B O N N E V I L L E   P O W E R   A D M I N I S T R A T I O N

Residential Heat Pump Water Heater Evaluation Project
Measurement & Verification Plan

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1. Introduction

This project seeks to answer the technical questions associated with residential heat pump water heater (HPWH) placement, design, and performance using lab testing of particular HPWH products that are likely to be available in the residential market. The approach has the advantage of providing tests with known parameters so performance can be monitored given the conditions under which the HPWHs may operate in Pacific Northwest applications. Consequently, the lab testing protocols will be geared around the important operating and interaction characteristics that are present for an HPWH installation in the Pacific Northwest.

The project will assess three HPWHs from three manufacturers currently bringing a product to market. These units are designed as a "drop-in" replacement for an existing electric water heater. This is an integrated unit with a tank, compressor and backup heating. The project will be focused to assess the equipment design and the house installation parameters needed to achieve optimum energy savings as well as performance over a range of operating conditions.

1.1. Project Goals

The project goal is to collect data to assess the determinants of consumption and savings specific to the Pacific Northwest region. This will:

a) develop a full range of performance characteristics of the HPWH equipment for ambient temperature conditions and DHW (domestic hot water) loads;

b) "prove" there are conditional impacts and encourage manufacturers to address them, or

c) "disprove" there are conditional impacts, allowing HPWH installations to commence in the Pacific Northwest; and

d) allow the estimation of electric energy savings in applications in the region.

The effort will determine/confirm the efficiency of the current HPWH technology from three HPWH manufacturers. The project will evaluate the results and provide manufacturer-specific feedback to assist BPA in driving Pacific Northwest-specific technology improvements.

2. Laboratory Testing Approach

The majority of the tests will revolve around answering the question of heat pump performance at various operating temperature conditions. There will be a series of "normal" operating condition tests to measure coefficient of performance (COP) and develop annual energy-use calculations, a series of tests to validate those calculations, and then a set of tests measuring non-performance-determining factors (e.g. noise). The water heaters under test generally have both a compressor for heat pump heating and a resistance heating element for backup heating. The possible operating modes therefore include: compressor only (generally not an option for the user to enable so the lab may need to take special measures to enable this mode), "hybrid" (compressor with element backup if set point is not met in a specified amount of time), "dual" (compressor and element running simultaneously), and resistance (electric element only).

2.1. Testing Conditions

The environmental conditions we seek to simulate in the lab come from four possible installation scenarios:

a) Conditioned garages
b) Unconditioned garages
c) Conditioned basements
d) Unconditioned basements.

These locations will determine the ambient temperature and relative humidity range encountered by the equipment. In addition to the ambient temperature conditions, the heat pump water heaters will interact with the spaces and further draw down the temperature. The exact temperatures of interest are specified in section 3.1. Other environmentally-determined conditions include inlet water temperature. In addition to the ambient conditions, a number of tests will simulate other aspects of heat pump water heater installation and use. These include, but are not limited to, the hot water draw profile and outlet temperature, restricted airflow across the condenser coils, noise level during operation, and condensate control issues.

2.2. Testing Overview

We plan to conduct a series of tests in a number of different categories. These categories include DOE standard rating point tests, COP tests, standby and tank heat loss rate tests, operating mode tests, and actual draw profile tests. Each category will be used in a different way: to compare to manufacturer's published data, develop an equipment performance curve, or verify predictions of annual energy consumption.

2.2.1. DOE Standard Rating Points

The DOE standard tests for water heater performance consist of determining a first hour rating (F_{hr}), recovery efficiency (η_r), and energy factor (E_f). The standard employs two test sequences to make the measurements. The first is a one-hour test consisting of periodic, repeated tank temperate draw downs. The second is a 24-hour test with two parts. The first part consists of six equal water draws (one every hour). The second part consists of no water draws for the remaining time period in order to measure standby heating losses. The tests are carried out at single-point, rated conditions which are summarized in Appendix A. The lab will conduct the series of DOE tests to provide direct comparison to the manufacturer's published data.

In effect, for HPWHs, the outcomes of the test, F_{hr}, η_r, and E_f contain the equipment coefficient of performance at the ambient conditions of the DOE testing protocol. That COP is only for the single-point testing conditions and draw pattern specified by the DOE.

2.2.2. COP Curve Development and Performance Mapping

To fully characterize the energy consumption of the HPWHs, we will conduct a series of tests to directly measure the equipment COP. These will cover a range of ambient temperature, inlet water, outlet water, and airflow scenarios. Once we have the COP data, we will develop a set of performance curves which will predict the equipment behavior based on the operating conditions.

Energy input to the tank will be a function of ambient temperature, inlet water temperature, outlet water temperature, airflow, and water mass:

$$E_{INPUT}(T_{AMBIENT}, T_{INLET}, T_{OUTLET}, f_{AIR}, m_{WATER}).$$

Hot water energy output will take a similar form:

$$DHW_{OUTPUT}(T_{AMBIENT}, T_{INLET}, T_{OUTLET}, f_{AIR}, m_{WATER}).$$

With these curves, we will, in effect be able to mathematically construct any simulated test we wish and predict their outcomes without ever physically conducting the tests (including the DOE tests). Likewise we can predict the energy use – hourly, daily and yearly – of any number of simulated draw patterns. Additionally, the COP data will also describe how much heat is extracted from the space where the water heater is located, allowing us to analytically model the space heating/cooling interactions. To validate the modeled COP curves, we will conduct tests of several draw profiles.

The general method for the COP tests will be to disable the auxiliary resistance heating element to allow compressor-only operation, turn the tank off, fill it with cold inlet water (~35F), turn the HPWH on, and monitor the energy input and tank temperature every minute until the thermostat is satisfied. The energy input, combined with the known temperature rise of the water, will be used to calculate the COP. The actual COP will vary with tank water temperature as energy transfer across the heat exchanger is more effective at larger temperature differences. By starting the test at a cold inlet water temperature, we will be able to test over the entire range of inlet temperature possibilities as the tank warms up through 40F, 45F, 55F, and so on. To account for heat losses through the tank during the test period, a heat loss rate, as determined in other tests, will be applied to the COP curves.

Figures 1 and 2 illustrate how one possible COP curve may look. These figures are idealized constructs containing no real data. We expect the lab data to be different but behave in a similar fashion, with COP decreasing as the inlet water temperature decreases and increasing as the ambient air temperature increases.

