ELECTRIC POWER RESEARCH INSTITUTE

Performance Test Results: CTA-2045 Water Heater

Testing Conducted at the National Renewable Energy Laboratory

3002011760

Performance Test Results: CTA-2045 Water Heater

Testing Conducted at the National Renewable Energy Laboratory

3002011760

Technical Update, November 2017

EPRI Project Manager

C. Thomas

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

THE ELECTRIC POWER RESEARCH INSTITUTE (EPRI) PREPARED THIS REPORT.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

ACKNOWLEDGMENTS

The Electric Power Research Institute (EPRI) prepared this report.

Principal Investigators
B. Seal
C. Thomas

This report describes research carried out at the National Renewable Energy Laboratory, under the INTEGRATE project Topic 1 focus area.

This report was developed based upon funding from the Alliance for Sustainable Energy, LLC, Managing and Operating Contractor for the National Renewable Energy Laboratory for the U.S. Department of Energy.

This publication is a corporate document that should be cited in the literature in the following manner:

Performance Test Results: CTA-2045 Water Heater: Testing Conducted at the National Renewable Energy Laboratory. EPRI, Palo Alto, CA: 2017. 3002011760.

ABSTRACT

Utilities and manufacturers are assessing the CTA-2045 communication standard, published by the Consumer Technology Association (CTA) (previously Consumer Electronics Association (CEA)) to determine the degree to which it meets the needs of consumers, aggregators, and utilities. The Electric Power Research Institute (EPRI) is facilitating a collaborative project specifically studying the extent to which CTA-2045 provides compatibility and interoperability with the wide range of systems into which consumer loads might be connected. If a modular interface works as intended, achieving interoperability and being self-installable by consumers, it could significantly advance the state of demand response worldwide. One of these systems is a Water Heater, and this report details laboratory evaluations of the system's capabilities.

Keywords
CEA-2045
CTA-2045
Water heater
Smart grid
Demand response
DR ready

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

In 2013 the Consumer Electronics Association[1] (now called the Consumer Technology Association) released the ANSI/CEA-2045 standard. This standard defines a modular communication interface intended to be designed into end-use loads to enable demand response (DR). The CEA-2045 standard has been described in detail in EPRI report 3002004020, *Introduction to the CEA-2045 Standard*[2].

Utilities and manufacturers are assessing this new standard to determine the degree to which it meets the needs of consumers, aggregators, and utilities. Electric Power Research Institute (EPRI) is facilitating a collaborative project that is specifically studying the extent to which CEA-2045 provides compatibility and interoperability with the wide range of systems into which consumer loads might be connected. If a modular interface works as intended, achieving interoperability and being self-installable by consumers, it could significantly advance the state of demand response worldwide. A detailed description of the CEA-2045 Field Demonstration project, including its goals and plan, has been provided in EPRI report 3002004009, *ANSI/CEA-2045 Field Demonstration Project Description*[3].

In addition to the field demonstration described above, the EPRI and a team of partners were selected by the National Renewable Energy Laboratory (NREL) to carry out a project to develop and test how smart, connected consumer devices can act to enable the use of more clean energy technologies on the electric power grid. This project was a component of the NREL Integrated Network Test-bed for Energy Grid Research and Technology (INTEGRATE) initiative and was awarded under RFP Number RCS-4-42326, Topic 1, "Connected Devices".

The project team includes the following end-use technologies and companies, each of which are market leaders in their fields. All of which were installed and tested at NREL's Energy Systems Integration Facility (ESIF) in Golden Colorado.

- Electric Vehicle Supply Equipment (Siemens)
- Thermostat (Emerson)
- Solar Inverter (Fronious)
- Pool Pump (Pentair)
- Water Heaters (AO Smith)

---

[1] Now known as the Consumer Technology Association.

[2] http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002004020

[3] http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002004009

Device-Type Specific Requirements for CTA-2045 Devices

The end-use devices (loads) tested in this project were all designed using device-type specific requirements. These requirements and links to each document are listed in Table 1-1. The requirements were created through a collaborative effort by which utilities and technology providers participated. The intent of these requirements is to provide guidance by which manufacturers of end-use devices, communication hardware, and other service providers could use to help create a predictable, interoperable, data rich architecture.

Table 1-1
Device-Type Specific Requirements

Document Name	EPRI Product ID
Demand Response-Ready Domestic Water Heater Specification, Preliminary Requirements for CEA-2045 Field Demonstration	3002002710
Demand Response-Ready Thermostat Specification, Preliminary Requirements for CEA-2045 Field Demonstration	3002002711
Demand Response-Ready Electric Vehicle Service Equipment Specification, Preliminary Requirements for CEA-2045 Field Demonstration	3002002712
Demand Response-Ready Heat Pump Water Heater Specification, Preliminary Requirements for CEA-2045 Field Demonstration	3002002719
Demand Response-Ready Variable-Speed Pool Pump Specification: Preliminary Requirements for CEA-2045 Field Demonstration	3002008320

The tests conducted at NREL were done so to measure the performance characteristics of each end-use device so that their potential to support the integration of renewables can be evaluated. This report includes include the results from tests performed on a water heater designed to meet the requirements defined in Demand Response-Ready Domestic Water Heater Specification, Preliminary Requirements for CEA-2045 Field Demonstration, .

2
WATER HEATER

This document presents the test results from the AO Smith resistive and heat pump water heaters. The same AO Smith controller is used for both products, making most behaviors identical, but there are some differences in relation to the power consumption and logic for running the heat pump.

Testing was performed at EPRI and at NREL during a series of onsite visits by team members.

The test plan that guided this testing has been documented separately.

