

Residential Appliance Demand Response Testing

Scott Mitchell, Rafik Sarhadian, Sean Guow, Bruce Coburn, John Lutton, Ishtiaq Chisti, Devin Rauss, Carlos Haiad, Southern California Edison

ABSTRACT

Achieving the goals of the Smart Grid will require deployment of a wide array of communicating devices, enabling customers and utilities to better manage energy use at home across the electric grid, respectively. In the residential sector, smart appliances are a significant part of realizing the full potential benefits of the Smart Grid. These appliances not only achieve high levels of energy efficiency during normal operation, but also are capable of responding to Demand Response (DR) events – where utilities need to reduce electric load quickly during peak usage times to avoid widespread power outages, or at the consumer’s request in response to high electric prices. Appliance manufacturers are incorporating this functionality and are beginning to release DR-capable products into the market.

At the 2012 ACEEE Summer Study, Southern California Edison (SCE) presented laboratory test results for a DR-capable clothes washer. (Mitchell et al. 2012) Since that time, SCE has tested multiple other appliances (dishwashers, clothes washers, and refrigerators) from multiple manufacturers. This paper shares the comprehensive results including each device’s reaction to DR events initiated during the various stages of operation.

The results show that typical responses offer either a large load reduction for a short duration DR event, or a smaller reduction for a longer event. The manner of response varies between manufacturers and appliance types, which could create challenges for utility DR program design. Additionally, the newer appliances are very energy efficient and have lower average connected load, and therefore reduced DR potential, than appliances of a slightly older vintage.

Furthermore, Energy Star® recently incorporated “Connected” functionality into several of its appliance specifications. This paper includes a discussion of the specifications and test methods and how they align with or run counter to current utility DR programs and future plans.

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 will employ vast networks of communicating equipment that will enable much improved visibility and control over how and when we consume energy. 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 respond to

adverse grid conditions. Demand Response (DR) is one of the capabilities included in these smart appliances”.

The communication link to end devices is the key to enabling DR participation. Once that link is established, a number of other opportunities may be present as well. For certain residential devices (primarily, pool pumps and electric water heaters) the possibility of turning them on via this link is also being explored to better match load profiles to renewable generation profiles.

What is Demand Response?

Conceptually, DR functionality allows a customer to reduce 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 (TOU) or real time pricing energy tariffs, which may become mandatory for residential customers in California. (CPUC 2012) The high cost of peak time energy also corresponds to higher GHG emissions from peaker plants, so avoiding usage during this time has a double impact. Many utilities offer rebates for customers participating in DR events.

In the event of a reliability issue the electric utility sends a signal requesting a reduction in connected load. The DR signal reaches smart appliances, either directly or through a HAN, which react by reducing load as much as possible during the DR event. 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 project is aimed at testing three types of residential appliances: refrigerators, clothes washers, and dishwashers. This report presents findings from these appliances from two manufacturers. Testing of additional appliances is on-going and results will be available at a later date.

Communication Pathway

The appliances tested here all communicated directly with the utility Smart Meter via ZigBee® consistent with early visions of smart device connectivity for SCE. As the market for smart appliances developed, many appliance manufacturers have demonstrated a preference to use Wi-Fi® as the communication pathway to the device. This enables the consumer to take advantage of a broader range of services requiring an outside communication link.

The issues surrounding communication pathways have been addressed in great detail in several of the recent Energy Star specification development efforts for residential appliances like refrigerators, clothes washers, and pool pumps (EPA 2012-13; especially CEE 2013). In principle, the actual DR response of the device is not dependent on the pathway through which the signal is conveyed.

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 petition suggested energy efficiency credits in exchange for connectivity functionality, and recommended specific approaches for implementing DR capability in the various types of appliances.

In May 2013, Energy Star adopted the Product Specification for Residential Refrigerators and Freezers based primarily on the Joint Petition. It defines a “Connected” refrigerator, freezer, or refrigerator freezer system as including “all elements (hardware, software) required to enable communication in response to consumer-authorized energy related commands” (EPA 2013). Similar definitions have been developed or are in development for other residential appliances.

DR Events

DR events can take several forms. The Joint Petition specifies two different types of events: Spinning Reserve and Delay Load. They are differentiated by the event duration characteristic of 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. These events may be scheduled to start immediately upon receipt or at some time in the future. 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. The user has the ability to override any DR event by pushing a button on the user interface if they are not able to participate in an event for any reason.

