CODES AND STANDARDS ENHANCEMENT INITIATIVE (CASE)

Development of a Title 24 Compliance Model for Residential Drain Water Heat Recovery Devices

2016 CALIFORNIA BUILDING ENERGY EFFICIENCY STANDARDS

California Utilities Statewide Codes and Standards Team July 2016

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NOMENCLATURE

a = Constant for t2 in the draw duration second order regression

ATS = Applied Technology Services laboratory at Pacific Gas and Electric Company

b = Constant for t in the draw duration second order regression

Btu = British thermal unit

c = Constant in the draw duration second order regression

C_P = Specific heat of water (Btu/lb.-°F)

C_{PL} = Pipe loss coefficient used in the RESNET algorithm

CBECC = California Building Energy Code Compliance

CSA = Canadian Standards Association

CSE = California Simulation Engine

DWHR = Drain water heat recovery

ε = Effectiveness

ε_{CSA} = Effectiveness rating from the CSA test protocol

ε_{Draw} = Effectiveness of a draw, including the initial transient period

ε_{Est} = Effectiveness estimated using the regressions

ε_{Mea} = Measured effectiveness

$\varepsilon_{\dot{V}}(t)$ = Effectiveness as a function of draw duration at a specified flow rate

f_{Dur} = Factor used to adjust draw effectiveness as a function of draw duration

f_{Fix} = Fixture factor used in the RESNET algorithm used to adjust DWHR savings based on the percent of showers connected to the device

f_{Loc} = Location factor used to describe the installation in the RESNET algorithm. 1 for Equal Flow installations, 0.777 for unequal flow installations

$f_{T,C,I}$ = Factor used to adjust draw effectiveness as a function of cold-side inlet temperature

$f_{\dot{V}}$ = Factor used to adjust draw effectiveness as a function of flow rate. The equation to identify this factor changes depending on whether the installation is equal or unequal flow

gpm = Gallons per minute

I_{Frac} = Fraction of hot water used in the house which passes through the DWHR unit

$\dot{Q}$ = Rate of heat transfer (Btu/hr)

$\dot{Q}_{Avg}$ = Average rate of heat transfer to the cold water during a draw (Btu/hr)

t = Time. Used to signify the duration of a draw (Minutes)

$T_{C,O}$ = Cold-side outlet temperature (°F)

$T_{C,I}$ = Cold-side inlet temperature (°F)

$T_{D,I}$ = Drain-side inlet temperature (°F)

ΔT_{Mains} = Temperature increase, relative to mains temperature, of water across the DWHR unit (°F)

$\dot{V}$ = Volumetric flow rate on both sides of the DWHR device in equal flow installations, and draw durations regressions (gpm)

$\dot{V}_C$ = Cold-side flow rate (gpm)

$\dot{V}_D$ = Drain-side flow rate (gpm)

ρ = Density of water (lb/gal)

EXECUTIVE SUMMARY

The Codes and Standards Enhancement (CASE) initiative presents recommendations to support California Energy Commission's (CEC) efforts to update California's Building Energy Efficiency Standards (Title 24) to include new requirements or to upgrade existing requirements for various technologies. The four California Investor Owned Utilities (IOUs) – Pacific Gas and Electric Company, San Diego Gas and Electric, Southern California Edison and Southern California Gas Company – and Los Angeles Department of Water and Power (LADWP) sponsored this effort. The program goal is to prepare and submit proposals that will result in cost-effective enhancements to energy efficiency in buildings. This report and the code change proposal presented herein is a part of the effort to develop technical and cost-effectiveness information for proposed regulations on building energy efficient design practices and technologies.

Domestic water heating is responsible for an estimated 49 percent of natural gas use in California homes, creating a large opportunity for untapped energy savings. Drain water heat recovery (DWHR) is a technology that captures waste heat in the drain line during a shower event, using the reclaimed heat to pre-heat cold water that is then delivered either to the shower or the water heater. These devices are gaining popularity in Canada and northern US states, because lower cold water inlet temperatures in those climates increase the ability of the DWHR device to economically reclaim waste heat. The device can be installed in either an Equal Flow configuration (with preheated water being routed to both the water heater and the shower) or an Unequal Flow configuration (preheated water directed to either the water heater or shower). The energy harvested from a DWHR device is maximized in an equal flow configuration.

Tests of the effectiveness of a single DWHR device were performed at the PG&E Applied Technology Services (ATS) lab in San Ramon, CA. The testing for equal flow installations was based on the Canadian Standards Association (CSA) test protocol, the current rating protocol for DWHR equipment. Additional tests were added to study the effects of unequal flow rates, and different inlet temperatures.

An algorithm predicting the effectiveness of a DWHR unit as a function of draw conditions was created based on the analyzed data. This algorithm can be used for equal and unequal flow configurations and accounts for varying cold side inlet temperatures and draw durations. The algorithm was tested in four cases, and was within ±3.85 percent of the measured effectiveness in all cases. This error is less than the test lab measurement uncertainty, suggesting that the model provides a good representation of performance under varying conditions. With the device effectiveness specified for unique operating conditions, the algorithm then calculates the energy added to the cold water entering the device.

Initial simulations showed that savings in California may be significantly lower than Canadian predictions indicate. This is due to two primary factors: 1) The mains water temperatures in California are higher than in Canada, and 2) The CSA algorithm assumes complete wetting of the drain side of the DWHR unit, while initial testing has shown that may not be the case in low flow situations. These two factors can combine to cause a possible 45 percent reduction from expected Canadian savings.

Expected savings in an unequal flow installation in California range from 12.9 to 19.6 therm/year assuming two 10 minute showers/day passing through the device. Increasing the number of showers would scale the expected savings linearly. Equal flow installations, which appear to be the less common installation method due to increased installation complexity and cost, would increase savings by 40 percent on average. Note that these estimates are based on a theoretical draw pattern. A more precise estimate should be made when the 2016 ACM draw pattern is available.

It is recommended that connecting the master bath to the DWHR device be considered a basic eligibility requirement if DWHR is added as a compliance option to the ACM. Additionally, three inputs should be added to the CBECC-Res interface to provide a reasonable characterization of performance. These inputs are:

1. The CSA rating for the proposed device.
2. The installation configuration (Equal, Unequal – Shower, and Unequal – Water Heater), and
3. The percent of shower stalls connected to the DWHR device.

