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Interim Report and Preliminary Assessment of AO Smith Voltex PHPT-80 Hybrid Heat Pump Water Heater

12 July 2011

Prepared for
Bonneville Power Administration
Contact: Kacie Bedney, P.E.

Prepared by
Ben Larson, Ecotope Inc.

Contract Number 44717

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Residential Heat Pump Water Heater Evaluation Project

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Revision 1

Revision History

Rev #	Date	Details of Change	Reason
0	4-20-2011		First release
1	7-11-2011	Clarified defrost discussion and corrected typos.	

Introduction

Using the measurement and verification (M&V) plan developed by Ecotope to assess heat pump water heaters (HPWH), the AO Smith Voltex was evaluated at the National Renewable Energy Lab. The M&V plan consists of a series of tests to assess equipment performance under a wide range of operating conditions. The tests include measurement of basic characteristics and performance including first hour rating and DOE Energy Factor (EF), description of operating modes, measurement of heat pump system efficiency and the effects of restricted airflow. For a detailed description of the tests and conditions, refer to the M&V plan document.

This report is the third of three preliminary assessments of three different equipment models. The report is intended as a "first look" at the results and, as such, should still be considered a preliminary assessment. A final assessment will be prepared and delivered later which will include all three HPWH models. This report focuses primarily on the equipment operation and performance itself and not on the interactions with the building in which it is installed.

Basic Equipment Characteristics

The AO Smith Voltex Hybrid PHPT-80, is an all electric water heater consisting of a heat pump integrated with a hot water tank. The equipment has two methods of heating water:

(1) by using a heat pump to extract energy from the ambient air and transferring it to the water, or
(2) by using resistance heating elements immersed within the tank.

The heat pump compressor and evaporator are located on top of the tank. A single-speed fan draws ambient air from the left side of the unit (when viewing the control panel) through a washable filter, across the evaporator coils, and exhausts colder air out the right side. The refrigerant condenser, which transfers heat to the water, is wrapped around the tank outside.

The lab conducted a series of measurements amounting to a basic descriptive characterization of the equipment. These are given in Table 1 and discussed in the rest of this section. For comparison purposes, the table also shows the values given by AO Smith's equipment specification.

As with traditional, electric tank water heaters, the Voltex has an upper and lower resistance heating element. Unlike most traditional tanks, the elements draw differing amounts of power. With a 240V supply, the upper element draws 4.5kW while the lower element draws 2.0kW. Traditional tanks have 4.5kW elements which operate separately. Both of the Voltex elements operate independently. The larger upper element acts as an on-demand heater while the lower element is responsible for topping off the overall tank temperature.

The controls for the Voltex are configured to operate either the compressor, upper element or lower element one at a time. This limits the total power draw to 4.5kW, the amount of the upper element. Measurements show the compressor draws 550-1100W depending on both tank water and ambient air conditions. Lower temperatures for both water and air result in lower power draws while higher temperatures result in larger power draws. Two other components of the equipment also consume power. The fan, which moves 475 CFM of air, draws 85W. The control circuits use 8W constantly. The tank also employs a powered anode rod to protect against corrosion which draws 50mA maximum. This was not measured separately in the lab so its power use is not confirmed.

The Voltex is marketed and sold as having an 80 gallon capacity but careful measurements showed the unit in the lab held 75.0 gallons. National guidelines on the sizing of equipment allow a 10% variation in nominal versus actual size. This water heater fits within those guidelines in a similar way to the GE GeoSpring (45 gal) and Rheem EcoSense (45 gal) in that all three have lower actual volumes. It should be noted that the difference in nominal size vs actual size is not unique to HPWHs and occurs with traditional electric resistance tanks as well. The larger capacity of the Voltex is significant for performance. It is clearly able to meet higher peak loads and, because of the large storage capacity, it can generally spend more recovery time using the compressor only while still being able to satisfy hot water demand.

Lastly, the Voltex uses R-134a refrigerant. Compared to R-410a, which is the refrigerant of choice for split-system space conditioning heat pumps, and is also used by some HPWH manufacturers, R-134a allows the compressor to heat the water to a higher set point. The high end range of the Voltex is 150°F.

Also of note regarding the Voltex is its size. In order to hold 75 gallons of water and accommodate the heat pump components, the unit is large. It measures 81.5" tall with a 24.5" diameter. Placing it on a stand, as is common practice, will take the top of the unit to 7'.

Table 1. Basic Characteristics for AO Smith Voltex Hybrid PHPT-80

	Laboratory Measurement	Manufacturer's Specification
Power		
Upper* Element (W)	4500	
Lower* Element (W)	2000	
Compressor** (W)	550-1100	700
Standby (W)	8	--
Fan (W)	85	--
Airflow Path	Inlet on left side. Exhaust to right side.	
Airflow (cfm)	475	--
Refrigerant	R-134a	
*elements interlocked. 240V supply		
**range depends on water T and ambient T. Power increases with both		

Operating Modes and Sequence of Heating Firing

The HPWH has an integrated circuit control board which may be programmed in a number of ways to control when the heating components, compressor or resistance elements, turn on and off. AO Smith has developed several control strategies, referred to as "operating modes" to determine equipment operation. The Voltex HPWH has three basic modes of operation from which the user may select. They are, in order of most efficient to least efficient:

- "Efficiency" – compressor only unless ambient temperature is outside of range (45°F – 109°F) or tank temperature below 58°F.
- "Hybrid" – combination of compressor and resistance elements
- "Electric Only" – resistance heat elements only

Of the three equipment models tested, AO Smith provided the most information and the most clear description of their operating modes. The water heater has two thermistors mounted on the exterior of the tank but underneath the insulation. The upper thermistor covers about the top 1/6 of the tank volume while the lower is placed at about the lower 1/3 of the volume. The equipment then monitors an average tank temperature and upper and lower temperature with the following equation:

$$T_{tank} = (3*T_{upper} + T_{lower})/4$$

The M&V plan called for a set of tests to explore the control strategies for the water heater modes of operation. Each test began with the water heater full of water at a set point of either 120°F or 140°F. A draw was initiated and continued until the compressor turned on (if possible for that mode of operation). The draw was then stopped and the unit was allowed to recover. A second draw was performed for the same air conditions and set point. This second draw was allowed to continue until the electric heaters came on or until 70 gallons of water had been drawn. The units were then allowed to recover. This same procedure was followed for air at 67°F dry bulb for efficiency, hybrid and electric modes, and 95°F dry bulb for hybrid mode.

