Demand Response Capabilities of a Residential Clothes Washer

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ABSTRACT

Achieving the goals of the Smart Grid will require deployment of a wide array of communicating devices, enabling utilities to better manage energy use across the electric grid. In the residential sector, Smart Appliances are the key to realizing the full potential benefits of the Smart Grid. These appliances not only achieve the highest levels of energy efficiency during normal operation, but also are capable of responding to Demand Response (DR) events – where utilities need to drop electric load during critical peak pricing periods and grid reliability events. Appliance manufacturers have embraced this functionality and are just beginning to release their first DR-capable products.

This paper shares results from an on-going laboratory evaluation of the DR potential of various Smart Appliances (dishwashers, clothes washers, and refrigerators) from several manufacturers. Testing will capture each device's reaction to DR events, initiated during the various stages of its operation. Unfortunately, standardized test methodologies to quantify the benefits of Smart Appliances have not yet been fully developed by the industry, or other interested stakeholders, even though their value is widely recognized. A discussion of the creation of test methods used in this investigation is included.

Introduction

In response to major electrical grid failures over the past few decades, coupled with the emergence of widespread renewable generation and increased awareness of energy efficiency, there has been a growing push for an electric "Smart Grid". The Smart Grid is envisioned to employ vast networks of communicating equipment that will enable much improved visibility and control over how and when we consume energy. While utilities have taken the lead on the smart meter and upstream components of the transmission and distribution system, progress has been slower on the customer side of the meter. In order to fully take advantage of the Smart Grid, energy consumers need access to equipment and appliances that enable communication of rates and grid conditions, and offer integrated control capabilities to respond to the information received.

In the residential space, a combination of Smart Meters, Home Area Networks (HANs) with energy supervisory software, and Smart Appliances will be needed to achieve a true Smart Grid. Several appliance manufacturers have begun implementing advanced control features into their products that are specifically focused on energy reduction and the ability to react to adverse grid conditions. Demand Response (DR) is one of the capabilities included in these "Smart Appliances."

What is Demand Response?

Conceptually, DR functionality allows a customer to drop load in two situations. The first is at peak times in response to a utility signal indicating that the grid may experience critical reliability issues. These may take the form of day-ahead, same day, or instantaneous DR events. The second allows a customer to optimize its energy usage profile under time-of-use energy tariffs, which are becoming mandatory for certain utility customers. Many utilities already offer rebates for customers participating in DR events. (SCE 2011)

The DR capability allows the electric utility to send a signal to a customer's Smart Meter requesting a reduction in connected load. The DR signal is then re-broadcast from the Smart Meter to the Smart Appliances, either directly or through a HAN, which react by reducing load as much as possible. Smart Appliances have algorithms built into them that determine whether they can respond to the signal, and to what extent, while maintaining a minimal level of service to the consumer.

Several appliance manufacturers have recently developed DR-capable products, but little is known about how DR capabilities will be implemented. This project seeks to evaluate DR capabilities of various residential Smart Appliances in a laboratory environment. This testing will give Southern California Edison (SCE) a better understanding of how specific appliances will react to certain DR signals before they are installed at customer sites.

The overarching DR Appliance project is aimed at three types of residential appliances: refrigerators, dish washers, and clothes washers. This report is focused on a clothes washer from a single manufacturer. Testing of additional appliances is on-going and may be included in the conference presentation.

Background

In 2010, joint petitioners to the US Department of Energy (DOE) (including the Association of Home Appliance Manufacturers (AHAM)) proposed a guideline (AHAM et al. 2011) for defining "Smart Appliances", which included implementation of DR strategies.