Currently, only durational DR signals are sent by the utility. However, it is envisioned that in the future, residential time of use (TOU) price signals will be sent, thus allowing the Smart Appliance to optimize performance based on total cost of operation. In California, the policy-driven widespread adoption of renewable energy generation is causing major changes in the grid daily load profile and energy pricing, highlighting the need for DR-capable equipment. Recently, there have also been discussions about using this DR capability to turn devices on during times of excess renewable generation capacity. In the residential market this functionality is mainly limited to pool pumps and water heaters, not the appliances tested here.

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. Longer interruptions may have a detrimental effect and are applied only where deemed absolutely safe by the manufacturer.

DR Responses

The Joint Petition also defines minimum DR response requirements for each type of appliance in response to both Spinning Reserve and Delay Load events. These requirements are by and large incorporated into the various Energy Star specifications that have been finalized or are in development. However, manufacturers are able to implement other functionality as they

see fit as long as minimum criteria are satisfied. Through the course of this testing, it became apparent that the different manufacturers actually used slightly different triggers to initiate their DR responses. Some manufacturers have adapted these requirements into response algorithms based on slightly different trigger signals.

One manufacturer bases its DR actions on the price level of the signal received, not necessarily the duration of the DR event. The signal contains multiple pieces of information, one of which is the utility's current price. Four levels (Low, Normal, High, and Critical) are used for this component.

This could be problematic if many appliances end up directly connected to the meter because the dispatch signal for a DR program would have to ensure that it triggers ALL of the various appliances. However, given that manufacturers are shifting toward a cloud-based Wi-Fi® connected system, this becomes less of a concern.

Project Goals

The goals of this project were to:

1. Learn how manufacturers incorporated DR capability into various residential appliances (refrigerators, clothes washers, and dishwashers) through detailed discussion with their technical staff.
2. Conduct laboratory testing to quantify the DR potential of each appliance during its discrete stages of operation in response to different DR signals.
3. Leverage findings to inform utility decision makers, industry engineers, regulatory agencies, and other interested parties.

Test Plans

Arrangements were made with 3 major manufacturers to obtain early (prototype or non-commercially available) DR-capable appliances for testing in SCE's Technology Test Centers, in Irwindale, CA. Through detailed discussion and collaboration with appliance manufacturers, SCE staff gained a thorough understanding of the DR response schemes incorporated into each appliance. A test plan was developed to quantify the demand reduction potential for each of these situations.

Baseline tests were conducted to run appliances under normal operating conditions. These tests were then repeated with a specified DR signal being sent at a particular time during the appliance's operation scheme. Signals were sent via Zigbee® from a laboratory version of SCE's smart meter paired with the appliance and located in the test room. Data was collected in minimum 20-second intervals for critical data points including temperature, water flow, total power, and major component power. Approximately 30 different test conditions were conducted for each appliance.

Testing conditions were loosely based on existing industry standard energy testing protocols (such as DOE 2011 for refrigerators). However, because the main purpose here was quantification of the DR potential under realistic operating conditions, deviations were made where deemed appropriate. For example, the DOE refrigerator energy test method (DOE 2011) specifies an empty refrigerator compartment. We believed that most consumers would have some amount of food in their refrigerator and that the presence of thermal mass inside the refrigerator would affect its ability to maintain proper product temperature when responding to

DR events Therefore, our tests included some food simulators being stored in the refrigerator. Further details on the individual test plans can be found in the individual test reports.

Results

This section presents high level results from each of the five appliances (from two manufacturers) tested thus far. Only a small portion of the extensive data collected is included here. Full details of the test plans and results can be obtained from the comprehensive individual project reports (SCE 2012a, 2012b, 2012c, 2012d, and 2013). Testing on an additional refrigerator and clothes washer from a third manufacturer are currently in progress.

Refrigerators

Refrigerators are by far the most difficult residential appliances in which to implement DR. On one hand, they are good candidates because they are found in virtually every residence (CEC 2009), operate 24 hours a day 7 days a week, and are drawing power during peak load periods. On the other hand, they must maintain safe temperatures in order to avoid risking the safety of products inside. Furthermore, today's higher-end refrigerators (which are the only place you'll find DR capability) are extremely energy efficient and draw much less power on average than models of just a few years ago. Thus, the opportunity for instantaneous power reduction lies in interrupting the cooling function for short periods of time or changing operation of auxiliary components (ice makers, defrost heaters, etc.). Even in the highest power modes, the power reduction potential per unit is minimal compared to other potential DR targeted devices (HVAC, pool pumps, TVs, etc.).