The water heater only engages one heating component (element or compressor) at a time. The following operational strategies were confirmed with the operating mode tests:

Efficiency Mode: The operating mode is straightforward. If T_{tank} falls 9°F below the tank set point, the compressor turns on to reheat the tank. For example, in the operating mode tests, the lab observed a draw of 13 gallons ($T_{set\ point}$ = 120°F, $T_{water\ in}$ = 60°F) triggered the compressor. This aligns with the described control strategy. Resistance elements do not run unless the ambient temperature is beyond 45°F-109°F or T_{tank} is below 58°F.

Hybrid Mode: Much as in "Efficiency Mode," the compressor will always turn on for an 8-10°F T_{tank} drop. Additionally, if the temperature at T_{upper} falls 18-20°F below set point, the upper element will turn on. When the upper thermistor reaches set point, the upper element cycles off and the compressor turns on again to finish heating the lower portion of the tank.

Electric Only Mode: As the name implies, only the electric elements are used in this mode. A drop of 5°F in T_{tank} will activate the upper element. When the temperature recovers, the lower element switches on to finish heating the tank.

According to the AO Smith engineering team, the lower element was specifically sized to 2.0kW, and not bigger, in order to match the heat input provided by the compressor. This deliberate choice ensures that there is no advantage to heating water quickly by using the all electric resistance mode over the Hybrid operation mode. In fact, for ambient air conditions around 50F and above, Hybrid (or Efficiency) mode would heat the tank more quickly than Electric Only. Therefore, this design choice is likely to steer home owners towards the more efficient operating modes which also provide greater volumes of hot water.

First Hour Rating and Energy Factor

To rank the comparative performance of heat pump water heaters the Department of Energy has established two tests. The first produces a first hour rating which determines how much useable hot water the heater makes in one hour. The second, a 24-hr simulated use test, produces an energy factor (EF) which relates how much input energy is needed to generate the 64.3 gallons of hot water used in the simulated 24 hour period. For tank-type water heaters, the first hour rating depends largely on tank volume and heating output capacity. The energy factor depends on the heating system efficiency and the heat loss rate of the tank. The normative performance characteristics of the equipment are shown in Table 2 and discussed in the rest of this section. Importantly, although the lab carried out the tests in alignment with the DOE specification, the outputs here should not be considered official ratings – those are the ones reported by the manufacturer.

Table 2. Performance Characteristics for AO Smith Voltex PHTP-80

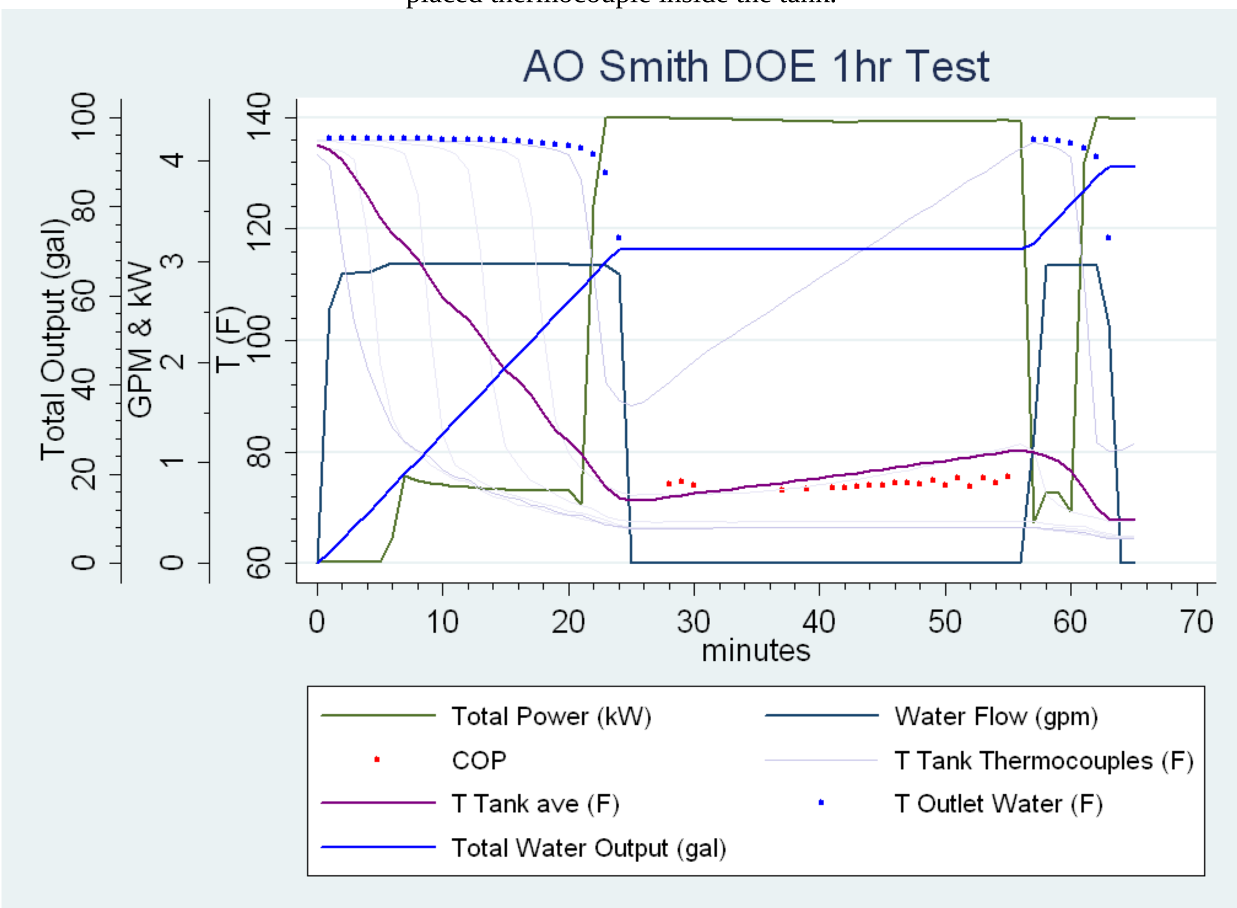
	Laboratory Measurement	**Manufacturer's Specification**
Tank Volume (gal)	75.0	80
First Hr Rating (gal)		
Efficiency Mode	--	70
Hybrid Mode	87	84
Electric Mode	--	76
Energy Factor		
Efficiency Mode	--	2.3
Hybrid Mode	2.29*, 2.33**	2.33
Electric Mode	--	0.85
Tank Heat Loss Rate (Btu/hrF)	3.9	--
*DOE Method for EF calculation **"Simple" method of EF calculation – see text for explanation		

The lab conducted both the 1-hr and 24-hr tests to demonstrate repeatability with the manufacturer's data. The tests are conducted in "Hybrid" mode which is the default setting on the equipment when shipped by AO Smith. The manufacturer reported values for additional modes which were not tested in this project. Those are displayed in Table 2 for reference. All tests were conducted per the DOE specification.