There are still several items related to DWHR units which warrant further study. They are:

1. **Partial wetting:** Tests have identified partial wetting, and low heat transfer effectiveness, at low flow rates. The causes and impacts have only been briefly studied. Further research should determine when it is likely to occur, how the selection of DWHR unit and installation design impact this effect, and the extent to which it impacts the potential savings. Preliminary simulations have shown that this effect has the potential to reduce savings by 11.5 percent, or 297 Btu/shower[1].
2. **Cost-effectiveness estimates:** The estimates of savings should be repeated using the draw patterns for the 2016 version of CBECC. Doing so will provide a more accurate estimate of savings, and determine whether or not future research is warranted. Additionally, more cost-effective applications (multi-family shared shower drains, dormitories, hotel/motel, etc.) have more complicated installation variations that should ideally be evaluated in the lab.
3. **Comparison to field installations:** It is possible that, through a combination of fouling, different installations, draw profiles, and differences between manufacturers, the lab results do not match the results in field installations. Testing on a used DWHR device, units from different manufacturers, and field studies should be performed to ensure that these results can be extrapolated or the algorithm can be modified to account for these differences.
4. **Distribution losses:** The heat lost in the distribution pipes after being recovered by the DWHR unit was not thoroughly studied. Further efforts should be made to identify how the units are typically installed, and how much heat is still in the pipe after the draw.

[1] Assuming a 10-minute shower, at 2 gpm, with a 105 °F shower temperature, and a 120 °F water heater set point.

5. **Horizontal:** Only vertical DWHR units were studied while horizontal, unlike vertical, DWHR units could be used in first floor shower stalls. Performing testing on those units would allow for the inclusion of these devices in the algorithm.

The scope for Phase 2 is currently being defined. It is expected to focus on testing of additional units, studying how real-world installation conditions impact DWHR performance, and a detailed economic analysis in different buildings and climate zones.

1. PROJECT OVERVIEW

The Codes and Standards Enhancement (CASE) initiative presents recommendations to support California Energy Commission's (CEC) efforts to update California's Building Energy Efficiency Standards (Title 24) to include new requirements or to upgrade existing requirements for various technologies. The four California Investor Owned Utilities (IOUs) – Pacific Gas and Electric Company, San Diego Gas and Electric, Southern California Edison and Southern California Gas Company – and Los Angeles Department of Water and Power (LADWP) sponsored this effort. The program goal is to prepare and submit proposals that will result in cost-effective enhancements to energy efficiency in buildings. This report and the code change proposal presented herein is a part of the effort to develop technical and cost-effectiveness information for proposed regulations on building energy efficient design practices and technologies.

The primary objective of this study was to test a single drain water heat recovery device under controlled conditions to develop a performance characterization appropriate to California climates and applications. Using a high quality lab as the testing site, precise measurements were completed. Using laboratory findings, performance algorithms were created to estimate performance under a range of operating conditions anticipated in California residential applications. The resulting algorithm is proposed to be used in CBECC-Res 2016 to identify energy savings from this technology.

2. INTRODUCTION

Drain water heat recovery (DWHR) devices are an application of a counter-flow tube in tube heat exchanger used to reclaim waste heat for pre-heating of domestic hot water. In single and multi-family residential applications, the DWHR device is typically installed on the main drain line (usually in close proximity to one or more bathrooms), and uses the waste heat to preheat potable cold water piped through the device. DWHR devices are made of copper. Figure 1 provides a conceptual diagram and gives a general understanding of how DWHR units operate. As drain waste water flows through the larger diameter copper pipe, heat is conducted through the pipe wall to smaller diameter copper tubing containing cold potable water. The device relies on the falling film effect where the surface tension of water causes the waste flow to cling to the pipe wall rather than falling through the center of the drain pipe, more effectively conducting heat to the device. Typical DWHR device specifications vary based on the application and expected load, with typical single family residential devices having a 2″ to 4″ drain diameter, and 4′ to 5′ lengths. Multi-family and nonresidential applications are often longer and can benefit from potentially combining more hot water drain flow on a single device.

DWHR units use the drain waste heat to preheat the incoming cold water, reducing the load on the water heater. They can achieve this goal using three different installation configurations:

1. **Equal Flow:** In this flow configuration the preheated cold water leaving the DWHR device is routed to both the water heater and the cold inlet of the fixture. Therefore, all of the water used in the draw event passes through the cold side of the DWHR unit. As a result, the cold and drain side flows are equal[2], resulting in the maximum energy yield from the device.
2. **Unequal – Flow to the Water Heater:** In this configuration the preheated potable water is piped directly to the water heater. The flow rate through the cold side of the DWHR device will match the hot water flow rate from the water heater. The draw at the fixture (i.e. shower) will likely be a combination of hot and cold water, and will cause a higher flow rate through the drain side than the cold side of the DWHR unit. Because these flow rates differ, this configuration is referred to as an unequal flow situation.
3. **Unequal – Flow to the Shower:** In this configuration the preheated water is sent to the cold inlet of the fixture and not to the water heater. Similar to the prior unequal configuration, this will often result in higher flow rates on the drain side than the cold side.

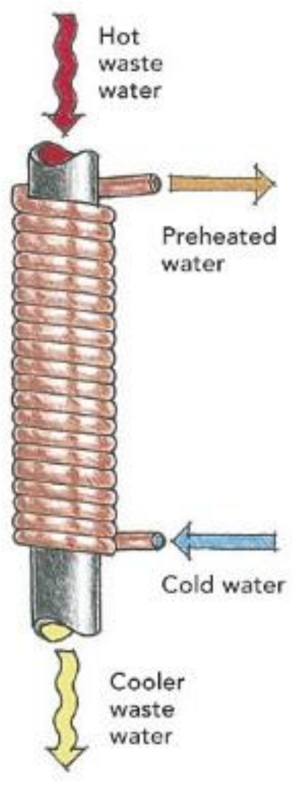

Figure 1: Conceptual Diagram of a Drain Water Heat Recovery Device

DWHR devices do not employ storage, rendering storage of heat over time largely ineffective. Due to this limitation, they function best in long draws with simultaneous drain and cold flows.

[2] Unequal flow is possible if a second draw, not connected to the DWHR device, occurs at the same time.

In residential applications, they are primarily used to harvest energy from the drain during showers. Figure 2 brings these concepts together by presenting a typical Unequal – Flow to the Water Heater installation. In this example, a single shower is connected to the device, although multiple showers could conceivably be connected, increasing the potential energy savings.