Normal operation profiles. The refrigerators tested were French Door style with bottom freezer compartments from two manufacturers.

Refrigerator "B". This refrigerator operated in the conventional manner where the compressor cycles on for cooling drawing ~80 W, then cycles off for a period when the freezer temperature setpoint is satisfied (Figure 1). A duct fan moved freezer air into the refrigerator section to maintain the refrigerator setpoint. The ice maker produced a batch of ice cubes approximately every hour and forty-five minutes until the bin was full.

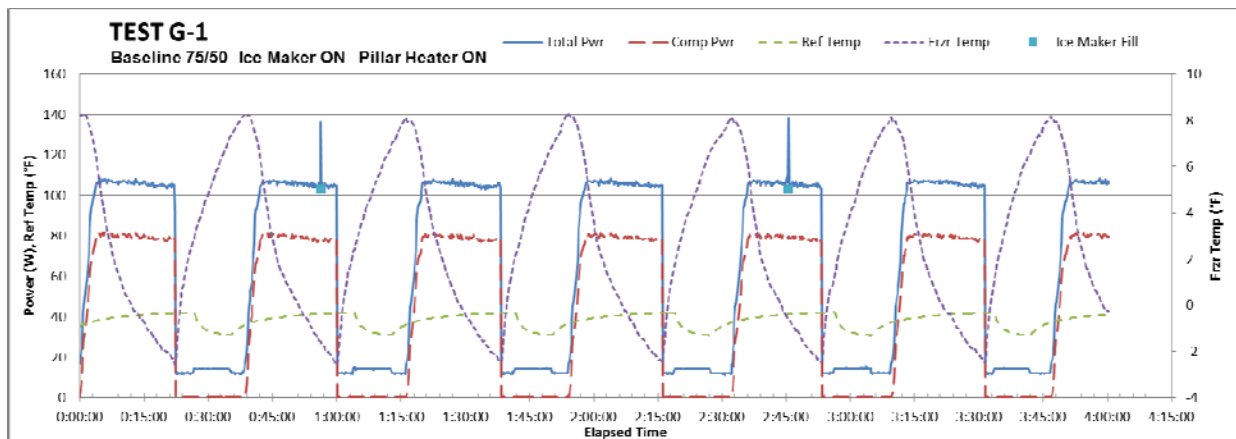


Figure 1. Refrigerator B operational and power profile.

Refrigerator “A”. Incorporation of a variable speed compressor motor resulted in an unconventional power usage profile with much longer compressor on cycles at lower power draw of ~55-70 W (Figure 2). This refrigerator had two separate evaporator coils, one for the freezer and one for the refrigerator, and could serve them in different combinations (via a 3-way valve) depending on need. The ice maker produced a batch of ice cubes approximately every hour and 15 minutes until the bin was full.

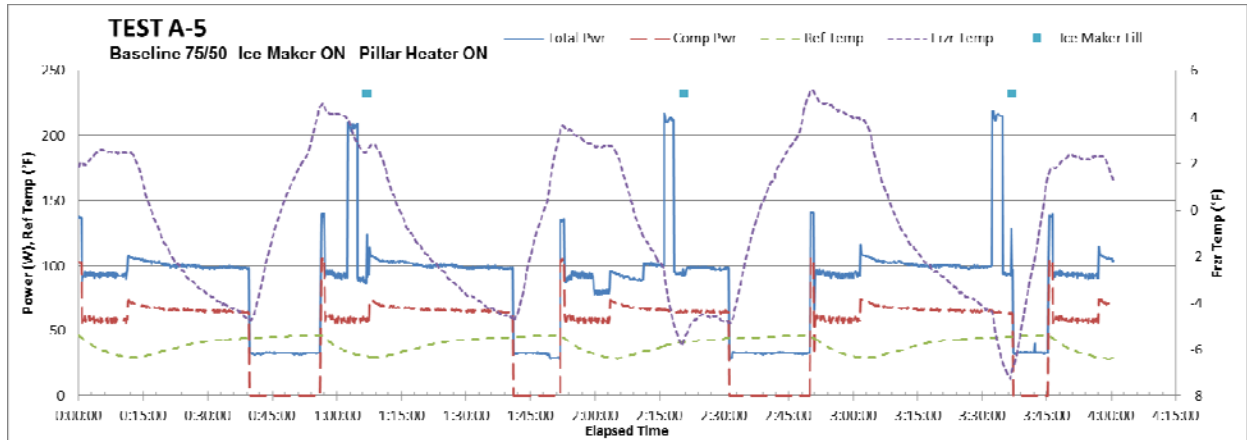


Figure 2. Refrigerator A operational and power profile.