The data from the one hour test at 135°F set point are plotted in Figure 1. The test begins with a 3gpm draw. Approximately 5 minutes into the first draw, the heat pump activates (green line showing 0.8kW). As the draw continues past 20 minutes, the T_{tank} falls far enough below set point (18°F) to engage the upper heating element (green line to 4.5kW), turning off the compressor in the process. At 55 minutes, the upper portion of the tank has recovered to set point so the equipment switches to the compressor. Per the DOE test method, this triggers another draw since the water at the top of the tank is now hot. The draw continues past minute 60 when the resistance element engages again. Shortly thereafter, the test is terminated.

Figure 1. DOE One Hour Test.

The dark blue line shows the prescribed water draws at a 3gpm flow rate. The bright blue line shows the cumulative water drawn during the test. The green line plots the total equipment power consumption. The thick purple line displays the average tank temperature while the thin lavender lines show the temperatures reported from the six thermocouples placed at different heights (corresponding to equal volume segments) within the tank (in effect a temperature profile of the tank at any point in the test). The red dots, plot the minute-to-minute COP. Lastly, the blue dots plot the output water temperature. Output water temperature is always just slightly warmer than the highest placed thermocouple inside the tank.



The 24-hr simulated use test consists of six, 10.7 gallon draws equally spaced over six hours followed by 18 hours of standby. The standard test conditions are 67.5°F, 50% RH ambient air, 135°F tank set point and 58°F incoming water temperature. As with the first hour rating, the heater operating mode was set to Hybrid. Figure 2a shows the first seven hours of the test so the draw events and recovery can be examined in more detail. Figure 2b shows the full 24 hours which also demonstrates the tank heat loss rate.

At the most basic level, an energy factor (EF) is the ratio of total useful energy output to total energy input. The DOE test method prescribes a standard set of operating conditions to use for the test and for normalization purposes in the calculation of the EF. The previous two preliminary assessments considered only the “simple” EF calculation. This calculation divided energy output by energy input and did not normalize to standard conditions. The extent that the simple EF agrees with the DOE method EF, reflects how tightly the lab (and the equipment tested) held to the standard conditions. Both EF calculations are given in Table 2. For comparison to the manufacturer's data, the DOE method EF should be used. By calculating the EF in two ways, we can demonstrate that the lab held very closely to the test tolerances.

Figure 2a plots much of the same data as Figure 1. One distinction is the exclusive use of the compressor for heating unlike the 1hr test which shows both compressor heat and resistance element heat to meet the high demands of the test. For the 24 hr simulated use test, the large tank capacity and efficient compressor operation more than sufficiently meet the hot water demand so no resistance heating is needed.

Figure 2a also plots the instantaneous COP which is a measure of how much heat is added to the hot water in a given time interval divided by the energy used to create or deliver that heat in that interval (in this case one minute). For electric resistance heat, the COP is generally assumed to be 1. In contrast, the COP for heat pumps can vary greatly depending largely on the ambient air conditions (heat source) and the tank temperature (heat sink). The downward trend of the COP in Figure 2a with each recovery cycle reflects the changing tank temperature. The scatter in the COP plots is due to uneven, short-term fluctuations in the tank temperatures but the general trend is clear. For the recovery cycles in this test, the COP ranges from about 3.5 to 2.3. More discussion of the COP occurs later.

Figure 2a. DOE 24hr Simulated Use Test.
First 6 hours of test covers all six draws and full tank recovery.