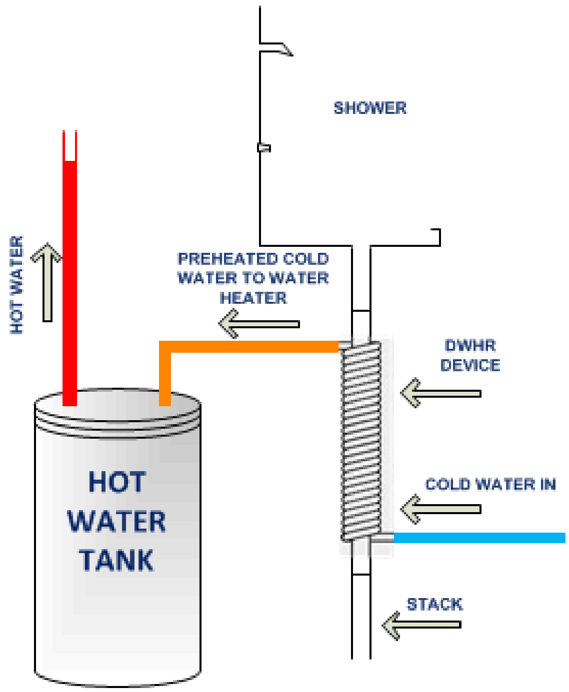

Figure 2: System Schematic of a DWHR Device in the Unequal Flow - Water Heater Configuration

As an example of counter flow shell and tube heat exchangers, DWHR units are typically characterized in terms of their effectiveness. Heat exchanger effectiveness is a ratio comparing the rate of heat transfer to the maximum possible heat transfer rate and is calculated using Equation (1).

$$\varepsilon = \frac{\dot{V}_C}{\min(\dot{V}_C, \dot{V}_D)} \frac{T_{C,O} - T_{C,I}}{T_{D,I} - T_{C,I}} \qquad \textbf{Equation (1)}$$

DWHR devices have been installed in some areas of the U.S., but seem to have greatest popularity in much colder climates such as Canada. This is largely due to the benefit of the device being greater when the drain water to cold inlet water temperature difference is larger. In California, DWHR devices are anticipated to have lower benefit because cold water temperatures are considerably higher than the Canadian conditions. However interest in this technology exists among California energy efficiency advocates as the Title 24 Energy Code continues to explore opportunities that could help the state achieve a Zero Net Energy (ZNE)[3] goal for residential new construction for 2020. With water heating representing 49 percent of typical California household natural gas consumption, identifying cost-effective solutions

[3] ZNE in California is based on the concept of Time Dependent Valuation which values electrical and gas energy on a broader societal value. For electricity in particular, summer peak demand is valued highly.

addressing that end use is of high importance [1]. Showers typically consume approximately 51 percent of hot water in California single family homes, and are responsible for a corresponding percentage of hot water use [2].

DWHR is now required by some model codes in specific applications. The International Code Council′s (ICC) International Green Construction Code requires that DWHR units be connected to showers in multi-family residential buildings, such as apartment buildings and dormitories [3]. The ICC also specifies laundry machines in factories, short-term residential buildings such as hotels, and recreational buildings such as health clubs or spas as applications requiring DWHR.

The Canadian Standards Association (CSA) has written a test protocol to rate the steady state effectiveness of DWHR units under equal flow conditions [4]. It prescribes a test protocol and testing at 1.45, 1.85, 2.38, 2.64, 3.17 and 3.70 gpm flow rates to develop a regression curve for estimating the device effectiveness at a nominal 2.51 gpm rating point. Inlet and outlet temperatures are respectively approximately 50°F and 100.4°F, and the results are normalized. The final rating for each unit is the estimated effectiveness at 2.51 gpm. Application of the results typically assumes that the cold-side inlet temperature is 50°F and the drain-side inlet temperature is 100.4°F.

Estimating the effectiveness of DWHR units allows calculating the amount of energy saved in a given draw. The rate of heat transfer during a draw can be calculated using Equation (2).

$$\dot{\boldsymbol{Q}} = \boldsymbol{\varepsilon} * \mathbf{min}(\dot{\boldsymbol{V}}_{\boldsymbol{C}}, \dot{\boldsymbol{V}}_{\boldsymbol{D}}) * \boldsymbol{\rho} * \boldsymbol{C}_{\boldsymbol{p}} * (\boldsymbol{T}_{\boldsymbol{D,I}} - \boldsymbol{T}_{\boldsymbol{C,I}}) * \mathbf{60}$$ **Equation (2)**

Where, the 60 is used to convert the flow rate from gpm to gal/hr.

Note that the $\min(\dot{V}_C, \dot{V}_D)$ term is in the denominator in Equation (1) and numerator in Equation (2). As a result, it is possible for changes in draw conditions to impact effectiveness and heat transfer in opposite ways (e.g. reduced heat transfer despite an increase in effectiveness).

2.1 Literature Review

In 2011 the American Council for an Energy-Efficient Economy (ACEEE) studied 16 different energy efficient water heating technologies, including DWHR [5]. They stated that preliminary testing has shown potential shower energy savings of 46 to 67 percent, which the authors extrapolated to 30 percent of whole-house water heating energy. The savings will be higher in cold climates, where the cold inlet temperature is lower and the total water heating load is proportionally higher.

The installation costs of DWHR devices (In 2010 dollars) were estimated to be approximately $1000 for retrofits, or $800 for new construction cases. The ACEEE study did not expect the installed cost to decrease dramatically in the future because DWHR devices 1) are made of copper, which likely will not decrease in price, 2) do not employ any moving parts, and 3) do not use any electrical parts. Price decreases are expected to be modest, and driven by increased manufacturing efficiency and plumber experience.

In 2015, BR Laboratories completed a lab study of a Device-P DWHR device and that, except for very low flow rates at very low shower drain temperatures, the minimum gas use reduction due to preheating was very close to 30 percent [6]. This was true for drain water flow rates at 2.0 and 2.5 gpm, with shower temperatures between 95 and 100°F, and ambient and cold water temperatures around 65°F. Insulating both the hot water pipes leaving the Device-P and the device itself increased the gas savings only slightly.

2015 monitoring at the Honda Smart Home[4] included reporting of DWHR savings at the occupied test house. The family of four residing in the house used an average of 34 gal/day for all domestic hot water purposes over the twelve-month period. The DHWR device connected to both upstairs bathrooms and the clothes washer was found to provide 16 percent of the water heating load over the course of the year, ranging from a high of just over 20 percent in the winter months to a low of 5 to 8 percent in the mid-summer months. Contrasting these California specific field savings results to results from colder climates suggests that the Honda Smart Home case may be an above average performer due to its compact configuration and ability to reclaim heat from all second floor uses. A 2012 Building America study at two Wisconsin high performance homes found average annual water heating recovery load savings in the 6 to 11 percent range.

