Pacific Gas and Electric Company

Evaluation of the General Electric Heat Pump Water Heater Demand Response Module

(San Ramon, CA)

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Project Manager:	**Bashar Kellow** **Pacific Gas and Electric Company**
Prepared By:	**PG&E Applied Technology Services** **Performance Testing and Analysis Unit** **ATS Report #: 491-10.03**

Prepared by:

Robert A. Davis
Senior Mechanical Engineer

Reviewed and Approved by:

Emanuel G. D'Albora
Supervising Mechanical Engineer

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ACKNOWLEDGMENTS

The following list of people contributed to the testing project and the production of this report:

- Arthur Anderson – Communications Lab Manager, Technology Innovation Center (TIC)
- Robert Davis – Senior Mechanical Engineer, Applied Technology Services (ATS)
- Lian Jiang – Senior Engineer, Technology Innovation Center (TIC)

INTRODUCTION

Background

While electric water heaters are less commonplace in PG&E's residential service territory than natural gas units, where they are used, they can represent a significant portion of a home's electric demand (up to 5 kW). As a potentially large power user, electric water heaters are likely candidates for demand response (DR) measures when electric supplies are tight. A typical DR measure for a standard electric water heater would be to lock out the heating elements during the event (similar to the PG&E SmartAC devices that prevent operation of air conditioner compressors). Since most water heaters store thermal energy using a large volume of water, they may be able to pass through a DR event without using any energy, even without a device that locks out the elements. However, if there is a large demand for hot water during an event, the elements would need to activate or the user would eventually run out of hot water, which may not be tolerable to the user.

The recent resurgence in interest in alternative heat pump water heaters (HPWHs) offers users an intermediate step between all or nothing during an event. HPWHs capture some of the thermal energy that is put into the water from another source (air, water, ground), and thus typically have much higher efficiencies than standard resistance heaters. In addition, the heat pump normally has a lower power demand than the resistance elements used in electric water heaters, although most HPWHs retain them to react to large demands for hot water.

The new GeoSpring™ hybrid HPWH from General Electric is a recently introduced (December 2009) air-source heat pump water heater. The unit is equipped with three heat sources that are not allowed to operate simultaneously: upper and lower resistance elements (4.5 kW each at 240V), and the heat pump that is approximately equivalent to a 1.5 kW element while using only 0.5 kW of power. The unit has four modes of operation:

- eHeat™ Mode - will only operate the heat pump to maximize energy savings.
- Hybrid Mode – the default mode of operation, which is heat pump priority. It will switch to resistance elements following large water draws to speed recovery time.
- High Demand Mode – similar to Hybrid mode, but switches to resistance heat sooner. In addition, if the upper resistance element was activated by a large draw, it switches to the lower element when the upper thermostat is satisfied rather than back to the heat pump.
- Standard Mode – only runs the resistance elements like a standard electric water heater. May be used occasionally when the environment around the water heater is cold (<45°F) or when the cold air discharged from the unit is not acceptable.

This HPWH is one example of a household appliance designed to be part of a home area network and respond to demand reduction or price signals. As an option, users can install a DR Module to curtail large power demand during events if the water heater needs to operate in that period. The module is designed to respond to a Zigbee® radio frequency signal relayed by a SmartMeter™ or an Energy Management System, based on either price or electric supply emergencies. The response of the water heater is to enter one of three levels of demand response:

- Level 1 (Medium) locks out the resistance heating elements, and the unit will only operate the heat pump (puts the system in eHeat™ mode for the duration of the event).
- Level 2 (High) also allows only the heat pump to operate, but also resets the thermostat setpoint from the user set temperature to 110°F.
- Level 3 (Critical) takes Level 2 a bit farther by reducing the setpoint to 100°F.

The largest potential demand reduction is obtained from Level 1, assuming the unit was or could be operating with resistance heat. The two temperature setback levels create additional demand savings in two ways. First, since the water in the tank is not heated to as high of a temperature, it will switch off sooner, resulting in energy savings as well as the demand going to nearly zero. Second, an operating characteristic of any heat pump water heater is that the power demand rises as a function of the water temperature.[1] Thus, by lowering the thermostat, it limits the maximum power the system will consume just before shutoff when the thermostat is satisfied.

The objectives of this project were to check the functional range of operation of the demand response module, and to quantify the potential demand and energy savings from its use. The scope of work was to conduct tests in different modes of HPWH operation to observe its response to the DR signal.

Prior Research

This project is an adjunct to a thermal performance test conducted on the same water heater, which is being done as a second phase of a HPWH evaluation study described in Reference 3. This project builds upon the 2008 PG&E Emerging Technologies gas water heater evaluation, described in Reference 2.

METHODOLOGY

Communications Interface

In order to check the function of the DR Module and the reaction from the water heater, simulated event signals would need to be sent to it. The apparatus to provide these signals consisted of an access point simulator to simulate the broadcast of an demand response event. A local SmartMeter™ received the broadcast signal through its automated metering infrastructure (AMI) interface, and passed it through its Home Area Network (HAN) radio to the HPWH DR Module. Establishment of the communications links between the components had been previously done at PG&E's Technology Innovation Center communications lab. This included "pairing" of the DR Module and the meter such that the module would only respond to signals from this particular meter.