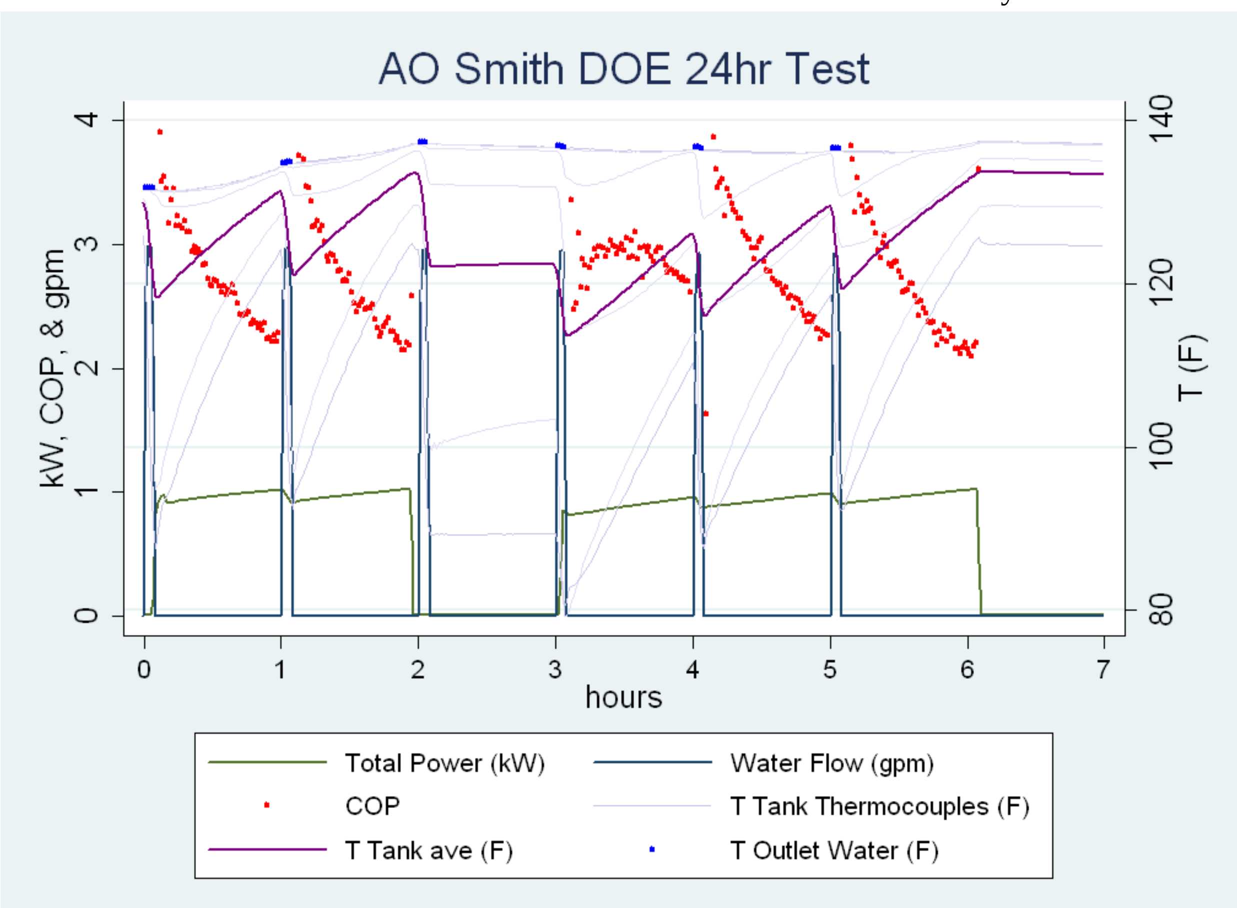
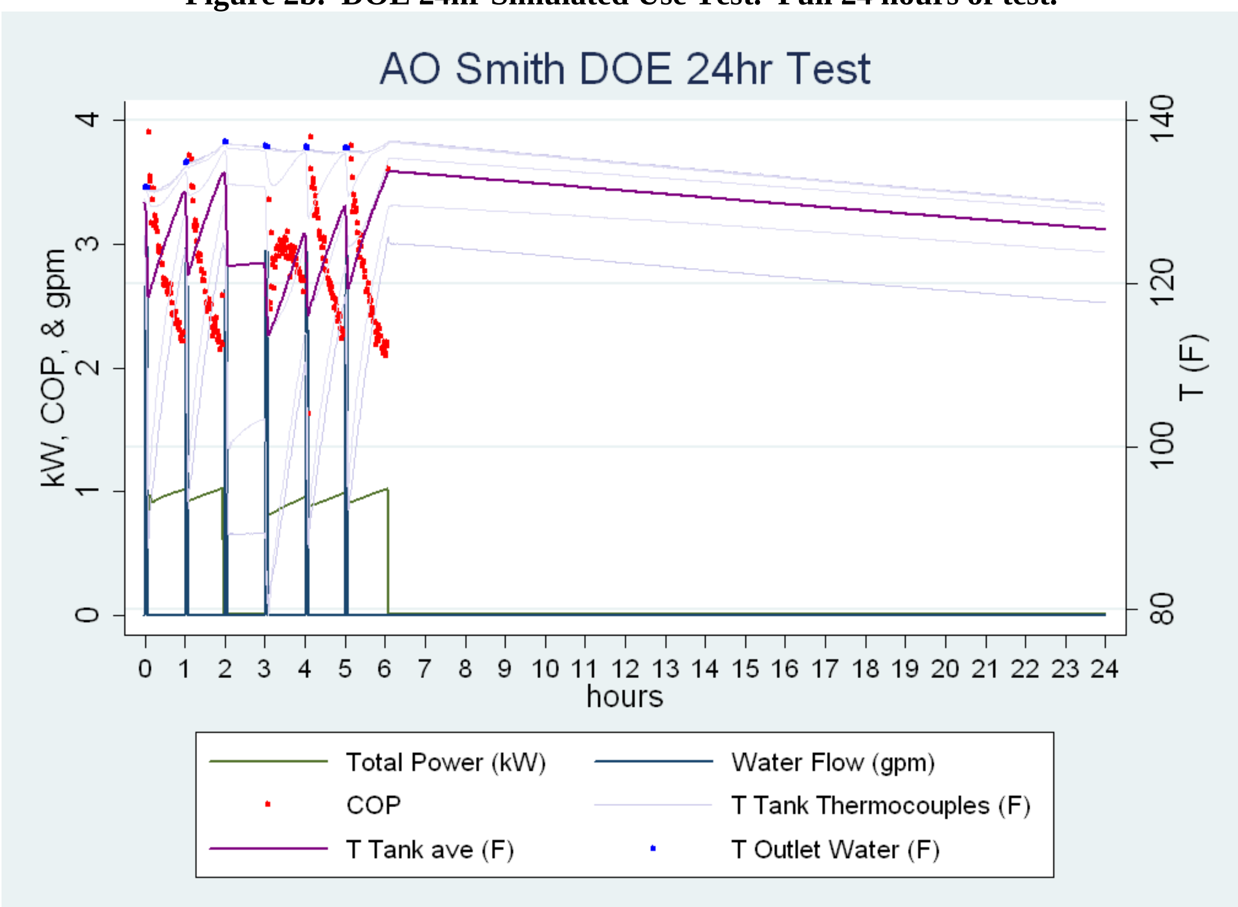


Figure 2b shows the full 24hrs of data. From shortly after hour 6 for the remainder of the test, the tank is in standby mode with the only power draw being 8W for the control circuits. From the change in average water temperature over this period, a heat loss rate of 3.9 Btu/hr°F (1.15 W/°F) was calculated for the tank. For a tank installed inside a house with a set point of 120°F, this heat loss amounts to 504 kWh/yr. If installed in a garage with an average year round temperature of 50°F, the losses amount to 705 kWh/yr. Unlike traditional electric tanks which recover the standby loss with a COP of 1, Figure 2a shows the AO Smith HPWH, using the compressor, will recover standby losses with a COP of 2.25 thereby reducing that portion of annual energy use by over half.