Test conditions. Residential refrigerators typically operate in conditioned environments with most accessories (including ice makers and Anti-Sweat Heaters (ASH)) operational. Thus, the condition of 75°F and 50% RH with those accessories turned on was deemed to be standard operating condition. Testing was also conducted at ambient conditions of 90°F/30% RH and 105°F/19.5% RH, with various combinations of components operating, and then repeated with DR signals sent to the unit.

Anticipated responses. The Joint Petition defines minimum requirements for each type of appliance. For refrigerator/freezers, it requires:

Table 1. Refrigerator requirements by DR event type

DR Event Type	Duration	Minimum Requirement
Spinning Reserve	Up to 10 minutes	the product must restrict its average energy consumption during this time period to a maximum of 50 percent of the average load over a 24 hour period (unless there is a consumer initiated function, such as door opening or ice or water dispensing).
Delay Load	10 minutes to 4 hours	the product must shift defrost cycles beyond the delay period and do one of the following – (1) shift ice maker cycles beyond the delay period, or (2) reduce average wattage during the delay period by at least 9.6 watts relative to average load over a 24 hour period, and may shift this wattage beyond the delay period
---	Over 4 hours	No response required

Source: (AHAM 2011).

Refrigerator “B”. The first refrigerator followed this scheme very closely. At a high level, the DR algorithms programmed into the refrigerator aimed at performing the following tasks:

- For Spinning Reserve events, the compressor and ASH turn off during the entire event (thus reducing energy by greater than 50% during the DR period, as required by the AHAM guideline).
- For Delay Load events, the controller (1) resets freezer temperature, (2) changes pillar ASH operation timing (3) delays defrost until after event has cleared (4) changes ice maker fan operation.

The refrigerator has two energy-related operating modes available for the user to select via the touch screen menu. One enables the refrigerator to respond to DR events. The other puts the refrigerator into a low energy operating mode for 4 hours during a pre-selected low usage time (typically during night hours). Unfortunately, the controls will not allow energy savings and Smart Grid modes to both be active at the same time. Ideally, the user would be able to benefit from both the continual energy savings and the DR related savings of Smart Grid. The control system algorithms should be able to determine whether or not the energy savings mode could be used on a day in which the Smart Grid features were called upon.

Refrigerator “A”. The second refrigerator used a triggering scheme that was based on criticality (pricing) level, not solely duration of the DR events. At a high level, the DR algorithms programmed into the refrigerator aimed at performing the following tasks:

- For “High” price events, the freezer setpoint temperature raises causing the refrigeration components to turn off for a time, defrosts are delayed, anti-sweat heaters (ASH) are disabled, and special cooling functions are disallowed.
- For “Critical” price events, all of the “High” actions are taken as well as a mandatory 10 minute off time for the compressor and fans.

Actual Responses

Refrigerator “B”. (Full report: SCE 2012c) In response to Spinning Reserve events, the refrigerator immediately reduced to about 15 W, a drop of 90 W if the compressor was on when the signal was received. If the compressor was off, there were no savings unless it delayed the start of the next compressor cycle. Due to the event definition, the longest duration of this was 10 minutes.

During Delay Load events a slight (~10 W) reduction in power was observed believed to be due to a change in the ice maker fan operation. Interestingly, on several occasions there was a several minute delay from initiation of the event until a response was actually observed. None of the data collected indicated that a freezer temperature reset or ASH operation change occurred in response to a Delay Load signal.

Refrigerator “A”. (Full report: SCE 2013) The refrigerator exhibited inconsistent responses to High price events. In all instances there was clearly a change in the freezer setpoint and a reduction of ~20 W from normal operation, but in some cases these came several minutes after the event was initiated. Thus the large power reductions from turning the compressor off as a

result of the changed setpoint were unpredictable. There may have been a compressor protection measure that required a minimum amount of on time before it could turn off.