Figure 1: Communications Test Apparatus

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[1] In any refrigeration or heat pumping system, power demand goes up with the amount of work that the compressor has to do: the greater the pressure rise or "lift", the higher the power. Since the pressure rise is associated with the evaporating and condensing temperatures of the heat pump, power goes up with a rising difference between the air temperature and the water temperature, and it takes more energy to heat up each unit of water.

Various scripts were developed to instruct the access point to send the appropriate signals to put the HPWH DR Module into the various modes.

Test Apparatus

In order to observe the effects from the DR Module, the water heater needs to be in a mode where it is actively heating. In most cases, it is desirable to have the system operating with resistance heat, since all of the DR modes will only allow the heat pump to operate. Activating the water heater requires a draw of a certain quantity of hot water, which is replaced by cold near the bottom of the tank. This eventually causes the thermostats in the tank to turn on one of the three heat sources as appropriate. In order to activate the upper heating element in the tank, a relatively large draw is necessary (more than half of the tank volume).

The GE HPWH was installed in one of the six test stands in the ATS water heater lab for prior performance testing. The stands were designed according to the guidelines in DOE and ASHRAE standards for testing residential water heater performance. The system is designed to provide tempered supply water to each test unit, and measure the quantity and flow rate of hot water drawn from them. Simulated draws may be made based on different combinations of flow rate, volume, or duration. A more thorough description of the test apparatus may be found in the references of previous research.

Figure 2: GE HPWH installed in Water Heater Laboratory with DR Module

Test Procedure

Most of the tests were just observations of the response of the water heater to the signals received by the DR Module. As such, there was not much to measure other than to confirm that the unit responded appropriately.

To quantify the potential energy and demand savings resulting from activation of the DR Module, a special test procedure was developed based on taking a single large draw sufficient to activate the upper heating element. To maintain consistency between tests and to properly compare the energy consumption between modes of operation, the volume and energy content of this draw should be roughly the same for all tests. The methodology is based on the procedure in the DOE water heater test standard for the first draw of the First Hour Rating test. This test is started with a pre-draw sufficient to activate a heat source. Once the unit has recovered from the pre-draw (the thermostat is satisfied and all heat sources switch off completely), a long draw is started at a flow rate of 3 gpm and with the inlet water temperature set to 58°F. The maximum outlet temperature is recorded and the draw continues until the outlet temperature has dropped by 25°F from this maximum. The system is then allowed to fully recover to its thermostat setpoint, and the total energy consumed from the start of the draw is measured, as well as the maximum power demand. (Subsequent tests following the recovery do not need the pre-draw.) The test procedure specifies an average tank temperature setpoint of 135°F, and this was used for consistency even though the normal recommended operating setpoint for the GE HPWH is 120°F.

RESULTS

Demand Response Module Observations

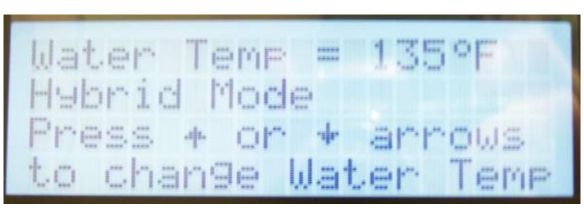
On a whole, the behavior of the demand response module has been as described in the product literature, and no abnormalities were observed. Upon initial power-up (the DR Module is plugged into a provided socket on the water heater via a CAT-5 cable through which it receives power, and a switch on the back of the module is toggled on), the module begins searching for a communications signal from the SmartMeter™. While the search is continuing, four indicator lights on the front of the module flash in sequence. If communications are not established after 1 minute, the lights turn off; however, if the communication link is established, the green light at the far left stays on. (An inadvertent test occurred when power was shut off to the SmartMeter™; at which point the module went back into search mode and eventually went into idle when the signal could not be found.) The control panel on the HPWH is fully operable with the ability to change heating modes or setpoint temperature.

Figure 3: DR Module and HPWH Display in Normal or "Low" Mode

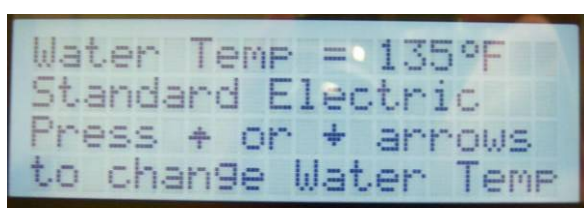
Green Light, on left
indicates communications working
and no DR events active

Display in High Demand Mode
(Note LED over button)