The guideline defines a Smart Appliance as:

> *"…a product that uses electricity for its main power source which has the capability to receive, interpret and act on a signal received from a utility, third party energy service provider or home energy management device, and automatically adjust its operation depending on both the signal's contents and settings from the consumer. The product will be sold with this capability, which can be built-in or added through an external device that easily connects to the appliance. The costs of such devices shall be included in the product purchase price.*
>
> *"These signals must include (but are not limited to) appliance delay load, time-based pricing and notifications for load-shedding to meet spinning reserve requirements. Any appliance operation settings or modes shall be easy for an average, non-technical consumer to activate or implement. Additionally, a smart appliance or added device may or may not have the capability to provide alerts and information to consumers via either visual or audible means. The appliance may not be shipped with pre-set time duration limits that are less than those listed below, but may allow consumer-set time duration limits on smart operating modes, and will also allow consumers to override any specific*

mode (e.g. override a delay to allow immediate operation, limit delays to no more than a certain number of hours, or maintain a set room temperature)." (AHAM et al. 2011)

DR Event Definitions

The document breaks DR into 2 specific types of events: Spinning Reserve and Delay Load. They are differentiated by the event duration characteristic that accompanies the DR signal. DR events with duration of 10 minutes or less are categorized as Spinning Reserve while those lasting 10 minutes to 4 hours are categorized as Delay Load. A particular appliance's ability to reduce load depends on the type of signal received as well as its operational status when the signal is received. Currently, only durational DR signals are sent by the utility. However, it is envisioned that in the future time of use (TOU) price signals will be sent, thus allowing the Smart Appliance to optimize performance based on total cost of operation.

As an overarching requirement, the DR capable appliances must still be able to provide consumers the anticipated value of their operation without detrimentally affecting performance. For example, a DR capable clothes washer should still be able to clean the clothes and not damage them by enacting a DR event. Similarly, a refrigerator must maintain safe temperatures even though it is responding to a DR event. In most cases, short interruptions of appliance operation would not significantly affect performance.

Clothes Washer Definitions

The document further defines minimum requirements for each type of appliance. For clothes washers, it requires:

- *"Delay load capability - upon receipt of a signal requesting a delay of load for a time duration not exceeding either 4 hours or such other period that the consumer may select, the product must automatically delay the start of the operating cycle beyond the delay period, and*
- *"Spinning reserve capability - upon receipt of a signal requesting the start of a reduced load period for a time duration not exceeding 10 minutes, the product must automatically reduce its average wattage during this time period by at least 50 percent relative to average wattage during this period in the operating cycle under DOE test conditions."* (AHAM 2011)

Objectives

The goal of this project is to observe the clothes washer's response to DR signals and quantify the demand reduction that can be expected during different portions of the wash cycle.

The four main objectives for this project are:

- Observe and quantify response when Spinning Reserve DR signal is received during each of the stages of the wash cycle
- Observe and quantify response when Spinning Reserve DR signal is received for various water temperature settings

- Observe and quantify response when Spinning Reserve DR signal is received for various clothing loads
- Observe and quantify response when Delay Load DR signal is received during the wash cycle and in between wash cycles

Technical Approach

The manufacturer supplied a prototype DR-capable clothes washer for testing. The product is based on a commercially available model, with the addition of an LCD user interface, Zigbee® communication hardware, and an integrated smart control system.

At a high level, the manufacturer claimed the DR algorithms programmed into the clothes washer aimed at performing the following tasks:

- For Spinning Reserve events, all washer operations would immediately cease until the event cleared (thus reducing energy by greater than 50% during the DR period, as required by the AHAM guideline).
- For Delay Load events, it would allow any wash cycle in-progress to finish, then delay any subsequent wash cycle until the event had cleared.

If they function as desired, both of these algorithms meet the requirement of the AHAM guideline.

The scope of tests both verifies the functionality of these algorithms and provide quantification of the DR potential during various phases of operation. Testing was conducted in a laboratory environment in SCE's Technology Test Centers. This enables repeated testing of the appliance using identical loads in controlled environment conditions, including control of the DR signal characteristics. Thus, the influence of uncontrolled variables is minimized. Furthermore, existing data acquisition equipment could be utilized with little infrastructure investment.

Following a series of discussions between the manufacturer and SCE, a comprehensive document was compiled to document the control algorithms implemented to meet the Smart Appliance requirements for clothes washers. Subsequently, a test plan was developed to monitor the washer's performance under various baseline operating conditions as well as in response to DR events. The DR test scenarios were geared toward validating the intended operation algorithms rather than being a comprehensive demonstration of ALL potential DR event situations.

Test Plan

The test plan was loosely modeled after Appendix J1 of 10 CFR 430 Subpart B, the DOE Uniform Test Method for Measuring the Energy Consumption of Automatic and Semi-Automatic Clothes Washers (DOE, 2011). However, because the goal here was determining DR potential rather than quantifying energy performance, compliance was limited to instrumentation and general appliance installation and testing practices.