For Critical events, mandatory compressor and fan off cycles in combination with increased temperature setpoint provided predictable long-lasting power reductions of 70-80 W. Based on these observations, it is unlikely that savings would persist more than an hour as temperatures would begin to creep up and compressors would start to cool the space back down.

Defrosts. For both refrigerators, testing the ability to shift defrosts proved to be extremely complicated. This stems from the fact that manufacturers use proprietary algorithms to determine defrost schedules and will not divulge the algorithms. Thus, it is nearly impossible to prove that a defrost was actually shifted because there is no knowledge of when it was supposed to happen in the first place. This issue was discussed in detail during the Energy Star development process and is still being investigated.

Clothes Washers

Clothes washers are good candidates for DR implementation because the wash cycles can be interrupted for a period of time with minimal effect on performance. However, they are located in ~80% residences (CEC 2009) with many multi-family units sharing coin-operated washers that may be less optimal DR candidates. Furthermore, their operation patterns are believed to favor off-peak hours which limit their usefulness to the prevalent DR schemes. Additional research is needed to quantify the DR potential based on real usage patterns.

Normal operation profiles. The clothes washers tested were top loading (Mfr B, Figure 3) and front loading (Mfr. A, Figure 4) varieties. Each had several different wash cycle selections that incorporated optional features that affect energy consumption. Our testing and analysis mainly focused on the “normal” wash cycle.

A normal wash cycle typically has 5 unique operational phases: 1) Fill, 2) Wash, 3) Drain, 4) Rinse, and 5) Drain/Spin. The main power consuming component is the tub motor that is most active during the wash, rinse, and spin phases. For clothes washer A, the motor was an electronically commutated type inherently having a high cycling power profile. Additionally, depending on the wash cycle temperature settings and the supply water temperature, internal resistance heaters (900 W) are utilized.

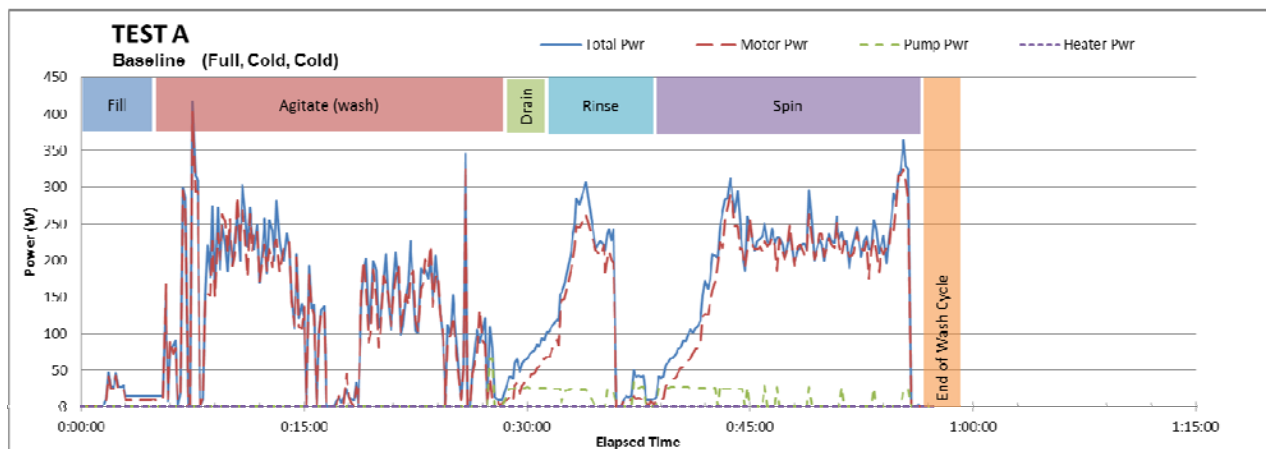


Figure 3. Clothes washer B power profile.