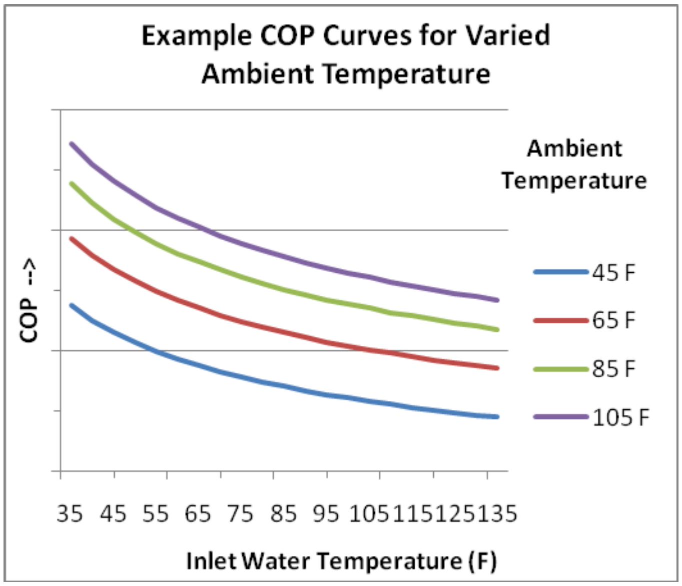

Figure 1.

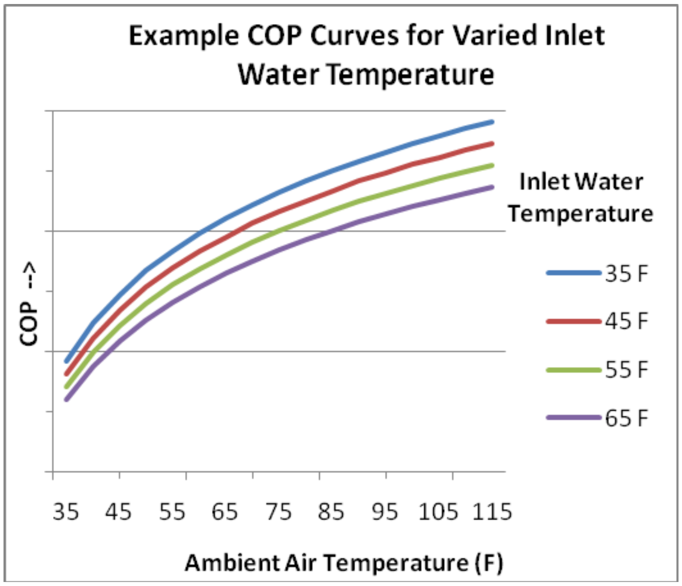

Figure 2.

2.2.3. Single Use Point Tests

These tests will verify the linearity of the ratio of water heater input to output (energy factor or E_f) over a full cycle of standby followed by a varied draw volume. See Appendix B for a detailed test procedure. The tests will expand on the DOE standard test (as proposed by the ASHRAE 118.2 Standards Committee). The test first simulates a single high-load condition. This is followed by an extended period with no draw to simulate standby conditions. Finally, a single low-load condition is conducted. The standby test will add confirmation to our standby measurements and calculation in our repeated tests. Further, we will be able to use these as a check against our modeled COP curves developed from the performance mapping tests.

2.2.4. Standby Loss and Tank Heat Loss Rate

The standby losses and tank heat loss rate will be observed over the course of other tests, namely the DOE tests and the modified single use points. These losses will be used to calculate annual energy-use numbers. We will use data from the portion of the other tests where no water is being drawn but the heat pump cycles on and off to maintain the tank temperature. Both of these measurements will be used to provide corrections, if necessary, to the COP tests.

2.2.5. Operating Mode Tests

Most of the heat pumps in production offer three operating modes: hybrid (compressor with element backup), dual (simultaneous compressor and resistance element use), and element only. The most efficient mode is the hybrid one. Even in this mode, if the demand on the tank is large, the resistance elements will turn on. Some manufacturers offer different time delays between when the compressor operates alone and when the resistance element turns on. Knowing under what conditions this occurs is important for determining annual energy use. These tests will stress the equipment to measure those switchover conditions. We expect to examine the control logic in detail and to test alternative interaction controls between the compressor and the elements. This control logic is likely critical to the optimal performance of the HPWH being tested.

2.2.6. Draw Profiles

The draw profile has a significant impact on annual energy use as it will effect when the heat pump switches to its backup resistance heating elements. From a controls perspective the question is “How much temperature change do you allow in outgoing water before the resistance element kicks in?” This can only be determined by conducting actual draw tests. It is important for characterizing how the entire system works (compressor + resistance element). The data observed from the draw profile tests will be used to validate our modeled performance curves.

2.2.7. Airflow Restrictions

Dirty air filters or restricted/blocked airflow will reduce the heat pump performance. The filter could become clogged with dust, while the air intake could become blocked with a storage box or have simply been installed too close to a wall or ceiling, thus restricting flow. The airflow restriction will also be another component in our COP curves.

2.3. Space Heating Interaction and Analytical Calculations

Once the HPWH operating conditions are characterized, we will be able to determine the space heating/cooling interactions of the equipment. These interactions are not a direct test; rather, they are a goal of the testing process. The performance curves will calculate the energy required to heat the water as well as the heat removed from the space. To fully characterize the space interaction, some modeling will be needed. This is because as the water heater operates, it lowers the space temperatures in otherwise unconditioned spaces, thus lowering the equipment COP. The water heater use also varies with time. To truly capture these effects, an interactive model is needed. The full analytical calculations will be done after the testing has been completed.

At this point we are using the SUNCODE hourly simulation model for preliminary calculations. The SUNCODE model is a multi-zone, finite element model with the capability to characterize spaces such as basements and garages to account for the impacts of envelope insulation and thermal mass. Because this is an annual simulation tool the interaction between the conditioned living area and the HPWH operating in the buffer or conditioned spaces can be shown. This will also allow for the description of the impact of the HPWH on energy use in the conditioned spaces that are either a part of or adjacent to the location of the HPWH.

3. Testing Conditions Discussion

The testing conditions are governed by the kinds of questions we seek to answer in the project. Specifically, these will be suited to typical Pacific Northwest installations and operating conditions. Refer to Appendix C for a summary test matrix. In conjunction with this document, the test matrix can be used to conduct the tests.