The Unit Under Test (UUT) was installed in TTC's controlled environment room 1. Hot and cold water were supplied and a standpipe configuration was established in a neighboring floor drain.

A set of baseline tests were intended to capture data on normal wash cycle based on different clothing fill levels and wash water temperatures (Table 1, Tests A thru E). Test F was designed to activate the UUT's 1,000 W internal heater by creating a need for hot water, but only supplying cold water.

Table 1. Baseline Test Scenarios

Scenario	Description	Clothing Fill Level	Wash Water Temp	Rinse Water Temp
A	Baseline A	Full	Cold	Cold
B	Baseline B	Full	Warm	Cold
C	Baseline C	Full	Hot	Cold
D	Baseline D	2/3	Cold	Cold
E	Baseline E	1/3	Cold	Cold
F	Baseline F (no HWS, only CWS)	Full	Hot	Cold

Source: SCE

Clothing was replicated using uniform white cotton cloths. A full load was determined to be 10.6 lbs by completely filling the UUT washtub volume with dry unpacked cloth. The 2/3 and 1/3 loads were 7.1 lbs and 3.5 lbs, respectively. The cloth was dried between wash tests.

The test plan called for water temperature to be maintained at 135±5°F (Hot), 90±5°F (Warm), and 60±5°F (Cold) with water pressure at 35±2.5 psig. The wash settings used were: Material – Cotton/Normal, Soil Level – Normal, Spin – High. While many more settings were available, testing every permutation would have vastly increased the time and effort needed to complete this project. The selected settings are believed to represent the most commonly used settings in normal operation, thus the most probable condition during a real DR event.

A second set of tests was designed to capture the clothes washer's reaction to Spinning Reserve and Delay Load events initiated during various portions of the wash cycle and with various wash conditions (Table 2). The corresponding baseline for each DR test is indicated in the table. Figure 1 in the Results section details the loads observed in each portion of a typical wash cycle.

A laboratory version of SCE's Smart Meter was used to generate the DR signals, which were wirelessly communicated to the clothes washer via Zigbee® interface. Software allowed the test technician to control all of the signal characteristics, including event duration. The Spinning Reserve signal contained a duration code for 8 minutes, while the Delay Load signal duration was 60 minutes. The test period was considered to be the length of the entire wash cycle, except for the Delay Load tests which were focused on verifying functionality of the algorithms. (Delay Load scenarios merely shift the entire wash cycle until the time the DR event clears, thus the actual wash performance is identical to what is seen in baseline Test A.)

Table 2. DR Test Scenarios

Designation	Baseline	Scenario	Clothing Fill Level	Wash Water Temp	Rinse Water Temp
Spinning Reserve Event (duration = 8 min)					
G	A	DR initiated during fill	Full	Cold	Cold
H	A	DR initiated during wash cycle	Full	Cold	Cold
I	A	DR initiated during drain	Full	Cold	Cold
J	A	DR initiated during rinse	Full	Cold	Cold
K	A	DR initiated during spin	Full	Cold	Cold
L	D	DR initiated during spin	2/3	Cold	Cold
M	E	DR initiated during spin	1/3	Cold	Cold
N	C	DR initiated during fill	Full	Hot	Cold
O	C	DR initiated during rinse	Full	Hot	Cold
S	C	DR initiated during spin	Full	Hot	Cold
R	F	DR initiated during heater on	Full	Hot	Cold
U	A	DR memory test – turn off smart grid function, start wash cycle, initiate DR event, turn on smart grid function	Full	Cold	Cold
Delay Load Event (duration = 60 min)					
P	A	Delay Load event initiated between wash loads	Full	Cold	Cold
Q	A	Delay Load event initiated during wash load	Full	Cold	Cold
T	A	Delay Load event initiated during wash load, attempt to start new load afterward	Full	Cold	Cold

Instrumentation and Data Analysis

Data was collected on 21 channels every 10 seconds. Table 3 lists all of the points used to monitor performance of the UUT. All sensors were calibrated to NIST-traceable standards prior to installation.

