.0 % O_2, remove locks/tags and open chamber door. **Do not enter chamber.** Turn off lab exhaust fan and chamber fan after 15 minutes.

Results and Analysis

Following a gradual displacement of the chamber atmosphere with pure N_2 at a rate of approximately 20 L/min, the decay of this oxygen depleted environment occurred from 6:00 pm in the evening to the following morning at 8:00 am. Conditions in the laboratory and gas analysis room are as follows:

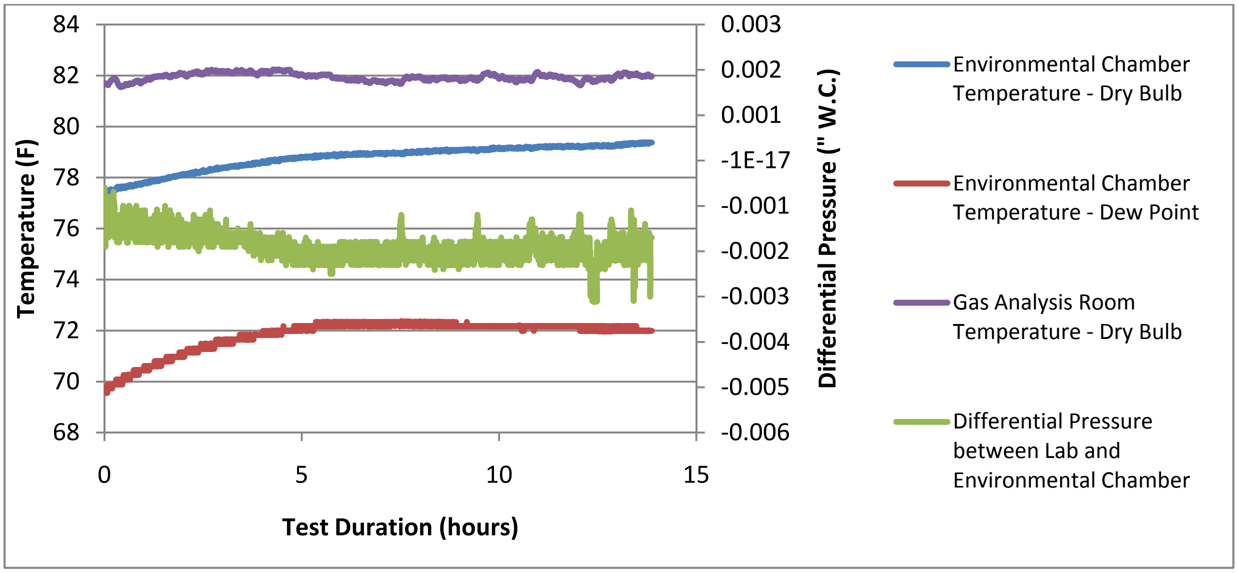


Figure 33: Chamber and Laboratory Conditions During Leakage Test

The O_2 as measured follows a First Order curve, as shown below:

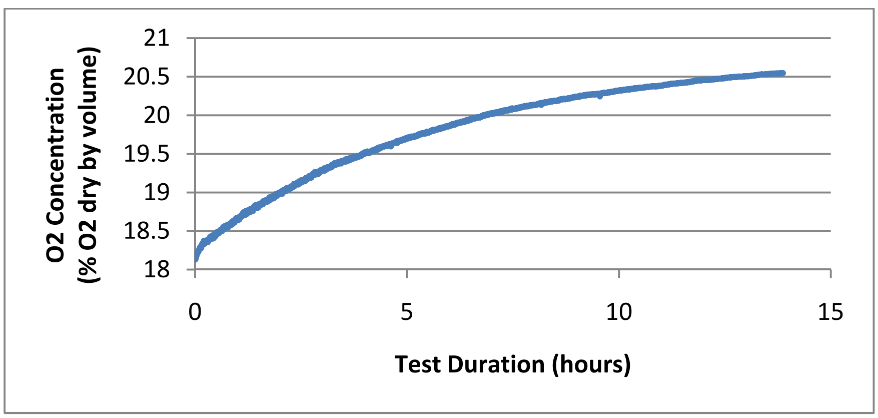


Figure 34: Measured O_2 Concentration (percent volume, dry) in Chamber During Leakage Test

To test this proposition of First Order behavior, assume the *Oxygen Depletion* (departure from ambient conditions) follows a First Order decay as follows:

$\frac{dN}{dt} = -kN$; whereby N is the volumetric O2 depletion and the decay constant k is:

$$\ln\left(\frac{N(t)}{N(0)}\right) = -kN(t)$$

Using the beginning and end of the test, N(0) = $V_{chamber}$*0.1812 and N(13 hrs) = $V_{chamber}$*0.2050, yielding a decay constant of approximately -0.155. Comparing this First Order decay model up against the measured dataset shows sufficient agreement to continue with this First Order approximation.

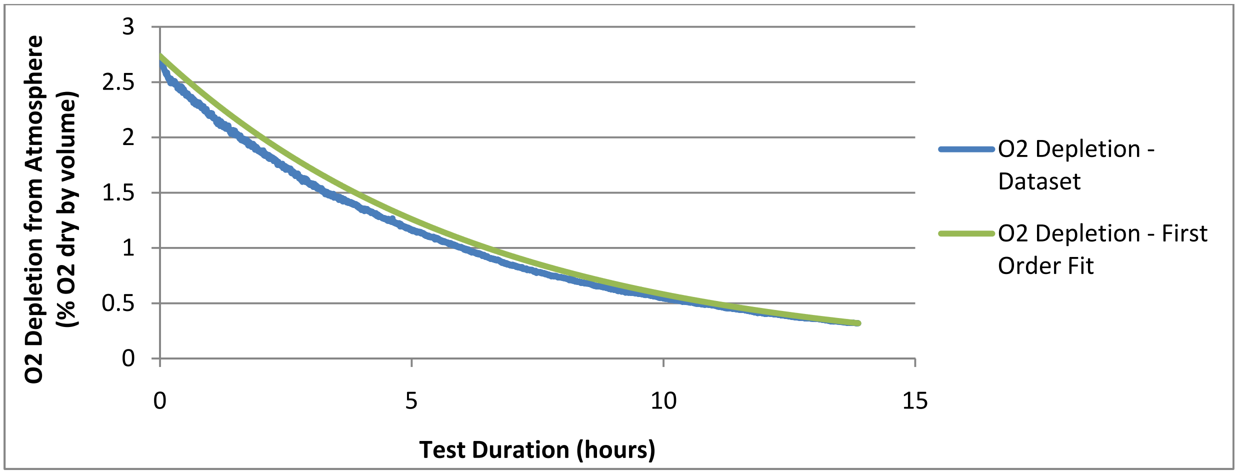


Figure 35: O_2 Depletion Rate with First Order Decay Curve Fit

The leakage rate, $\dot{V}_L$, will be calculated both empirically and analytically to assure accuracy, starting with analytical. During the leakage test, there are two flows to the environmental chamber (hereafter "EC), the sampling to the gas analysis equipment, $\dot{V}_S$, held at 5.5 SCFH, and the leakage itself, a circulation between the EC and the greater laboratory represented as a net infiltration of O_2. Using a First Order model for the conserved moles of O_2 (approximated as volumes), a mass balance for the EC is as follows:

$$\frac{dN}{dt} = Source - Sink = \dot{V}_L y_{O2,\infty} - \dot{V}_S \frac{N}{V_{chamber}}$$; where yO2,∞ = atmospheric mole fraction of O2 at 20.9%

Following through the derivation:

$$\frac{dN}{\left(\dot{V}_L y_{O2,\infty} - \dot{V}_S \frac{N}{V_{chamber}}\right)} = dt\ ; \left(-\frac{V_{chamber}}{\dot{V}_S}\right)\left|\dot{V}_L y_{O2,\infty} - \dot{V}_S \frac{N}{V_{chamber}}\right|_0^t = t\Big|_0^t ;$$

$$\frac{\left(\dot{V}_L y_{O2,\infty} - \dot{V}_S \frac{N(t)}{V_{chamber}}\right)}{\left(\dot{V}_L y_{O2,\infty} - \dot{V}_S \frac{N(0)}{V_{chamber}}\right)} = \exp\left(-\frac{\dot{V}_S}{V_{chamber}} t\right); \text{ solving for } \dot{V}_L :$$

$$\frac{\left(\frac{\dot{V}_S}{V_{chamber}}\left(N(t) - N(0)\exp\left(-\frac{\dot{V}_S}{V_{chamber}} t\right)\right)\right)}{y_{O2,\infty}\left(1 - \exp\left(-\frac{\dot{V}_S}{V_{chamber}} t\right)\right)} = \dot{V}_L$$

Using N(13 hrs) = $V_{chamber}$*0.2050, N(0) = $V_{chamber}$*0.1812, $V_{chamber}$ = 914 ft^3 (measured), $y_{O2,\infty}$= 0.209, and $\dot{V}_S$ = 5.5 CFH, $\dot{V}_L$ **= 13.3 CFH yielding a leakage rate of 0.015 ACH.** Note that the chamber and laboratory are treated as standard conditions, while an adjustment is made for the warmer gas analysis room where the sample is taken.

To compare with an analytical value for $\dot{V}_L$ using the dataset, the following instantaneous balance is used:

$$V_{chamber}\left(y_{O_2,final} - y_{O_2,initial}\right) = \sum_{i=0} t_i\left(\dot{V}_L \cdot (.209) - \dot{V}_S y_{O_2,i}\right)$$

Using the dataset at each hour, the following table results:

Test Hour	Measured EC O_2	Calculated Leakage Rate (CFH)
1	0.187	4.92
2	0.190	12.41
3	0.193	14.33
4	0.195	14.62
5	0.197	14.35
6	0.199	14.06
7	0.200	13.78
8	0.201	13.37
9	0.202	13.01
10	0.203	12.62
11	0.204	12.24
12	0.205	11.92

Throwing out the first hour, which does not provide a sufficient duration for approximating First Order decay, the **average leakage rate calculated is 13.2 CFH, rather close to the analytical approximation**.

Appendix B: Detailed Test Results - First Hour Rating

First Hour Rating

Table 13: Summary of HPWH First-Hour Ratings

HPWH	Appliance Mode	First-Hour Rating (gallons)
Mfr A	Efficient	49.5
	Electric	67.2
	Hybrid	66.4
	At 120°F Set Point	65.0
Mfr B	Efficient	36.2
	Electric	52.0
	Hybrid	58.3
	At 120°F Set Point	57.4
	High Demand	50.2
Mfr C	Efficient	52.5
	Electric	65.9
	Hybrid	67.2
	At 120 F Set Point	65.0