3.1. Ambient Temperature Range

The HPWH location largely defines the temperature and relative humidity (RH) conditions under which the equipment will operate. The equipment will likely encounter a different range based on location. The broadest temperature swings will occur in unconditioned garages, followed by unconditioned basements, with much smaller ranges in conditioned basements and conditioned garages.

In an unconditioned garage, with the outside door left open, the temperatures would only differ slightly from outside conditions. Likewise, a leaky garage with a high air change rate would also closely track ambient conditions. In many situations, the temperature could drop well below the operating conditions of the equipment. For instance, AO Smith lists a safe operating range of 45F-109F while Rheem lists 40F-120F. In an unconditioned basement with substantial air leakage temperatures can easily drop to 45F (or colder) in the winter in places like Boise, ID. The further pull down of the air by heat pump operation will likely drop the air to 35F or below if the equipment were still permitted to operate.

The ambient temperature testing points of interest are: 27F, 37F, 47F, 57F, 67F, 77F, 90F, 105F.

The effects of location on energy savings are more an analytical question to be solved after we have lab test results. But this temperature range would provide the data to explore these issues after the testing is complete. The SUNCODE program offers the capability of scheduling the operation of the HPWH over the course of a day. The output of the lab testing will be used to determine the amount of heat removed from the space at each component of the draw tests. We will use the simulation to determine the temperature impacts in various climates of these heat removal patterns. Runs describing baseline conditions will be done and the increased space heating requirements in each test location will be calculated.

The SUNCODE runs will be divided into those runs characterizing conditioned zones and runs characterizing unconditioned buffer zones. In the conditioned runs, the extra heat needed to maintain the temperature would be determined. In the unconditioned runs, the depression in the temperature (and thus the HPWH COP) will be calculated.

3.2. Inlet Water Temperature

Inlet water temperatures in the PNW can vary from 40F to 72F based on Typical Meteorological Year (TMY3) weather data calculations. Because of the way we have structured the standard COP test, all inlet water temperatures, starting with the coldest input temperature, can be measured in a single test run. Therefore, we plan to start at 35F.

3.3. Outlet Water Temperature

The DOE test procedure specifies 135F as the outlet water temperature. This is, however, quite hot and presents a scalding risk in some households. Indeed, the Washington and Oregon energy codes specify that tanks shall be preset to 120F. Most manufacturers set their thermostat default to 120F. Nevertheless it will be important to test over a range of outlet water conditions. Again, because of the way we have structured the standard COP test, all outlet water temperatures, up to the highest point, can be tested in a single run. Therefore, we plan to test up to 135F.

3.4. Draw Profiles

We propose three draw profiles to test:

1) Average use with diversity
2) High demand with high peak use
3) Small, repeated draws.

A number of different sources have been investigated to find a realistic draw profile. The most useful and reliable data come from Becker (1990), Fairey (2004), Lutz (2006), and Hendron (2008). The first three present, among other things, average hourly use profiles. Those profiles are shown in Figure 3. As can be seen, they are all quite similar. The Fairey paper provides an excellent comparative discussion of more studies which have widely differing results. We have determined that the three presented here come from the most reliable data.

For the first draw profile (1), we propose to use the profile of Becker mainly because of its slightly higher diversity than the rest. Being an average profile, this actually represents hot water load demand from many sources (i.e. the average daily residential load of a city).

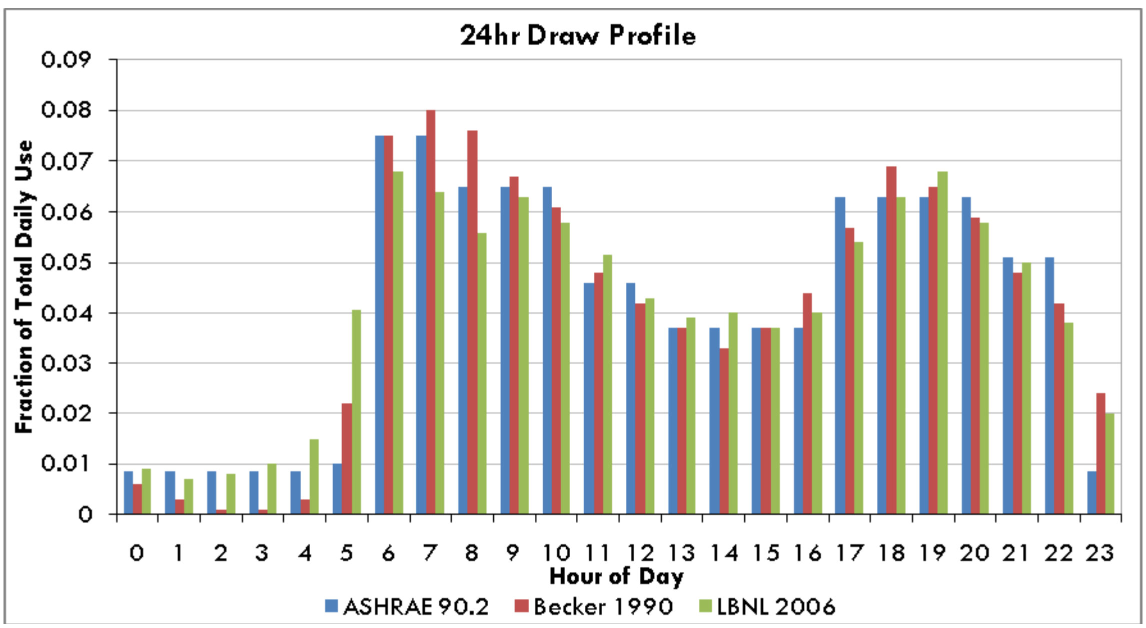

Figure 3. Average daily DHW profiles.

In addition to the hourly draw profile, the actual number and size of draws within the hours needs to be specified. Both the Lutz and Hendron reports describe and reference some possibilities. The precise pattern is specified in section 4.2.5.

The second draw profile (2) to test will be one with high demand and high peak use. It will have high morning use from 6am-8am, no midday use, and then medium use from 5pm-10pm. It will represent a four-person household that works away from home during the day. The "peaky-ness" of this profile will stress the equipment more than the other profiles.

The third draw profile (3) will test the effects of repeated, small draws. These often have the tendency to reduce the actual operating efficiency of the equipment as it cycles on and off. The profile will have many ~1gal uses scattered every 5-10 minutes over several hours.

The last piece of the draw profile is the total daily water consumption. The Lutz report suggests an average use of approximately 20 gallons per person per day. This is consistent with past Ecotope findings. The first draw profile will be tested with four people and 90 gallons/day. The second and third tests will be for only a portion of the day; however, the second profile will target 80 gallons total and the third will target 40 gallons of total DHW usage.