Table 3. Monitoring Points

Ambient temperature (10 channels)	Hot water inlet temperature	Total power
Cold water inlet temperature	Hot water inlet pressure	Pump power
Cold water inlet pressure	Hot water inlet flow	Motor power
Cold water inlet flow	Clothing weight	Heater power

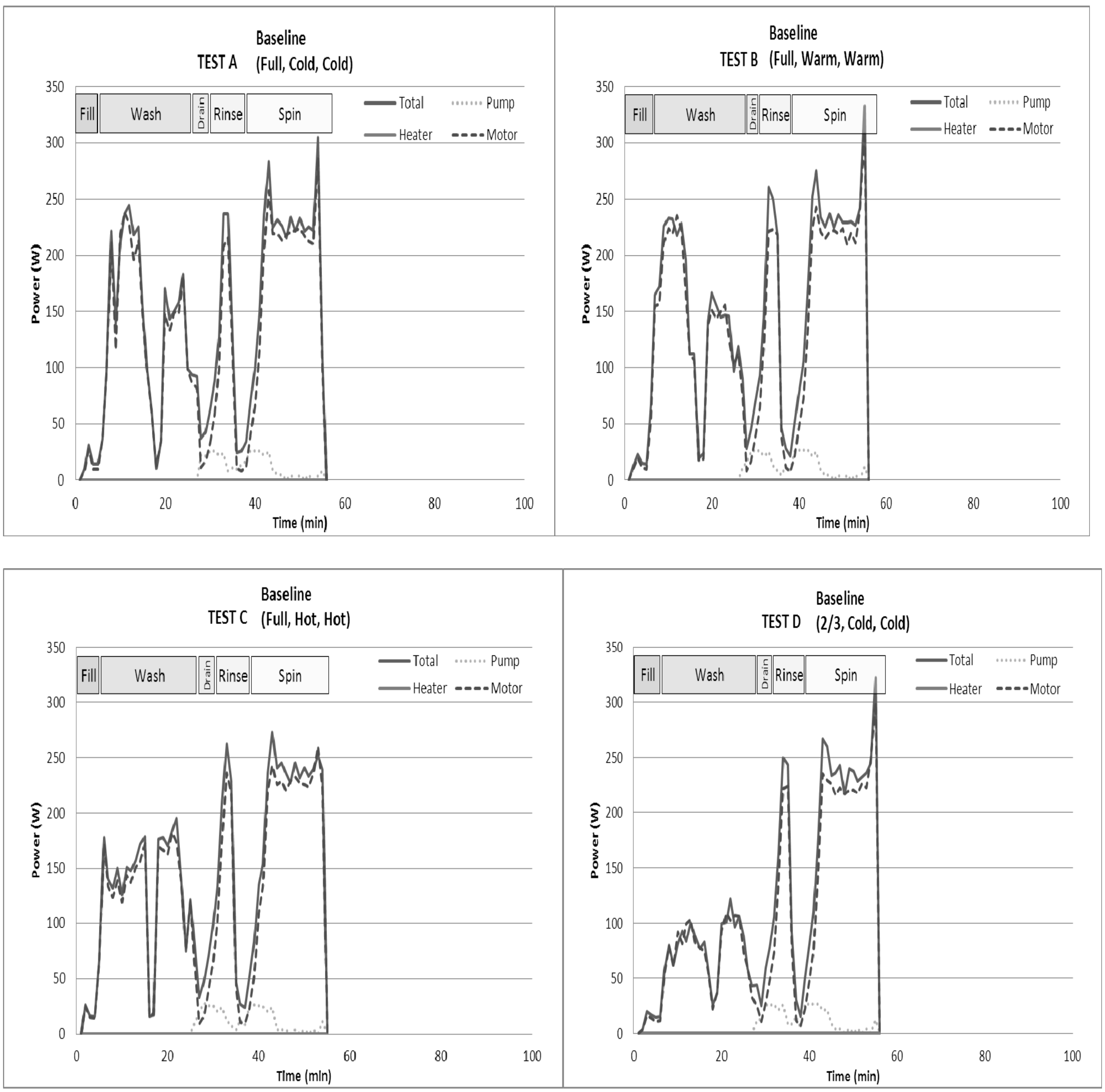
The 10-second raw data collected in each test scenario was reduced into 1-minute average values. Data analysis and graphical representations are based on the 1-minute data.