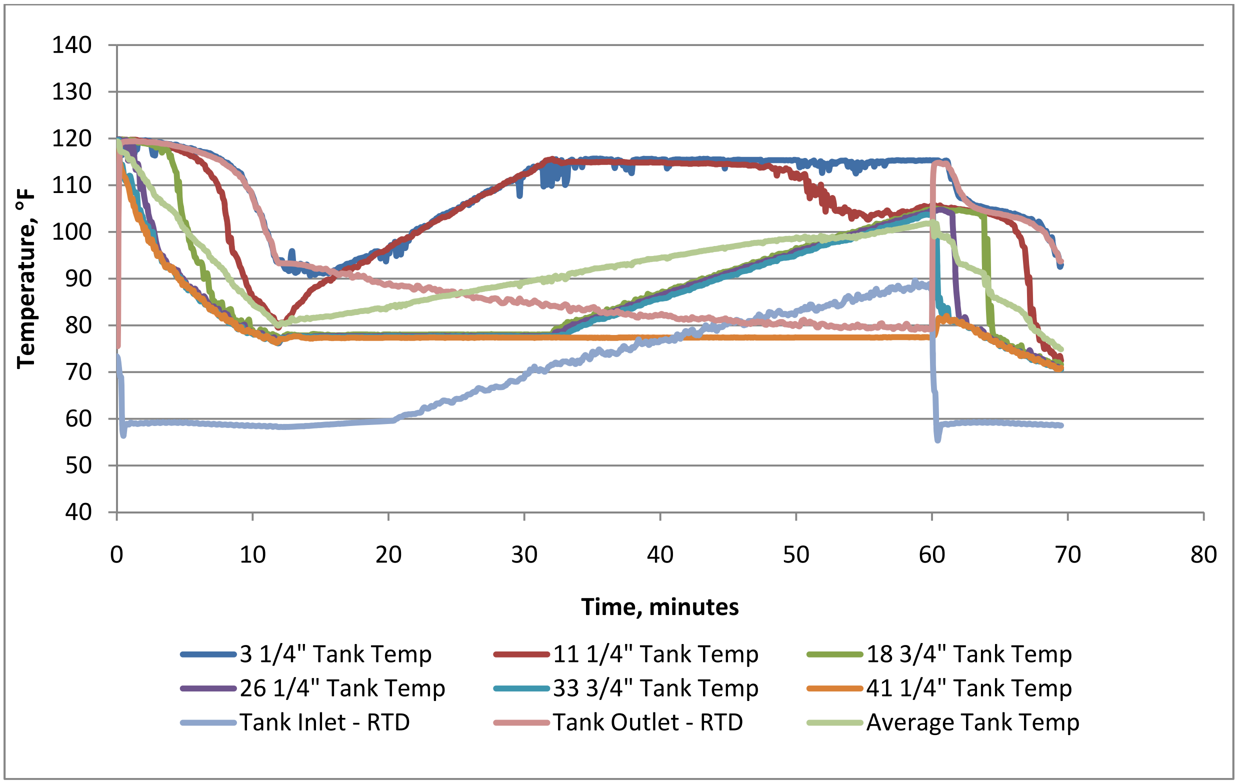


Figure 36: Mfr B First-Hour Rating with 120°F Setpoint

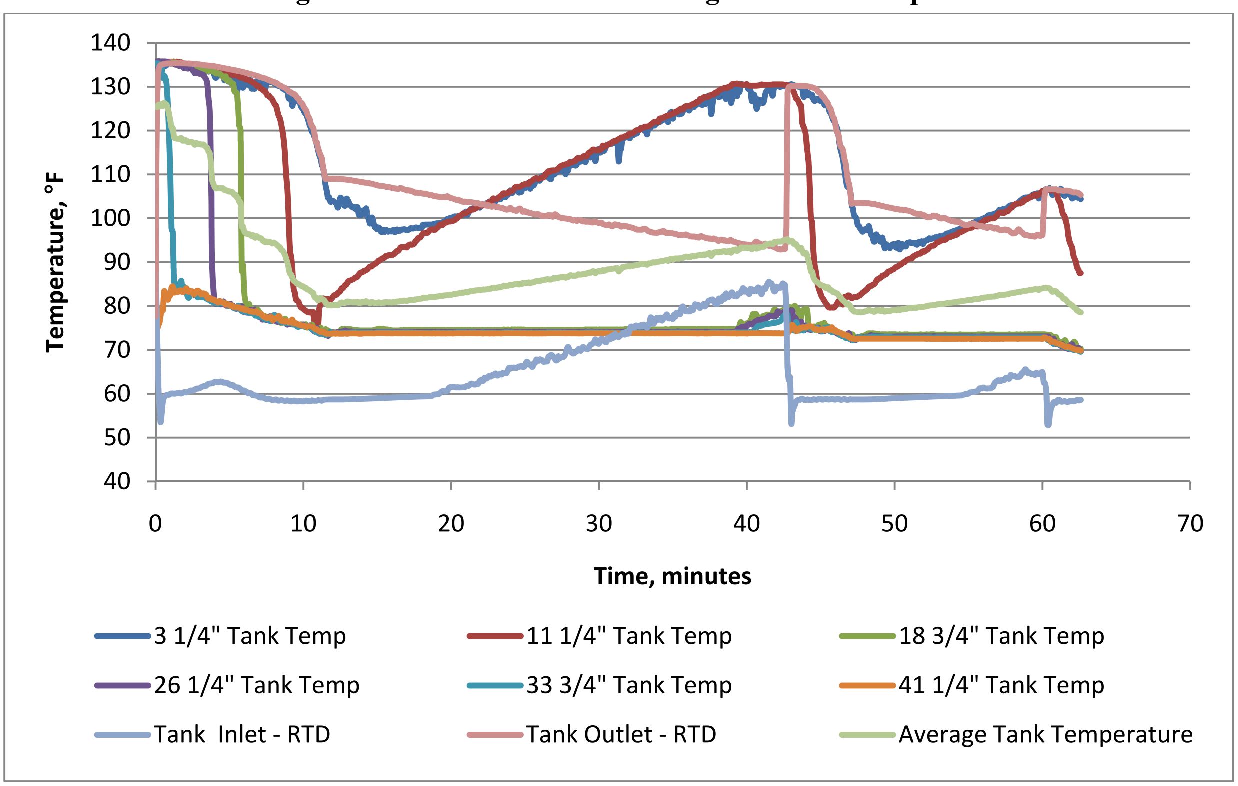


Figure 37: Mfr B First-Hour Rating in High-Demand Mode

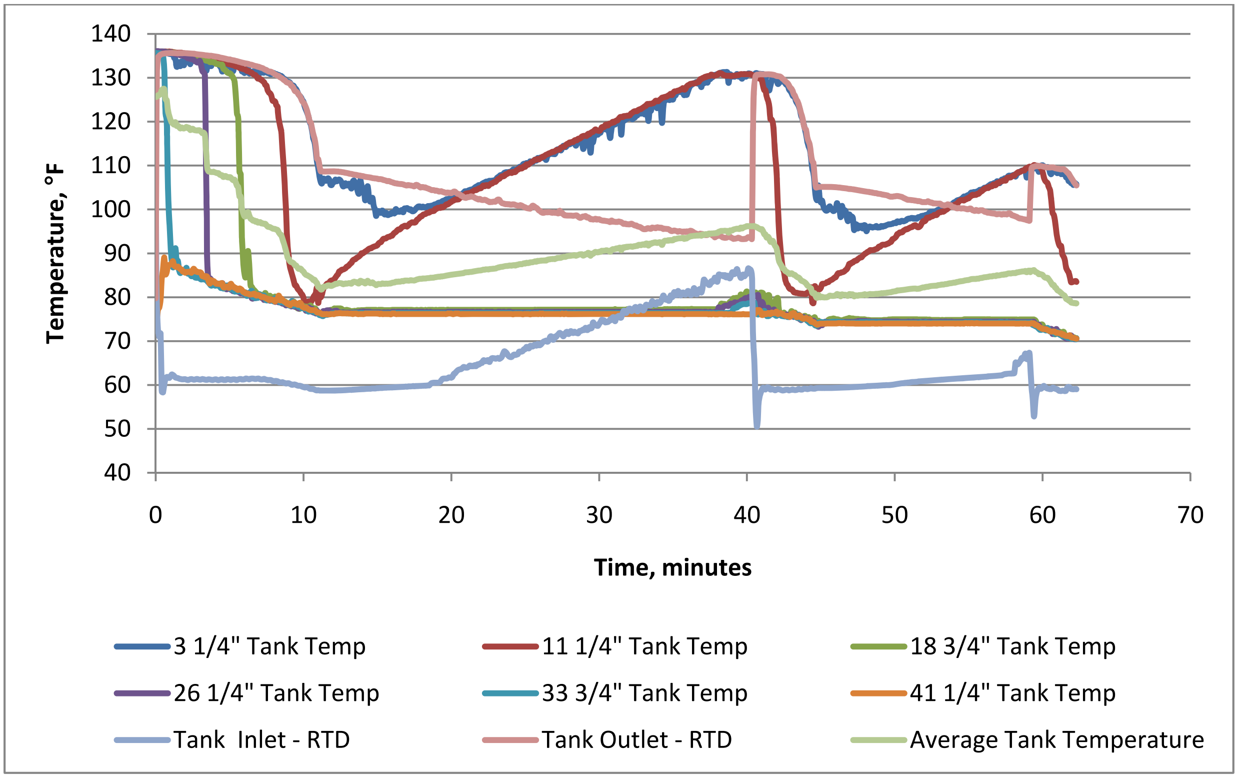


Figure 38: Mfr B First-Hour Rating in All-Resistance Mode

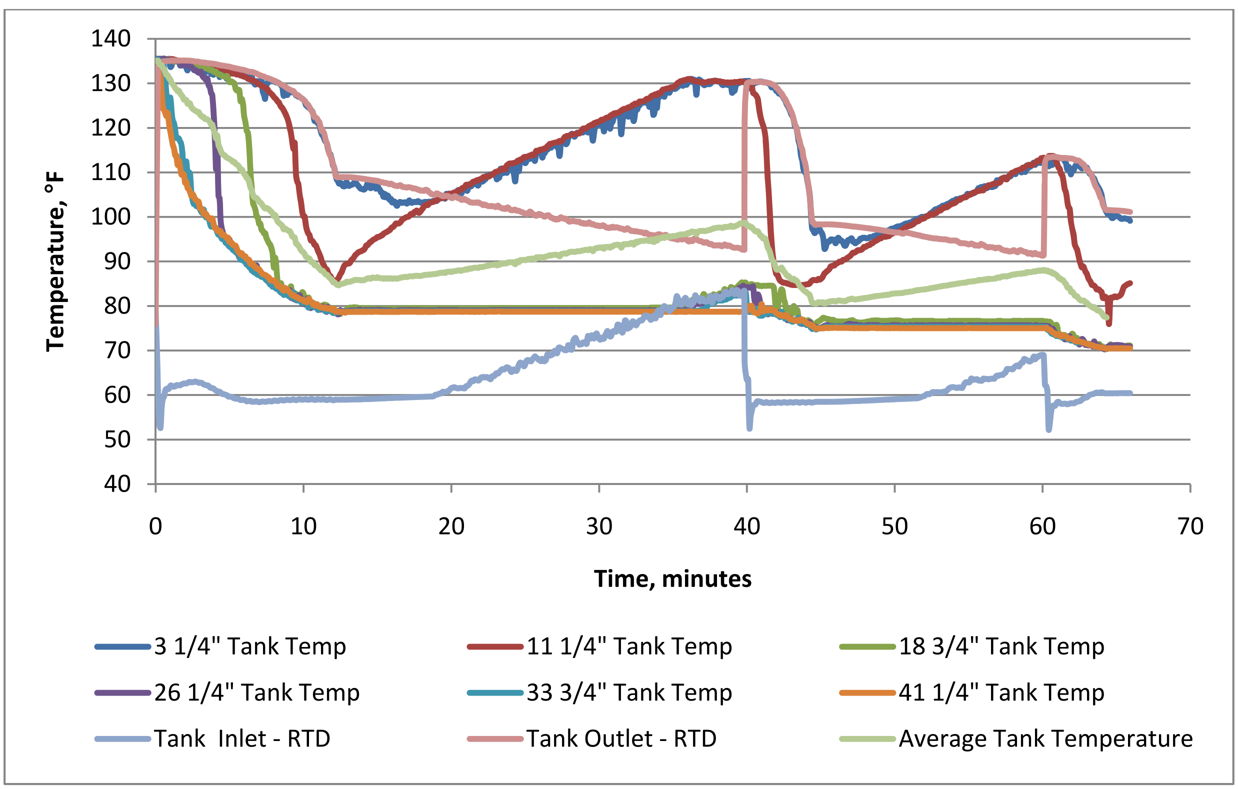


Figure 39: Mfr B First-Hour Rating in Hybrid Mode

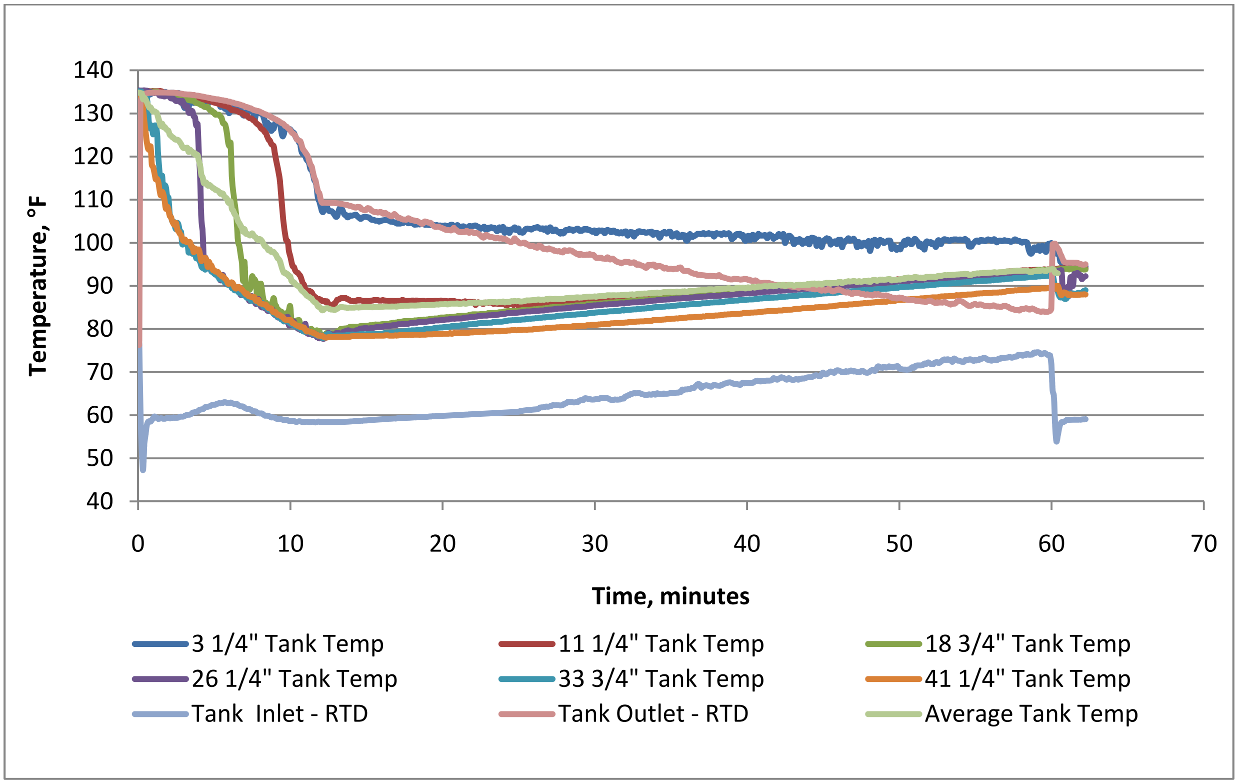


Figure 40: Mfr B First-Hour Rating in High-Efficiency Mode

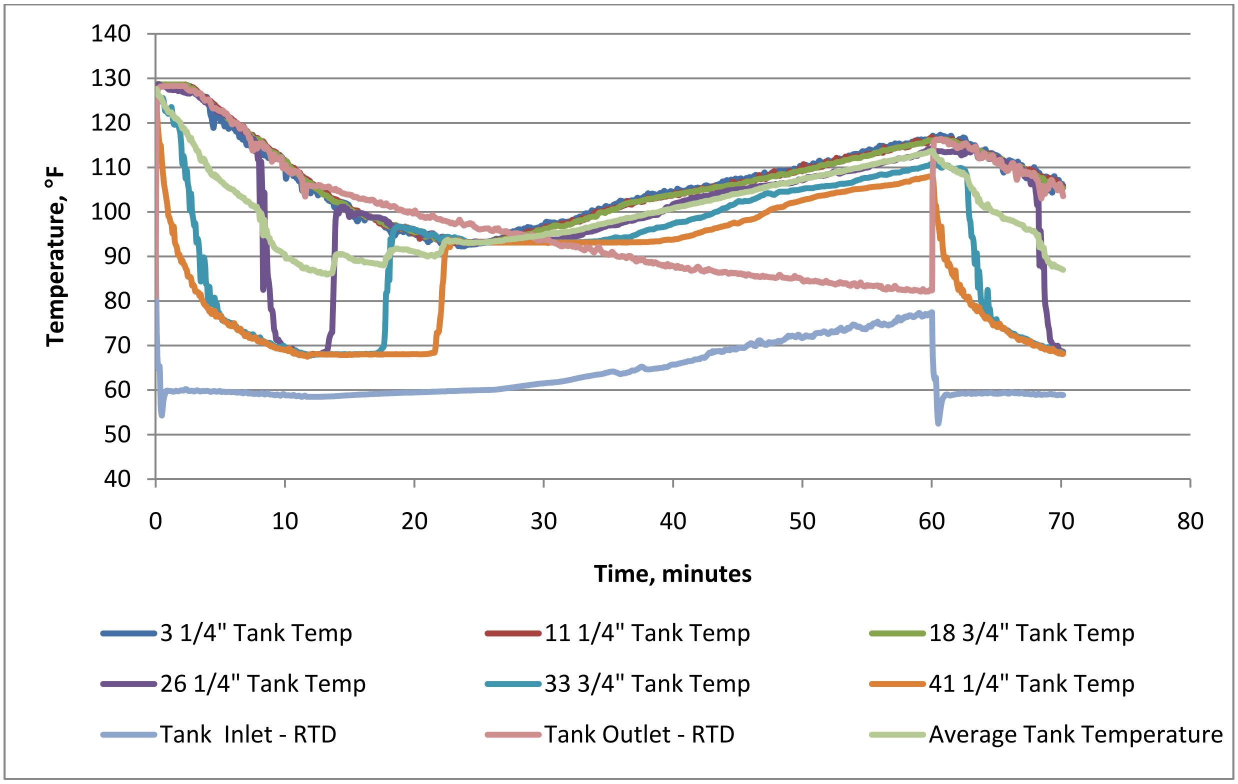


Figure 41: Mfr C First-Hour Rating with 120°F Setpoint

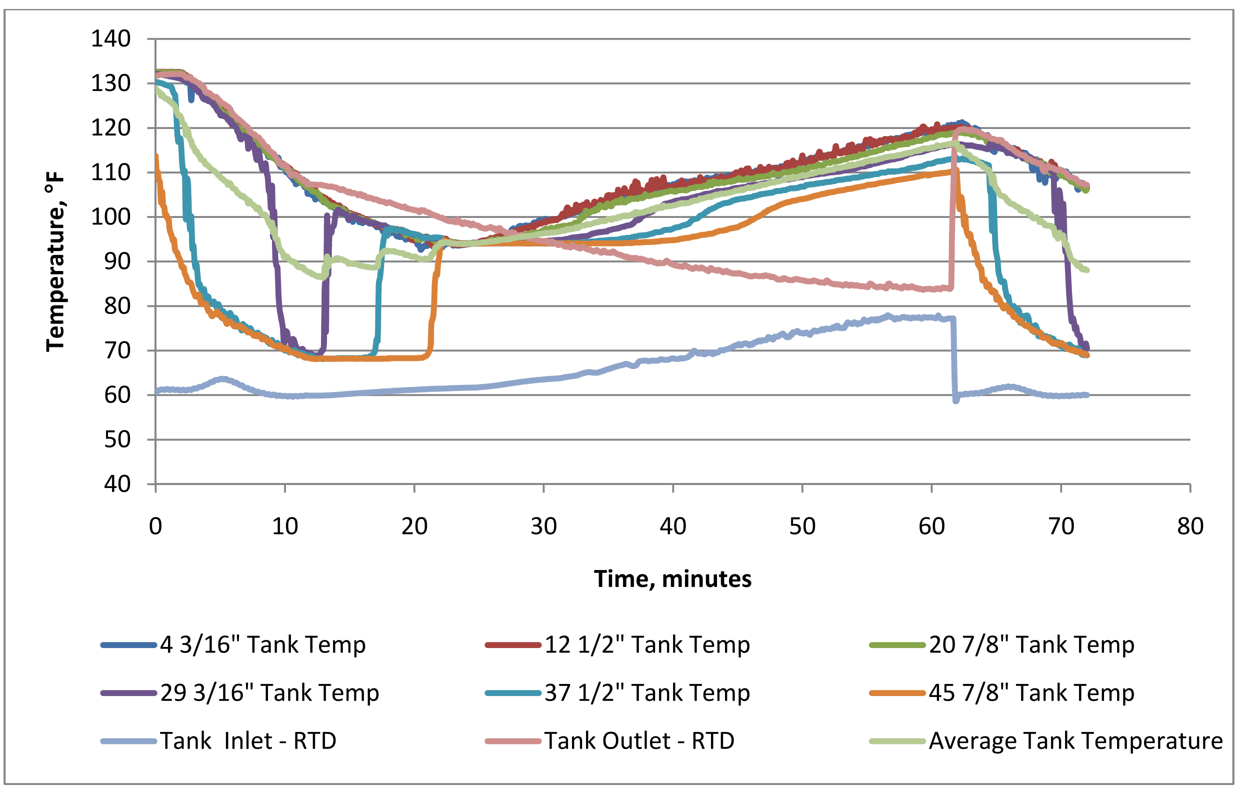


Figure 42: Mfr C First-Hour Rating in Efficiency Mode

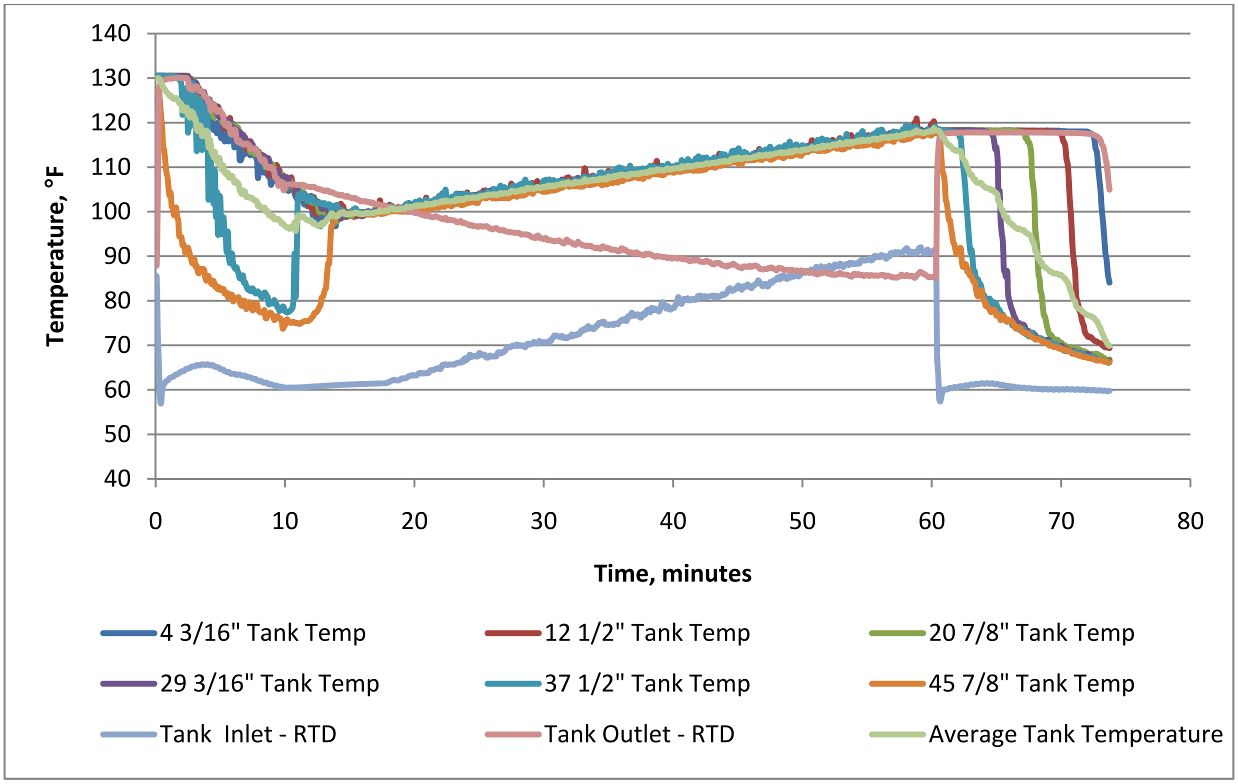


Figure 43: Mfr C First-Hour Rating in All-Resistance Mode

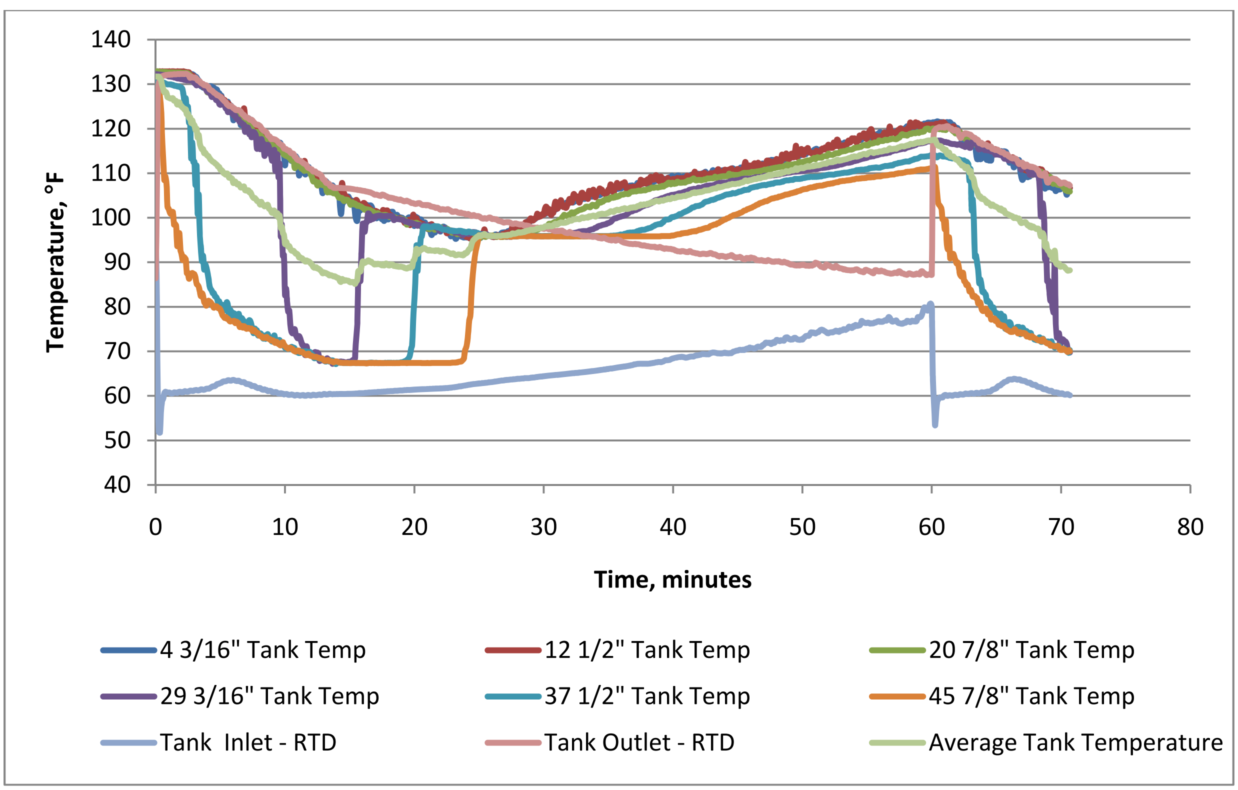


Figure 44: Mfr C First-Hour Rating in Hybrid Mode

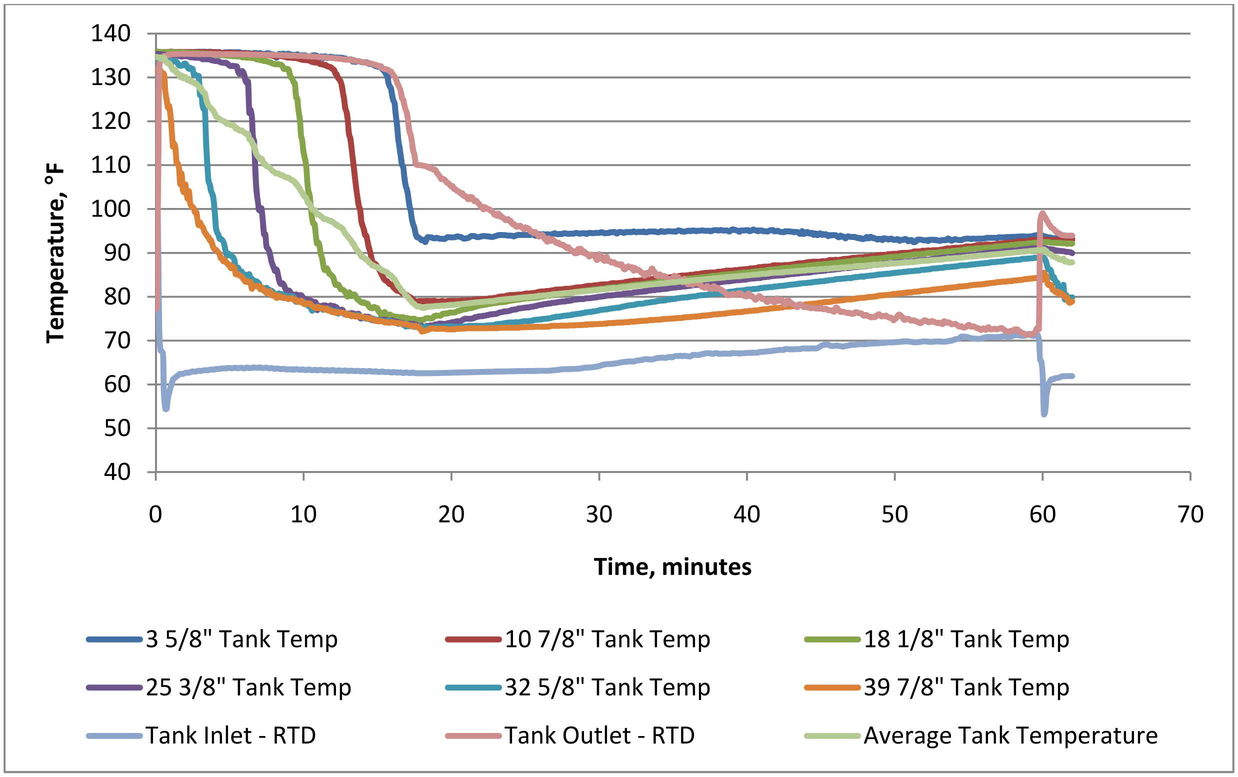