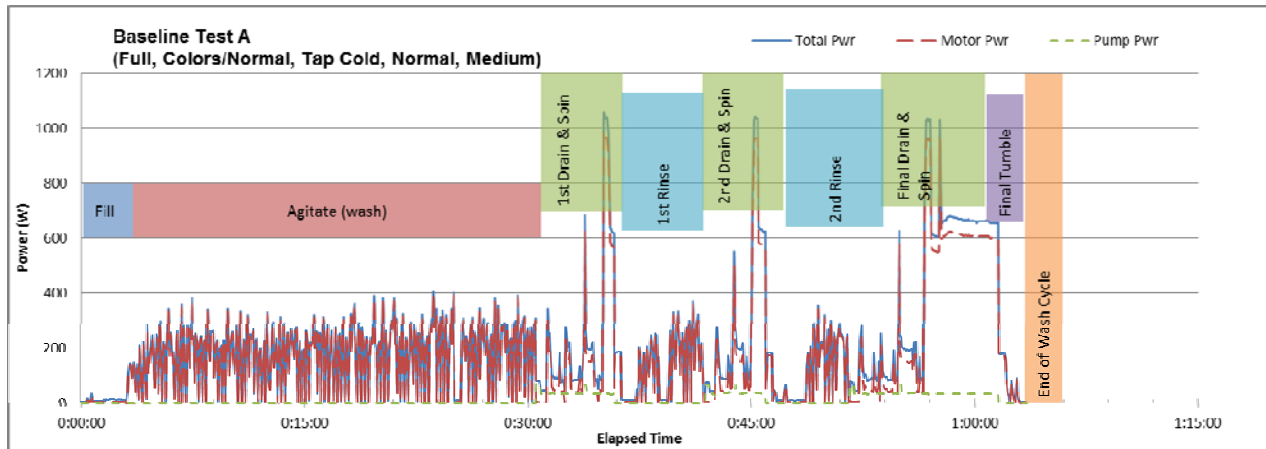


Figure 4. Clothes washer A power profile.

Test Conditions. The clothes washers were run through a series of baseline tests with varying degrees of load (determined by clothing weight), wash water temperatures, and soil levels (Mfr. A only). These tests were then repeated with DR events added at various points in the wash cycle.

Anticipated responses. The Joint Petition defines minimum requirements for each type of appliance. For clothes washers, it requires:

Table 1. Clothes washer requirements by DR event type

DR Event Type	Duration	Minimum Requirement
Spinning Reserve	Up to 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
Delay Load	10 minutes to 4 hours	the product must automatically delay the start of the operating cycle beyond the delay period
---	Over 4 hours	No response required

Source: (AHAM 2011).

Clothes washer “B”. The first clothes washer followed this scheme very closely. At a high level, 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
- For Delay Load events, allow any wash cycle in-progress to finish, then delay any subsequent wash cycle until the event had cleared.

Clothes washer “A”. The second clothes washer used a triggering scheme that was based on criticality (pricing) level, not solely duration of the DR events. At a high level, the DR algorithms programmed into the washer aimed at performing the following tasks:

- For “High” price events, delay the start of any wash cycle until the event has cleared.

- For “Critical” price events, all of the “High” actions are taken as well as reduce duty cycle wash and duty cycle heater at 50%.

Actual Responses

Clothes washer “B”. (Full report: SCE 2012b) In response to Spinning Reserve events, the washer immediately reduced its load to 0 for the duration of the event, regardless of the point in the wash cycle in which the signal was received. After the interruption, the cycle resumed where it left off and continued through to normal completion. Demand reduction depended on the normal power consumption during the particular phase of wash cycle that was affected.

For Delay Load events, a wash cycle already in progress continued uninterrupted. However, any attempted start of a new wash cycle was delayed beyond the event clearing time.

Clothes washer “A”. (Full report: SCE 2012a) Attempts to start the clothes washer when a High event was active resulted in the cycle starting after the event cleared. A High event had no effect on a wash cycle already in progress.

When Critical events were initiated, the motor duty cycle and heater duty cycle (if any) were reduced by nearly 50%, but the duration of that particular phase of the wash was extended. Thus, reductions in average power up to 53% were observed during the DR event, but the total wash cycle energy consumption was only slightly reduced. Critical events also prohibited the user from starting a new wash cycle.

Dishwashers

Dishwashers may be better candidates for DR than clothes washers due to their high resistance heater loads that operate every wash cycle (not just for particular cycles). However, they are only present in ~67% of residences (cite) and operation patterns for dishwashers likely favor off-peak usage. Again, additional research may be necessary to fully appreciate their value to DR programs.

Normal operation profiles. The dishwasher tested (from Mfr. A, Figure 5) was a built-in under-counter unit with top control. The user selects from 10 different wash cycles and 4 cycle enhancements. Testing and analysis mainly focused on the “normal” wash cycle with no enhancements.