A more detailed evaluation of DWHR devices is presented in the M.S. thesis of Ramin Manoucheri. In his work, he performed laboratory testing studying the steady state effectiveness of DWHR units [7]. He then used the results to create an algorithm that can be used to extrapolate results from the CSA test protocol. Testing included a thorough study of the impacts of both drain and cold-side flow rates in equal and unequal configurations, as well as the impact of drain and cold-side inlet temperatures. Equal flow tests ranged from 1.45 to 6.6 gpm, and unequal flow tests used a matrix approach to study several drain / cold flow rate combinations with each flow ranging independently from 1.45 to 3.7 gpm. Tests focusing on inlet temperature ranged from 41 to 86°F on the cold side, and 77 to 113°F on the drain inlet.

The two main findings from this work are:

1. The falling film on the drain-side of the heat exchanger does not always develop fully at low flow rates. Particularly below 1.45 gpm, incomplete wetting on the drain-side of the heat exchanger can result in lowered effectiveness and non-repeatable results. Because of this, Manoucheri concluded that results from the CSA test cannot be used to estimate the effectiveness of DWHR units below 1.45 gpm.
2. Developing an algorithm to predict the effectiveness of a DWHR unit as a function of cold-side flow rate, drain-side flow rate, cold-side inlet temperature, and drain-side inlet temperature is feasible.

The Manoucheri work represents a thorough study of DWHR units, and a valid model for steady state effectiveness of DWHR units. However, there was no discussion of the thermal mass of DWHR units or how it impacts the effectiveness of the unit across a full draw. An algorithm predicting the energy saved for a typical shower, as is needed for CSE, must be able to estimate the effectiveness of draws of varying lengths, including the transient effects at the start of a draw.

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[4] http://www.hondasmarthome.com/

In 2015, RESNET completed revisions to its water heating modeling to accommodate various measures including DWHR [8]. The ANSI/RESNET 301-2014 Addendum A-2015 incorporates an algorithm to identify the impact of DWHR devices on water temperature at both the water heater and fixtures. The increase in cold inlet water temperature is then used in other relationships to estimate the reduction in hot water use, caused by an increase in cold water temperature at the shower, and water heating energy, caused by both the increase in cold water temperature and reduction in hot water use. The RESNET algorithm for increase in cold water temperature is shown in Equation (3).

$$\Delta \boldsymbol{T}_{\boldsymbol{Mains}} = \boldsymbol{I}_{\boldsymbol{Frac}} * (\boldsymbol{T}_{\boldsymbol{D,I}} - \boldsymbol{T}_{\boldsymbol{C,I}}) * \boldsymbol{\varepsilon}_{\boldsymbol{CSA}} * \boldsymbol{C}_{\boldsymbol{PL}} * \boldsymbol{f}_{\boldsymbol{Loc}} * \boldsymbol{f}_{\boldsymbol{Fix}} \qquad \textbf{Equation (3)}$$

Some notable items in the RESNET implementation include the following:

1. The RESNET algorithms assume that the preheated water is directed to both the shower and the water heater (Equal flow). This assumption is used whether the physical installation is equal or unequal flow.
2. In unequal flow installations (Where the preheated water is directed to only the water heater or the shower) the temperature rise is reduced to 77.7 percent of the equal flow temperature rise.
3. RESNET method includes a factor describing the number of showers in a building connected to the DWHR device. It uses some assumptions to estimate the percentage of showers taken in DWHR connected devices.

There are several strengths and shortcomings to the RESNET implementation. The strengths include:

1. The RESNET implementation includes an algorithm to estimate the increase in outlet temperature and associated energy savings in a building.
2. It includes a factor for configurations with less than 100 percent of all showers connected to the device and reduces the energy savings potential accordingly.
3. Additionally, the method includes a term describing the temperature reduction caused by heat loss in the pipes.

The main shortcomings of the RESNET implementation are:

1. The assumption that pre-heated water is always directed to both the water heater and the shower is unrealistic.
2. As shown by the unequal flow results in Manoucheri, a 77.7 percent derate factor for unequal flow installations is overly simplistic and may result in inaccurate energy savings predictions depending on the cold-side inlet water temperature and shower flow rate. Manoucheri found unequal flow derate factors that ranged from 34.3 percent to 78.7 percent.
3. The RESNET implementation always uses the CSA rated effectiveness, which assumes a draw flow rate of 2.51 gpm. Per the results in Manoucheri, it is expected that the

effectiveness of the DWHR device will vary with flow rate. Unless all showers have 2.51 gpm shower heads this simplification will cause inaccurate energy savings predictions.[5]

3. METHODS

PG&E was interested in developing a compliance option modeling approach within the Residential ACM to accommodate DWHR devices. Davis Energy Group, in conjunction with TRC and PG&E Applied Technology Services (ATS) lab personnel, developed an approach to test the behavior of a single representative DWHR unit at the PG&E ATS lab in San Ramon, California. The ATS test lab includes highly sophisticated testing capabilities including LabView automated control for experiments. The goal of the ATS testing was to generate data for algorithm development. The test plan was designed with three main objectives in mind.

1. **Mimic the CSA rating test**. This data was intended to be used to identify the effectiveness at equal flow conditions as a function of flow rate, with cold and drain side inlet temperatures of 50°F and 100.4°F respectively. Additionally, this test allowed for direct comparison against the published effectiveness of the DWHR device.
2. **Unequal flow conditions.** Several of the tests were used to assess effectiveness sensitivity to both drain and cold flow rates in unequal flow conditions. This data allowed creation of a performance map, simplifying the estimation of effectiveness across a broad range of flow rates.
3. **Varying inlet temperature.** The remainder of the tests were used to determine the impact of changing inlet temperatures on draw effectiveness. This focused primarily on cold-side inlet temperature, as it varies significantly with the dramatic climatic and seasonal changes in California.

A single DWRH device was tested at the ATS lab for this initial assessment. A Power-Pipe R3-48 (3″ diameter, 48″ length, 46.6 percent CSA rated effectiveness) was selected as a representative device for a California residential application with a 3″ drain line. Although the test results are of course specific to this unit, the goal was to utilize the performance results to extrapolate to other similar devices based on their CSA rating specification.

A copy of the proposed matrix of lab tests is provided in Appendix 1. The matrix lists the specific flow rates and inlet temperatures for each test. The following points describe how the test plan supports the previously stated goals.

1. Tests 1 through 7 are the same tests used in the CSA protocol. Higher flows were used in other research by Manoucheri, so those flow rates were included in tests 8 and 9 as well. Additional testing, not included in the original lab test plan, added equal flow tests at 4.14, 4.58, 5.01, 5.89, 6.3, and 6.76 gpm.
2. Tests 10 through 36 study the impact of unequal flows on draw effectiveness. On the drain side, the flow rate varies from 1.45 gpm to 3.7 gpm. This covers the range from one

[5] California standards adopted in 2015 require showerheads to have a maximum 2.0 gpm flow rate, with a further reduction in the maximum showerhead flow to 1.8 gpm by July 2018 [9]

shower with a low-flow showerhead to two showers. The cold side flow rates vary from 0.4 to 5.5 gpm, effectively covering many situations with very low cold side flow, or other cold water draws occurring simultaneously. Note that the range of cold flow rates differed for each drain flow rate. Additional testing, not included in the original test plan expanded the cold-side flow range for all drain-side flow rates to 0.4 to 5.4 gpm.