3.5. Airflow

To test airflow scenarios we propose two simulated conditions in addition to all other tests which will be conducted at normal flow. The two cases of restricted flow will be 1/3 and 2/3 of the filter rack area blocked. To save time, only a subset of ambient temperature ranges will be used for airflow blockage tests. This subset will help us understand the performance impacts of reduced airflow and should allow us to extrapolate it to the other operating conditions.

4. Test Procedures and Measurement

All performance tests shall be conducted in a temperature- and humidity-controlled environment (preferably a psychrometric chamber). Unless described differently in the testing section, the procedures and instrumentation shall follow the DOE, AHRI, and ASHRAE Std 118.2-2006 requirements. Data shall be collected in accordance with these standards and any measurements shall be made to within the accuracies specified. At all times, the energy input and outputs to the tank shall be monitored.

4.1. Data to Collect

Data to collect includes but is not limited to:

- Space temperature and RH (inlet air conditions).
- Inlet air flow. Flow may be a one-time measurement, but it may also be necessary to measure continuously during operation. (TBD)
- Outlet air temperature and RH. Due to the complicated geometry of the exhaust air, an accurate, averaged outlet air temperature is unlikely to be measured. A spot measurement of exhaust air will be useful, however. At least two sensors should be installed in different locations in the exhaust air stream.
- Heat pump water heater input true power and power factor.
- Independent measurements of fan, compressor, and resistance element power.
- Inlet water temperature.
- Outlet water temperature.
- Tank internal temperature at six equal volume partitions.
- Outlet water flow rate.
- Inlet water pressure.
- Noise level.
- Coil icing conditions.
- Condensate drainage observations.
- Evaporator-side refrigerant temperature and pressure. This is potentially an optional measurement dependent on the expertise of the lab. It would most likely require a slight modification to the equipment but would be minimally invasive.

4.1.1. Data Collection for COP Measurement

The COP curve development test sequence will not measure the COP instantaneously but will instead measure it over an integrated time interval (one minute). In this approach, data will be logged at every minute to give a measure of performance producing the curves (or similar) shown in Figures 1 and 2.

There are at least three alternate methods for measuring COP instantaneously: air temperature drop across the evaporator coil, water temperature rise across the heat exchanger, and refrigerant heat balance. All three of these have drawbacks and are more complicated than the COP measurement method discussed in section 2.2.2; however, they may provide greater levels of accuracy. We will ask the labs to propose on each of the different measurement possibilities. The major challenge in measuring the air temperature change across the coil is accurately measuring an output temperature. The outlet geometry is highly asymmetrical requiring a detailed temperature sensor grid and assumptions about averaging them. The next two alternates require more invasive instrumentation. For the water temperature rise method, water flow and temperature could be measured before and after the water enters the heat exchanger. Clamp-on ultrasonic flow meters may be employed while the temperature sensors likely need to be carefully located and insulated clamp-on thermisters. The refrigerant heat balance method requires a refrigerant flow meter (inserted into the refrigerant line) and refrigerant temperature and pressure sensors (also in the line). Measuring refrigerant flows requires a certain level of expertise likely not found in all labs. Despite these challenges, it may be valuable to investigate one or more of the approaches.

4.2. Test Procedures

The following test procedures are meant to be used in conjunction with the testing matrix, the DOE standard tests and the ASHRAE 118.2-2006 testing protocols.

4.2.1. COP Curve Development

The test will follow the conditions in the testing matrix. To start the test, the unit shall be turned off and the resistance heating elements shall be disabled in such a way that will prevent them from operating. Based on the current understanding of the equipment, the Rheem unit prevents the compressor from operating at tank temperatures below 80F. This control, and similar controls on other units, shall be overridden for the test. The goal is to monitor only the compressor behavior. Next, the tank shall be filled with water of the specified inlet temperature. When full, the tank shall be turned on. Data will be recorded at one-minute intervals until the water heater tank thermostat has been satisfied. The water in the tank will heat up from 35F to 135F during the test. The load on the tank comes from the energy required to deliver the given temperature rise. Repeat for all specified ambient conditions.

4.2.2. DOE Standard Rating Points

Follow the test procedures and sequence to obtain a measurement of the DOE rating point as specified in the Federal Register 10 CFR Part 430 Appendix E to Subpart B. The loads for the water heater in the DOE tests result from the specified water draws and the incoming cold water needed to replace to outgoing hot water.

4.2.3. Single Use Point Tests

See Appendix B for the protocol for these tests.

4.2.4. Operating Mode Tests

The main goal of the operating mode tests is to observe under what conditions the resistance heating element operates and under what conditions the compressor operates. With the water heater on and at set point, initiate a significant water draw. The draw should be enough to ensure that the backup element will eventually turn on. The precise water draw will vary based on control strategy and unit. The lab shall explore the necessary conditions to examine all the operating modes. Data shall be recorded every minute. The time when then the resistance element turns on will be noted, as well as the total power draw during this combined operation. The tests shall be conducted under the DOE rating conditions.

4.2.5. Draw Profiles

The draw profiles to use during the tests are shown graphically in the following figures. Refer to Appendix D for the tables used to generate the profiles which specify the precise water amounts. Note that the draws are conducted at variable flow rates.

Draw profile (1), shown in Figure 4, represents an average daily use pattern with a high amount of diversity. The figure shows the amount of water to be drawn at the start of each hour. Use a flow rate of 1 gallon per minute for all draws during the test. Begin the test at hour 5 with a hot tank and conduct the test over 24 hours.