One feature of Figure 2b is that the water heater performs no standby firings during the test. Instead, it lets the average tank temperature fall from 133°F to 126°F. This follows from the control logic given. In a few more hours, the tank will perform a standby recovery. Because the same control logic is used for a setpoint of 120°F, the average tank temperature will fall about 9°F before a standby recovery occurs. This still leaves the hottest water at the top of the tank quite usable at 113-114°F.

Figure 2b. DOE 24hr Simulated Use Test. Full 24 hours of test.



Equipment COP and Operating Range

To fully understand the HPWH performance, the M&V plan called for a mapping of equipment COP at varied tank temperatures and ambient air conditions. These COP measurements reflect how efficiently the heat pump components of the HPWH are operating under any given set of conditions. These COP calculations do not apply when the resistance elements are operating, in which case the COP is assumed to be nearly 1. The performance map is extremely useful in understanding how well the equipment will operate in a conditions encountered in garages and unconditioned basements. The COP tests start with a full tank of cold water and the equipment off. The equipment is then switched on in compressor only mode and data is recorded as the tank heats up to set point. This is repeated for a set of ambient conditions. The test conditions are given in Table 3.

Table 3. Test conditions for COP Mapping

Test Name	Ambient Air Conditions					Inlet Water		Outlet Water	
	Dry-Bulb		Wet-Bulb						
	F	C	F	C	RH	F	C	F	C
COP-47	47	8	43	6	73%	35	2	135	57
COP-57	57	14	50	10	61%	35	2	135	57
COP-67	67.5	20	57	14	50%	35	2	135	57
COP-77	77	25	61	16	40%	35	2	135	57
COP-85	85	29	68	20	42%	35	2	135	57
COP-95	95	35	75	24	40%	35	2	135	57
COP-95 dry	95	35	66	19	20%	35	2	135	57
COP-105	105	41	84	29	42%	35	2	135	57
COP-105 dry	105	41	69	21	16%	35	2	135	57

When coil icing conditions are possible, the Voltex is designed to switch off the compressor and operate only in resistance heat mode. This applies to tank water conditions below 58°F. Therefore, in order to measure compressor performance at low tank temperatures, the lab developed on override control for the tank thermistors in order to get the compressor to run regardless of tank temperature. For actual installs in houses, the compressor would never run under these circumstances but this procedure allows the full characterization of the heat pump system. Artificially extending the compressor operating conditions also serves to produce better curve fits for an equipment performance model.

Operating Range

In addition to compressor operating condition limits due to the water temperature, the equipment limits compressor operation below 45°F and above 109°F ambient conditions. The low temperature limit exists to prevent operation of the compressor when frosting is likely because the equipment does not have an active defrost cycle. In the testing regime, the compressor operated continuously at the 47°F and 57°F ambient conditions. This is in contrast to the Rheem model which cycled the compressor on and off at those ambient conditions. The GE model cycled the compressor some but only at lower tank temperatures. This finding shows that the Voltex has the broadest operating range of the three models under test.

As with the other models tested, there was no active defrost cycle. Because no frosting conditions were encountered, no observations were available on how “passive” defrost operates on the equipment. A passive defrost cycle is a periodic cycling of the compressor to off (turning the resistance heat on) and attempting to restart it at some later time regardless of the ambient conditions. As observed with other HPWHs under test, passive defrosting can starting to be seen in the 50°F and lower ambient range. Since none we observed at the 47F COP test, it appears the equipment is designed, with adequate airflow and evaporator coil size to avoid defrost cycling altogether until 45°F and colder where it switches to resistance element only operation.

Equipment COP

Equipment efficiency is dependent on the water temperature in the tank, ambient air temperature, and ambient air moisture content. Figure 3 shows the change in COP with average tank temperature; a decreasing COP for increasing water temperatures, for the various tests. The curves in the plots are logarithmic fits to the measured data.

Figure 4 shows the COP dependence on ambient air dry bulb for a set of given tank temperatures. The COP actually depends on both dry bulb and wet bulb temperatures but, for simplicity, the wet bulb dependence is not shown in the plot. The fact that analysis of the test data shows dependence not only on wet bulb but also on dry bulb temperature suggests that the tests measured a difference in latent heat removal at the different testing conditions. Using regression techniques, the performance map was turned into a function so that efficiency can be predicted at any set of conditions.

$$COP = 1.865 - 0.02114*T_{tank} + 0.01736*T_{wb} + 0.03615*T_{db} - 0.0002883*T_{tank}T_{wb} - 0.0001862*T_{tank}T_{db} + 0.0001904*T_{db}^2$$

where Ttank = average tank temperature (F)
Tdb = ambient air dry bulb temperature (F)
Twb = ambient air wet bulb temperature (F)

Further implications of heat pump performance will be explored in later reports. Moreover, the functional form of the current COP curve has more terms compared to the GE or Rheem models. The fit is quite good but an attempt will be made to simplify and unify the models in the future.

Figure 3. The plotted lines are fits to measured data.