Test Setup

Figure 2-1 shows the test setup used for the water heater testing at NREL. Each water heater was tested one at a time. All testing was conducted using a normal grid connection feeding the AC circuit. The NREL laboratory SCADA system included the following sensors and controls that were used in this test:

Real power consumption of the water heater

- Water flow rate
- Outlet water temperature
- Outlet Valve control

In addition, EPRI monitored the following directly from the water heater using the CEA-2045 Simulator software:

- Present power consumption
- Cumulative energy consumption
- Present energy-take capability
- Present operating state
- Consumer override

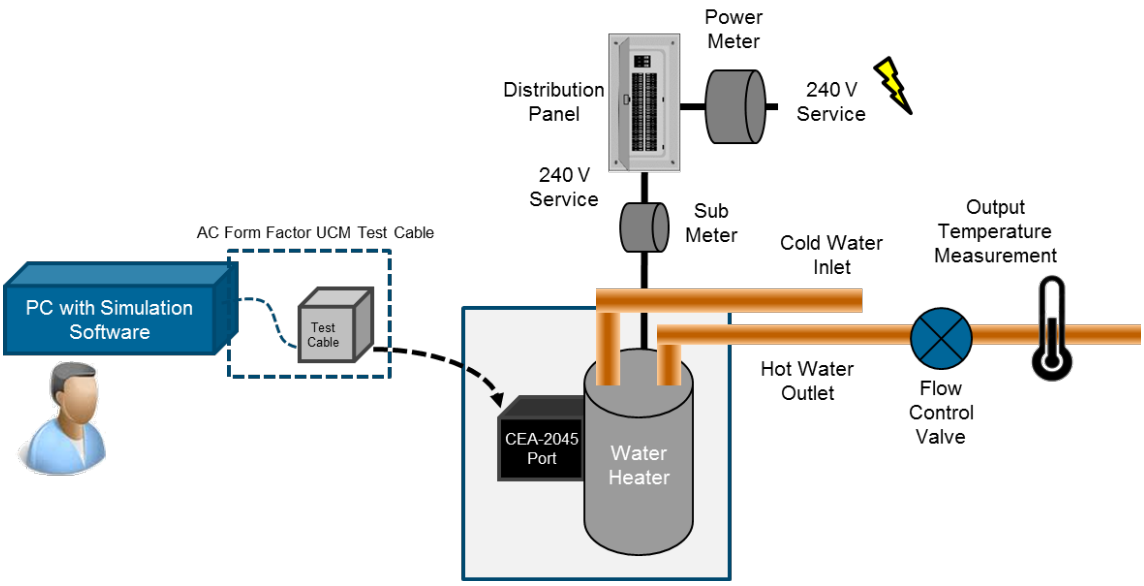

Figure 2-1
Water Heater Test Setup

Figure 2-2 shows the installed water heaters in the laboratory at NREL.

Figure 2-2
Resistive (left) and Heat Pump (right) Water Heaters at NREL

Figure 2-3 shows the plumbing connections and associated instrumentation for the heat-pump water heater. The control valve and flow rate sensor are visible in the top right corner of the picture. The outlet temperature sensor is located in the lower right portion of the picture.

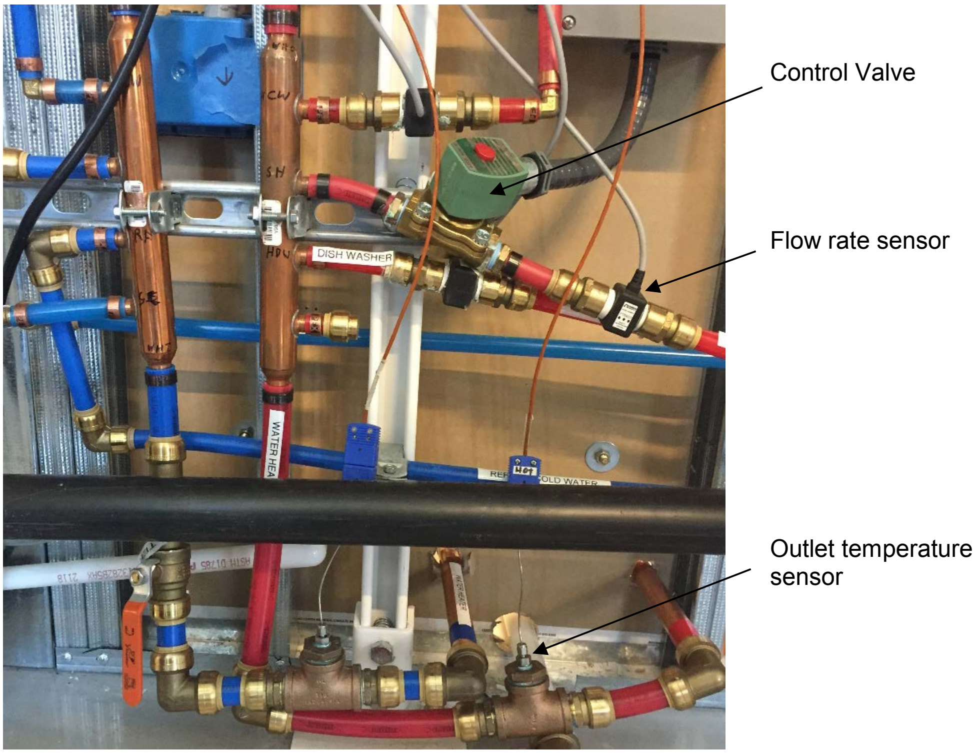

Figure 2-3
Water Heater Plumbing and Instrumentation

Device Identification

As indicated in Figure 2-1, the EPRI CEA-2045 Simulator software was used to communicate with the water heater, monitoring its status and managing its behavior throughout the test. This software is designed to plug-in directly to the CEA-2045 port interface at which communication modules would normally be connected.

The unit's identification was queried and reported as indicated in Figure 2-4. This includes a device-type code indicating "Water Heater – Electric", as well as a unique vendor ID, serial and model numbers. For the heat pump water heater, tested separately, this code reported as "Water Heater – Heat Pump".