3. Tests 1 through 36 use a cold inlet temperature of 50°F, while tests 37 to 106 use a cold inlet temperature of 70°F or 90°F. These temperatures were selected because they capture the vast majority of inlet water temperatures in California. Field study data has shown that 50°F is a reasonable value for Truckee in the winter, and 90°F is an upper limit for mid-summer conditions in hot desert areas like Palm Springs.

3.1 Test Apparatus

The test apparatus consisted of a fully instrumented DWHR device mounted in a temperature controlled laboratory. Temperature and flow modulated cold and drain water supply lines were fed to the respective inlets of the DWHR device. A chiller served as the cold water source while a commercial sized hot water heater served as the hot water source. A Labview script was written allowing full automation of tests with a variety of flow/temperature conditions.

Figure 3: DWHR Device Mounted and Instrumented in Laboratory

The test apparatus was instrumented to 1) account for all energy entering and exiting the system, and 2) provide all real-time measurements needed for full test automation.

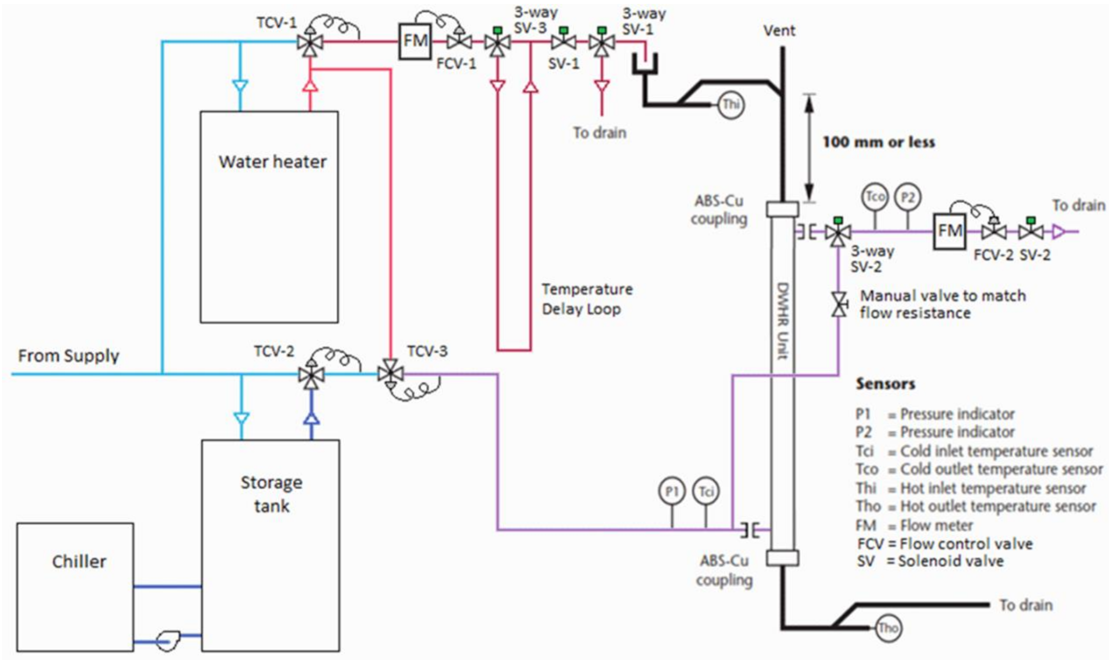

Figure 4: Fully Automated DWHR Device Test Apparatus at ATS

A 1.5-ton chiller coupled with a 75-gallon cold water storage tank was used to temper incoming city water. Hot water was provided by a 100-gallon commercial storage water heater. Three-way temperature modulating valves mixed city, cold, and hot water to the desired condition at both the drain and cold inlet of the DWHR device. Feedback for three way modulating valve position was provided from three resistance temperature detectors (RTDs). Bleed lines were added upstream of any flow measurement to improve the response time of the three-way temperature modulating valves. Nutating disc (positive displacement) hot water flow meters were used to measure the flow rate to each side (drain and cold) of the DWHR device under test. Two-way flow modulating valves were used to throttle flow on both the drain and cold sides of the heat exchanger. The nutating disc flowmeters provide feedback for control of the two-way flow modulating valve position.

Table 1: Lab Equipment and Instrumentation List

Equipment Description	Make/Model	Other Info
Water Chiller	Advantage M1-1.5A	1.5 Ton Rating
Cold Water Storage Tank	Unknown	75 Gallon Galvanized Tank
Water Heater	A.O. Smith Master Fit	199,000 Btuh Firing Rate 100 Gallon Tank
Water Flow Meter	Badger Meter M25-625-L-L-S-R-TT-GA-CS	20 gpm max flow, Analog and Pulse Output
Temperature Instrumentation	Burns Engineering 12″ Fast Response RTD	4-wire RTD Element in low mass tip
Three Way Modulating Valve	Siemens MXG461B20-5	3/4″ 3 Way Red Brass Magnetic Needle Valve
Two Way Modulating Valve	Siemens MXG461B15-3	1/2″ 3 Way Red Brass Magnetic Needle Valve

Figure 5: Chiller and Cold Water Storage Tank for Tempering Water in DWHR Testing

3.1.1 Temperature Measurement and Calibration

DWHR device surface temperatures were taken with evenly spaced type-T thermocouples. Surface temperature measurement provided some indication for whether or not the device was at steady state. An ambient temperature measurement was also taken within three feet of the device. All remaining temperatures were taken with fast response four wire RTDs. All water temperatures were taken in fully submerged locations within two feet of the DWHR device. RTDs were calibrated against a laboratory standard temperature sensor in an ice bath (32°F), and an isothermal block (113°F and 190°F). The range of calibration temperatures was selected to bound all temperatures seen by each probe during the course of testing. All temperature calibration data and NIST traceable calibration certificates are included in Appendices A through C. Calibrations were performed on all DWHR inlet and outlet RTDs prior to testing and were within their calibration interval during testing**.**

Figure 6: Drain Side Inlet Temperature Taken in Trap (Lower Left)