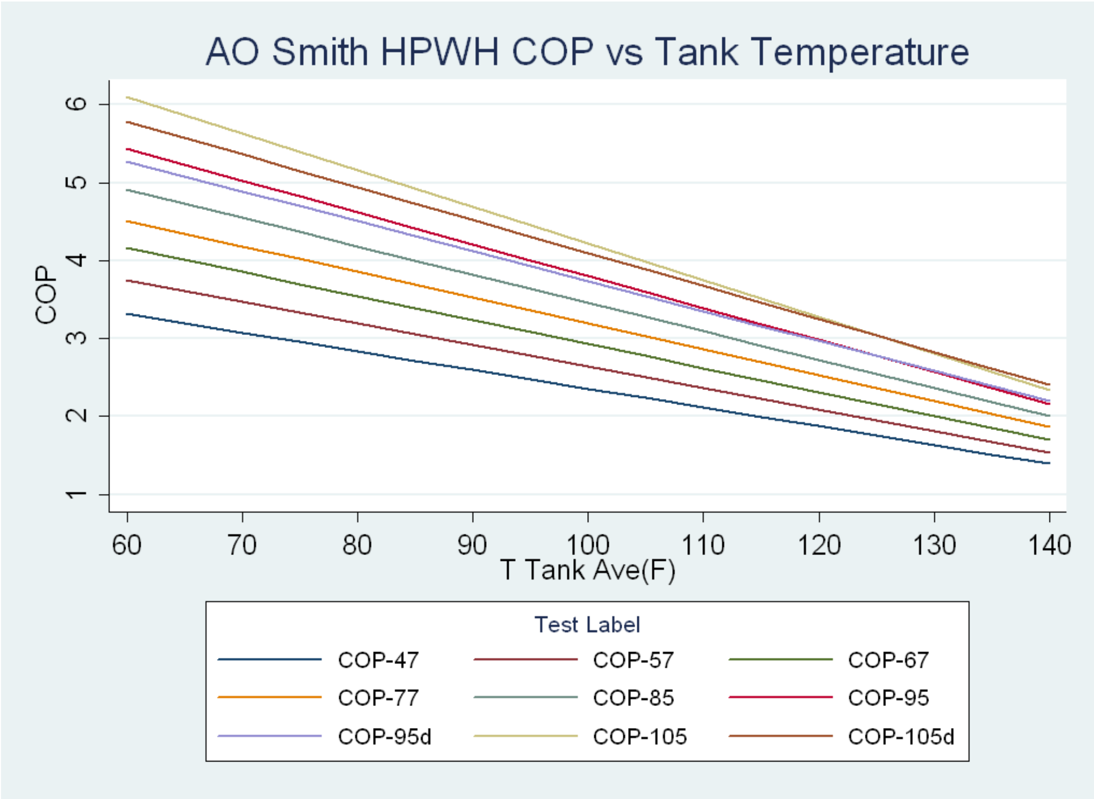
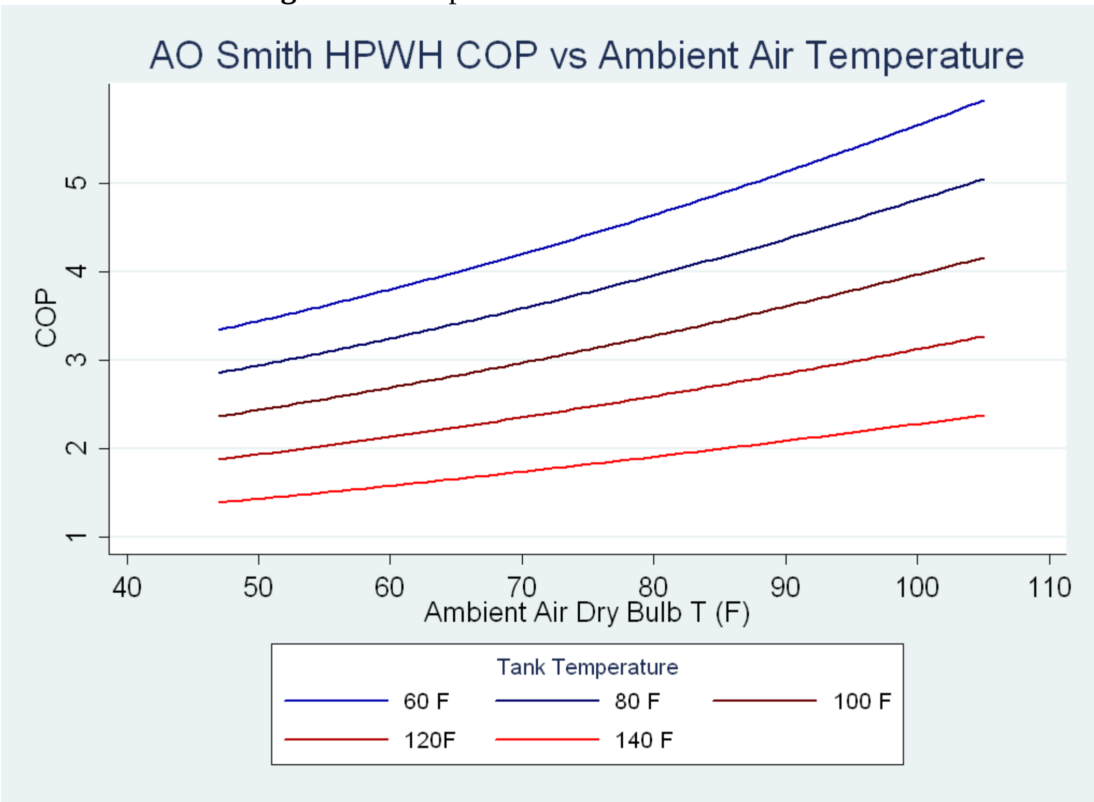


Figure 4. The plots are fits to measured data.



Air Flow Effects on Performance

To evaluate the effect of reduced airflow on the equipment operation, two tests were conducted. The filter area was restricted by 1/3 and 2/3 of its surface area for the measurements. The COP-67 test was then carried out. The measured airflow in each of the tests was:

- Full flow, no restriction: 475cfm
- 1/3 of filter blocked: 372cfm, 78% of full flow
- 2/3 of filter blocked: 284cfm, 60% of full flow

Figure 5 plots the COP vs average tank temperature for various airflows. The figure shows a slight decrease (3-5%) in system performance for the 1/3 blockage case. For the 2/3 blockage case, performance is decreased at lower tank temperatures but is comparable for higher tank temperatures. This crossover in performance is not completely understood.

Figure 6 shows airflow impacts on heating capacity and input power. It demonstrates that the reduced airflows lead to a slight decrease in water heating capacity. This amounts to a 5-6% reduction at most. The findings demonstrated in these figures show that the system can still operate well with reduced airflows. Therefore, the filter could be quite dirty before any change in performance is experienced.

Figure 5. Measured COP plotted as points. Fitted COP plotted as lines.