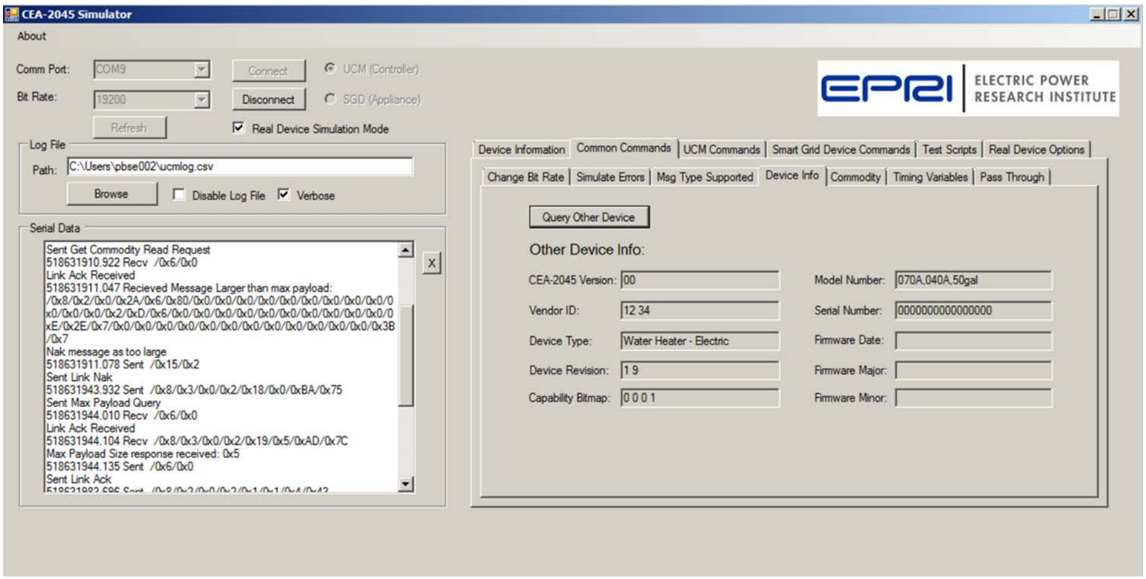

Figure 2-4
Communication Interface Showing Device Identification

Baseline Behavior

The CEA-2045 standard identifies four monitorable parameters that are of particular relevance to water heaters and were supported in the AO Smith units involved in this test:

- Present power consumption (an estimated value). The standard does not dictate how a manufacturer must make this estimation and it is not required that they reveal their approach. For a resistive water heater, for example, it could be assumed to be 0W when not operating and 4500W when operating.
- Cumulative energy consumption (based on the estimated power values)
- Total energy-take (energy storage) capability – a constant based on the water heater design.
- Present energy-take (energy storage) capability – a calculated value in Wh indicating how much energy the water heater can take at the present time.

Of these, the present energy-take parameter was of particular usage in the test plan. This is a readable quantity produced by the water heater. The exact algorithm for producing this estimated quantity is not defined by the standard and is left to the manufacturer. Because of the stratification of water temperature inside the tank, the outlet water temperature is a poor indicator of the state of charge of the system, and not useful as an indicator of the unit's present condition or ability to absorb energy.

Because the resistive and heat-pump water heater designs share the same communication interface adapter, many of the functional behaviors are the same. In this report, the test results for the resistive water are provided first and in greater detail, then additional data is provided to show the different behavior of the heat-pump water heater.

The baseline behavior of the resistive water heater is shown in Figure 2-5. Water draws were performed at two different flow rates. In each case, the water heater's energy-take capability (this parameter is read from the water heater through the communication interface) can be seen rising until the heater turns on. The exact level at which this occurs is under the control of the manufacturer's algorithm and represents the normal control band for the unit.

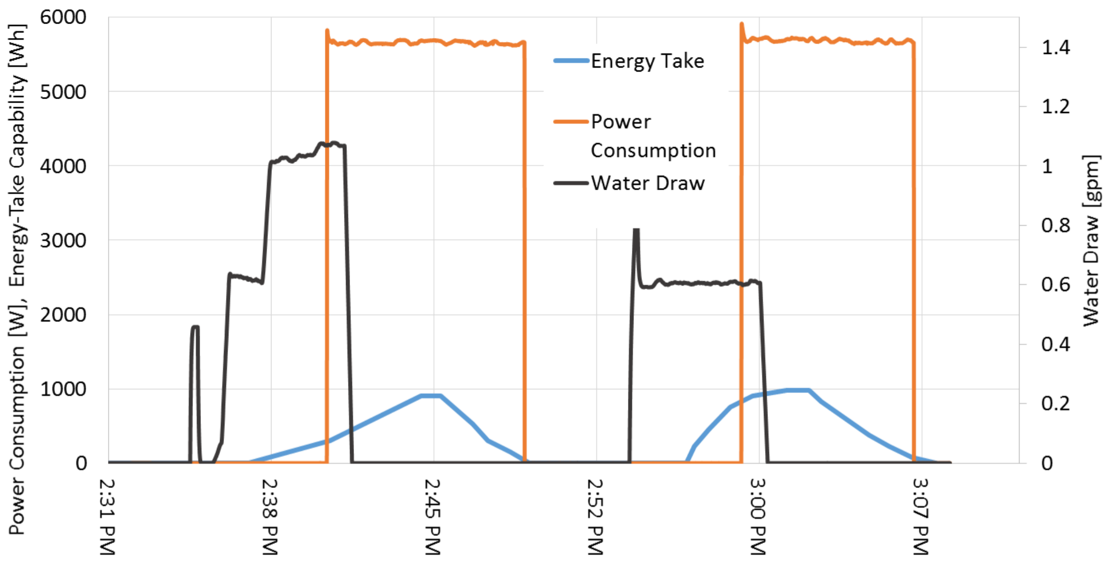

Figure 2-5
Resistive Water Heater Baseline Behavior

As indicated in the figure, the point at which the water heater turned on depended on the flow rate, notionally due to differences in the circulation patterns of water in the tank. At higher draw rates (1[gpm] or more) the unit turned on when the energy take reading was around 300[Wh]. At 0.6[gpm] this occurred at around 600-800[Wh] and at lower flow rates (not shown in this figure) the units turned on when the energy-take capacity was around 900[Wh].

In all cases, once the unit turned on, it remained on until the energy-take capability was zero (fully heated).

Visual Indicators

The water heaters included LED visual indicators as shown in Figure 2-6 on the resistive and heat pump water heaters.

Communicating: This indicator is illuminated based on the communication status messages delivered to the water heater from the communication system. If lit, this indicates that communication through to the headend system is good.

Grid Controlled: This indicator is illuminated when a control or event is in effect that alters the water heater's normal mode of operation in any way.