Figure 45: Mfr A First-Hour Rating in Efficiency Mode

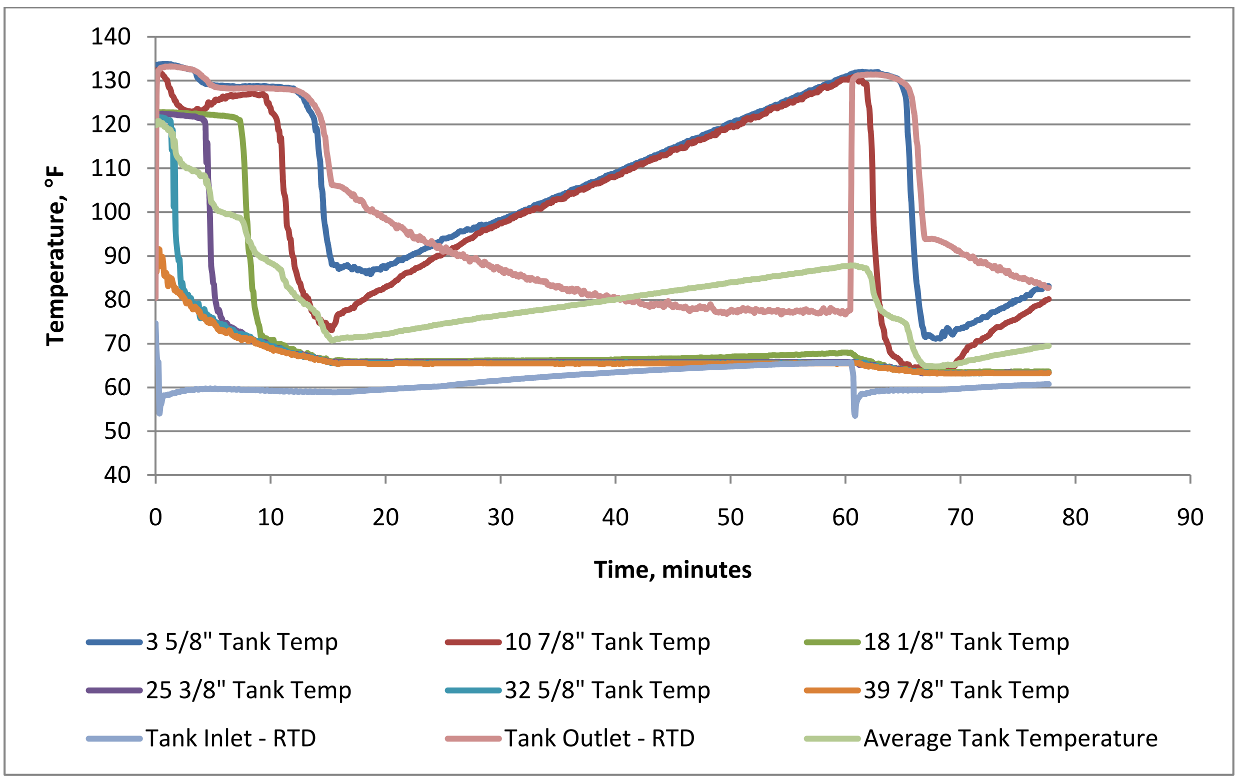


Figure 46: Mfr A First-Hour Rating in All-Resistance Mode

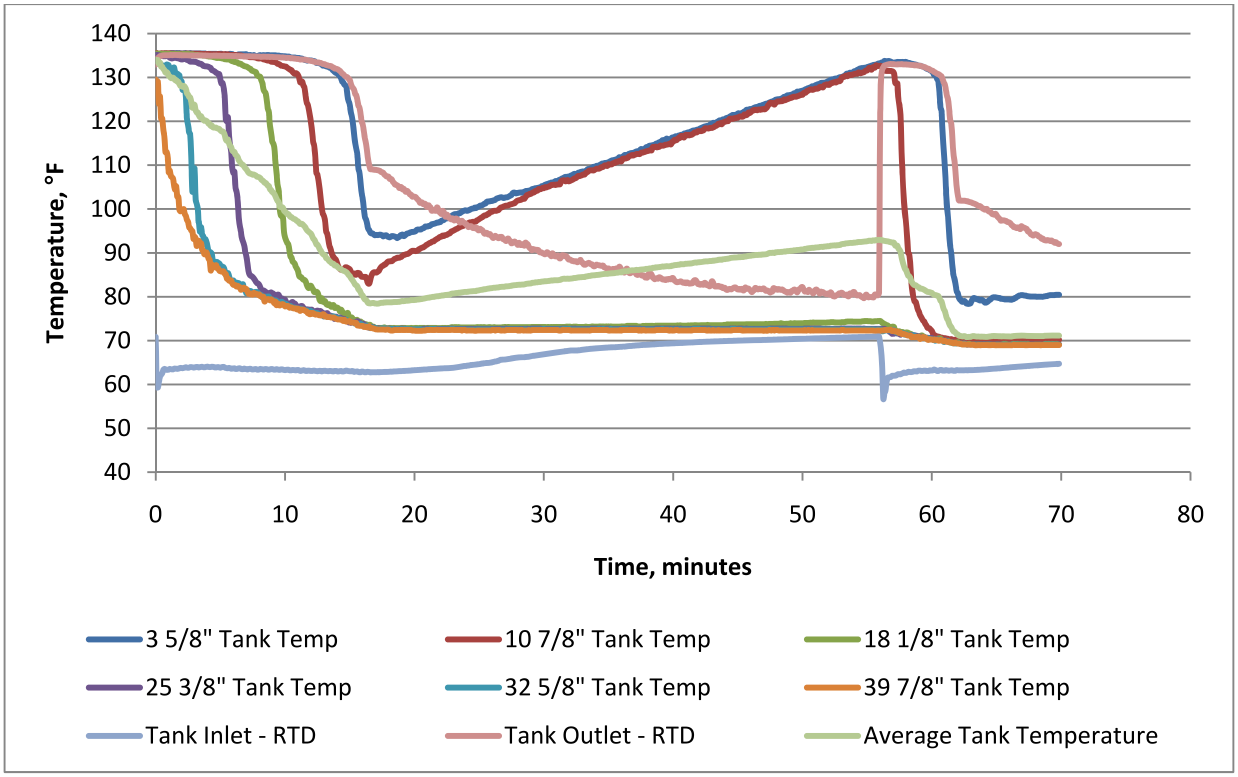


Figure 47: Mfr A First-Hour Rating in Hybrid Mode

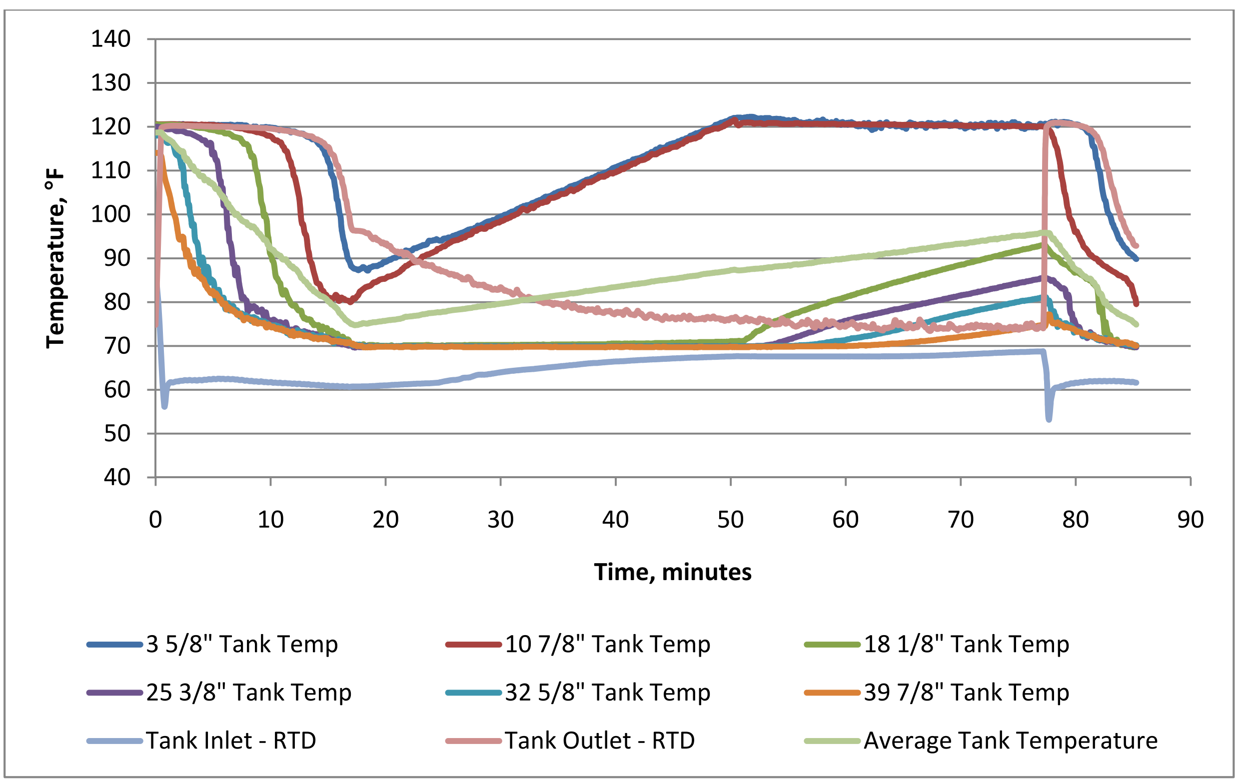


Figure 48: Mfr A First-Hour Rating with a 120°F Setpoint

Appendix C: Detailed Test Results – 24 Hour Simulated Use Test

Tests 5 through 12

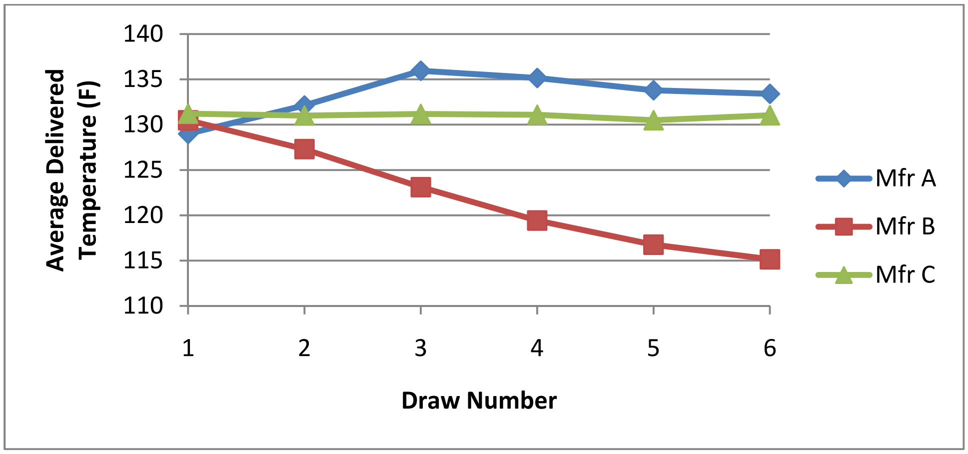


Figure 49: Average Delivered Water Temperature by Draw during DOE EF Test in Hybrid Mode

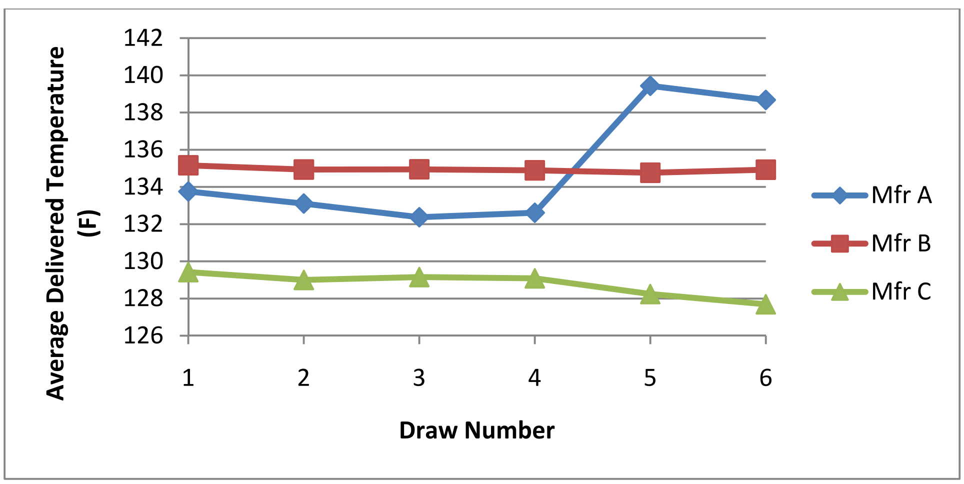


Figure 50: Average Delivered Water Temperature by Draw during DOE EF Test in All-Resistance Mode

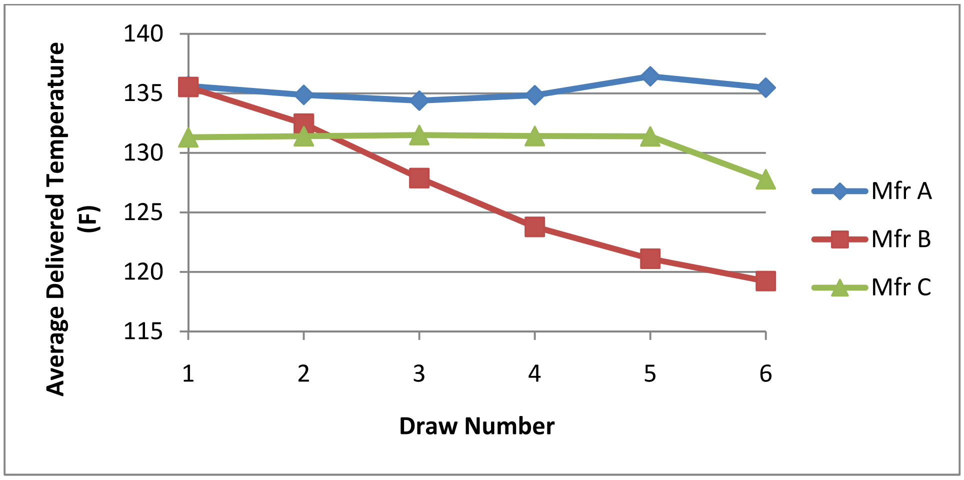


Figure 51: Average Delivered Water Temperature by Draw during DOE EF Test in High-Efficiency Mode

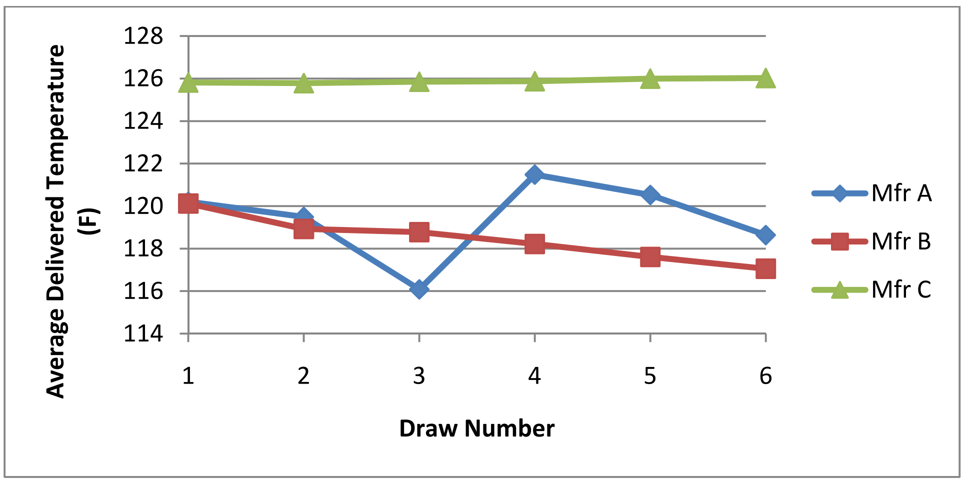


Figure 52: Average Delivered Water Temperature by Draw during DOE EF Test with a 120°F Thermostat Setpoint Mode