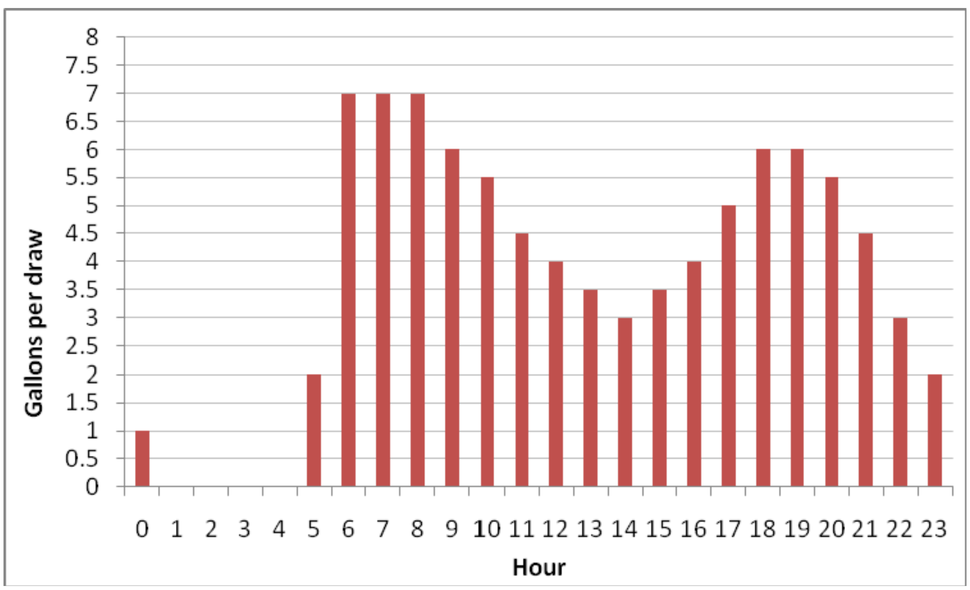

Figure 4. Draw profile (1).

Draw profile (2) represents a high demand situation with high peak use. Figures 5a and 5b depict the profile. Each vertical bar in the figure represents the flow rate to use for that minute of the test. The test begins with four large draws similar to shower use. After the fourth draw, wait for the tank to recover. Then, move on to the next series of draws in the next figure. It is not necessary to monitor tank losses for the intervening hours.

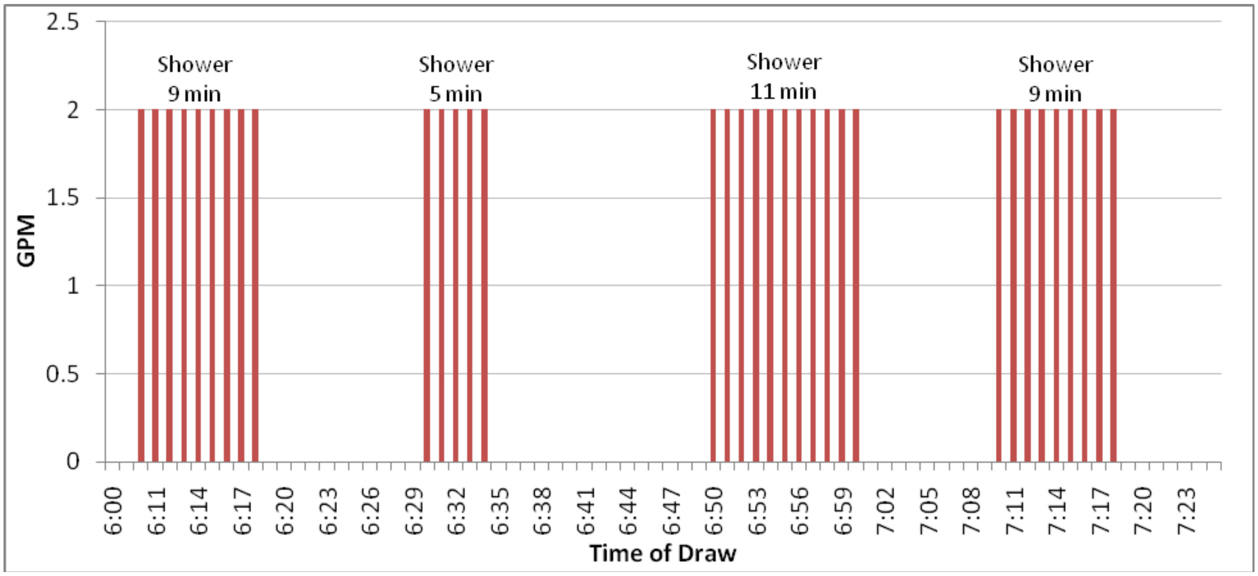

Figure 5a. Draw profile (2) morning segment.

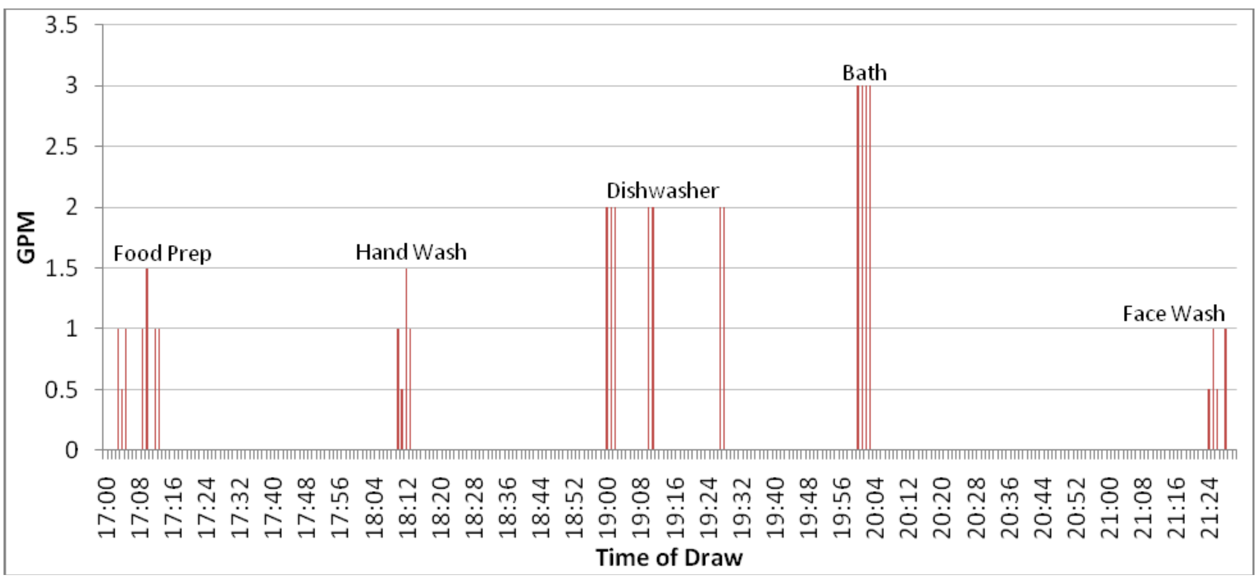

Figure 5b. Draw profile (2) evening segment.