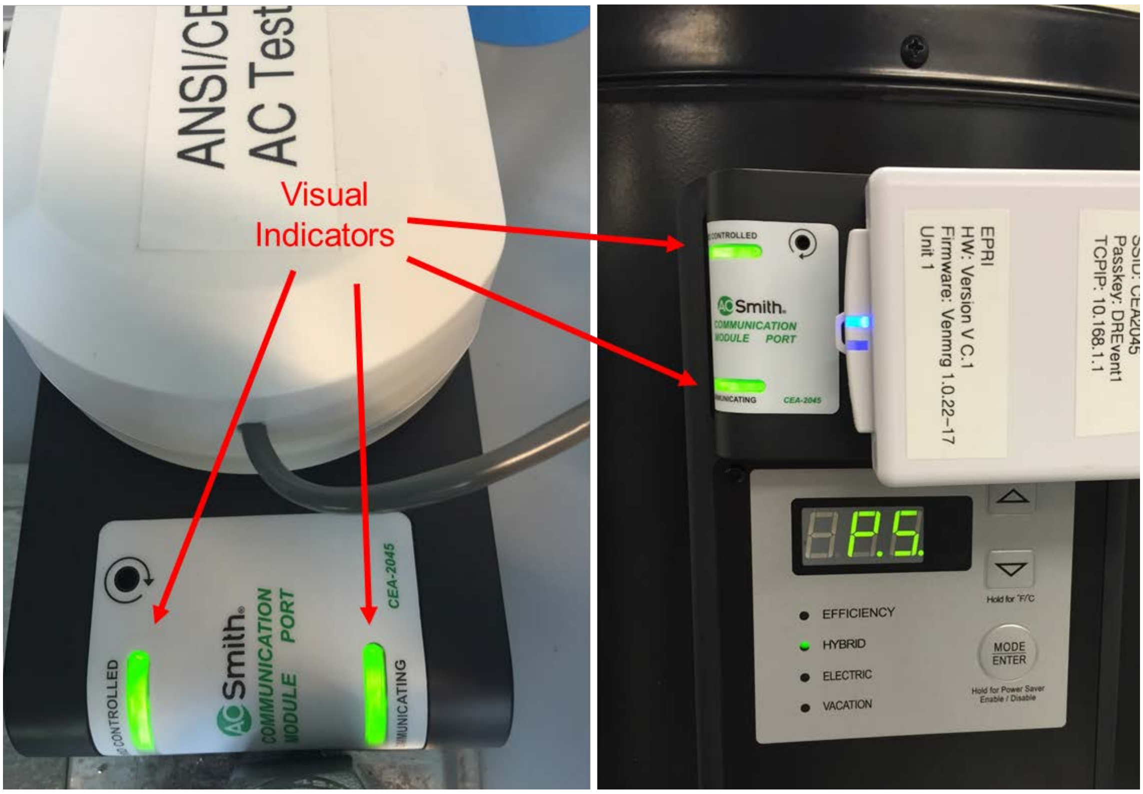

Figure 2-6
Visual Indicators on Resistive Water Heater (left) and Heat Pump Water Heater (right)

Shed Event

The results from the testing of the water heater's basic "Shed" function are summarized in Figure 2-7. This test was conducted on June 7th, 2016. The Shed event was sent with a 4 hour duration, but terminated manually once the behaviors were observed.

To the left side of the figure, prior to calling the Shed event, the water heater can be seen running in a normal mode of operation for reference. A water draw was performed and the unit turned on and returned to a topped-off state by 3:06 PM.

At 3:10PM, a basic "Shed" event was initiated. This event leaves the water heater in control, and requests that it reduce energy consumption as possible, but with vendor-selected protections for consumer comfort.

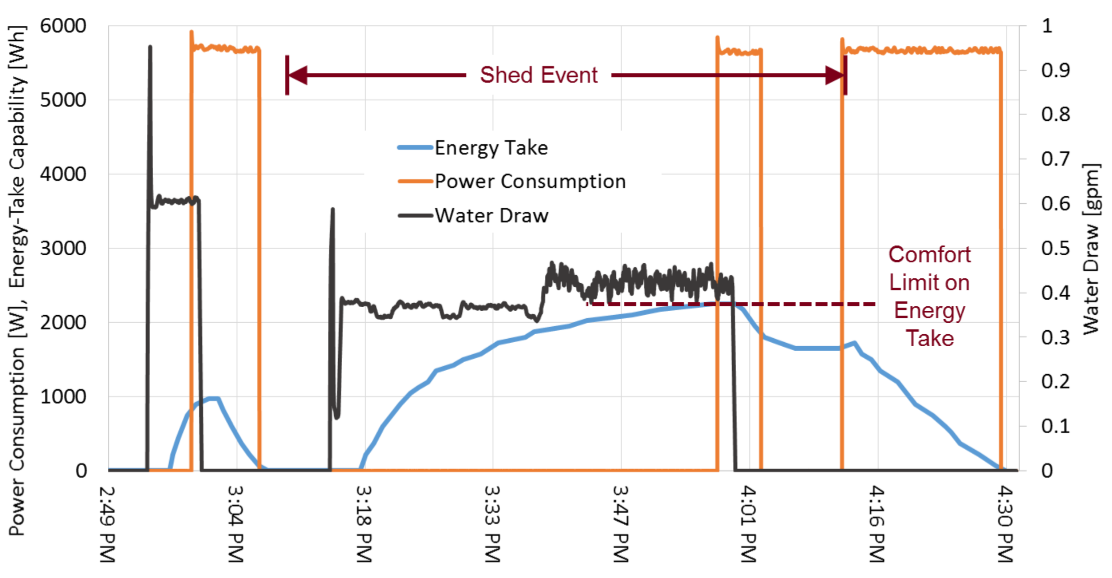

Figure 2-7
Shed Event

Slow water draw was initiated at 3:14PM. The Energy-Take parameter was monitored and can be seen to rise to 2250[Wh] before the water heater turned on at around 3:55 PM. Water draw was terminated after the unit turned on. The unit operated just long enough to recover to below 2000[Wh] of Energy-Take capability and turned off. This behavior is a key aspect of the project – using curtailment events ahead of periods in which excess solar energy exists so that there is more opportunity to locally take/use the solar energy. For example a remote utility DR system could curtail water heaters during the morning showering/use period so that they do not reheat right away. Then at midday when there is excess solar generation, the DR system could terminate the curtailment events, allowing the water heaters to reheat and utilize the excess solar energy.