Display in normal eHeat™ Mode



Display in Hybrid Mode



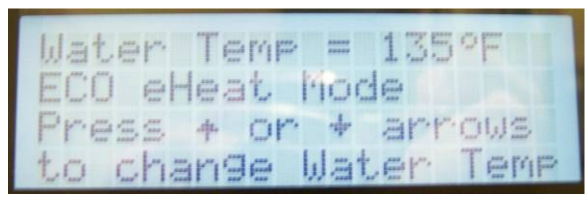
Display in Standard Electric Mode

Normally, the operating modes are set via the "Energy Menu", although some mode functions are available through special buttons on the front panel. As shown in the picture above, High Demand mode may be set through either the "Energy Menu" or the "High Demand" button on the front. The "Stop Cold Air" button puts the unit in Standard Electric mode, but with a timeout (defaults to three days), after which it returns to the previous set mode. The "Vacation Or Away" button resets the thermostat setpoint to 50°F. In this mode, the DR Module would likely have no effect (nor would there be a need for it) because the system is basically turned off. The vacation mode also has a timeout so that the unit can reactivate prior to the user's return. (The display illumination and temperature arrow LEDs are only on as shown following a button press. They turn off after a period of no activity to save power.)

When a signal is sent to enter DR Level 1 or "Medium", the yellow lamp on the DR Module illuminates (second from the left), and the HPWH display has changed to show that it has entered "ECO eHeat Mode", which only allows the heat pump to operate. At the conclusion of the event, the system returns to its previously set mode. While the control panel is still operable while in Level 1, changing the operating mode through the Energy Menu has no effect on the current operation (heat pump only), and only becomes effective when the DR event is released and the unit returns to normal operation. For example, if the unit was in Hybrid mode before the event, and the mode was changed to High Demand during the event, the water heater will continue to only operate the heat pump as needed until the event is cleared, at which time it will enter the programmed High Demand mode. The temperature setpoint is still controllable, and may be adjusted to any point in its operating range (100°F – 140°F) even while the event is active.

Figure 4: DR Module and HPWH Display in Level 1 / Medium Mode

Yellow light, second from left
indicates Level 1 response



When a signal is sent to enter DR Level 2 or "High", the orange lamp on the DR Module illuminates (second from the right), and the HPWH display has changed to show that it is again in "ECO eHeat Mode", but with an adjusted setpoint temperature of 110°F. The temperature setpoint adjustment is now disabled, and the blue LEDs that reflect the adjustment buttons are turned off.

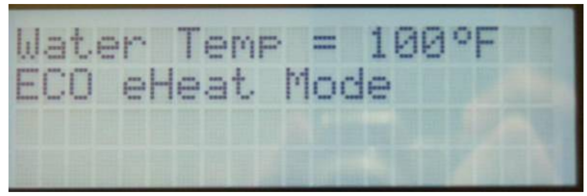
Figure 5: DR Module and HPWH Display in Level 2 / High Mode

Orange light, second from right
indicates Level 2 response

Finally, if a signal is sent to enter DR Level 3 or "Critical", the red lamp on the DR Module illuminates (far right), and the HPWH display has changed to show that it is again in "ECO eHeat Mode" with an adjusted setpoint temperature of 100°F. The temperature setpoint adjustment is again disabled.

Figure 6: DR Module and HPWH Display in Level 3 / Critical Mode

Red light, on right
indicates Level 3 response



The following is a summary of the scenarios conducted, and the resulting observations:

- In Hybrid, High Demand or Standard modes, if a DR signal is sent prior to drawing enough water to activate heating, the unit operates exclusively in eHeat™ mode without using the resistance elements, even if most of the hot water is removed from the tank.
- In Hybrid, High Demand or Standard modes, if enough water was drawn to activate either resistance element, entering any DR mode caused the element to shut off immediately and the system was put in eHeat™ mode.
- In all operating modes, entering a Level 2 event would only activate the heat pump compressor if the tank temperature at the thermostat was at or below ~105°F. (The 110°F setpoint is the upper limit, and the heating does not activate until there is at least a 5°F differential. Our average tank temperature measurement was high by about 1°F, with activation at 106°F and shutoff at 111°F.) If the heat pump was operating and the tank temperature was above 110°F, the compressor would immediately shut off (although the fan would continue to run). [2] If the heat pump was operating and the tank temperature was within the deadband, it would continue to operate until the thermostat was satisfied at the new setpoint.
- Likewise, entering a Level 3 event would only activate the heat pump if the tank temperature at the thermostat was at or below 95°F. If the resistance or heat pump were operating prior to the event, and the tank temperature at the thermostat was above 100°F, either operating component would shut off.
- If the system was in a Level 3 event, and the thermostat was satisfied with a tank temperature of 100°F, switching to a Level 2 event caused the heat pump to activate and raise the tank temperature to 110°F.
- Likewise, if the system was in a Level 2 or 3 event, and the thermostat was satisfied (system idle) with a tank temperature of 110°F or 100°F (respectively), switching to a Level 1 event caused the heat pump to activate and raise the tank temperature to its default setpoint. (In our case, 135°F.)
- In Standard mode, when the DR event is released before the normal setpoint temperature is reached, the water heater will switch from heat pump to resistance.