Table 14: Details for Low Use Hot Water Draw Pattern by HPWH

	Average Delivered Temperature (°F)	Total Input (Btus)	Total Output (Btus)	EF_{avg} / EF_{est}	% of Input as HP
Mfr A	128.7	8,980	18,030	2.01/1.94	83.5
Mfr B	129.8	8,470	19,240	2.27/2.21	98.1
Mfr C	127.2	14,450	17,740	1.23/1.13	42.3

Table 15: Details for Mid Use Hot Water Draw Pattern by HPWH

	Average Delivered Temperature (°F)	Total Input (Btus)	Total Output (Btus)	EF_{avg} / EF_{est}	% of Input as HP
Mfr A	131.7	16,760	40,520	2.42/2.42	84.6
Mfr B	131.9	18,250	42,300	2.32/2.51	98.5
Mfr C	129.4	33,630	39,570	1.18/1.16	25.4

Table 16: Details for High Use Hot Water Draw Pattern by HPWH

	Average Delivered Temperature (°F)	Total Input (Btus)	Total Output (Btus)	EF_{avg} / EF_{est}	% of Input as HP
Mfr A	131.3	23,370	64,950	2.78/2.79	84.9
Mfr B	130.6	23,700	62,910	2.66/2.66	98.2
Mfr C	128.9	47,980	56,040	1.17/1.17	21.5