At 4:12 PM the Shed event was terminated manually by sending a command through the CEA-2045 communication interface. Immediately, the water heater returned to normal operation, turning on and reheating the tank to the fully-heated state.

A calculation can be performed from this recovery to assess the water heater's self-estimation of Energy-Take capability. At the time that the Shed event was terminated, the Energy-Take value was 1650[Wh]. The SCADA system indicated that the unit then drew ~5660[W] from 4:12:17PM until 4:30:06 PM. 5560[W] * 0.297[Hours] = 1651[Wh]. In this particular case, the estimation was accurate, but in general it is known to be a rough estimation (many variables and uncertainties) that is of most use when averaged across a large number of water heaters.

Determining how much to curtail during an event is a matter of ongoing discussion. Stakeholders agree that ensuring consumer comfort is the highest priority in order to increase participation in advanced grid programs, and if a consumer has a 50 gallon water heater, they likely do not want the effective heated water to be substantially less due to a grid event. The energy-take value of 2250[Wh] noted in this test is an initial choice of the manufacturer, not specified in any standard, and could be changed to something more or less aggressive as more field experience with hot water heaters is gained.

Critical Peak Event

The results from the test of the water heater's "Critical Peak" function are summarized in Figure 2-8. This test was conducted on June 7th, 2016. The Critical Peak event was sent with a 6 hour duration, but terminated manually once the behaviors were observed.

The starting conditions are indicated at the left side of the chart, with the water heater in a fully-heated mode (energy-take capability near zero), the unit off, and no water draw.

At 5:11PM, a "Critical Peak" event was initiated. As with all CEA-2045 messages, this event leaves the water heater in control, and requests that it reduce energy consumption as possible, but with vendor-selected protections for consumer comfort. By definition in the CEA-2045 standard, Critical Peak events are distinguished from Shed Events only in that they are intended to be used only a few times a year (in association with Critical Peak DR programs) and therefore may result in a more aggressive response by the end-device manufacturer. In the case of the AO Smith water heater, the response to a Critical Peak event is seen to be slightly more aggressive than the response to a regular curtailment/Shed event.

Immediately following the initiation of the event, water draw was started and continued at a low rate until the unit turned on at 6:03 PM. At this time, the water heater reported its Energy-Take capability as 2475[Wh].

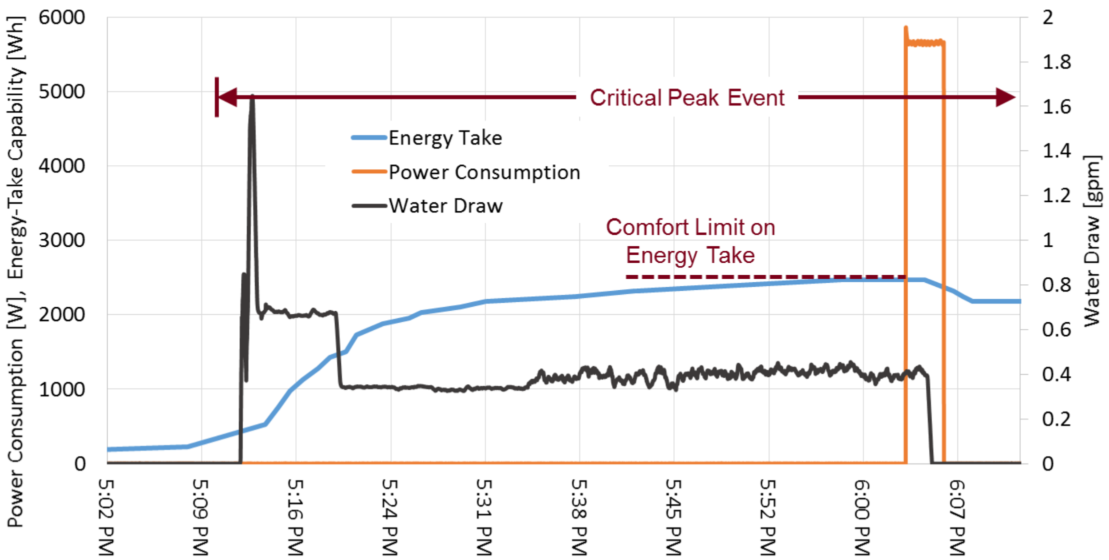

Figure 2-8
Critical Peak Event

When the unit turned on, it operated for 3 minutes, recovering until its reported Energy-Take level was 2175[Wh].

Consumer Override

Although not a functional requirement in terms of enabling more solar generation on the grid, consumer override is considered a required feature in order to ensure that the consumer is in control and to encourage program participation.

The results of the consumer override test are summarized in Figure 2-9. This test was performed on June 7th, 2016, immediately following the Critical Peak test. The starting conditions can be seen at the left side of the chart. A Critical Peak event was already in effect and remained so throughout the test. Accordingly, the unit was in a curtailed mode of operation, and as indicted at the center of Figure 2-9 was operating as required to sustain at a reduced level of thermal energy storage with an Energy-Take parameter of approximately 2200[Wh]. Specifically, the water heater can be seen top turn on at about 6:03PM while the event was in effect, but it only operated for 2-3 minutes instead of continuing to reheat the tank.