[2] The normal sequence of operation for the heat pump is that when the controls call for it to provide heating, the evaporator fan begins running at low speed for about 1 minute. After this short delay, the compressor begins operation to begin the heat pump cycle. At some point (depending on the water temperature and the ambient air conditions), the evaporator fan switches to high speed to increase its heat transfer rate. Once the thermostat is satisfied, the compressor cycles off, but the evaporator fan continues to operate at high speed for an additional 10 minutes. This may be to insure that no liquid remains in the evaporator that could migrate to the compressor when it restarts. There is a compressor restart lock-out that lasts for the first 3 of these 10 minutes, to prevent short cycling of the compressor.

- The response while in Hybrid or High Demand modes will depend on the difference between the setpoint and the current tank temperature. These same differentials apply its normal operation as to when to use resistance over the heat pump. It is not easy to determine at what temperature differential this decision is made as it normally will happen during a draw when the tank temperature is changing rapidly.
- DR events may only be partially overridden from the control panel. In all of the event levels, changing the operating mode only affects the mode that the unit will return to when the system returns to normal. It remains in eHeat™ mode throughout the event. In a Level 1 event, the setpoint temperature can be changed, while in Levels 2 or 3 it cannot.
- The end user can only override the DR event by powering off the DR Module, either by its switch or by disconnecting the cable. The response of the water heater is an immediate return to its normal mode of operation.

Quantification of Potential Savings

The actual savings potential from the response to a DR event will depend on the current status and demand for hot water. The demand savings range from zero (if the system is already idle), to about 4.5 kW (if the system goes from resistance heat to off). Transitioning to a heat pump operation from resistance will produce about 4 kW of demand savings, while still retain the ability to heat water.

As described earlier, a series of tests were conducted to determine the potential range of energy used and peak demand in the various modes of operation following a consistent draw of hot water. At least 3 tests were done in each operating mode, and the draw amounts that resulted in a 25°F drop in outlet temperature were all consistently about 35 gallons (±2.3% in standard deviation, or ±7.8% between maximum and minimum). These represented an average removal of 20,500 Btu (±3.5% SD / ±13.2% max-min). Charts representing the measurements over the course of an example of each of the tests are shown in Figure 7 through Figure 13 in the Appendix. Table 1 relates the average recovery performance following one of these draws.

Table 1: Summary of Recovery Statistics for Various Operating Modes

		Recovery Statistics		
Operating Mode	Temperature Setpoint	Duration	Energy (Wh)	Maximum Demand (W)
Standard Electric	135°F	1:38	6,080	3,847*
High Demand	135°F	1:37	5,915	3,845*
Savings			*165*	*2*
Hybrid	135°F	4:16	3,159	3,808*
Savings			*2,921*	*39*
eHeat™	135°F	4:48	2,204	555
Savings			*3,877*	*3,292*
eHeat™	110°F	2:44	1,144	488
Savings			*4,936*	*3,359*
eHeat™	100°F	1:55	760	465
Savings			*5,320*	*3,382*
eHeat™ (from 110°F)	135°F	2:11	1,114	550

*The measured demand of the resistance elements was below the rated 4.5 kW because we were operating at 225-230V instead of the rated 240V. ($P_1/P_2 = (V_1/V_2)^2$)

These results show that the difference between High Demand mode and Standard Electric is minimal since with this large, quick draw, the unit does not stay in heat pump mode very long. For Hybrid mode in this set of tests, it switched back to heat pump operation once the upper heating element thermostat was satisfied. Of particular interest is the maximum demand for the three eHeat tests at the different temperature setpoints. This means that the Level 2 event caps the demand by an additional 67 W compared with allowing it to raise the temperature up to 135°F, while the Level 3 mode shaves off another 23 W. (For reference, at the unit's maximum setpoint temperature of 140°F, the heat pump uses about 575 W.)

All of these tests were conducted using a consistent environmental condition in the test lab of around 68°F and 50% relative humidity. As air temperatures or humidity rises, the temperature difference between the water and the air decreases, which decreases the compressor lift. [3] This results in higher heating capacity and efficiency and lower power demand. Thus, since most DR events occur under high temperature conditions, the resulting savings from going from resistance heat to heat pump will likely be slightly larger than the amounts shown in the table.

Module Power Consumption

The demand response module adds only a minimal amount of demand to the total system. The measured demand for the module (based on changes in total system power when idle) was 1.0W when switched off, 1.4W when operational, and 1.5W when searching for a communication signal. (The display on the control panel is about 0.5W.)

CONCLUSIONS

This product evaluation was conducted to determine the response of the GE GeoSpring™ HPWH to signals from its optional demand response module. The results indicate that the system performs as described in the product literature, effectively locking out the high-demand electric resistance elements, and either switching over to heat pump operation if the thermostat is not satisfied, or shutting off completely if it is. The DR modes that lower the thermostat setting will more likely produce a shutdown, as well as lower the maximum power the system will use when the heat pump is operating.