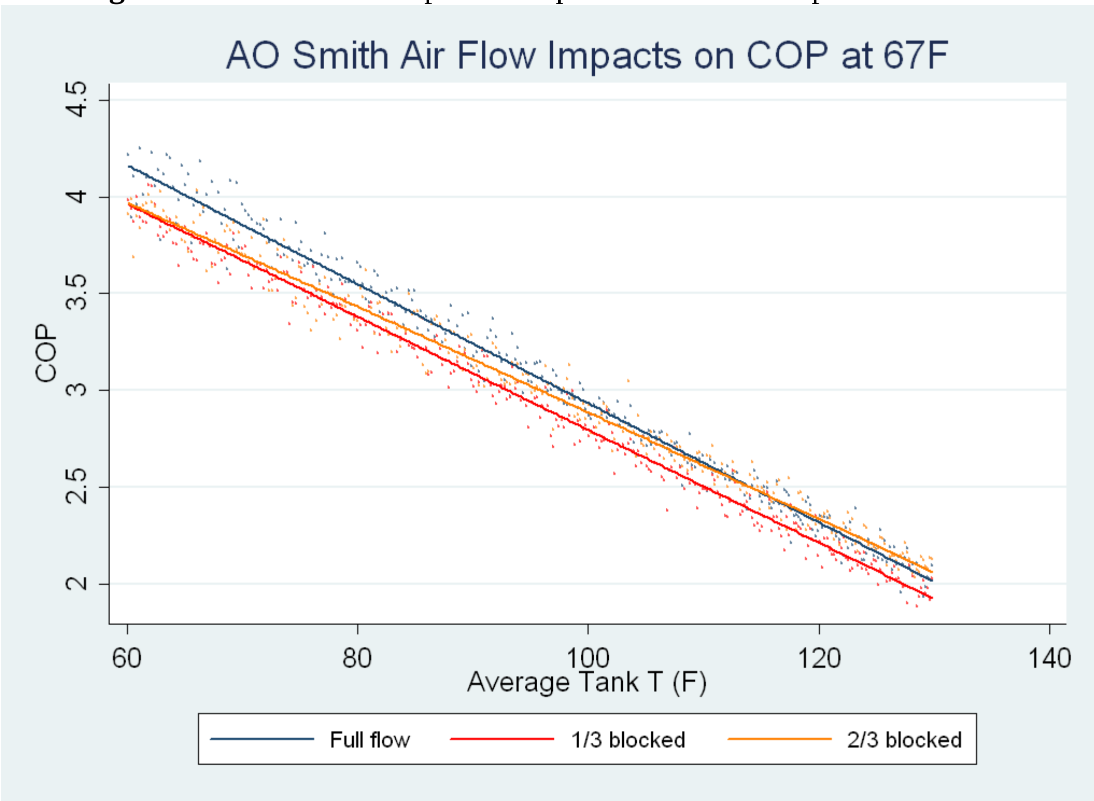
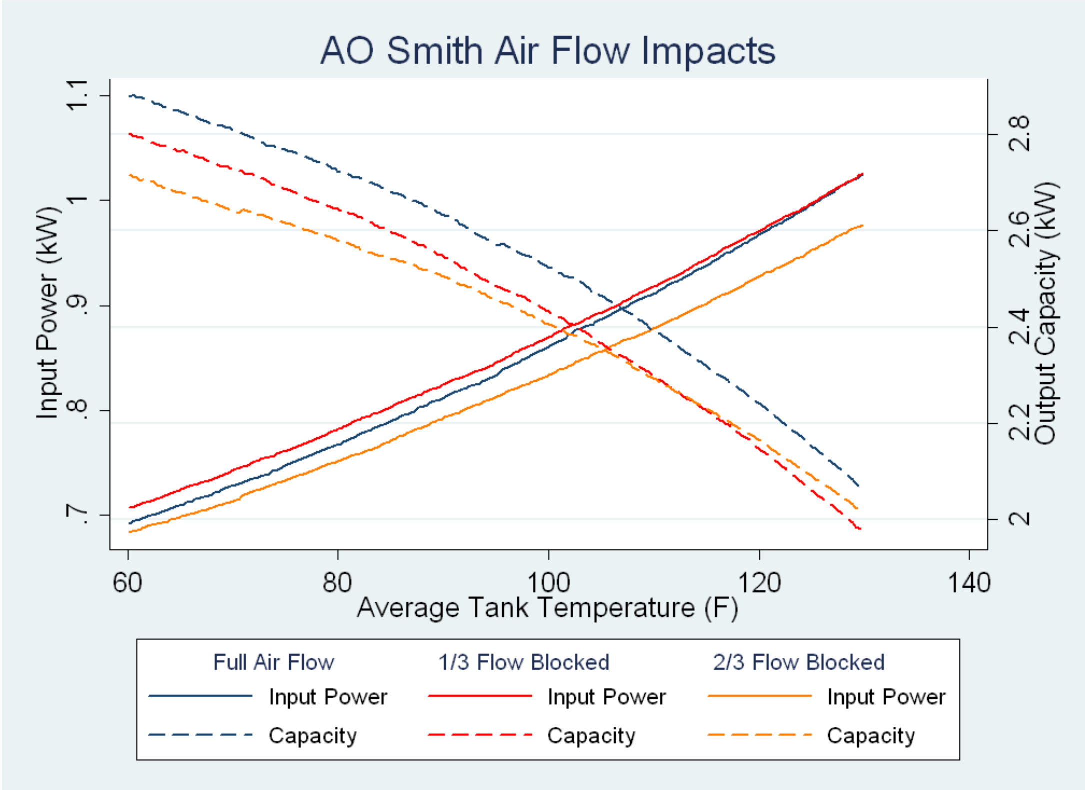


Figure 6. Air flow restriction impacts on input power and output capacity at 67F.