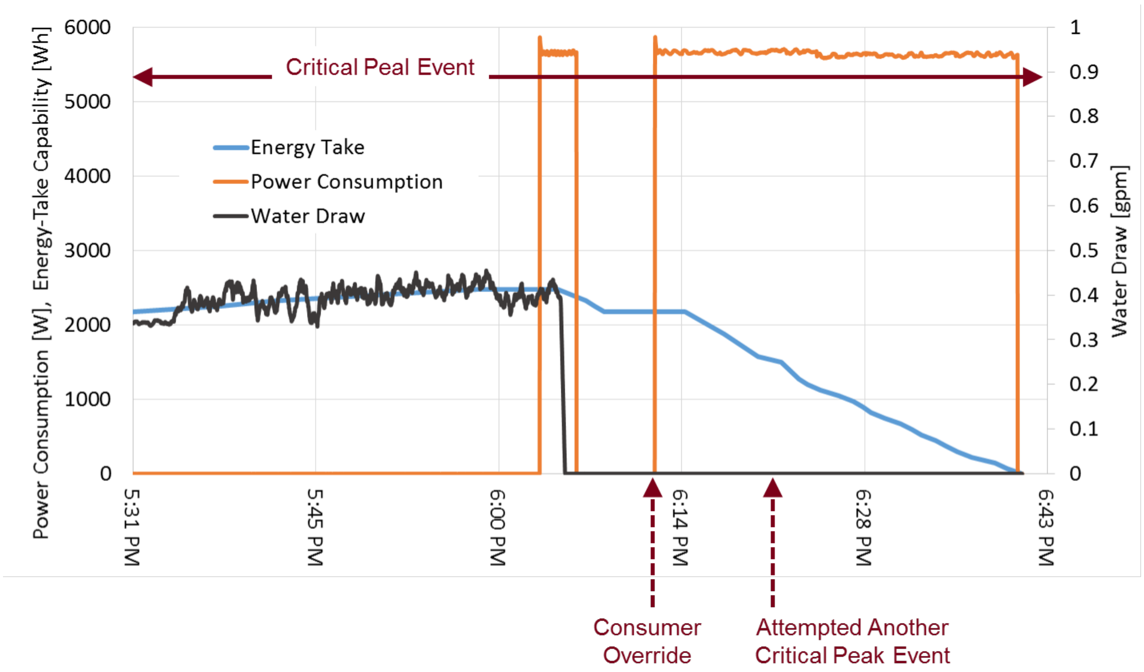

Figure 2-9
Consumer Override

At 6:12PM, a consumer override was initiated at the water heater by disabling the "Grid Enabled" mode. This is done by pressing the "Grid Enabled" button on the user interface as shown in Figure 2-11. When the Consumer Override was initiated, the water heater immediately turned on and operated normally, returning the unit to a fully-heated state. When this occurred, the water heater performed an unsolicited notification over the communication interface as indicated in Figure 2-10.

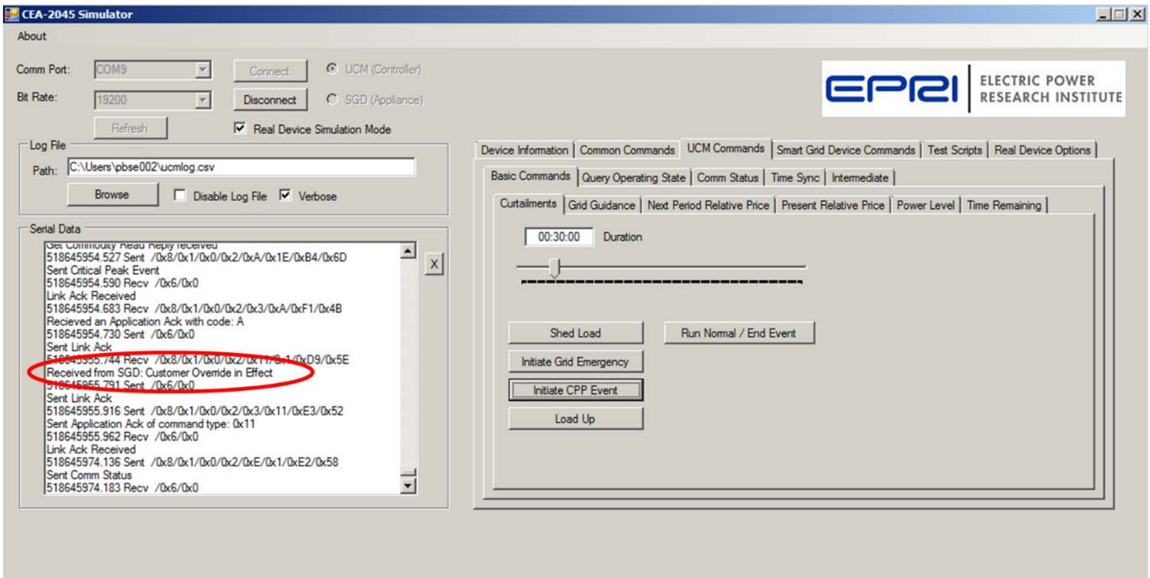

Figure 2-10
Communication Interface Showing Consumer Override

This recovery period provided another opportunity to assess the self-calculated Energy-Take parameter. At 6:12PM the value read was 2175[Wh]. This dropped linearly to zero at 6:41PM, or 0.483 hours. During this time, 5660[W]*0.483[hours] = 2733[Wh] was used to recover, indicating that in this case the energy-take estimate was ~ 20% low.

Figure 2-11
Water Heater User Interface

Load Up Event

The results from the testing of the water heater's "Load Up" function are summarized in Figure 2-12. This test was conducted on June 8th, 2016. The Load Up event was sent with an 8 hour duration, but terminated manually once the behaviors were observed.

To the left side of the figure, prior to calling the Load Up event, the water heater was operating in a normal mode of operation for reference. The tank was near topped-off, not heating, and reporting approximately 300[Wh] of Energy-Take capability.

At 8:54 PM, a basic "Load-Up" event was initiated. The intended response to this event is the opposite of a Shed command, instructing the water heater to use/take energy to the extent that it can do so productively and safely.

As expected, the water heater turned on immediately when the Load Up event was initiated. This occurred even though the reported Energy-Take value was only around 300[Wh]. The water heater continued to operate to hold the tank aggressively near a fully-heated state during the Load-Up event.

It is noted that this manufacturer does not increase the temperature setpoint during a Load-Up event due to safety concerns, although such responses are desirable from a grid perspective. There are different opinions among water heater manufacturers regarding what is allowed by UL and what is acceptable to consumers for this type of event.