The actual response of the water heater will be most affected by the end user's need for hot water during or just before a demand response event. If little hot water is used, it is likely that the system will only use the heat pump anyway to recover to the setpoint temperature (except if it is set in Standard Electric mode), or the unit may be able to coast through the event without needing to run at all. One advantage from this is that the user will likely not notice if the module has activated, leading to greater acceptance and adoption of the product. The DR Module will only show a significant impact if there is a large demand for hot water (>25 gallons) in a short period, that would normally result in activation of a resistance element. Numerous studies are underway by independent agencies (GTI, LBNL, CEC) to quantify typical residential hot water usage profiles, and these could be utilized to statistically determine the frequency at which large draw events will coincide with demand response events. This detailed analysis is needed to determine the ultimate benefit to the customer and to PG&E.

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[3] Higher ambient temperatures also result in a lower standby heat loss rate, which may result in less frequent operation.

REFERENCES

1. ANSI/ASHRAE Standard 118.2-2006: *"Method of Testing for Rating Residential Water Heaters"*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., 1791 Tullie Circle, NE, Atlanta, GA 30329, 2006.
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APPENDIX

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Table 2: Water Heater Lab Instrumentation List

Performance Parameter	Units	Sensor Type
Temperature		
Ambient Dry Bulb	°F	1/4" RTD Probe (3)
Heater Inlet Water	°F	1/4" RTD Probe
Heater Outlet Water	°F	1/4" RTD Probe
Cold water supply	°F	1/4" RTD Probe
Tempering tank outlet	°F	1/4" RTD Probe
Tempering valve outlet	°F	1/4" RTD Probe
End of supply header	°F	1/4" RTD Probe
At Coriolis meter	°F	1/4" RTD Probe
Storage Tank	°F	Type T thermocouple (6 inside tank)
Discharge Air Temperature	°F	Type K thermocouple
Relative Humidity		
Ambient	% RH	General Eastern MRH-1-V-OA
Pressure		
Barometric	in Hg	Qualimetrics 7105-A electronic barometer
Supply water	PSIG	Rosemount 3051C gage transmitter
Flow		
Common outlet water flow rate	pph	MicroMotion R050S Coriolis mass flow meter
Individual tank inlet water flow rate	gpm	Omega FTB4707 Single-jet paddle wheel flow meter
Power		
Power	W	Yokogawa 2533 3-element Power Meter
Other		
Flow control valves	gpm	Kates MFA1-1 (3)
Tempering water tank		Bradford-White M-2-50TSDS electric water heater
Tempering water tank chiller		Advantage M1-1.5AR