Draw profile (3), shown in Figure 6, contains many small draws over an extended time period. This pattern targets 40 gallons of use. The draws should be conducted at 1 gallon per minute. Each vertical bar in the figure represents the amount of water to be drawn at the designated time. These amounts are either 0.5 or 1.0 gallons. The draws occur at 5 minute or longer intervals.

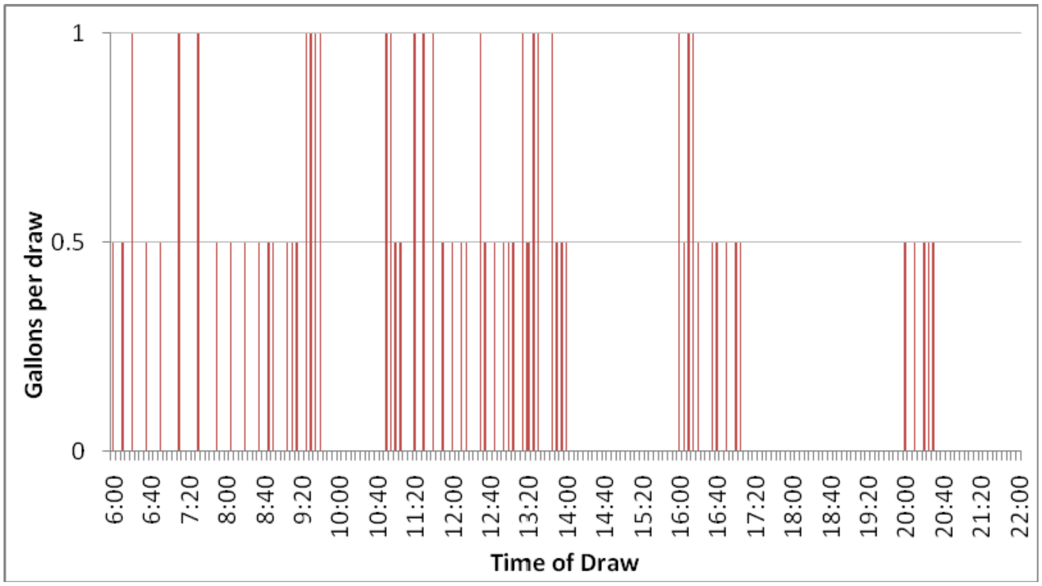

Figure 6. Draw profile (3).

4.2.6. Noise

To measure the sound from the HPWH, use a sound level meter. The measurements shall be taken 1 meter away from the equipment and 1.8 meters (about human ear-level) above the floor. If possible, based on the installation, take a measurement every ~60° around the circumference of the 1-meter circle. The measurements shall be conducted in the same way for every water heater tested. Efforts shall be made to limit the amount of ambient noise in the room; however, an acoustically isolated chamber is not necessary. The sound measurements shall be conducted both when the equipment fan is operating alone and when the compressor and fan are running. This will enable a somewhat isolated measure of the compressor noise. Sound measurements can be taken at any time during the other testing. We suggest recording the noise levels during the DOE-24hr tests or one of the draw profile tests.

4.2.7. Additional Observations

Observe coils for icing at cold conditions. Observe condensation accumulation and drainage method. Note if there is any system or method employed by the HPWH to detect condensate line blockage. Also note condensate line diameter.

References

ASHRAE Standard 90.2-1993. "Energy Efficient Design of Low-Rise Residential Buildings", Section 8.9.4, "Hourly Domestic Hot Water Fraction" and Table 8-4, "Daily Domestic Hot Water Load Profile", pp 53-54. American Society of Heating, Refrigeration and Air Conditioning Engineers, Atlanta, GA. 1993.

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Hendron, R. and J. Burch. "Development of Standardized Domestic Hot Water Event Schedules for Residential Buildings." NREL/CP-550-40874. National Renewable Energy Laboratory. Golden, CO. 2008.

Lutz, J.D., G. Ghatikar, E. Edleson, S. Meyers. "Hot Water Draw Patterns: Findings from Field Studies." Environmental Energy Technologies Division. Lawrence Berkeley National Laboratory. University of California. Berkeley, CA. 2006.

[10 CFR 430] US Department of Energy. Federal Register May 11, 1998 Part 430. "Energy Conservation Program for Consumer Products: Uniform Test Method for Measuring the Energy Consumption of Water Heaters" pp. 26008-26016. http://www1.eere.energy.gov/buildings/appliance_standards/residential/pdfs/wtrhtr.pdf

Appendix A: Summary of DOE Standard Test Procedures

This is an abbreviated summary of the DOE standard water heater test procedure found in the Federal Register 10 CFR Part 430. Use this for quick reference only. Refer to the DOE document for full testing specification.

Conditions:

Ambient Air Temperature: 67.5F ±1F, 50% ±1% RH

Storage Tank Temperature: 135F ±5F

Inlet Water Temperature: 58F ±2F

Daily hot water usage: 64.3gpd

Outlet water flow rate: 3gpm ±0.25gpm

Supply Water Pressure: >= 40psig when no water is being withdrawn

Electrical Supply: maintain voltage within ±1% of the center voltage range specified by water heater manufacturer.

Test Sequence for First Hour Rating Test:

Start with full tank at 135F. Time is now $\tau = 0$. Draw down tank until outlet temperature decreases to 135F-25F. Record outlet water temperature beginning 15s after draw down and then at 5s intervals. Following draw termination, determine the average outlet water temperature and the mass of water removed.

When tank recovers to 135F, begin a second draw down like the first. Continue with successive draws until 1 hour has elapsed. At the end of one hour, if in the middle of a draw, some special things need to be done to account for partial draws and energy input (see DOE procedure).

24-Hour Simulated Use Test:

Use 64.3 gallons in one day. Start with full tank at 135F (see DOE procedure for specifics of startup). Time is now $\tau = 0$. Begin first draw and remove 1/6 the daily volume or 10.7 gallons. Wait one hour, than repeat draw. Do a total of six times. After the last draw, let the unit recover and enter standby mode for remaining hours of test. At $\tau = 23$ hrs, turn off the electric supply.

Measurements of inlet and outlet temperature shall be made 15s after the start of every draw and every 5s throughout each draw. Record average storage tank and ambient temperature every 15 minutes throughout 24 hours unless a recovery or draw is occurring.

Appendix B: Single Use Point Test Procedure

The following appendix is excerpted from a memo to the ASHRAE 118.2 committee for residential water heater standards. It contains the procedures for testing our modified single use point tests.