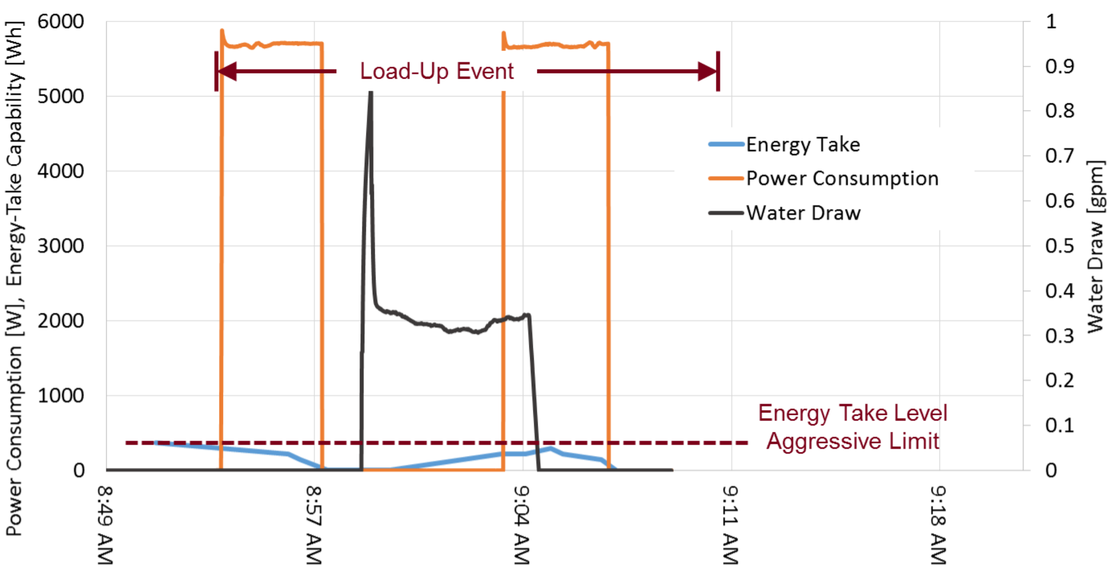

Figure 2-12
Load-Up Event

Autonomous Cycling

The autonomous cycling mode is used to spread responses over a longer period of time. For example, instead of keeping a water heater completely off until an event is over, or completely on until tank-temperature has recovered, the duty cycle mode allows variable levels of operation over time. The autonomous cycling function works in such a way that the end device cycles itself on and off throughout the control period to meet the specified duty cycle, hence the description as “autonomous”.

The results from the testing of the water heater’s “Autonomous Cycling” function are summarized in Figure 2-13. This test was conducted on June 8th, 2016. The Autonomous Cycling event was sent with an indefinite duration, but terminated manually once the behaviors were observed. Note: the autonomous cycling command format includes start time references and requires that the “Set UTC time” command be used prior in order to setup the water heater.

The starting condition was a fully-heated tank as indicated by the low “Energy-Take” value at the left of the chart. Water draws were performed as required during the cycling test in order to keep the unit at an intermediate state – neither fully heated nor at the point where operation is mandatory in order to protect consumer comfort.

The CEA-2045 Autonomous Duty Cycling function allows for any whole number (0-100%) to be sent to the end device, but manufacturers may round the received value to a lower granularity in their response algorithm.   In this test, the Autonomous Cycle command was sent for a 10% duty-cycle. The water heater manufacturer independently selected the period of cycling as one hour. Per the CEA-2045 standard, and duty cycle percentage can be requested, but manufacturer's internal logic may limit behavior to certain rounded values.

The data in Figure 2-13 shows the unit cycling through three periods, with 6 minute on-time and 60 minute cycle time for each. A stop-cycling message was sent at 2:06PM while the unit was in an off state. Immediately the unit returned to normal operation, turning on and fully heating the tank.

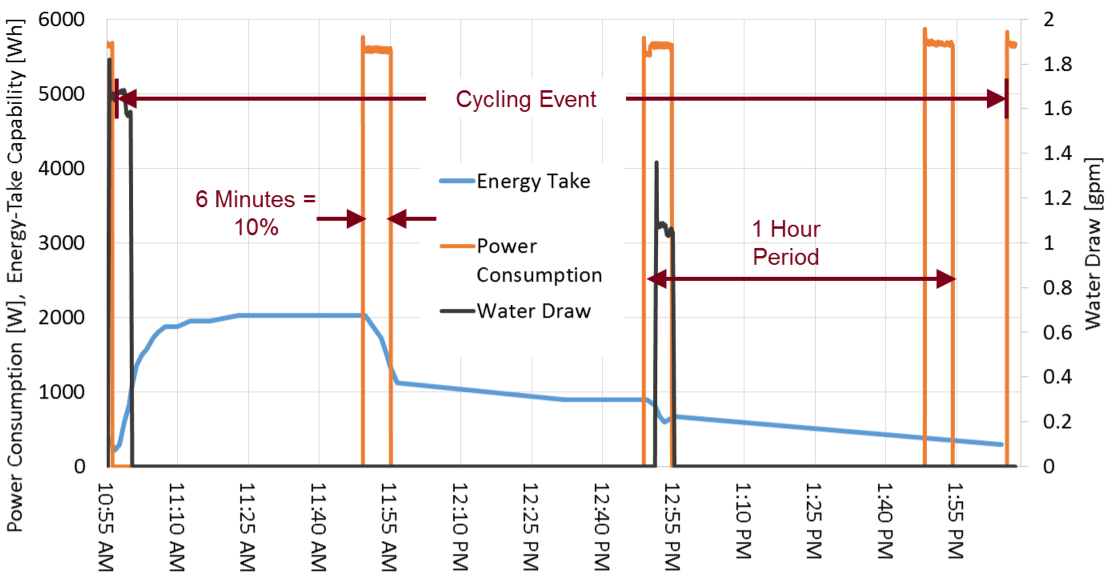

Figure 2-13
Autonomous Cycling Event

Loss of Communication

Although not a control function, this project included a verification that the water heaters would return to normal operation in the event that communication to the remote control system is lost. In the CEA-2045 standard, communication modules are required to provide the end device with a communication status message at least once every 5 minutes. The water heater design was such that if three periods pass (15 minutes) without successful notification, the unit will terminate active controls and return to normal operation.

The results are shown in Figure 2-14. While a curtailment control event was in effect, the EPRI software was used to halt sending the "Communication Good" status indicator at around 2:13PM. 15 minutes later, the water heater turned on and proceeded to fully reheat the tank even though the event had not timed-out and the thermal conditions inside the tank had not reached the manufacturer's consumer comfort limits.