Figure 7: Drain Side Outlet Temperature Taken in Trap

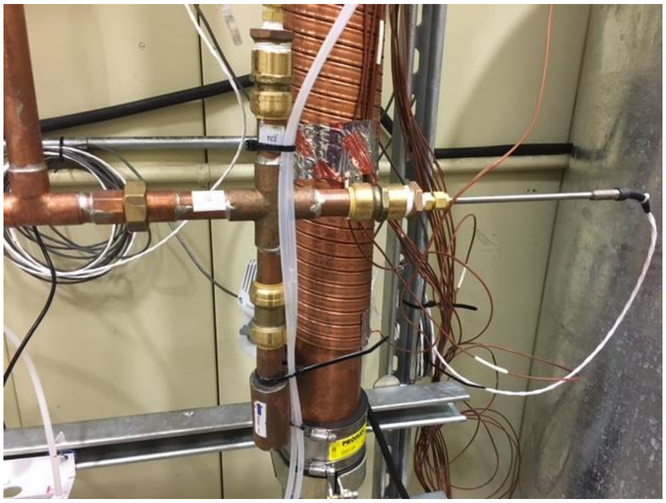

Figure 8: Cold Side Inlet Temperature, Taken Facing Flow with 12″ RTD

Figure 9: Cold Side Outlet Temperature, Taken Facing Flow with 12″ RTD

3.1.2 Flow Measurement and Calibration

A ½″ Coriolis flow standard was used to calibrate each of the two nutating disc water flow meters used during DWHR device testing. The NIST traceable calibration certificate for this Coriolis flow standard is included in Appendix D. Flow calibration results and a simple uncertainty analysis of the flow meters used during testing are documented in Appendix E. Calibrations were performed on both flow meters prior to testing and were within their calibration interval during testing.

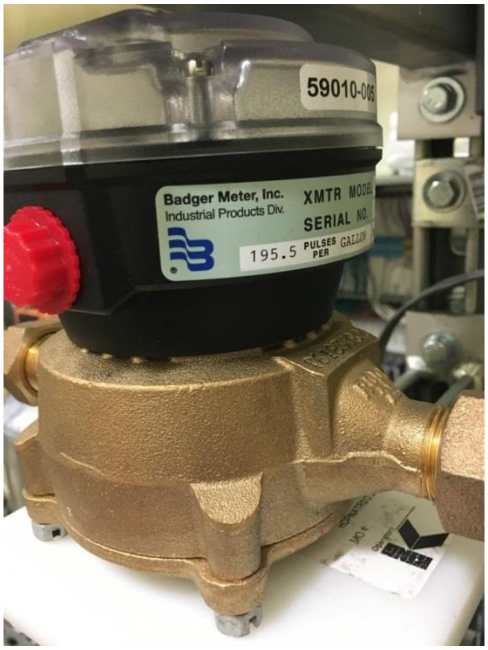

Figure 10: Nutating Disc Positive Displacement Water Flow Meter used for DWHR Device Testing

3.2 Data Acquisition and Test Control

All instrumentation was connected to multiple rack-mounted Compact Rio modules from National Instruments. The signal conditioning modules included different units for RTDs, thermocouples, voltage and pulse count (water meter) inputs, plus both analog and digital output modules for the solenoid, two way modulating, and three way modulating valves. Each rack included an Ethernet communications module that enabled the system to be accessed from anywhere on the local network.

A local computer connected to the Ethernet network ran a program written in National Instruments' LabVIEW graphical programming language. This program was developed to read all the measurement devices, display the readings and additional calculated values on screen, and save the data to disk for later analysis, as well as control all test conditions. The system was programmed such that all tests can be automated over as long a period as desired. The scan rate for sampling from the Compact Rio modules and updating the screen was set at 2 Hz, although the internal scan rate of the modules was at least 10 Hz.

A user interface built in LabView was designed for the test operator to visually monitor the test apparatus. The user interface integrates both manual and automatic controls where a test script is programmed to automatically run on the system. The logging interval was set to five seconds. All five second scans are a running average of a total of ten samples.

3.3 Test Uncertainty

Calibration was performed to mitigate the impact of instrument uncertainty.

Temperature uncertainty was calculated incorporating sources of bias error such as accuracy of the calibration standard, assumed drift over time, non-uniformity of the isothermal block and ice bath, worst deviations between test instrumentation and calibration standards, as well as uncertainty based on the location of the temperature measurement relative to the actual inlet of the DWHR device. Random error due to fluctuation of test data was also approximated using data from Test 1, where the standard deviation of the average temperature taken during the 16-minute test was computed. The overall uncertainty (95 percent confidence) of each temperature measurement was calculated to be about 0.5°F for all four conditions monitored on the DWHR device.

Flow uncertainty was calculated incorporating sources of bias error such as accuracy of the calibration standard, assumed drift over time and worst case deviations between test instrumentation and calibration standards. Random error due to fluctuation of test data was not included as it is assumed minimal compared to the bias error of the flow measurement. Overall water flow measurement uncertainty was calculated to be as high as 1.57 percent of indicated flow on the drain side and as high as 4.16 percent of indicated flow on the cold side. These uncertainty values are higher than one might anticipate, and are caused by the characteristics of flow meters at very low turndown ratios. For example, this meter is designed for a maximum of 20 gpm, but some tests required flows at or below 0.5 gpm. At very low flow rates a small deviation between instrument and flow standard can result in very high percent uncertainty values. For example, a deviation of 0.02 gpm at a nominal 0.5 gpm flow rate between test instrument and calibration standard is 4 percent difference. Generally, flow measurement accuracy degrades at turndown ratios lower than 10:1.

Total percent uncertainty in heat rate, for either side of the heat exchanger, can be identified by calculating the root sum square of the percent uncertainty of the average mass flow measurement with the percent uncertainty of the average specific heat and average temperature rise across the DWHR device (performed by taking the difference between two average inlet and outlet temperature measurements). With an average temperature measurement uncertainty of about 0.5°F at the inlet and outlet on either side of the DWHR device, the overall uncertainty in temperature rise is 0.707°F. If the temperature rise is 20°F, the percent uncertainty in temperature rise is 3.5 percent. If the temperature rise is only 10°F, the percent uncertainty in temperature rise is 7 percent. It is recommended that future studies require a sensitivity analysis be performed ahead of designing a test. With this information a determination can be made on desired accuracies of instrumentation based on the desired uncertainty of the effectiveness of the DWHR device. This will dictate the need for additional temperature calibration points to be taken, as well as possibly an additional flow meter for lower flow tests.

3.4 Description of Tests

Each individual test consisted of two phases. The first phase was a flush of the DWHR device to ensure consistent initial conditions for each test. This purge phase consisted of a four-minute flow at a four gpm flow rate of water conditioned to match the room ambient temperature. After the flush was complete, the test flow rate of hot drain water was initiated. Each test consisted of a 16-minute draw at the prescribed flow rates and temperatures (drain and cold water inlet). Figure 11 provides a sample time series plot of temperatures and flow during a single test.