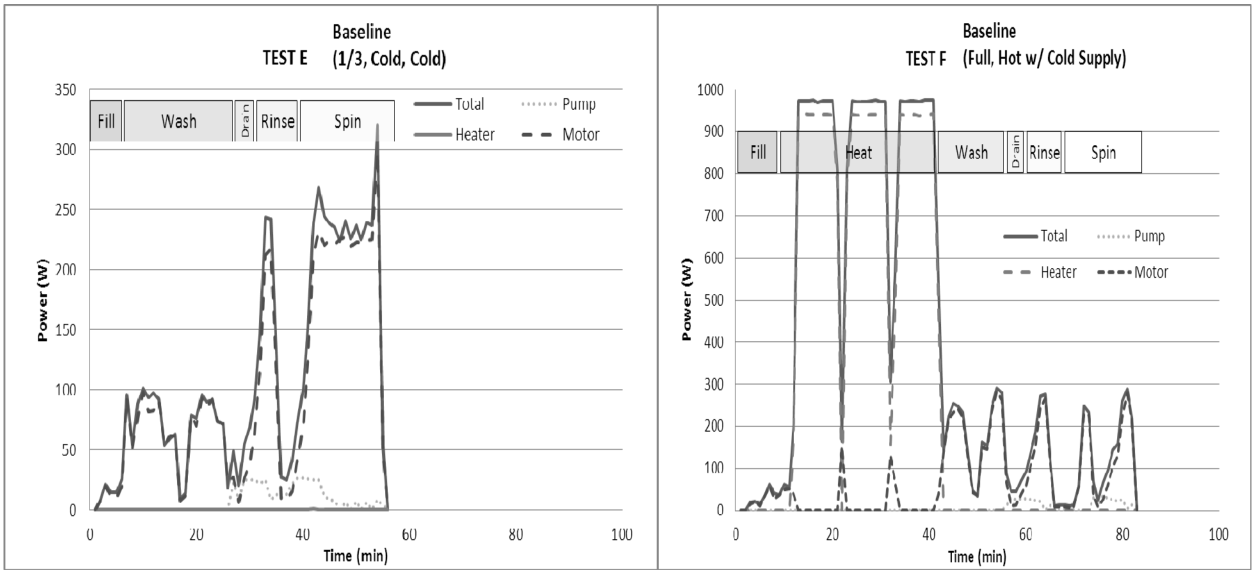
Results

Baseline Tests

Component-level power consumption profiles for each of the baseline tests are shown in Figure1. The bars on the top of each Figure give a general relation between power consumption and stages of the wash cycle. The same basic power profile is repeated in all of the test scenarios, with the exception of Test F where the heater was operating. Using warm water (Test B) had little effect while hot water reduced the wash peak by approximately 75W. Reducing the clothing load (Tests D and E) had a noticeable impact on the wash power, but little effect on the spin power.

Figure 1. Baseline Test Power Profiles





Spinning Reserve Events

Figure 2 gives a graphical representation of the DR potential values for measured data from the Baseline A test scenario. The thick solid line is the measured total power value from the test period. The theoretical DR potential can be calculated in multiple ways, with appropriateness depending on how the data will be used:

The thin solid line is a 5 minute moving that gives the average DR potential for an event of 5 minute duration which is initiated at a particular elapsed time into the wash cycle. For example, the point plotted at 20 minutes along the X-axis represents the average power over the length of a DR event initiated at the 20 minute mark and continuing thru the 25th minute. This assumes that all power consuming components shut off during the event, as indicated by the manufacturer. The long dashed line similarly represents the moving average for a 10 minute duration event.

The short dash line represents the maximum DR potential (i.e. peak) observed during the following 10 minutes. For example, the point plotted at 20 minutes along the X-axis represents the maximum power observed during a DR event initiated at the 20 minute mark and continuing thru the 30th minute. This also assumes that all power consuming components shut off during the event.