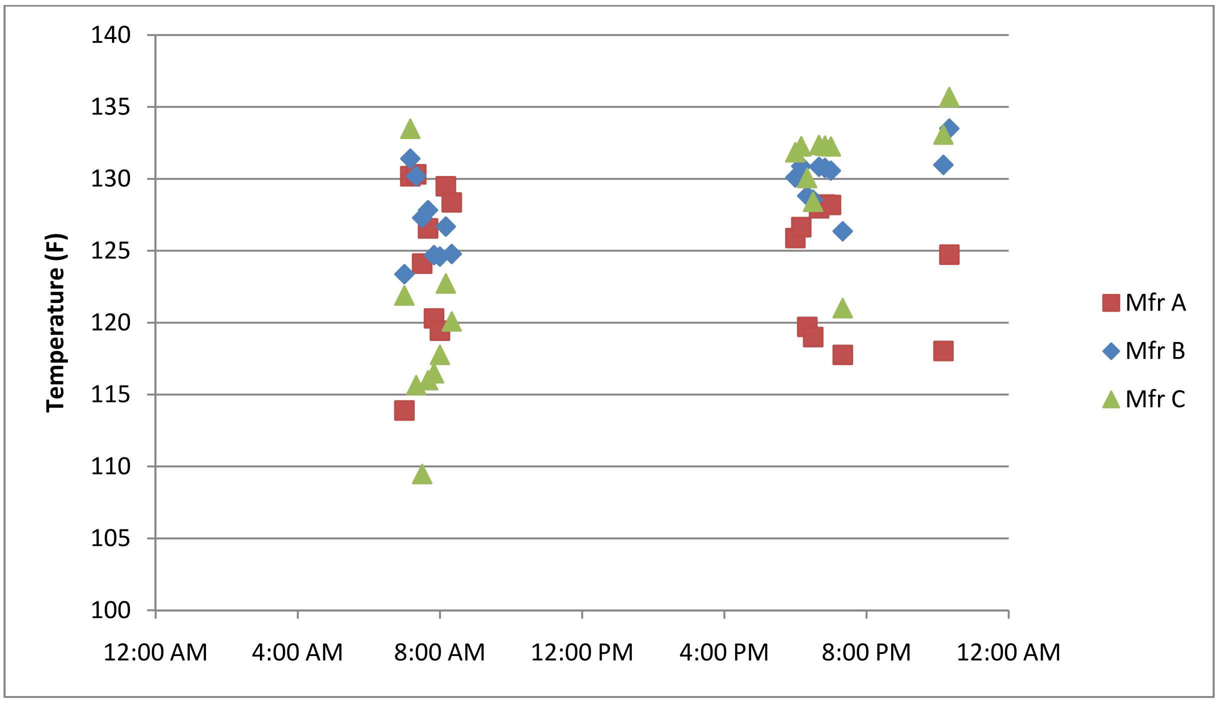


Figure 53: Delivered Temperature by Draw for Low Use Draw Pattern

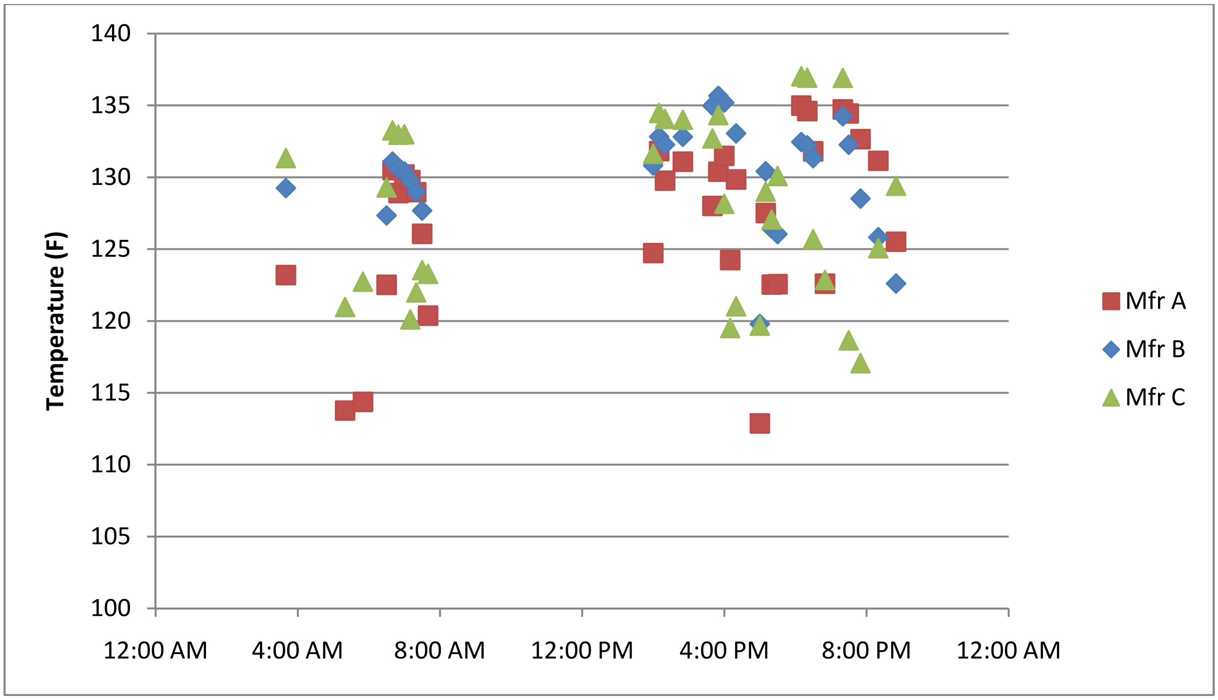


Figure 54: Delivered Temperature by Draw for Mid Use Draw Pattern

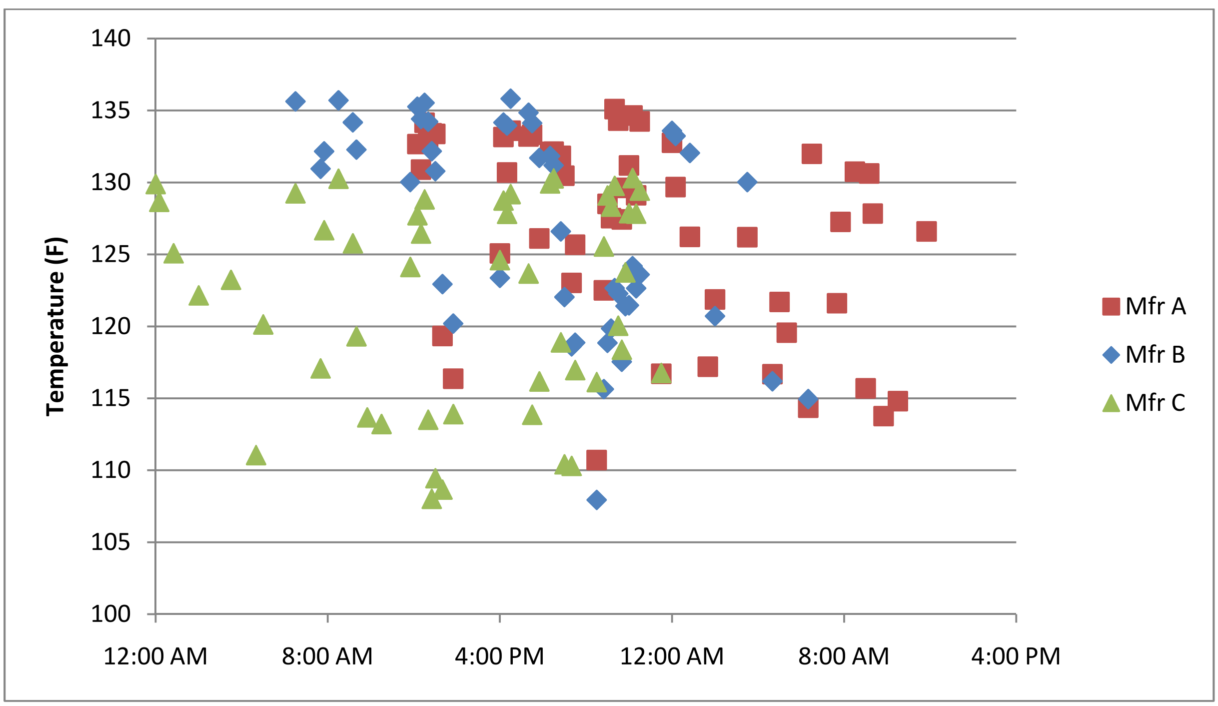


Figure 55: Delivered Temperature by Draw for High Use Draw Pattern[6]

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6 Note the time-shifting of the 24 hour “day” for Mfr A and Mfr B results, necessary to minimize the change stored average stored water temperature from start to finish.

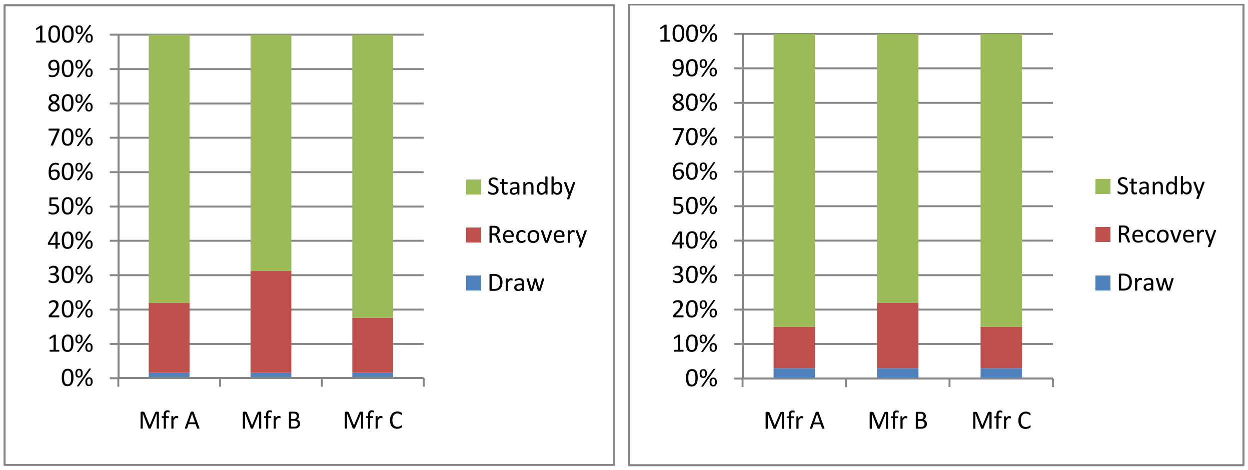


Figure 56: Percentage of Time in Standby, Recovery, and Draw during DOE (left) and Low Use (right) Tests

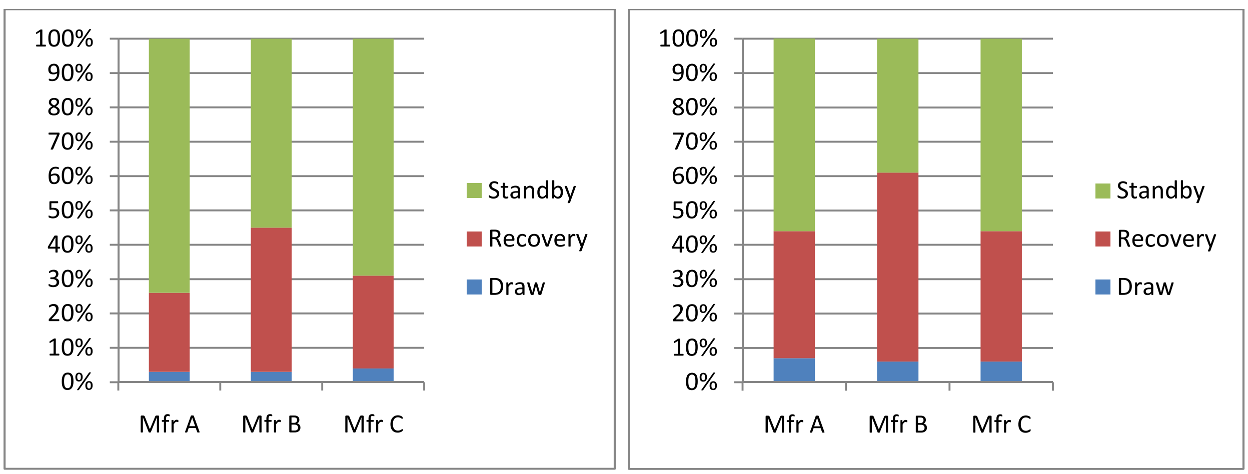


Figure 57: Percentage of Time in Standby, Recovery, and Draw during Mid Use (left) and High Use (right) Tests

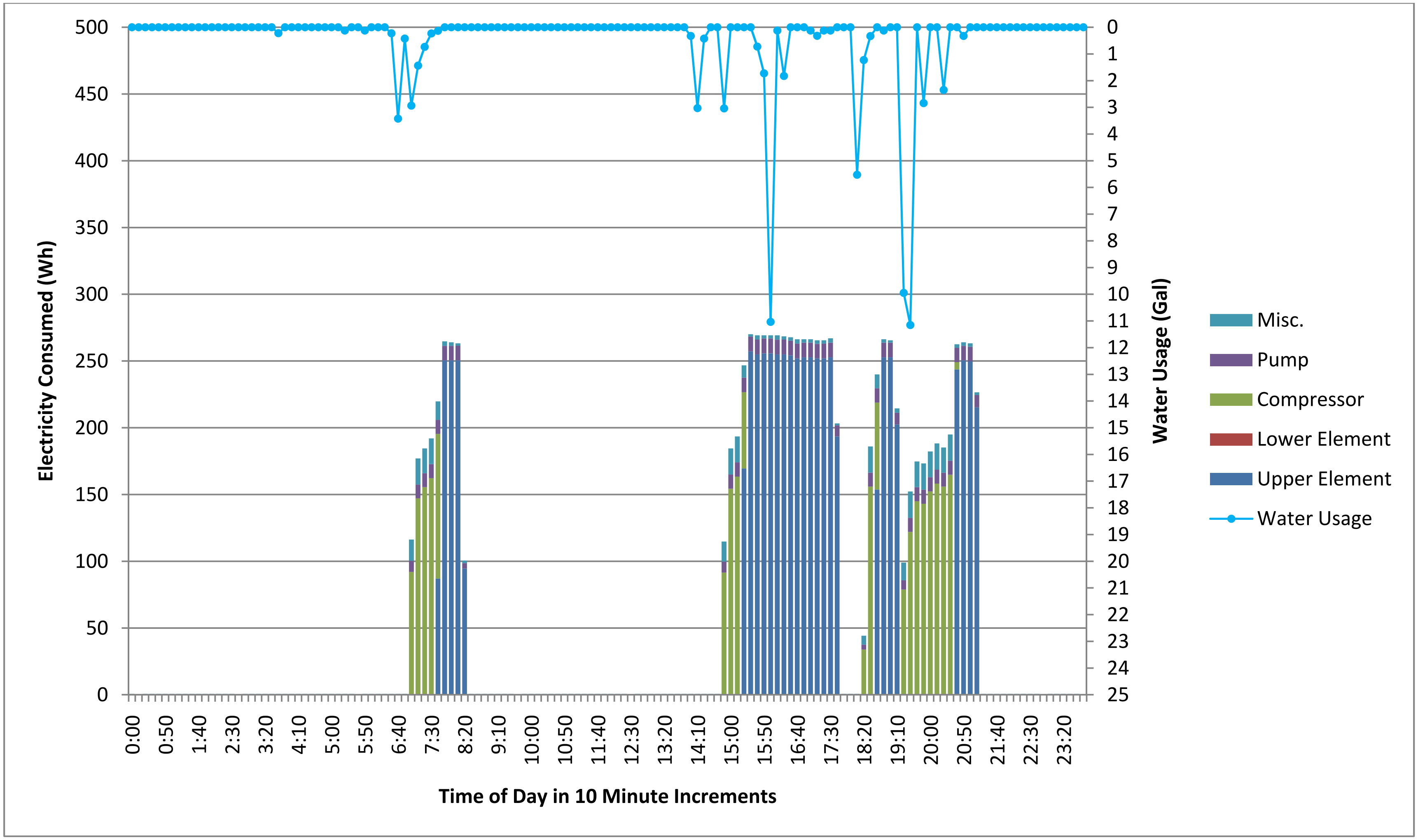


Figure 58: Diagram of Energy and Water Flows for Mfr C during Mid Use Draw Pattern

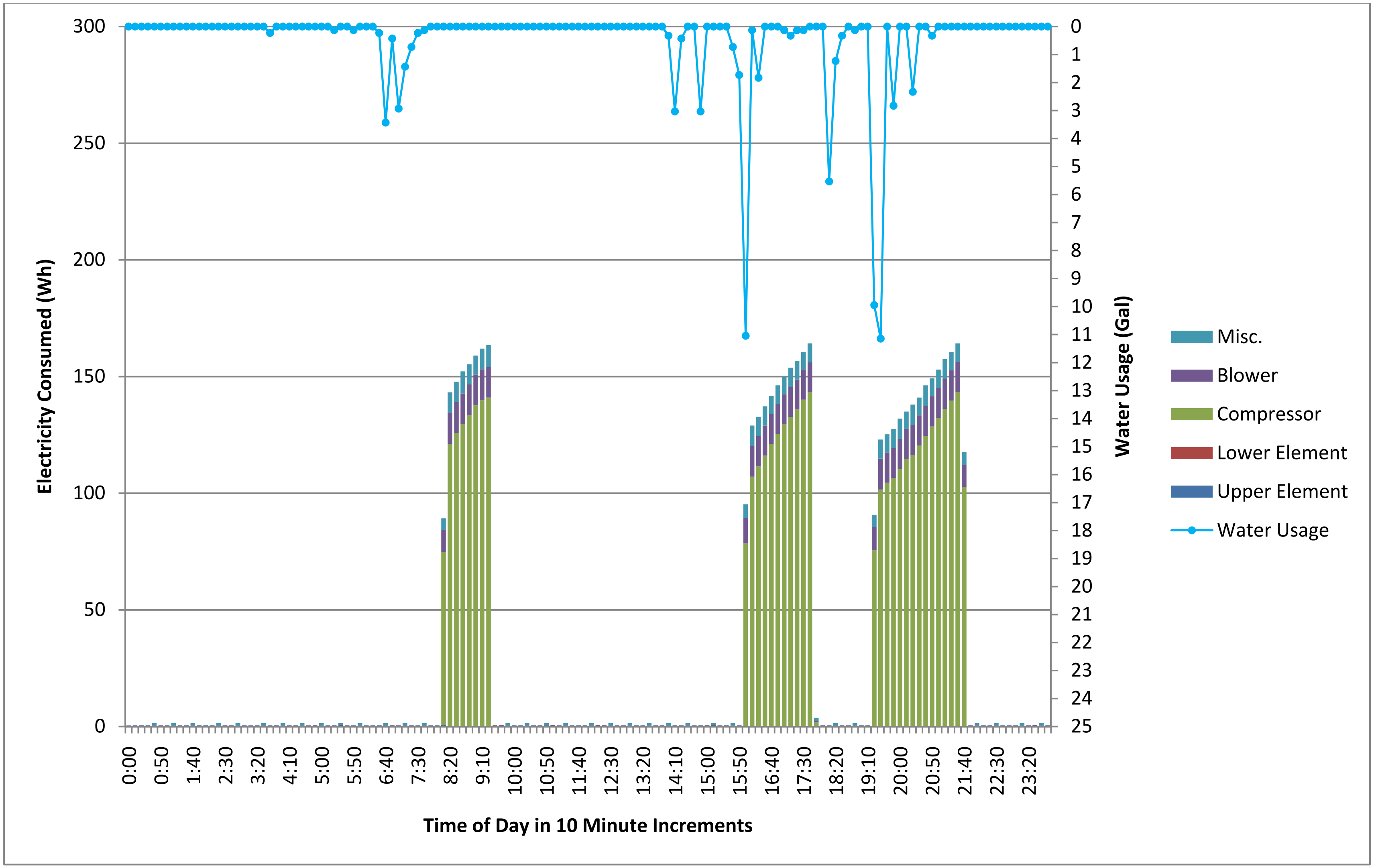


Figure 59: Diagram of Energy and Water Flows for Mfr A during Mid Use Draw Pattern