Figure 7: Example Standard Mode Recovery Test

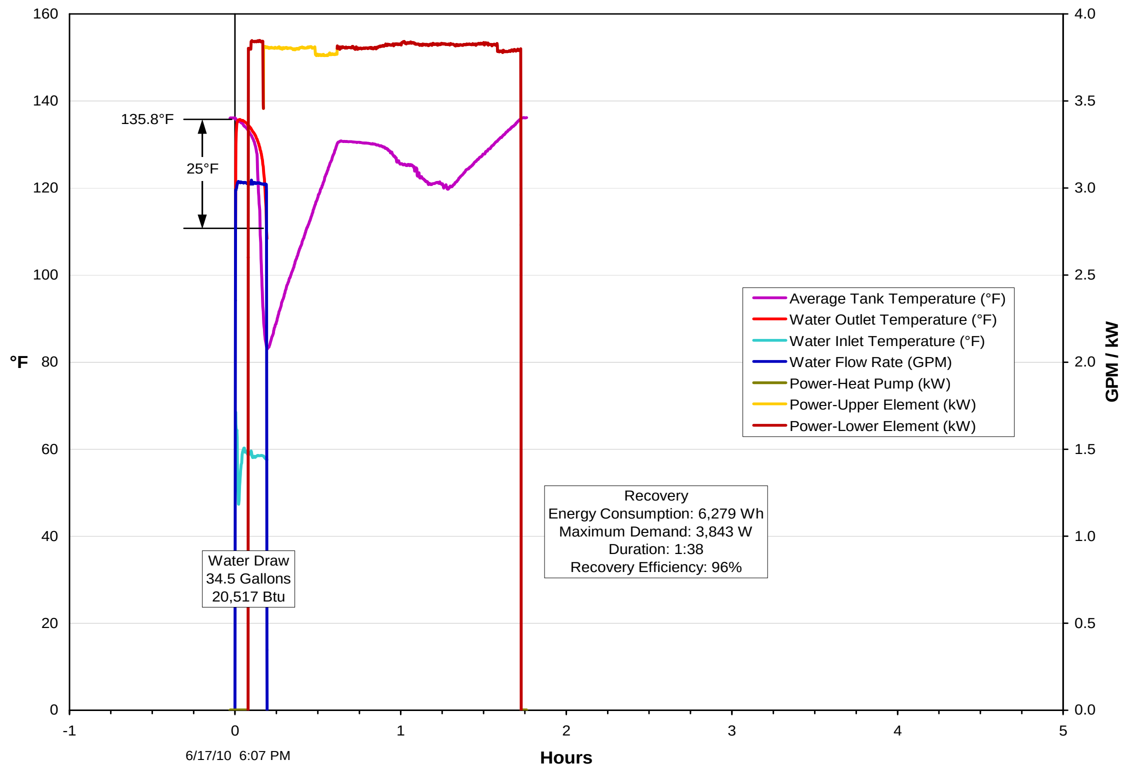

Figure 8: Example High-Demand Mode Recovery Test

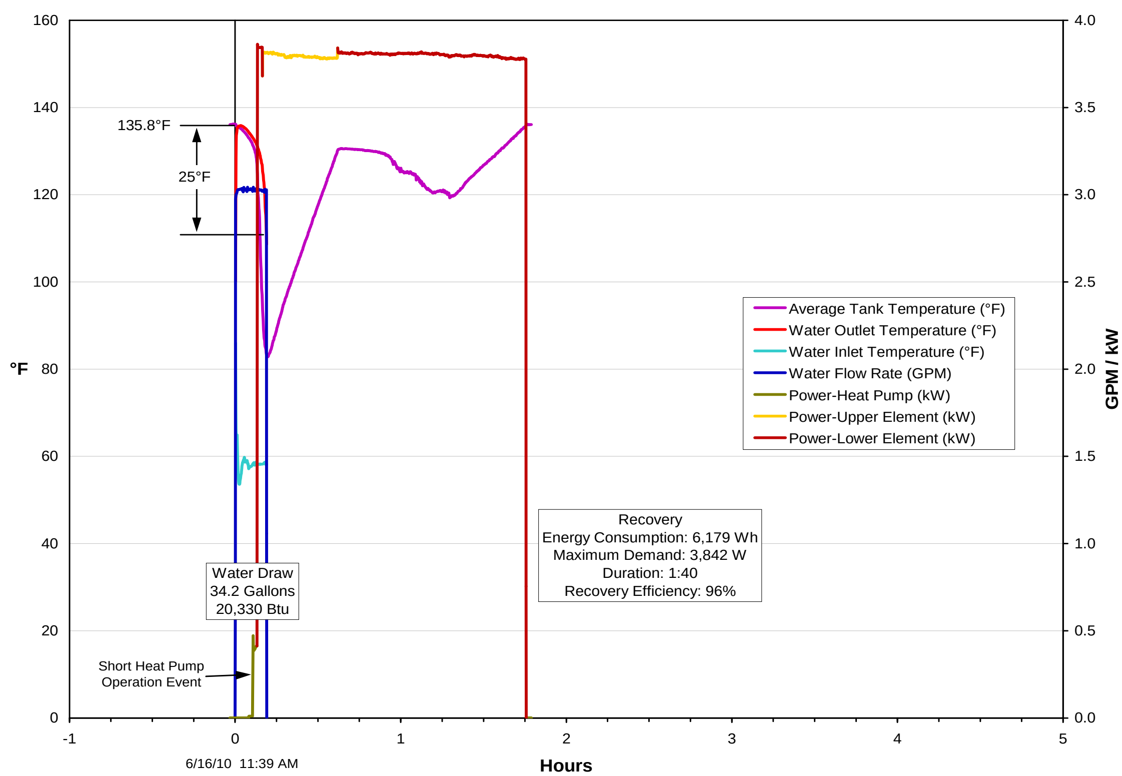

Figure 9: Example Hybrid Mode Recovery Test