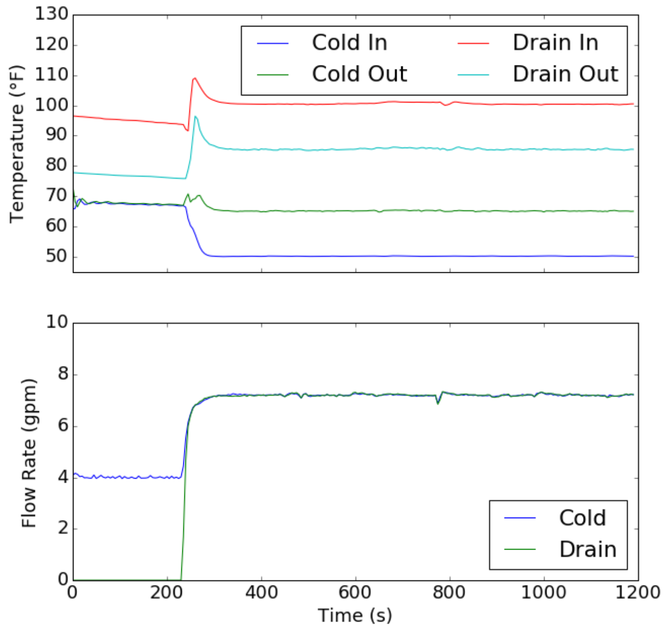

Figure 11: Sample Equal Flow Test Data (7.2 gpm, 50°F Cold Inlet Temperature, and 100.4°F Drain Inlet Temperature)

The two phases are clearly demonstrated in Figure 11. The top plot shows a small temperature difference on the cold side until 240 seconds into the test, while there is a large temperature difference on the drain side. This indicates a high flow rate on the cold side and no flow on the drain side, which matches the flow data in the bottom plot. After 240 seconds, the flow rate increases to 7.2 gpm on both sides. At the same time, the cold side inlet temperature decreases to 50°F and the drain side increases to 100.4°F. These inlet temperatures are maintained for the rest of the draw.

Note that there is a period of instability as the drain inlet temperatures transition to the draw temperatures. This is a known issue in the test controls, and ATS has plans to reduce the transition time for future, more detailed DWHR testing.

3.5 Data Analysis Methods

The data for each test was evaluated to identify both the instantaneous and average effectiveness over the course of a draw.

Figure 12 provides an example of the calculated instantaneous effectiveness over the course of a draw. Note that the temperature instability shown in Figure 3 causes a spike in effectiveness during the transition period as the DWHR device mass approaches steady state temperature. This spike should be reduced if ATS changes the test apparatus to improve the stability of inlet temperatures at the start of each test. Note that the first 240 seconds (4 minutes) is the flush of the cold water side of the heat exchanger, the actual meaurement of the heat exchanger effectiveness does not initiate until after 240 seconds. The effectivess of the heat exchanger stabilizes to a steady state value around 285 seconds from the beginning of the test or around 45 seconds into the portion of the test that measures effectiveness. This indicates the duration thermal mass effects for this relatively high flow rate (7.2 gpm).

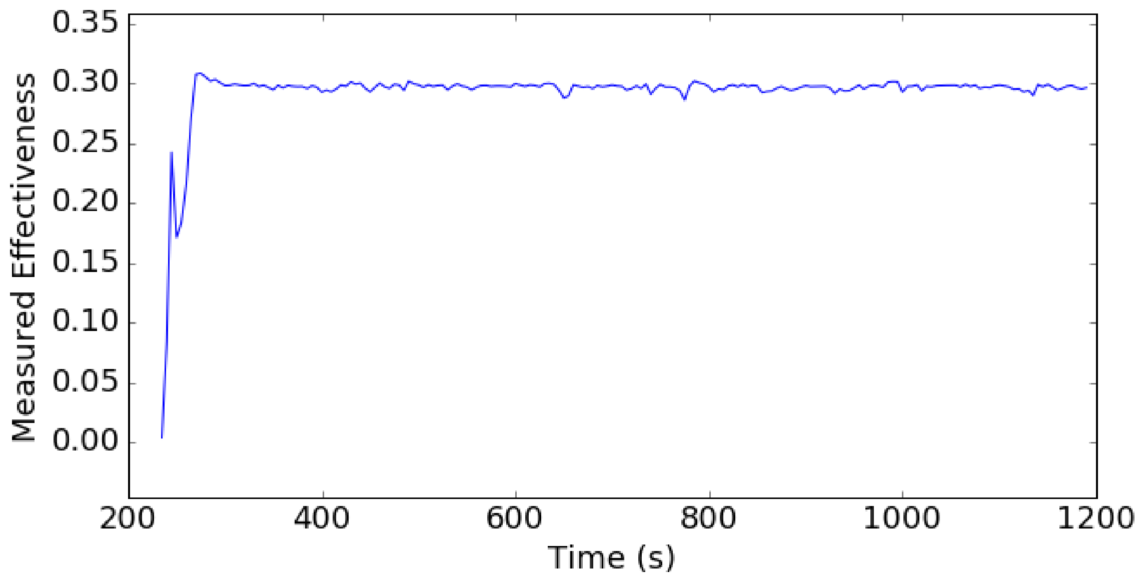

Figure 12: Measured Equal Flow Effectiveness (7.2 gpm, 50°F Cold Inlet Temperature, and 100.4°F Drain Inlet Temperature)

The effectiveness results were used to generate regressions to identify the effectiveness of a simulated draw as a function of the conditions. Regressions were created for the impact of:

1. Varying flow rates in equal flow installations
2. Draws of varying durations to assess start-up impact on overall draw performance
3. A range of flow rates in unequal flow installations
4. Draws with varying cold-side inlet temperatures
5. A preliminary investigation into changes in drain-side inlet temperature

Each of these topics is addressed in a separate section of the Results chapter.

4. RESULTS

The test results were analyzed to identify the effectiveness of the DWHR device during a draw as a function of several different conditions. These conditions were listed in Data Analysis Methods. The following sections describe the results of each investigation. Because of the previously discussed differences between the CSA test protocol and typical California conditions, there must be a method for adjusting drain water heat recovery effectiveness as a function of:

- Flow rate
- Inlet water temperature
- Duration of shower

4.1 Equal Flow Results

The equal flow tests were designed to replicate the reported CSA effectiveness of the tested device. Similar to the CSA protocol, a regression was developed and used to identify the effectiveness at 2.51 gpm. Figure 13 shows the test results and regression in the equal flow tests.