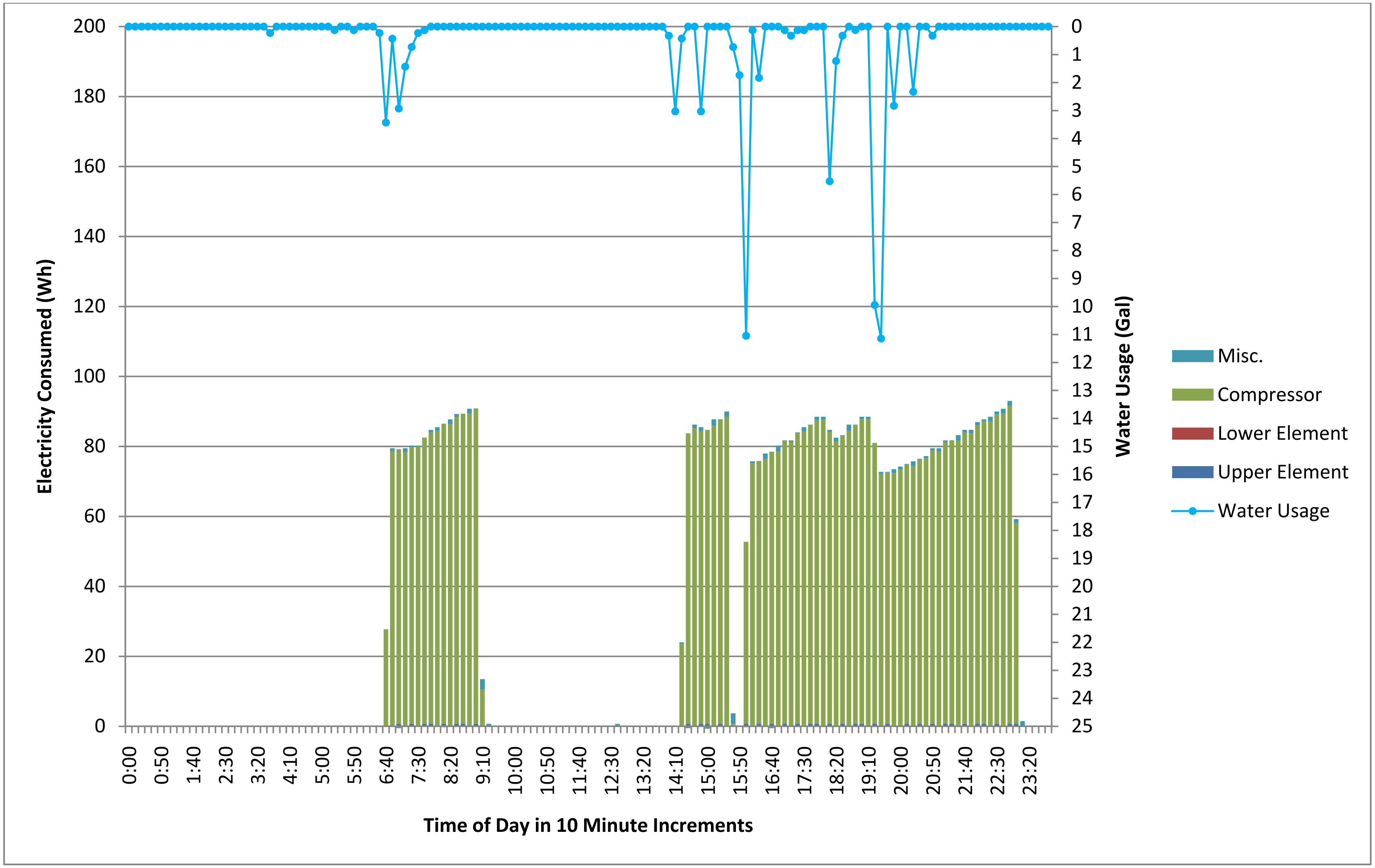


Figure 60: Diagram of Energy and Water Flows for Mfr B during Mid Use Draw Pattern

Tests 13 through 16

Table 17: Estimated Energy Factor at Hot/Humid and Cold Ambient Conditions in Hybrid Mode with Standard DOE Draw Pattern

HPWH	Lab Conditions	Lab Conditions with 120°F Setpoint	Hot/Humid Condition	Cold Condition
Mfr A	2.52	2.55	2.96	2.08
Mfr B	2.43	2.46	2.80	2.06
Mfr C	1.55	2.00	1.70	1.30

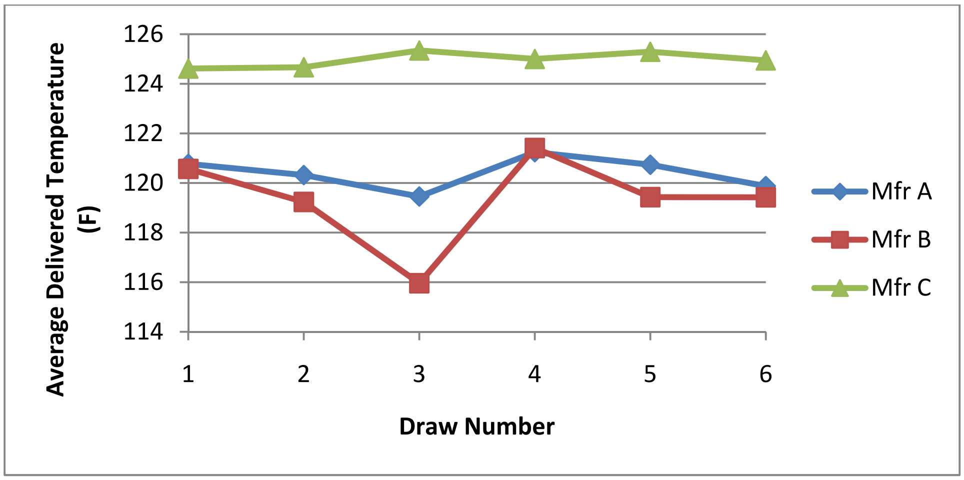


Figure 61: Average Delivered Water Temperature by Draw during DOE EF Test in Hybrid Mode at Hot/Humid Ambient Condition

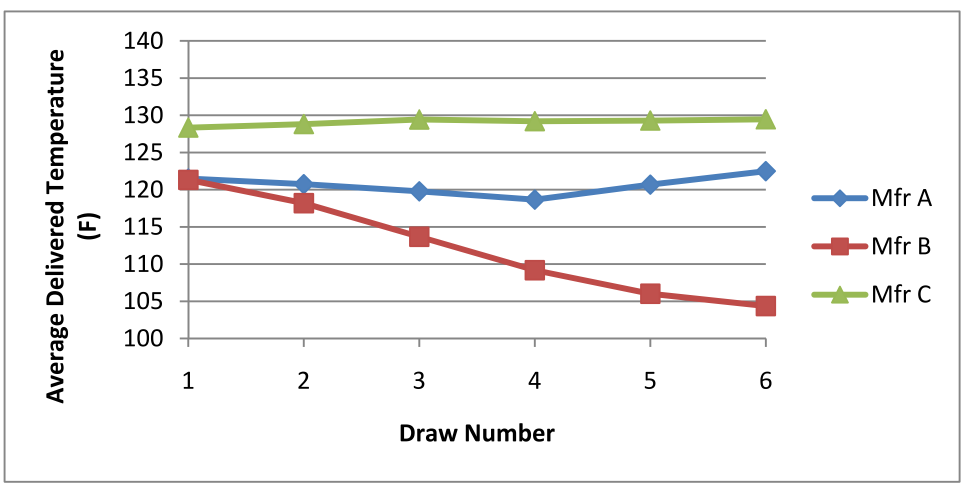


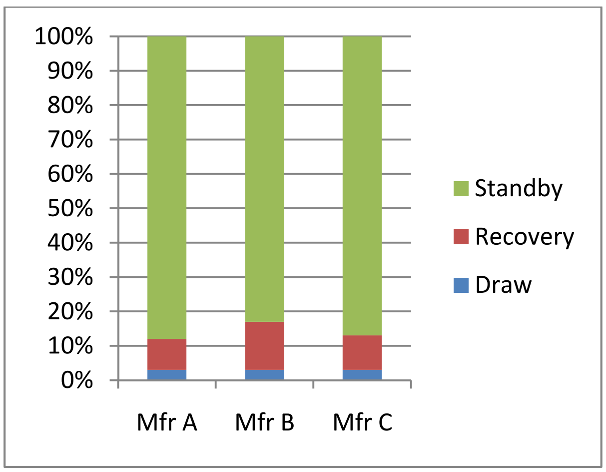
Figure 62: Average Delivered Water Temperature by Draw during DOE EF Test in Hybrid Mode at Cold Ambient Condition

Table 18: Details for Mid Use Hot Water Draw Pattern by HPWH at Hot/Humid Ambient Condition

	Average Delivered Temperature (°F)	Total Input (Btus)	Total Output (Btus)	EF_{avg} / EF_{est}	% of Input as HP
Mfr A	119.6	7,320	21,410	2.92/3.03	84.3%
Mfr B	117.9	7,340	21,050	2.87/2.87	99.0%
Mfr C	123.4	12,250	23,450	1.91/1.76	43.8%

Table 19: Details for Mid Use Hot Water Draw Pattern by HPWH at Cold Ambient Condition

	Average Delivered Temperature (°F)	Total Input (Btus)	Total Output (Btus)	EF_{avg} / EF_{est}	% of Input as HP
Mfr A	119.4	16,550	36,360	2.20/2.18	85.1%
Mfr B	114.3	15,470	33,450	2.16/2.15	98.2%
Mfr C	121.3	29,030	38,240	1.32/1.26	46.8%



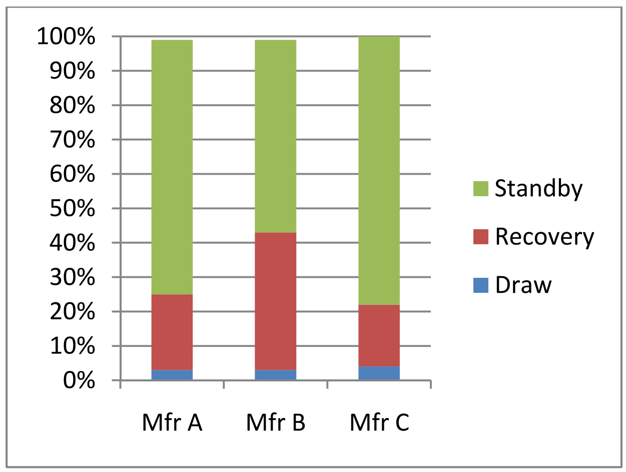


Figure 63: Percentage of Time in Standby, Recovery, and Draw during Mid Use at Hot/Humid (left) and Cold (right) Ambient Conditions

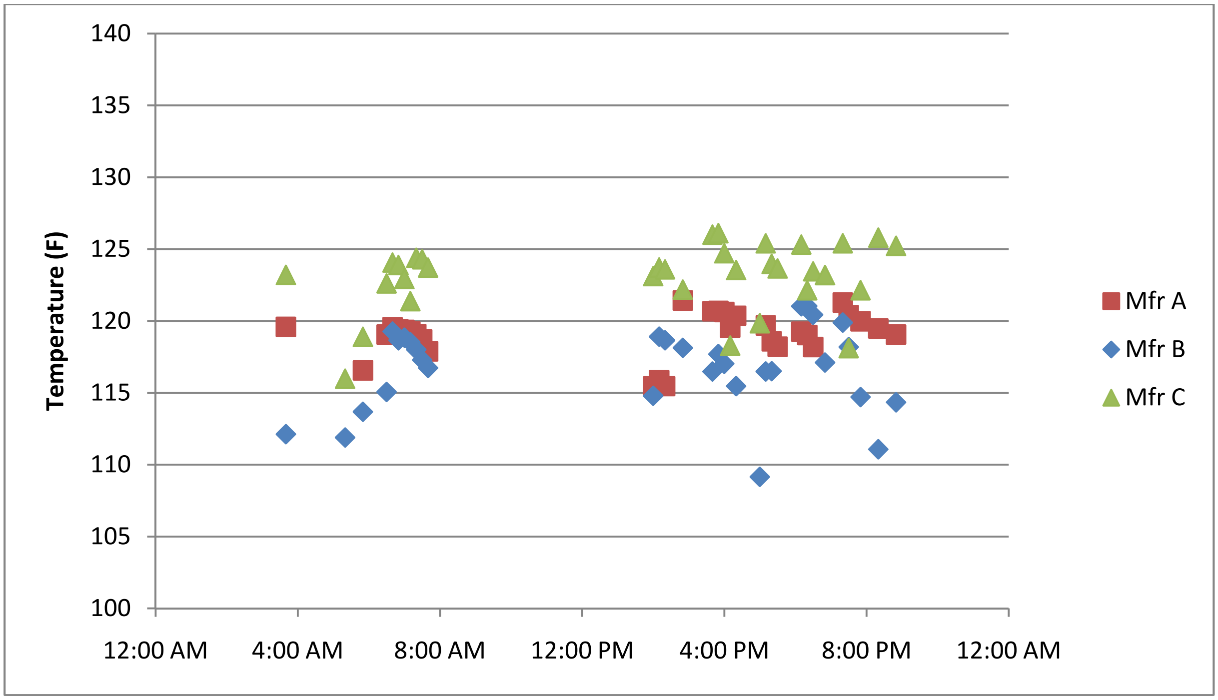


Figure 64: Delivered Temperature by Draw for Mid Use Draw Pattern at Hot/Humid Ambient Condition

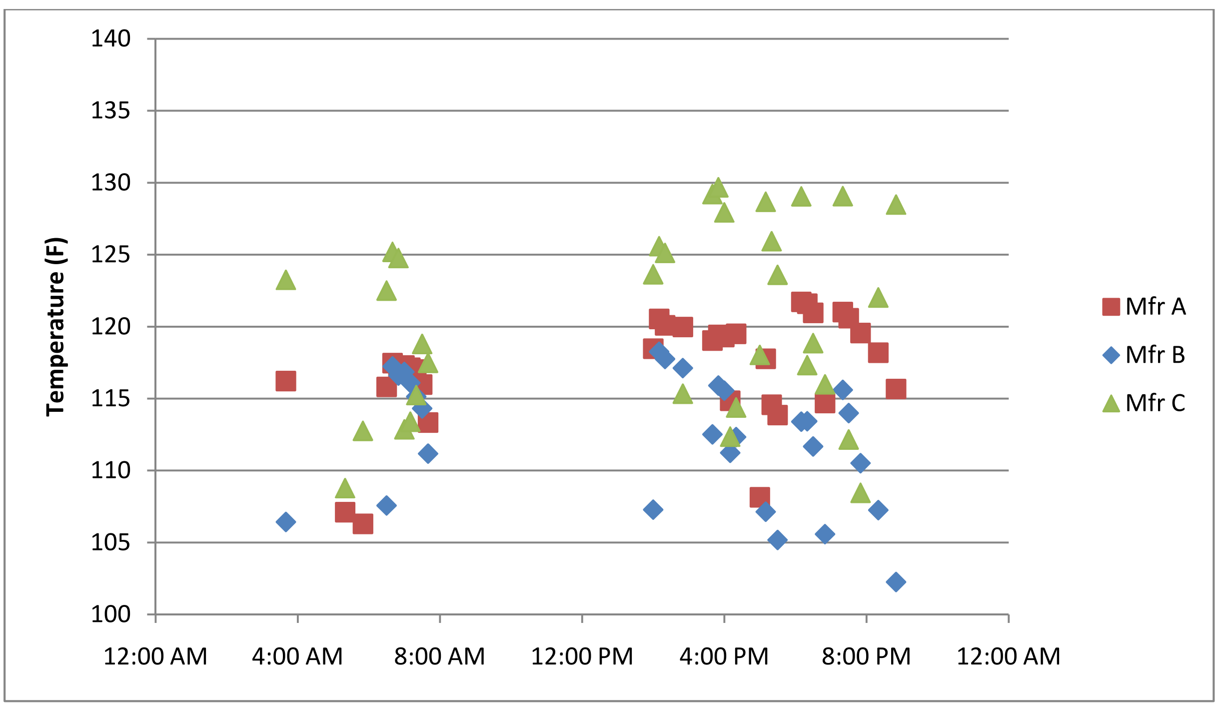


Figure 65: Delivered Temperature by Draw for Mid Use Draw Pattern at Cold Ambient Condition