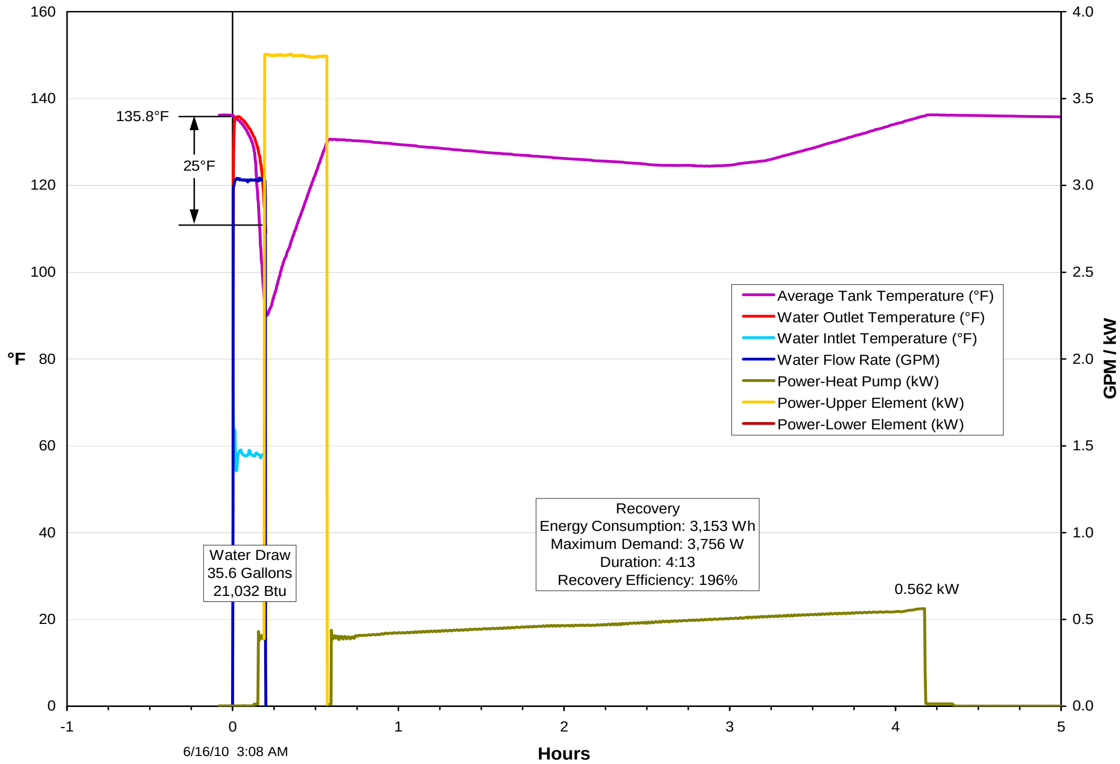

Figure 10: Example eHeat™ Mode Recovery Test

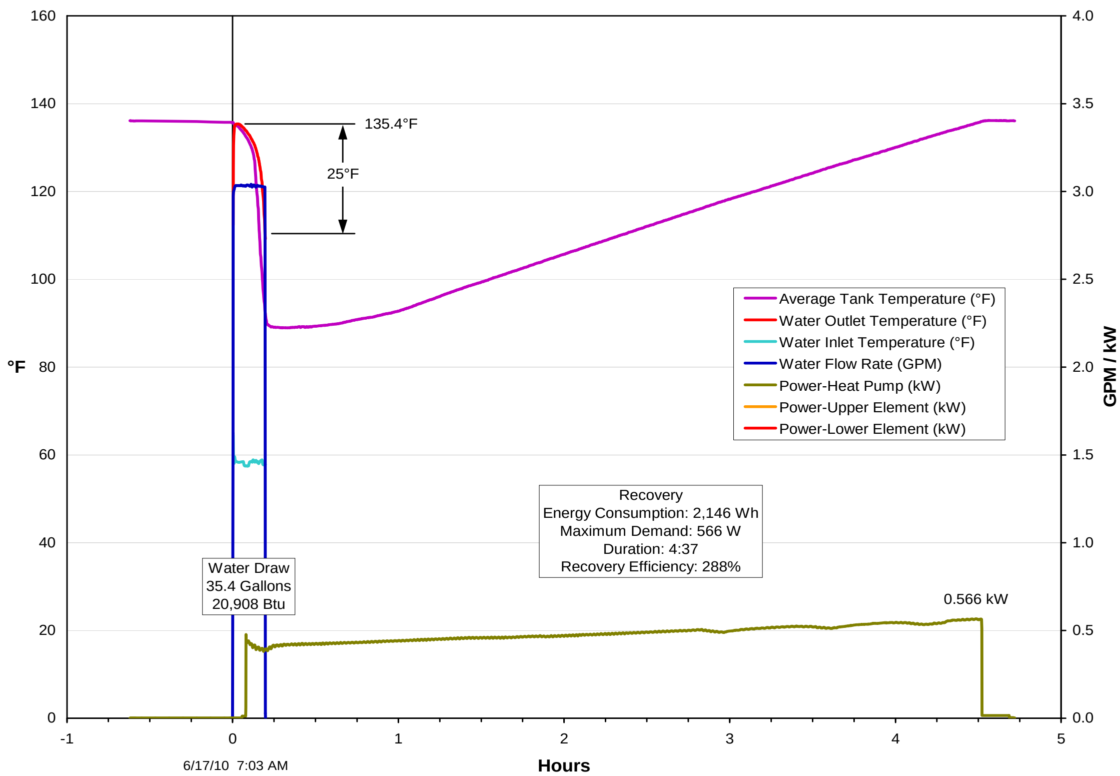

Figure 11: eHeat™ Mode Recovery Test – Thermostat Reset to 110°F