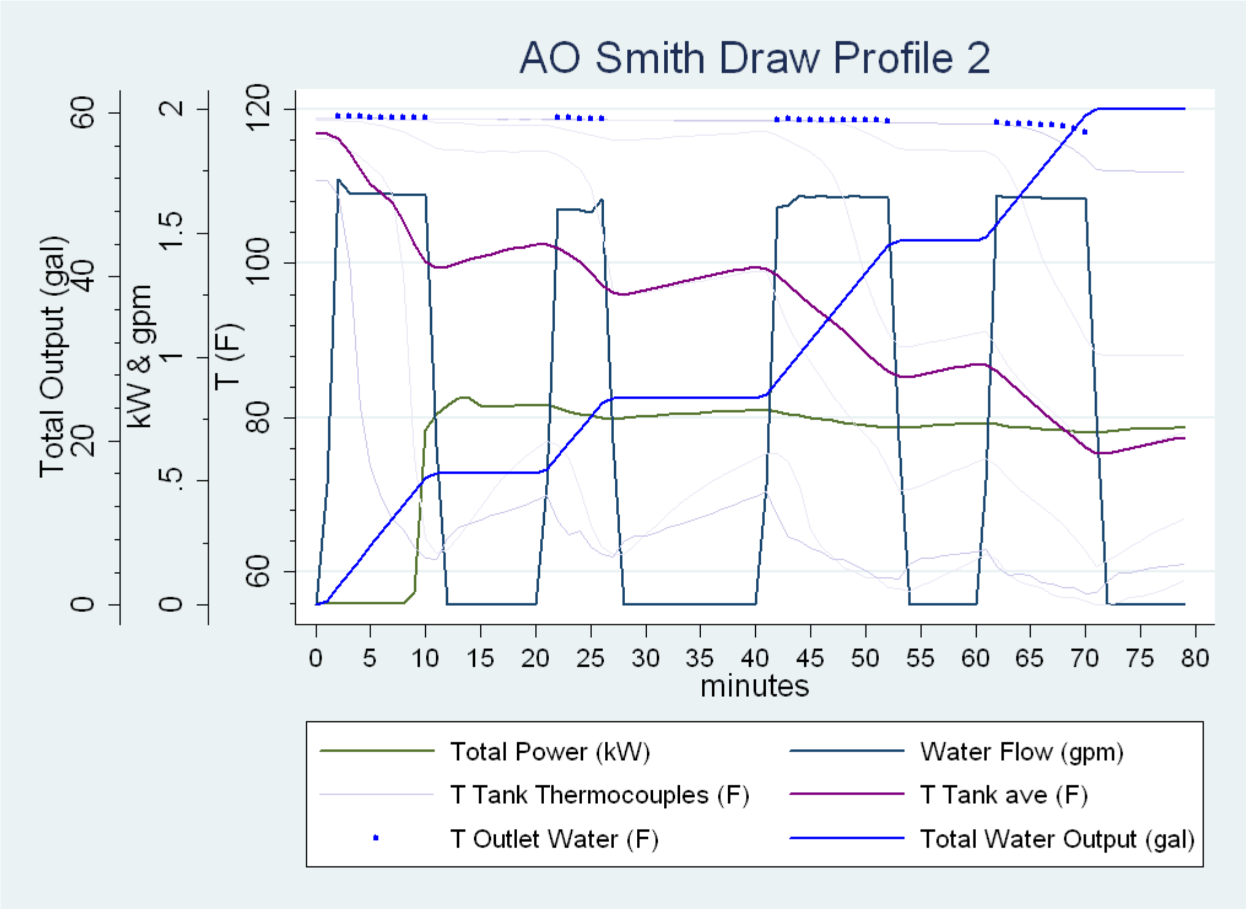
Draw Profile and Capacity

In addition to the standard DOE 24-hr draw profile, two supplemental draw profiles were conducted to observe the water heater under a wider range of potential, real-world, conditions. The first draw profile, referred to as DP-2 in the M&V plan simulated a heavy water use pattern targeting 110 gallons of water per day. The conditions used for DP-2 include: Hybrid mode, 120°F set point, 67.5°F ambient temperature, and 45°F inlet water (to simulate winter seasonal mains temperatures).

The results of running the profile show that the water heater has plenty of capacity (both storage and energy output) to meet the load imposed by this test. The test is very demanding (simulating an active family of four) and it is no surprise that an 80 gallon tank would meet the load. As expected, this stands in contrast to the two 50 gallon tanks tested which are suited only to meet smaller water loads.

Figure 7 shows the first 80 minutes of the test which consist of a total water draw of 60 gallons. Even though the average tank temperature falls to below 80F in the figure, the stratified tank still has enough hot water at the top to meet demand. Only at the very end of the last draw does the outlet water temperature begin to drop slightly. Had the draw continued for a few more minutes, the resistance element would have turned on. As it stands, the resistance elements never come on during any portion of the 9hr long draw profile. This suggests that the equipment could deliver significant energy savings even for houses with high water heating demands.

Figure 7. First 80 minutes of draw profile 2.



Observations on Equipment Design

The last section in the report discusses observations, in no particular order, on the equipment design and their implications for operation and performance.

- The tank capacity is large. At 75 gallons (nominally 80), the tank can meet all but the most demanding residential hot water loads. The larger tank capacity benefits are also realized in energy use. With a large storage capacity, the tank is able to heat water most of the time with the heat pump without resorting to the supplemental resistance elements.

- The flipside to having a large tank capacity is the large equipment size. At nearly 7' tall, the 80 gallon model could be a challenge to fit in certain locations. The air doesn't flow into or out of the top of the unit, however, so it can be installed near ceilings. The 60 gallon model is only 5'7" tall so may be more appropriate for space constrained installations. Both models have the same diameter.

- The design choice of a 2.0 kW bottom element, 4.5kW top element, and nominal heat pump capacity that can meet or exceed the bottom element output is aimed to provide energy savings. Further, the component selection and wrap-around condenser implementation provide high levels of efficient heat transfer. Additionally, the tank, despite its large size, has a relatively low heat loss rate for a HPWH.

- The operating modes on the equipment leverage the generous tank capacity to offer energy saving operation. The equipment is likely to use resistance heat only in very high demand applications because the rest of the demand can be met with stored capacity and the compressor. One mode not offered by the equipment is the simultaneous use of the upper element and compressor. This mode would provide maximum heat output while maintaining efficiency. The one consideration for this mode would be the maximum current draw from the equipment on the house circuit. 20A is typical for a water heater circuit so the current draw would be typically limited to that amount.

- To change the air filter a screw securing it to the heat pump shroud must be removed. This is only one screw but removing the filter is not simply as easy as sliding it out. This could lead to fewer owners cleaning the filter on a regular basis. The filter does slide out horizontally, however, so even with the tall top height of the unit, it is still possible to reach the filter.

- The control panel is simple and well laid out but the touch screen is not particularly responsive. The lab reported having to touch a button multiple times for it to be acknowledged.

- The airflow across the evaporator coil is surprisingly high. Other manufacturers are using significantly smaller flows for similar sized compressors. High air flows do optimize the heat transfer from the air but come at the expense of fan energy. A more efficient and lower volume fan could potentially increase the overall efficiency of the system.

- The operating range (45F-109F) and compressor performance of the Voltex is larger than either of the previously two tested models making it the most well suited for installations in the Pacific Northwest in buffered or semi-conditioned spaces.