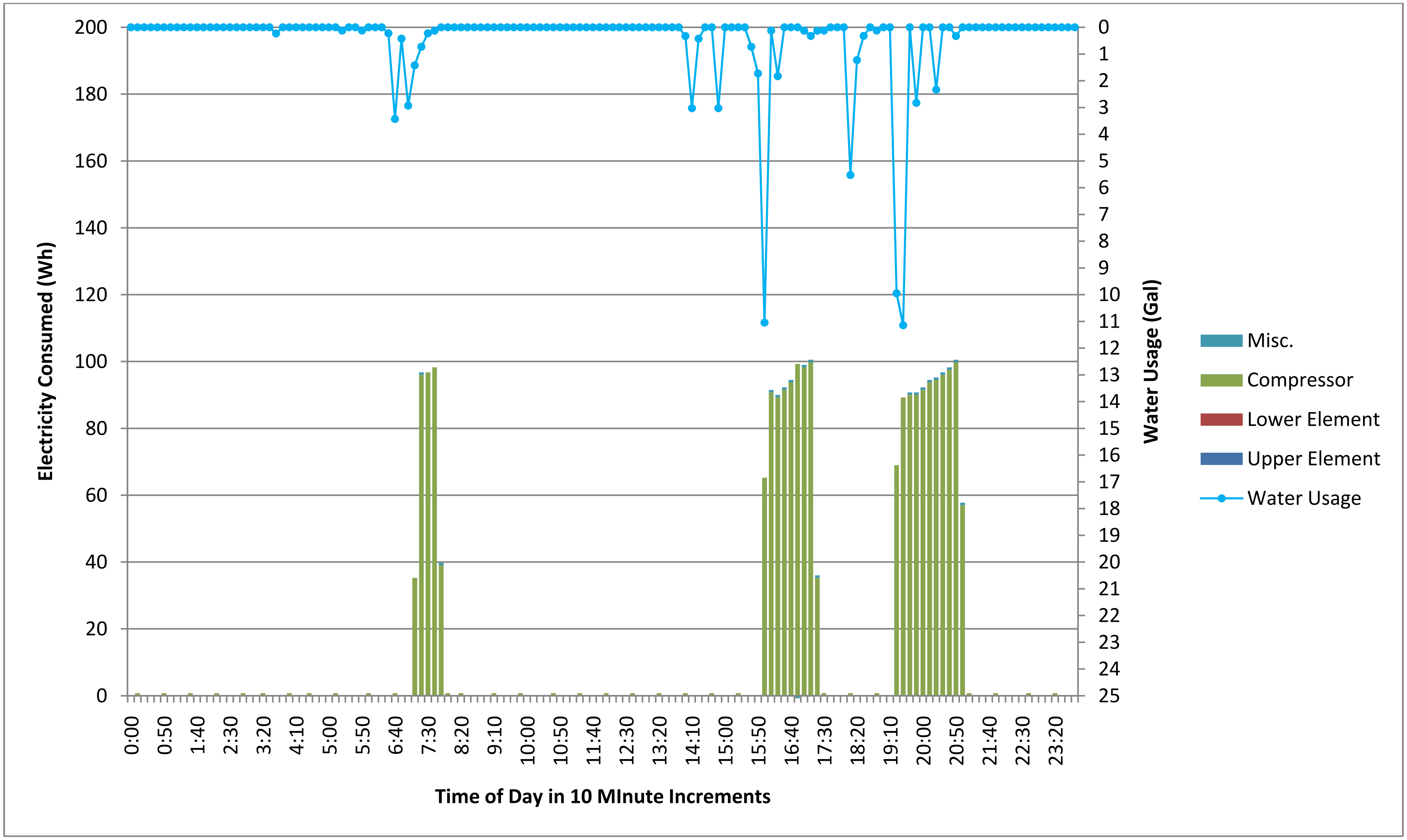


Figure 66: Diagram of Energy and Water Flows for Mfr B during Mid Use Draw Pattern at Hot/Humid Ambient Condition

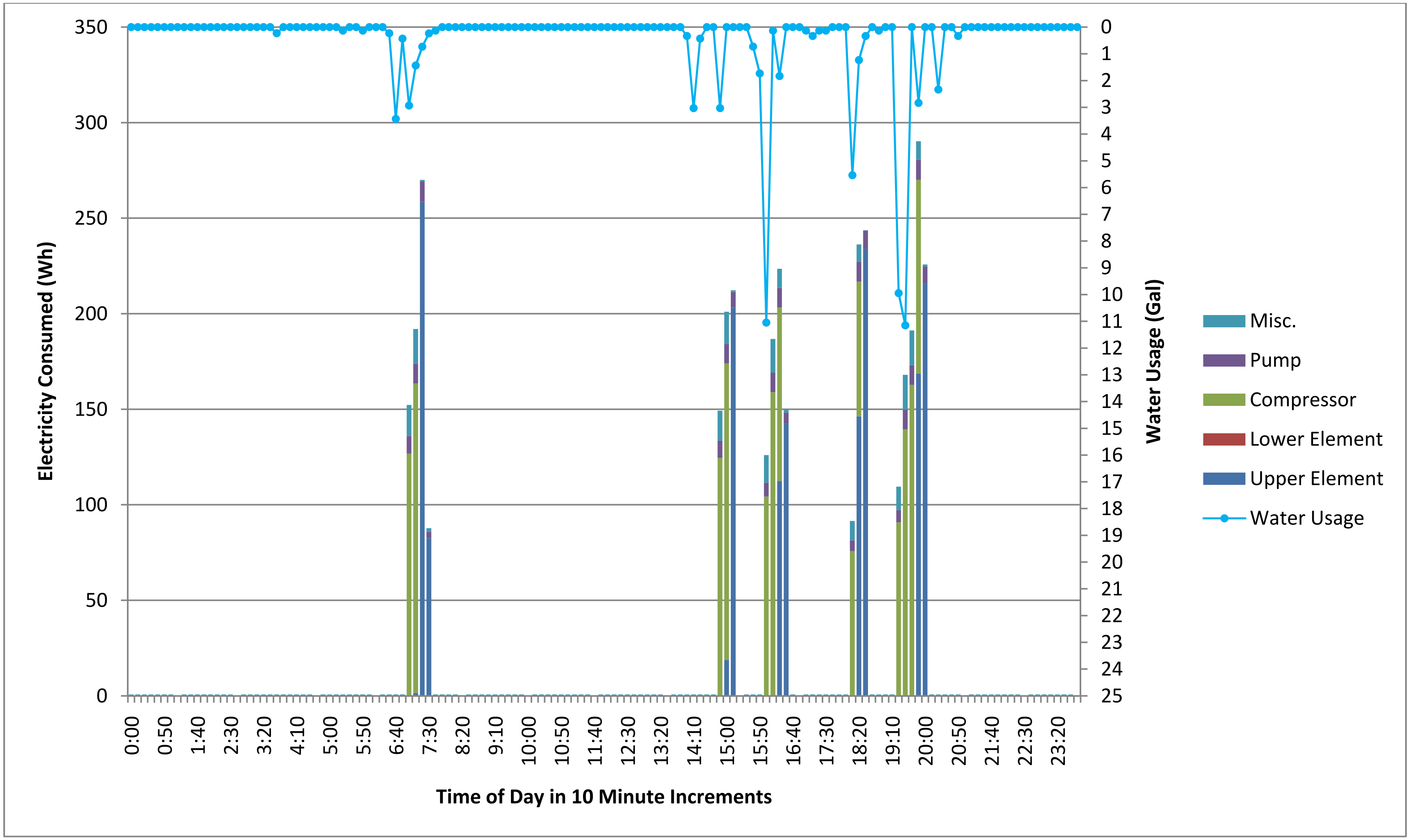


Figure 67: Diagram of Energy and Water Flows for Mfr C during Mid Use Draw Pattern at Hot/Humid Ambient Condition

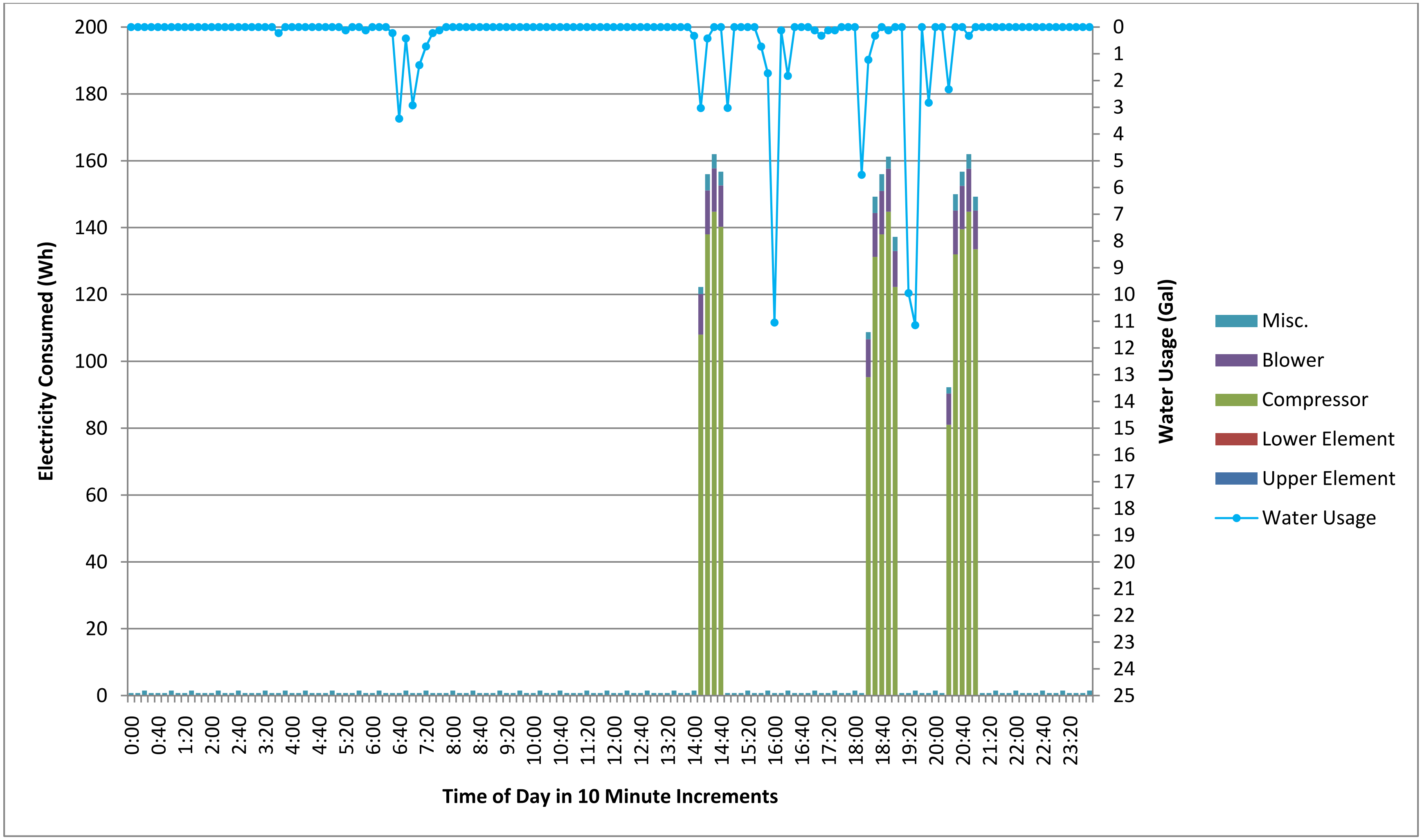


Figure 68: Diagram of Energy and Water Flows for Mfr A during Mid Use Draw Pattern at Hot/Humid Ambient Condition

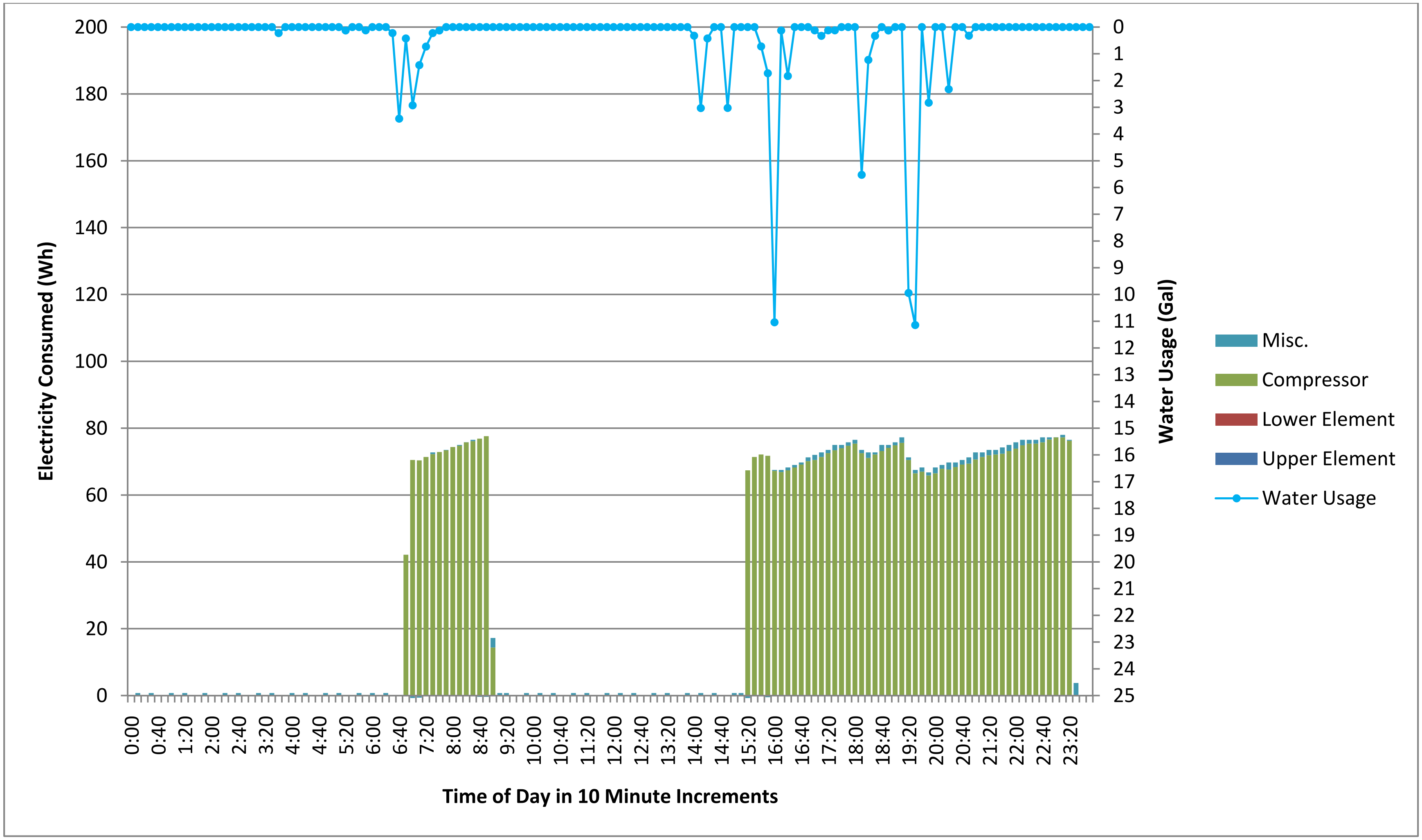


Figure 69: Diagram of Energy and Water Flows for Mfr B during Mid Use Draw Pattern at Cold Ambient Condition