Figure 2. DR Potential – Baseline A

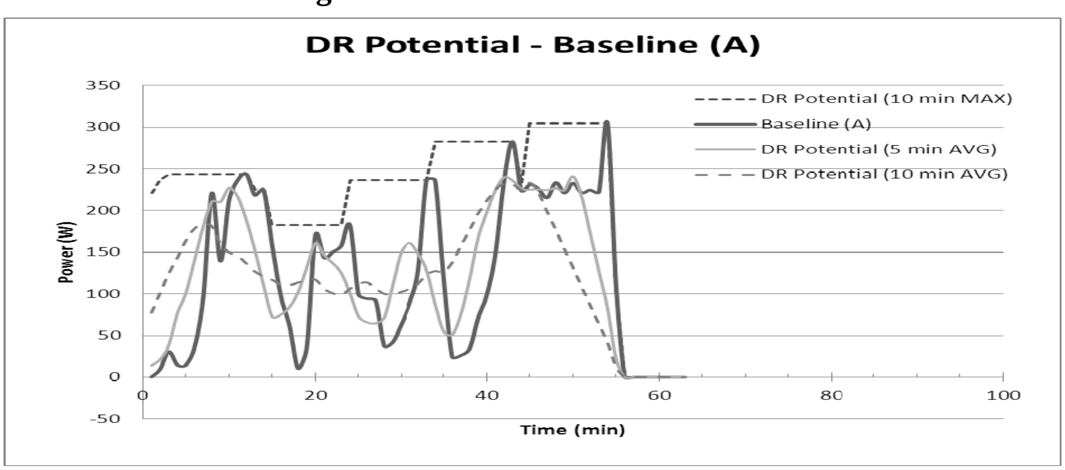
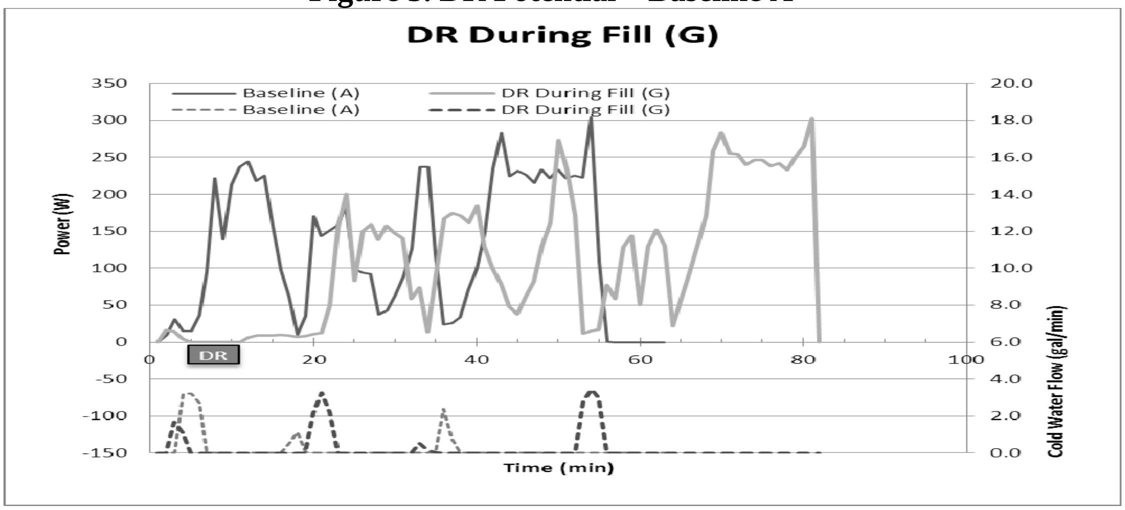


Figure 3 shows the performance of Test G with the DR event initiated during the fill cycle. The upper pair of lines on the graph is a comparison of power profiles while the lower pair compares cold water flow. Total energy consumption and water use are presented on the right side of the graphs. The "DR" block represents the 8-minute duration DR Spinning Reserve event.

Curiously, for this test an 8-minute DR event caused a 25 minute increase in the overall length of the wash cycle. The washer also used 19 Wh more energy and 6.3 gallons more water over the test period with the DR event. Test G was repeated to ensure this was not an abnormal result, and the same operation was observed. (Additional graphs available in full report.)

Figure 3. DR Potential – Baseline A



For the remaining Spinning Reserve events, 8 minute duration events resulted in approximately 8 minute increase in wash cycle time. Energy increase slightly over the baseline by 5-9 Wh, except for Test R where the increase was 16 Wh due to the heater load. Water use increased in the DR tests by anywhere from 0.1 to 1.5 gallons.