Attachment 2 Draft Test Protocol Version 3.0

To: ASHRAE 118.2

From: Tom Butcher, Martin Thomas, Bill Healy, & Jim Lutz

Date: Tuesday, August 04, 2009

Re: Draft test protocol for rating water heaters using input/output method

1st STEP:

Use the same test rig as specified in the current DOE test. Set the flow rates and temperatures the same as for the current DOE test procedure. For comparison purposes, heaters with tanks should be outfitted with the same internal temperature probes as specified in the DOE test procedure. Use the AHRI positioning guidelines for consistency in locating the thermocouples. This will allow exploring whether the low use point test reliably starts and ends with the water in the tank at the same temperature.

Mandatory Measurement Points

High Use Point:

This test point is designed to find the input/output ratio at a high level of use. It is similar to the current first hour rating test for storage water heaters and the maximum GPM rating test for tankless water heaters.

Begin with the water heater fully heated. Initiate a 3 GPM draw when the heater ends recovery from the conditioning draw.

Record the temperature of the outlet water; the maximum outlet water temperature achieved during the initial draw from the tank is assigned the value Tmax. For storage water heaters, record the maximum average stored water temperature, $T_{ST,max,}$ at the beginning and the end of the test. Record the times at which Tmax and $T_{ST,max}$ are observed. This will enable the calculation of the energy change in the stored volume of hot water - just in case it turns out to be significant. If the temperature of the water drawn from the heater decreases during the draw, terminate the draw when the outlet temperature decreases to Tmax - 25 °F. Initiate each successive draw when the heater has fully recovered and acts to reduce energy input as described in the First Hour Rating protocol. Repeat for 3 cycles.

If the temperature of the water being drawn from the heater stays constant (e.g., tankless water heaters), terminate the draw after 30 minutes.

Monitor the temperature of the inlet and outlet water to the water heater, the mass or volume of water drawn through the heater, the duration of the test, and all the energy used by the water heater from the beginning of the 1st cycle until the water heater fully recovers from the last draw.

Input (Btu/hr) is defined as:

$Q_{in,high}$ = total fuel and electrical energy (Btu) consumed / the high use test duration .

Where the test duration is defined by, $t_{test} = (t_{standby} + t_{draw} + t_{recovery})$ (hours)

Output (Btu/hr) is defined as:

$Q_{out,high}$ = energy output rate over the high use test (Btu/hr)

Where:

$Q_{out,high} = mf_{w,high} * (T_{out,high} – T_{in,high}) * Cp_w / (t_{standby} + t_{draw} + t_{recovery})$

$mf_{w,high}$ = total water mass of water drawn during the high use test (lb)

$T_{out,high}$ = average outlet temperature during the high use test (°F)

$T_{in,high}$ = average inlet temperature during the high use test (°F)

Cpw = water specific heat (Btu/lb-°F)

$t_{test} = (t_{standby} + t_{draw} + t_{recovery})$ = actual high use test duration (hours)

Low Use Point:

This test point is designed to find the input/output ratio at a low use point.

For this test, a cycle is defined as a draw preceded by a standby period and followed by a recovery period. Begin with the water heater fully heated. This is immediately after the water heater recovers from a conditioning draw that caused the water heater to fire.

For water heaters that are activated by temperature (i.e. storage water heaters), the low load test consists of a standby period and a small draw. To pre-condition the tank, initiate a draw of sufficient volume to initiate firing by the burner (or element or heat pump). Stop the draw at this time and allow the water heater to completely recover. At the end of the recovery period, the low load test commences with 12 hours of standby followed by a draw with a flow rate of 3 gallons per minute of sufficient volume to initiate firing by the burner (or element or heat pump). When the burner fires, stop the draw. Continue monitoring energy use until the heater fully recovers and acts to reduce the energy input.

Monitor the temperature of the inlet and outlet water to the water heater, the volume of water drawn through the heater, and all the energy used by the water heater from the beginning of the 1st draw until the water heater fully recovers from the last draw. Monitor and record $T_{ST,max}$ and the time of occurrence as in the High Use Point Test.

Appendix C: Heat Pump Water Heater Test Matrix

COP Curve Development - Performance Mapping

Test Name	Ambient Air Conditions					Inlet Water		Outlet Water		Airflow	Operating Mode	Notes	Further Discussion
	Dry-Bulb		Wet-Bulb										
	F	C	F	C	RH	F	C	F	C				
COP-27	27	-3	25	-4	80%	35	2	135	57	100%	Compressor Only	Method: Disable backup element operation. Fill tank with inlet water while equipment off. Turn on tank and monitor every minute until outlet water temperature reached.	Add Alternate
COP-37	37	3	35	2	80%	35	2	135	57	100%	Compressor Only		
COP-47	47	8	43	6	73%	35	2	135	57	100%	Compressor Only		
COP-57	57	14	50	10	61%	35	2	135	57	100%	Compressor Only		
COP-67	67.5	20	57	14	50%	35	2	135	57	100%	Compressor Only		
COP-77	77	25	61	16	40%	35	2	135	57	100%	Compressor Only		
COP-90	90	32	71	22	40%	35	2	135	57	100%	Compressor Only		
COP-105	105	41	83	28	30%	35	2	135	57	100%	Compressor Only		Add Alternate

DOE Standard Rating Point Tests

DOE-1hr	67.5	20	57	14	50%	58	14	135	57	100%	Factory Default	Follow test sequence in Federal Register 10 CFR Part 430 Section **5.1.4**	Rheem has no factory default setting. Rheem used "Energy Saver" mode for DOE tests
DOE-24hr	67.5	20	57	14	50%	58	14	135	57	100%	Factory Default	Follow test sequence in Federal Register 10 CFR Part 430 Section **5.1.5**	

Modified Single Use Point Tests

$SUP\text{-}67_{low}$	67.5	20	57	14	50%	58	14	135	57	100%	Factory Default	12 hr standby. Then 3 gpm draw until compressor turns on.	Used to verify linearity of EF over low to high flow range, verify standby losses, and perhaps observe operating mode switch over.
$SUP\text{-}67_{hi}$	67.5	20	57	14	50%	58	14	135	57	100%	Factory Default	3 gpm draw until T_{tank} < Tmax-25F. Repeat for 3 cycles.	