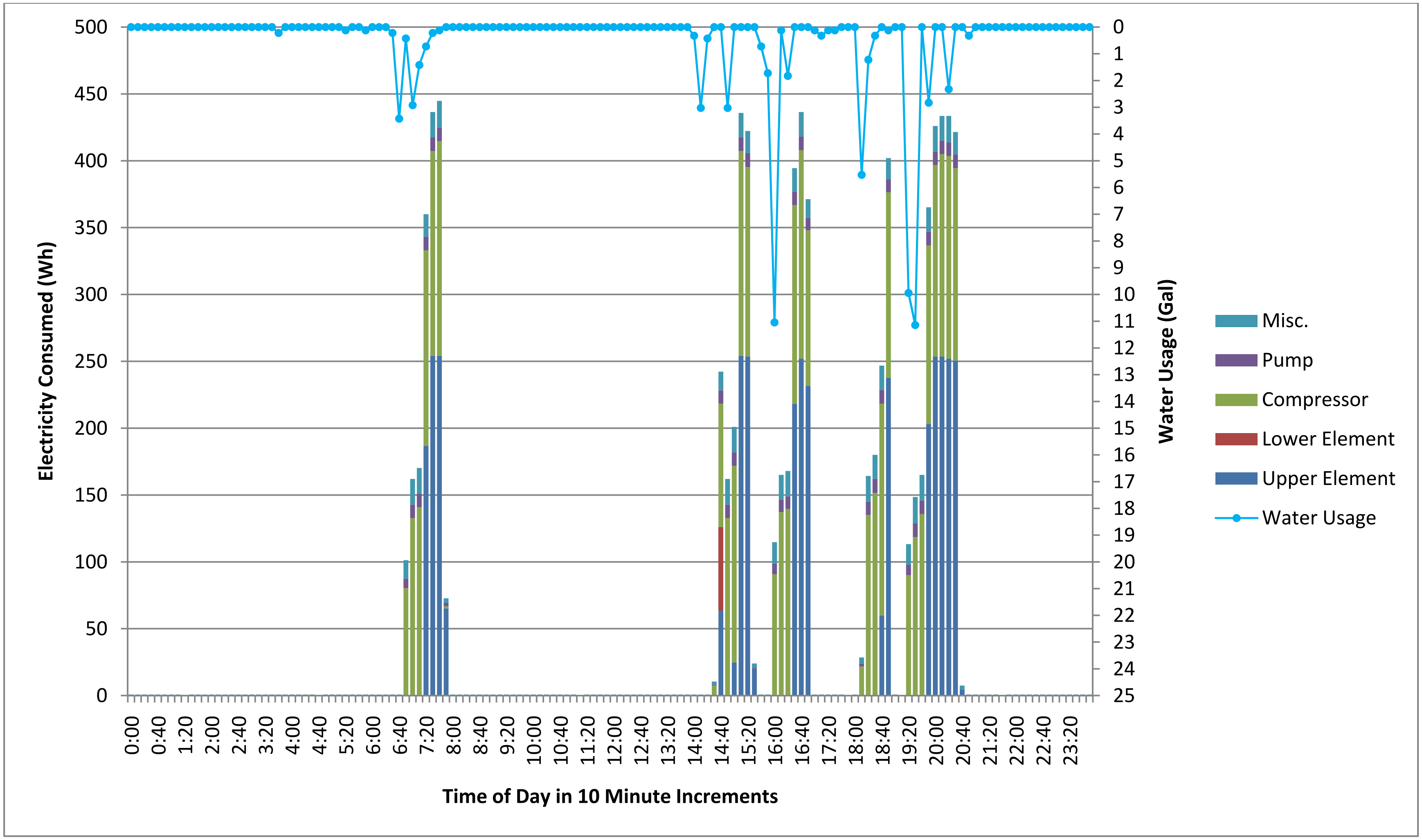


Figure 70: Diagram of Energy and Water Flows for Mfr C during Mid Use Draw Pattern at Cold Ambient Condition

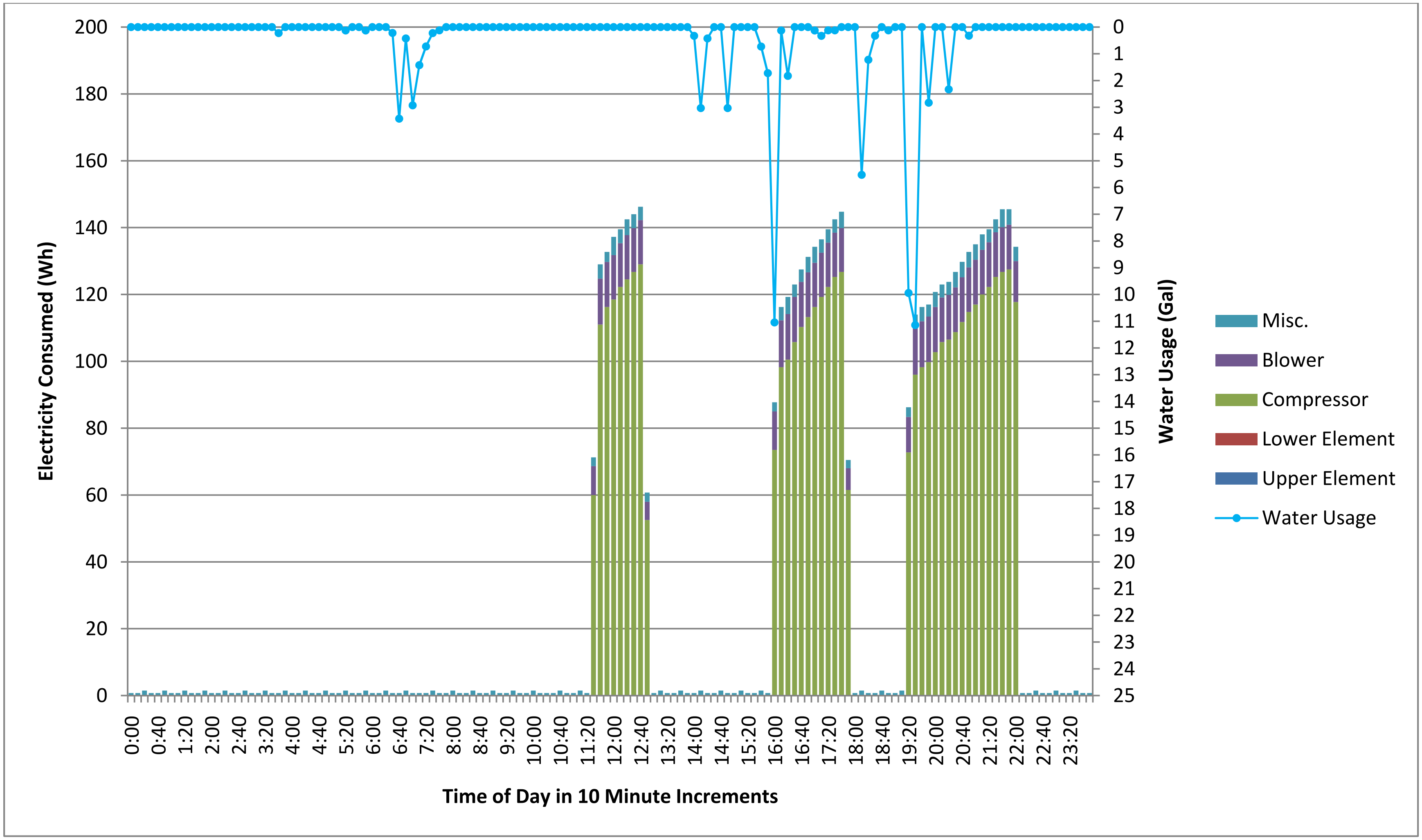


Figure 71: Diagram of Energy and Water Flows for Mfr A during Mid Use Draw Pattern at Cold Ambient Condition

Table 20: Average COP Calculated during Standard DOE Draw Pattern Tests

Manufacturer	Ambient Wet Bulb Temperature (F)								
	Lab Conditions 58°F wb			Hot/Humid Condition 80°F wb			Cold Condition 45°F wb		
Mfr A*	2.49	**3.22**	3.78	3.31	**4.43**	5.14	2.61	**2.98**	3.06
Mfr B*	1.88	**2.69**	3.08	2.05	**2.95**	3.24	1.90	**2.16**	2.49
Mfr C	**3.36**			**4.03**			**3.03**		

* Reported COPs are averaged at a bottom tank temperature of 125°F and 95°F in addition to averaged over the 24 hour period, reported in **bold**.

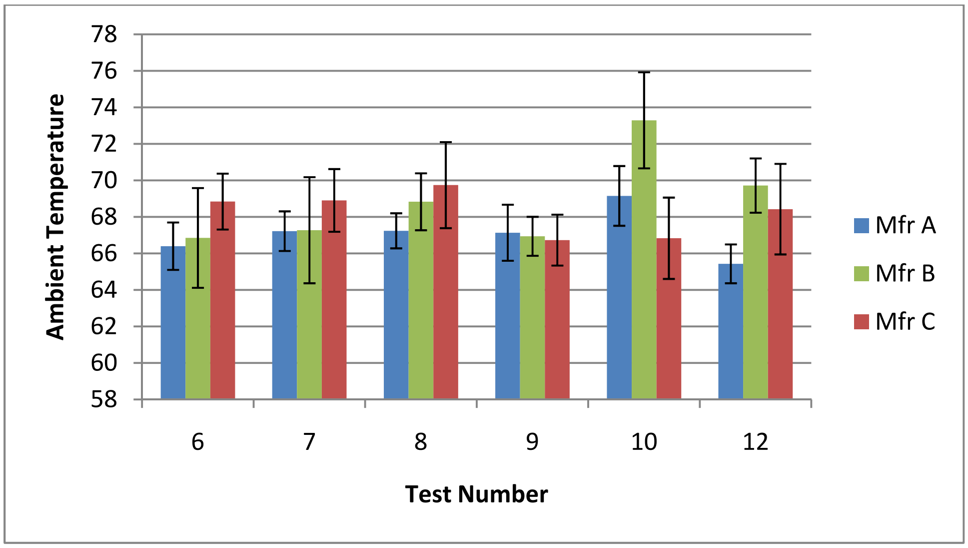


Figure 72: Average Ambient Temperature with One Std. Deviation for Laboratory Tests

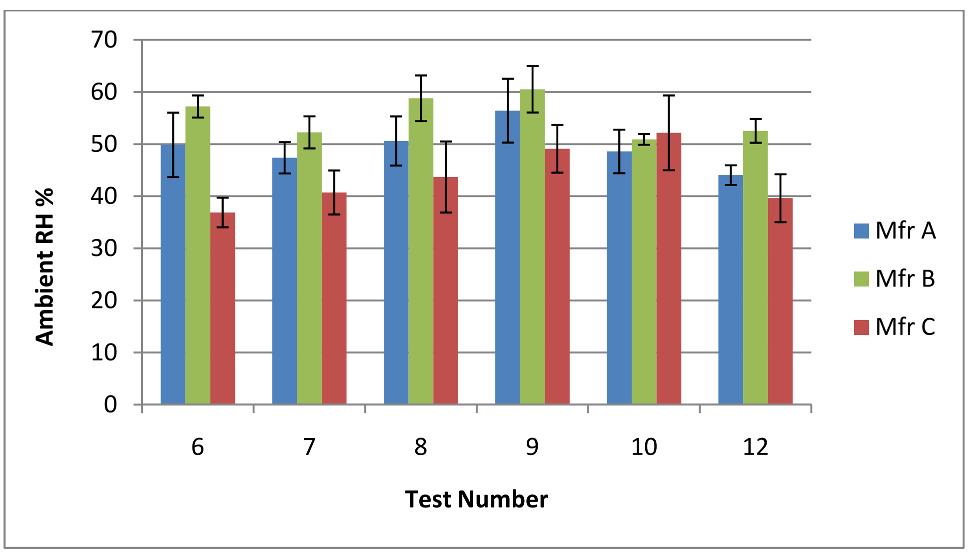


Figure 73: Average Relative Humidity with One Std. Deviation for Laboratory Tests

Space Conditioning Tests

Chamber Balance – Mfr C

Heat Supplied by heating	5,000	Btu/hr	Heat Leakage-Sensible	40	Btu/hr
Electric Energy Input-HPWH	3,260	Btu/hr	Heat Leakage-Latent	10	Btu/hr
Electric Energy Input-humidifier	2,200	Btu/hr	Heat of water extracted	5,770	Btu/hr
Latent Energy-humidifier	1,700	Btu/hr	Proportion of HP Heating	38%	

Enthalpy change over test (chamber)	0	Btus
Heat change of tank	110	Btus
HPWH Cooling balance	**6,390**	Btu/hr

Moisture Balance – Mfr C	13.4	15.8	hour mark
Scale Measurement	0	1785	g
Average T db	70.1	70.3	F
Average T dp	50.4	50.8	F
Chamber Pressure	13.92	13.98	psi
Water vapor pressure	0.18	0.18	psi
Absolute humidity, w	0.01	0.01	lb h2o/lb dry air
Specific volume, v	14.29	14.23	ft^3/lb dry air
Moisture loss through leakage	0.01	lb h2o/hr	
	0.02	lb h2o	
Moisture added through humidification	1.61	lb h2o/hr	
Moisture removed by HPWH	1.62	lb h2o/hr	

Chamber Balance – Mfr B

Heat Supplied by heating	error	Btu/hr	Heat Leakage-Sensible	110	Btu/hr
Electric Energy Input-HPWH	1,540	Btu/hr	Heat Leakage-Latent	10	Btu/hr
Electric Energy Input-humidifier	510	Btu/hr	Heat of water extracted	5,000	Btu/hr
Latent Energy-humidifier	140	Btu/hr	Proportion of HP Heating	100.0%	

Enthalpy change over test (chamber)	0	Btus
Heat change of tank	-80	Btus
HPWH Cooling balance	**3,390**	Btu/hr

Moisture Balance – Mfr B	9.7	17.5	hour mark
Scale Measurement	182	630	g
Average T db	69.9	69.8	F
Average T dp	50.4	50.8	F
Chamber Pressure	14.3	14.3	psi
Water vapor pressure	0.18	0.18	psi
Absolute humidity, w	0.01	0.01	lb h2o/lb dry air
Specific volume, v	13.89	13.88	ft^3/lb dry air
Moisture loss through leakage	0.01	lb h2o/hr	
	0.06	lb h2o	
Moisture added through humidification	0.13	lb h2o/hr	
Moisture removed by HPWH	0.13	lb h2o/hr	

Chamber Balance – Mfr A

Heat Supplied by heating	12,500	Btu/hr	Heat Leakage-Sensible	60	Btu/hr
Electric Energy Input-HPWH	2,930	Btu/hr	Heat Leakage-Latent	10	Btu/hr
Electric Energy Input-humidifier	420	Btu/hr	Heat of water extracted	9,300	Btu/hr
Latent Energy-humidifier	150	Btu/hr	Proportion of HP Heating	100.0%	

Enthalpy change over test (chamber)	0	Btus
Heat change of tank	120	Btus
HPWH Cooling balance	**6,620**	Btu/hr

Moisture Balance – Mfr A	0.13	13.42	hour mark
Scale Measurement	0	785	g
Average T db	70.3	70.0	F
Average T dp	51.3	50.8	F
Chamber Pressure	14.4	14.3	psi
Water vapor pressure	0.19	0.18	psi
Absolute humidity, w	0.01	0.01	lb h2o/lb dry air
Specific volume, v	13.86	13.90	ft^3/lb dry air
Moisture loss through leakage	0.01	lb h2o/hr	
	0.11	lb h2o	
Moisture added through humidification	0.14	lb h2o/hr	
Moisture removed by HPWH	0.13	lb h2o/hr	