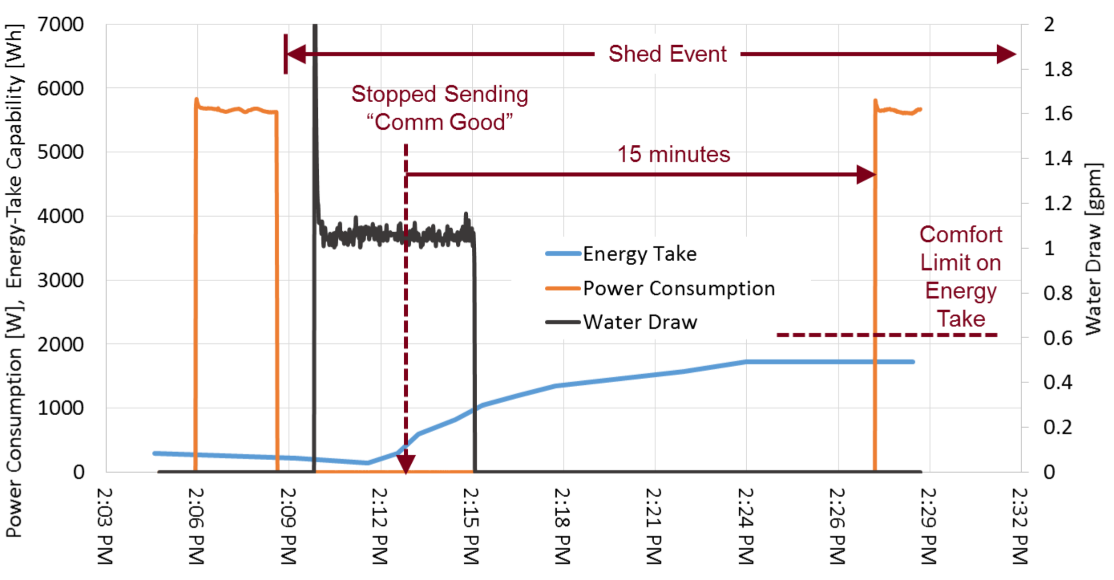

Figure 2-14
Communication Loss Timeout

Heat Pump Water Heater

The AO Smith heat pump water heater shared the same controller as the resistive water heater and behaved largely the same way. Two differences were noted and are illustrated in Figure 2-15.

The heat pump water heater has two modes of heating, heat pump and resistive. The heat pump component draws approximately 500[W] and the resistive approximately 4500[W]. When during a Shed event the unit reaches the consumer comfort limit, the water heater turns on both of these heating sources, doing everything possible to sustain at that level. This can be seen at time = 7:22 in Figure 2-15 where the total energy consumption is 5000[W].

Once the water heater recovers enough to sustain comfort, the resistive element turns off, but the heat pump remains on. This can be seen at time = 7:28 where the energy consumption dropped from 5000[W] to 500[W]. Heat pump operation then continued until the self-assessed Energy-Take value was around 600[Wh]. Although this behavior substantially reduces the energy consumption level during the Shed event, it eliminates the reserved energy-take capability that the Shed event might have been attempting to create. For example, if a Shed event is called during the morning in order to prepare for excess midday solar generation, the continued heat pump operation would eliminate much of the storage opportunity prior to the time that the storage is needed.

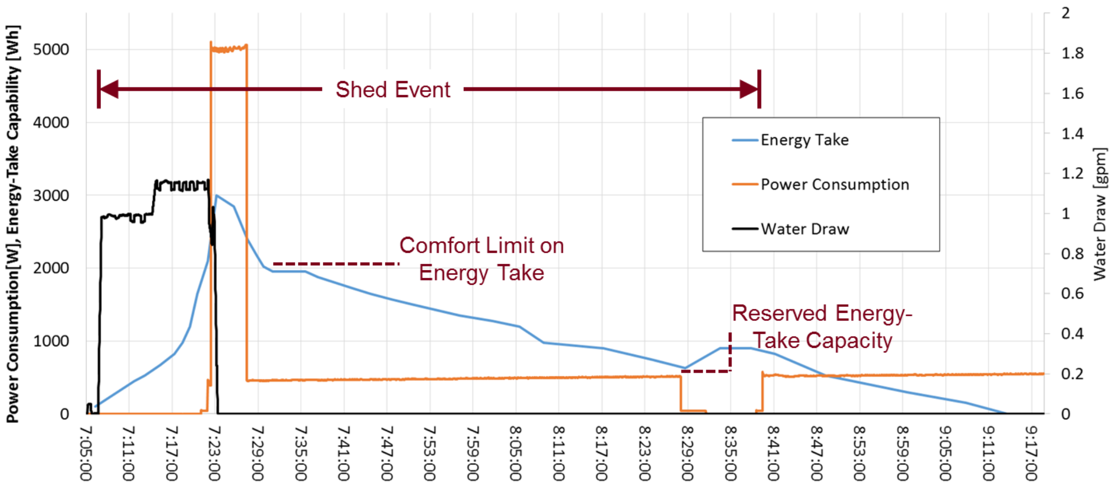

Figure 2-15
Heat Pump Water Heater with Shed Event

Conclusions

The AO Smith water heaters passed all the tests and are generally able to perform the services required by this project. As noted, the heat-pump water heater had the undesirable feature of continuing heat pump operation (reduced power) during curtailment events until the energy-take capability was substantially reduced.

The most useful way to characterize the condition of the water heater turned out to be through the "Energy-Take" parameter which could be read from the water heater at any time through the communication interface. The stratification of temperature in the tank made outlet water temperature quite useless in terms of indicating the state of the system.

Table 2-1
Water Heater Condition as Characterized by Energy Take Levels

	Energy Take Levels [Wh]		
Event	**Control Minimum**	**Control Maximum**	**Comments**
Normal Operation	0	900	Minimizing wear on controls.
Shed	2000	2200	Manufacturer's chosen limit for consumer comfort.
Critical Peak	2200	2500	Slightly more curtailment, less frequent events.
Load-Up	0	300	Tighter control to a fully-heated condition.
Duty Cycling	0	2200	Same comfort limit as a "Shed" event.

Working together with the other smart end devices, these services can enable the grid to accommodate more renewable energy. Achieving this outcome will require communication and control systems that can successfully connect to end devices and manage their behavior in a cohesive fashion. Such systems may also have wide-area awareness, making it possible for devices in one location to act in such a way as to address issues elsewhere that are not locally visible.

The AO Smith water heaters supported the functionality noted in this document using an open standard communication interface based on the CEA-2045 standard.

3002011760

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com