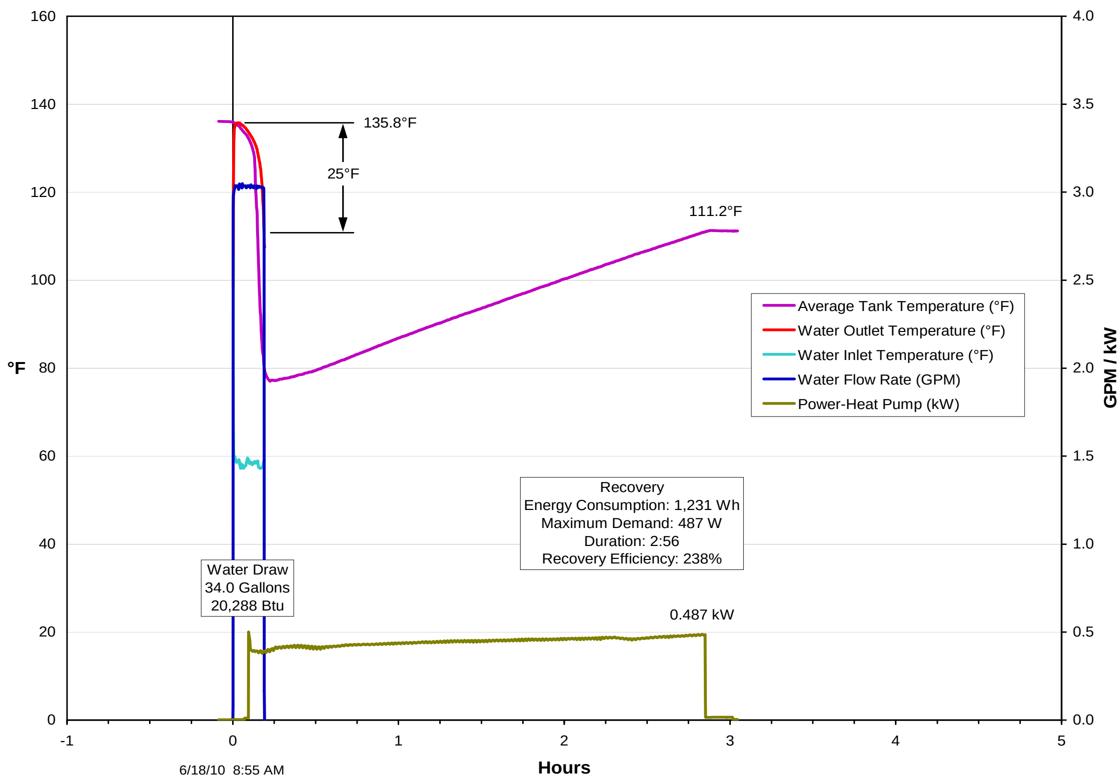

Figure 12: eHeat™ Mode Recovery Test – Thermostat Reset to 100°F

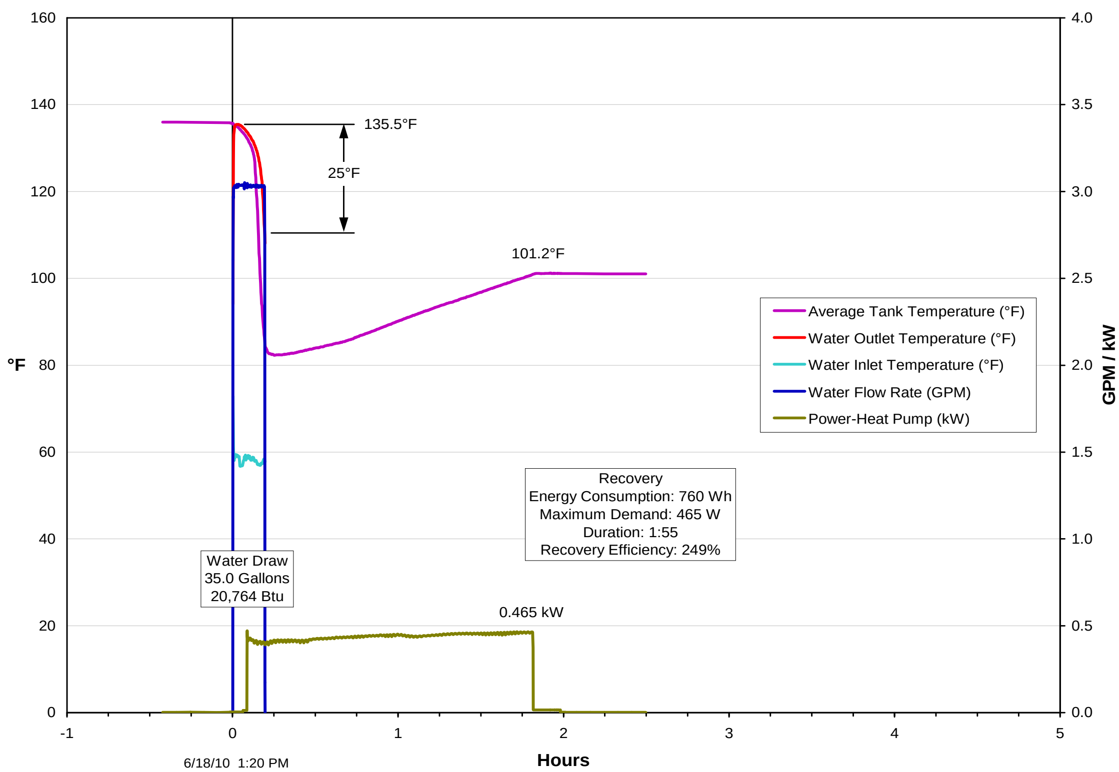

**Figure 13: eHeat™ Mode Recovery Test –
Thermostat Reset to 110°F, then Back to 135°F**