Delay Load Events

The series of Delay Load tests examines the clothes washer's response to DR events lasting longer than 10 minutes. It is envisioned that the majority of DR events called would fall into this category. A 60-minute duration event signal was sent at various stages of the wash cycle to observe its response. These tests used a cold wash cycle with full load of clothing (Baseline A).

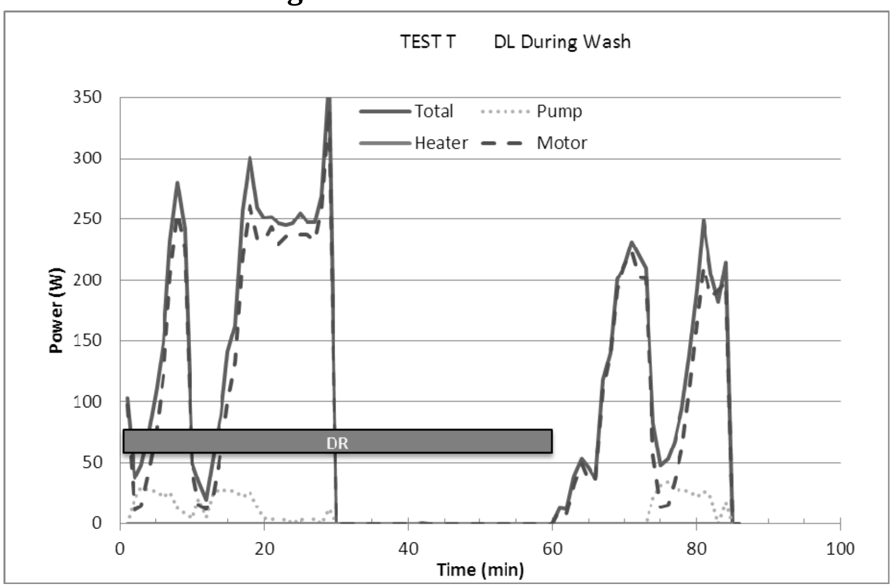
Results obtained from Test T conveniently summarize the observations from other Delay Load scenarios. Test T addressed an event initiated when the clothes washer was in the middle of a wash cycle, with a second wash cycle attempting to start immediately after the first was complete. Table 4 gives the time sequence of events used to conduct the test, while the power profile in Figure 4 shows no effect on the on-going wash cycle, but delay of the second cycle until after the DR event had cleared. The machine hesitated for a few seconds when the event was first received, but continued the wash cycle. The message "*Power consumption in your area is high. The utility has shifted the operation of your selected cycle to a period of lower energy* *consumption”* was displayed on the user interface once an attempt to start the second cycle was made.

Table 4. Time Sequence for Test T

Minute	Action
-26	First wash cycle started (not depicted in Figure 4)
1	Initiated a 60 minute duration DR event, machine hesitated for about 20 seconds, then continued normal operation
30	First wash cycle ended
31	Attempted to start second wash cycle, to no avail. Message appeared on user interface.
60	Second wash cycle started

Source: SCE

Figure 4. Test T Power Profile



Delay load event DR potential. Quantification of the DR potential for Delay Load events is complicated. It is a function of several variables: state of the machine when the signal is received, time remaining in the on-going wash cycle, duration of the DR event, and the user’s desire to start a new load during the event. Because the event does not interrupt wash cycles already in progress, the operation will follow the power profiles observed in Baseline A (or B thru F, depending on the circumstances of the particular load in progress). And the DR potential will only be realized if the user actually tries to start another load during the DR event. Thus, additional modeling using actual usage profiles will be necessary to estimate the a reasonable anticipated demand reduction.

DR Memory Functionality

Test U was intended to investigate the ability of the clothes washer to maintain DR events in memory, then later respond to those events when the DR functionality was enabled. Table 5 details the sequence of events.