A normal wash cycle typically has 5 unique operational phases: 1) Sensing, 2) Prewashing, 3) Washing, 4) Rinsing, and 5) Drying. In the Sensing phase, a sensor determines the amount of soil and water temperature. Drying may be either air-dry or heated dry. The main power consuming components are the water heater used to boost temperature of supply water to 180°F for sanitary purposes and the drying heater.

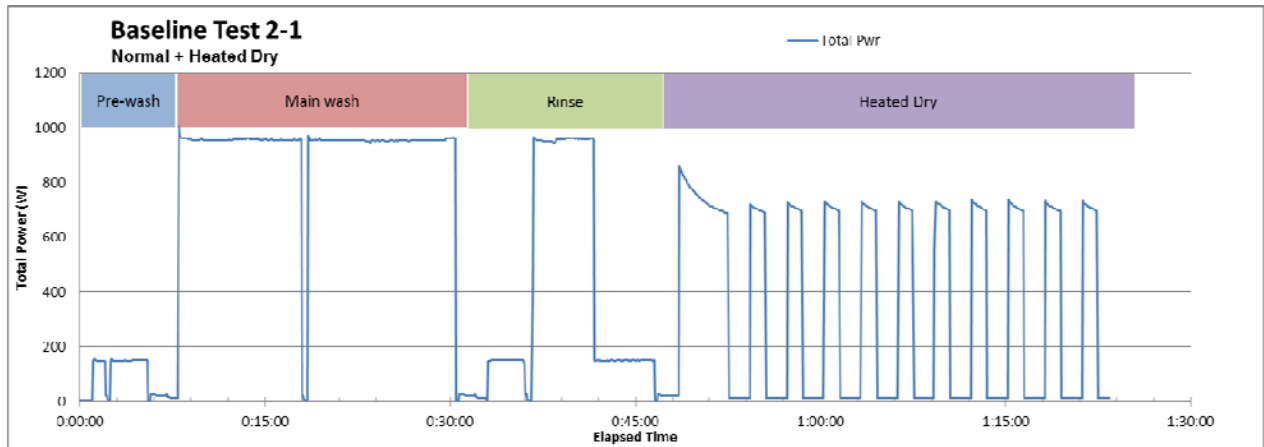


Figure 5. Normal dishwasher cycle power profile.

Test Conditions. The dishwasher was loaded with a standard set of dishware (without soiling) and run through a series of baseline tests with both air and heated drying. These tests were then repeated with DR events added at various points in the wash cycle. Additional tests investigated the power implications of several different wash cycles and cycle enhancements. Inlet water temperature was maintained at 120°F.

Anticipated responses. The Joint Petition defines minimum requirements for each type of appliance. For dishwashers, it requires:

Table 1. Dishwasher requirements by DR event type

DR Event Type	Duration	Minimum Requirement
Spinning Reserve	Up to 10 minutes	the product must automatically reduce its average wattage during this period by at least 50 percent relative to average wattage during this period in the operating cycle under the DOE test conditions
Delay Load	10 minutes to 4 hours	the product must automatically delay the start of the operating cycle beyond the delay period
---	Over 4 hours	No response required

Source: (AHAM 2011).

The dishwasher used a triggering scheme that was based on criticality (pricing) level, not solely duration of the DR events. At a high level, the DR algorithms programmed into the dishwasher aimed at performing the following tasks:

- For “High” price events, delay the start of any wash cycle until the event has cleared.
- For “Critical” price events, all of the “High” actions are taken plus turn heated dry off.

Actual Responses. (Full report 2012d) The dishwasher delayed the cycle start in response to both High and Critical events. This response worked properly, even in instances where a manual 1-hour cycle delay was input by the user. For Critical events, it eliminated the heated dry cycle during the DR event. In some instances the heater came on after the event cleared (where the event ended before the heater would normally have ended) and in others it switched to a no-

heater air dry (where the event lasted longer than the normal end of the dry cycle). No change in power occurred during the sensing or wash phases of the cycle.

Conclusions & Recommendations

The results presented thus far quantify the per-unit DR potential for residential smart appliances under various operating scenarios. Further work is necessary to fully understand typical operating patterns and their relation to peak load periods in order to fully calculate the value of the DR capability. SCE is currently conducting several small scale efforts to better understand some of these phenomena. Additional modelling efforts will be necessary to fully understand the impact of the DR capability of Smart Appliances and other residential loads.

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