Operating Mode Tests

OM-67	67.5	20	57	14	50%	58	14	135	57	100%	All factory control possibilities	Goal is to observe when backup resistance heating elements turn on	

Test Name	Ambient Air Conditions					Inlet Water		Outlet Water		Airflow	Operating Mode	Notes	Further Discussion
	Dry-Bulb		Wet-Bulb										
	F	C	F	C	RH	F	C	F	C				
Draw Profiles													
DP-1	67.5	20	57	14	50%	45	7	135	57	100%	Factory Default	Draw Profile (1). 60 gpd using Becker 1990 profile with added detail	
DP-2	67.5	20	57	14	50%	45	7	135	57	100%	Factory Default	Draw Profile (2). High peak demand. Target 110 gpd.	
DP-3	67.5	20	57	14	50%	45	7	135	57	100%	Factory Default	Draw Profile (3). Frequent, repeated, smaller draws.	
Airflow													
AF-1/3	67.5	20	57	14	50%	35	2	135	57	66%	Factory Default	Block 1/3 area of filter rack with cardboard. Then perform standard COP test.	
AF-2/3	67.5	20	57	14	50%	35	2	135	57	33%	Factory Default	Block 2/3 area of filter rack with cardboard. Then perform standard COP test.	
Noise Measurement													
NOI-F	Make independent measure of fan noise									100%	Fan Only	Run with fan only to measure fan noise. Measure sound at 1 meter away, 1.8 meters high.	
NOI-FC	During first hour phase of DOE-24hr test									100%	Fan & Compressor	Measure in typical operation. Measure sound at 1 meter away, 6' high.	Ideally we would run the compressor only for noise testing but that is not practical.
Additional Observations													
AO-ICE	During the cold temperature tests T<=47F, observe evaporator coils for evidence of icing												
AO-CND	Observe condensate drainage and note effectiveness											Note if there is any system in unit to detect blockage	

Appendix D: Draw Profile Tables

Draw Profile (1):

Hour	Gal/draw
0	1
1	0
2	0
3	0
4	0
5	2
6	7
7	7
8	7
9	6
10	5.5
11	4.5
12	4
13	3.5
14	3
15	3.5
16	4
17	5
18	6
19	6
20	5.5
21	4.5
22	3
23	2
Total	90 gal

Draw Profile (2):

Time	GPM
6:10	2.0
6:11	2.0
6:12	2.0
6:13	2.0
6:14	2.0
6:15	2.0
6:16	2.0
6:17	2.0
6:18	2.0
6:19	0.0
6:20	0.0
6:21	0.0
6:22	0.0
6:23	0.0
6:24	0.0
6:25	0.0
6:26	0.0
6:27	0.0
6:28	0.0
6:29	0.0
6:30	2.0
6:31	2.0
6:32	2.0
6:33	2.0
6:34	2.0
6:35	0.0
6:36	0.0
6:37	0.0
6:38	0.0
6:39	0.0
6:40	0.0
6:41	0.0
6:42	0.0
6:43	0.0
6:44	0.0

Time	GPM
6:45	0.0
6:46	0.0
6:47	0.0
6:48	0.0
6:49	0.0
6:50	2.0
6:51	2.0
6:52	2.0
6:53	2.0
6:54	2.0
6:55	2.0
6:56	2.0
6:57	2.0
6:58	2.0
6:59	2.0
7:00	2.0
7:01	0.0
7:02	0.0
7:03	0.0
7:04	0.0
7:05	0.0
7:06	0.0
7:07	0.0
7:08	0.0
7:09	0.0
7:10	2.0
7:11	2.0
7:12	2.0
7:13	2.0
7:14	2.0
7:15	2.0
7:16	2.0
7:17	2.0
7:18	2.0
7:19	0.0

Time	GPM
17:03	1.0
17:04	0.5
17:05	1.0
17:06	0.0
17:07	0.0
17:08	0.0
17:09	1.0
17:10	1.5
17:11	0.0
17:12	1.0
17:13	1.0
17:14	0.0
…	…
18:09	0.0
18:10	1.0
18:11	0.5
18:12	1.5
18:13	1.0
18:14	0.0
…	…
18:59	0.0
19:00	2.0
19:01	2.0
19:02	2.0
19:03	0.0
…	…
19:05	0.0
19:10	2.0
19:11	2.0
19:08	0.0
…	…
19:26	0.0
19:27	2.0
19:28	2.0
19:29	0.0

Time	GPM
19:59	0.0
20:00	3.0
20:01	3.0
20:02	3.0
20:03	3.0
20:04	0.0
…	…
21:23	0.0
21:24	0.5
21:25	1.0
21:26	0.5
21:27	0.0
21:28	1.0
21:29	0.0
21:30	0.0

Draw Profile (3):

Time	Gal/draw
6:00	0.5
6:05	0
6:10	0.5
6:15	0
6:20	1
6:25	0
6:30	0
6:35	0.5
6:40	0
6:45	0
6:50	0.5
6:55	0
7:00	0
7:05	0
7:10	1
7:15	0
7:20	0
7:25	0
7:30	1
7:35	0
7:40	0
7:45	0
7:50	0.5
7:55	0
8:00	0
8:05	0.5
8:10	0
8:15	0
8:20	0.5
8:25	0
8:30	0
8:35	0.5
8:40	0
8:45	0.5
8:50	0.5

Time	Gal/draw
8:55	0
9:00	0
9:05	0.5
9:10	0.5
9:15	0.5
9:20	0
9:25	1
9:30	1
9:35	1
9:40	1
9:45	0
…	…
10:45	0
10:50	1
10:55	1
11:00	0.5
11:05	0.5
11:10	0
11:15	0
11:20	1
11:25	0
11:30	1
11:35	0
11:40	1
11:45	0
11:50	0.5
11:55	0
12:00	0.5
12:05	0
12:10	0.5
12:15	0.5
12:20	0
12:25	0
12:30	1
12:35	0.5

Time	Gal/draw
12:40	0
12:45	0.5
12:50	0
12:55	0.5
13:00	0.5
13:05	0.5
13:10	0
13:15	1
13:20	0.5
13:25	1
13:30	1
13:35	0
13:40	0
13:45	1
13:50	0.5
13:55	0.5
14:00	0.5
14:05	0
…	…
15:55	0
16:00	1
16:05	0.5
16:10	1
16:15	1
16:20	0.5
16:25	0
16:30	0
16:35	0.5
16:40	0.5
16:45	0
16:50	0.5
16:55	0
17:00	0.5
17:05	0.5
17:10	0

Time	Gal/draw
…	…
19:55	0
20:00	0.5
20:05	0
20:10	0.5
20:15	0
20:20	0.5
20:25	0.5
20:30	0.5
20:35	0