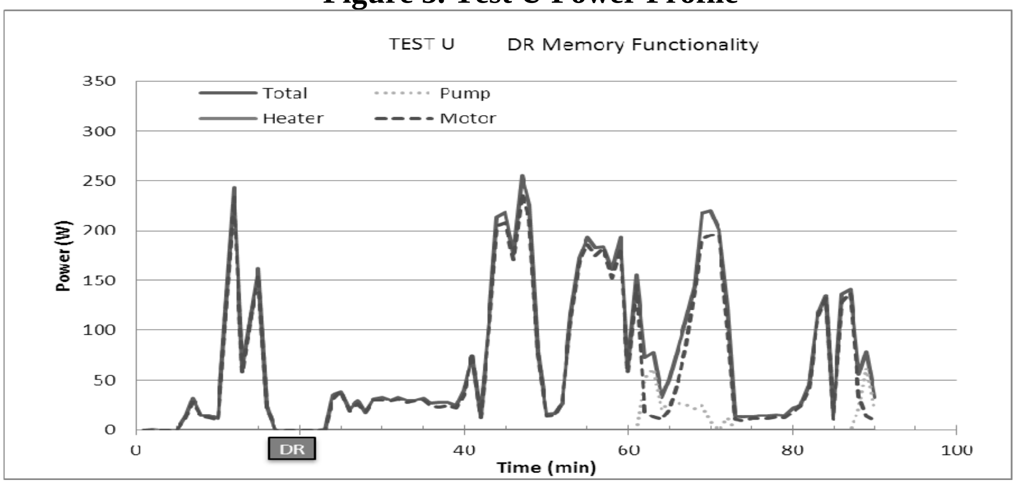
Figure 5 shows the power profile for Test U, including approximately 20 minutes of unusual operation immediately following the DR event. This resulted in a significant increase in the length of the overall wash cycle

Table 5. Time Sequence for Test U

Minute	Action
0	DR functionality turned off through touch screen user interface
4	Wash load initiated
14	Initiated an 8 minute duration DR event
15	DR functionality activated – machine instantly turned off due to DR event in progress
22	Operation resumed

Source: SCE

Figure 5. Test U Power Profile



Conclusions & Recommendations

Overall, the clothes washer performed as intended for each of the test scenarios. For Spinning Reserve events it immediately ceased operation until the event cleared, then resumed normal operation (with the exception of the 25 minute delay in Test G) to complete the cycle. For Delay Load events it allowed any in-progress wash cycles to complete, then delayed any new wash cycles until the event cleared. The discrepancy in Test G reiterates the need for appliance manufacturers to fully test their control algorithms to ensure that customers do not have unexpected detrimental experiences. These operations satisfy the requirements established in the AHAM guidelines and were executed under test. However, there appears to be a disconnect between utility needs during DR events and the AHAM definitions of Spinning Reserve and Delay Load, and what a clothes washer is required to do in response to each type of signal.

DR events are typically initiated in response to some sort of isolated catastrophic event on the grid. Whether it is the loss of a high voltage transmission corridor due to excessive wind or an automobile accident taking out a more localized distribution pole, the need for demand reduction on the affected circuits is immediate and the duration may be unknown. In order to get the most beneficial demand reduction, the DR scheme adopted by AHAM forces the utility to choose to either:

1. send a signal for a short Spinning Reserve that will immediately provide reduction for all clothes washers currently operating and hope that the problem is solved before they all come back on in 10 minutes, or
2. send a signal for a longer Delay Load event that will give no immediate reduction but will prevent additional clothes washer load from coming on-line.

Each of these options has advantages and disadvantages, but there will not be time for the grid operator to properly weigh these before sending out the DR signal. It may be several minutes before the cause of an event is known and any estimate of its duration can be made.

It is unclear how this problem may be further impacted by other types of DR capable appliances. Subsequent testing and future increased interaction with AHAM and standards-setting agencies will attempt to address these issues.

References

[AHAM] Association of Home Appliance Manufacturers, et al. 2011. "Joint Petition to ENERGY STAR to Adopt Joint Stakeholder Agreement as it Relates to Smart Appliances." http://www.energystar.gov/ia/partners/prod_development/revisions/downloads/room_air_conditioners/Petition_to_ENERGY_STAR_from_Joint_Stakeholders.pdf.

[SCE] Southern California Edison. 2011. "Smart Grid Deployment Plan." http://docs.cpuc.ca.gov/efile/A/138423.pdf.