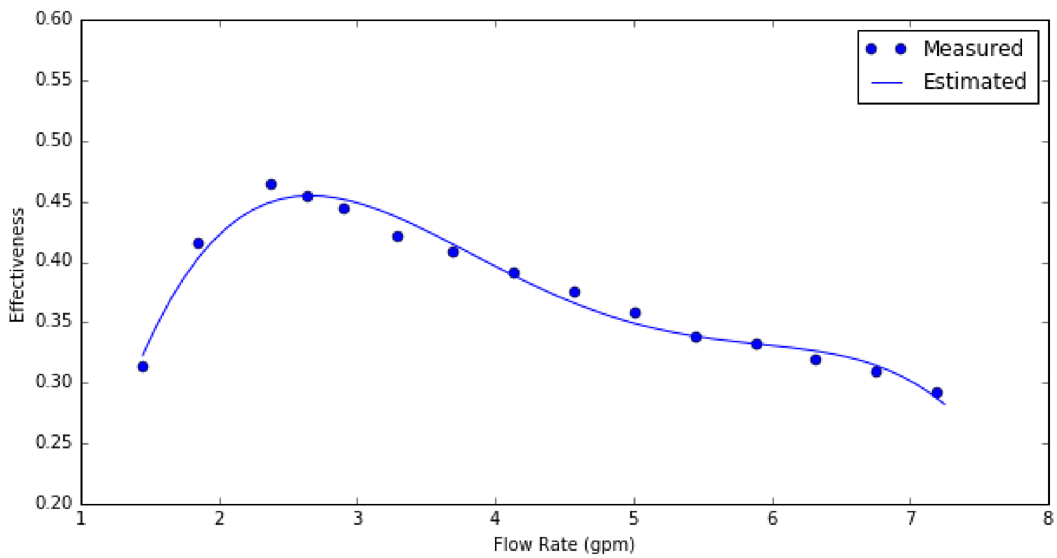

Figure 13: Draw Effectiveness in Equal Flow Configuration as a Function of Flow-Rate (Cold-Side Inlet Temperature = 50°F)

The plotted regression curve closely matches the measured data across the entire range of the data set. A fourth-order regression was used to match the data set, and is shown in Equation (4).

$$\boldsymbol{\varepsilon = -0.00258 * \dot{V}^4 + 0.0503 * \dot{V}^3 - 0.35 * \dot{V}^2 + 0.989 * \dot{V} - 0.518} \qquad \textbf{Equation (4)}$$

This regression differs from the results in previous work. Manoucheri used a regression of the form $\varepsilon = \frac{1}{G * \dot{V} + H}$, and the CSA test. This difference is a result of differences in the test protocol. Manoucheri used a test protocol with a high-flow flush on both the drain and cold sides of the heat exchanger prior to the draw. The flow rate was then reduced to the test flow rate for measurement. This study used a flush on only the cold side. The high-flow drain side flush had the effect of pre-wetting the drain side of the heat exchanger, which improved wetting and effectiveness during the tests at flow rates below 2 gpm. Those tests were repeated with a 4 gpm flush on the drain side to determine whether or not this theory was correct. The resulting effectiveness values are shown in Table 2, and the full set of results with a pre-wet heat exchanger is shown in Figure 14.

Table 2: Impact of Pre-Wetting on Equal Flow Effectiveness at Low Flow Rates

$\dot{V}$(gpm)	ε_{Mea}, not pre-wet (%)	ε_{Mea}, pre-wet (%)
1.45	31.3	54.5
1.85	41.5	51.8

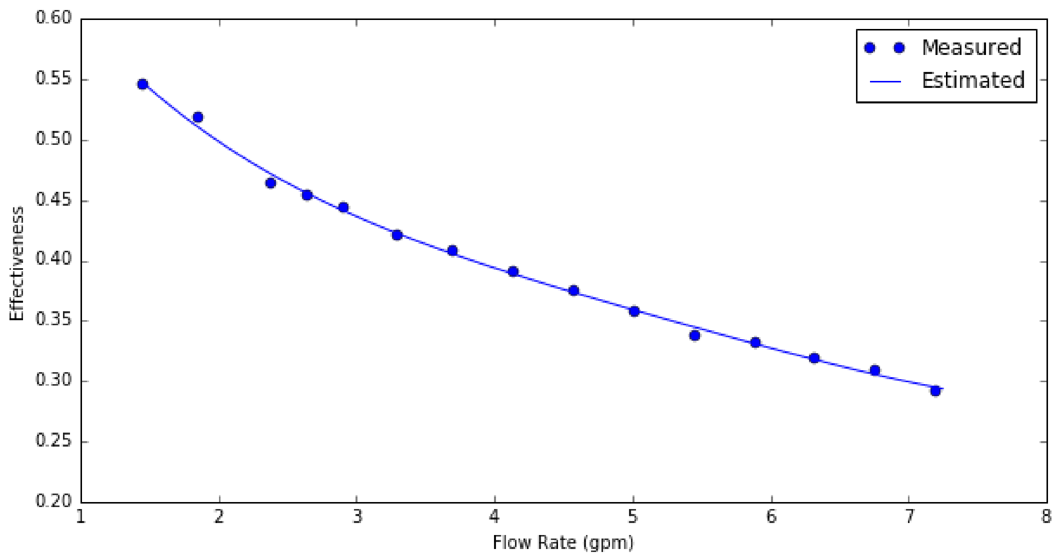

Figure 14: Effectiveness in Equal Flow Configuration as a Function of Flow-Rate with a Drain Side Flush (Cold-Side Inlet Temperature = 50°F)

Note that the form of the regression used by Manoucheri could be applied to the data shown in Figure 14.

To check the accuracy of this work, the regressed effectiveness (ε_{Est}) at 2.51 gpm was compared to both an experimental result at 2.51 gpm (ε_{Mea}), and the published CSA rating (ε_{CSA}) for the Power-Pipe R3-48. All three values closely agree as shown in

Table 3.

Table 3: Effectiveness at 2.51 GPM

ε_{CSA}	ε_{Mea}	ε_{Est}
46.6 %	47.1 %	45.4 %

4.2 Duration of Draw Results

With the current changes being implemented in the Title 24 ACM water heating methodology, we anticipate that the standard hot water draw profiles for the 2016 code implementation will specify discrete showers of different durations. To accommodate this approach, a regression relationship was created to identify an ″average″ effectiveness of a draw as a function of the draw duration at a given flow rate. This was done by calculating the effectiveness during CSA tests for different draw durations, ranging from 2 to 16 minutes at 2 minute intervals (e.g. 2, 4, 6, …, 16). A regression was developed to match the results. Figure 15 compares the predictions of the regression to the measured results at three different flow rates.

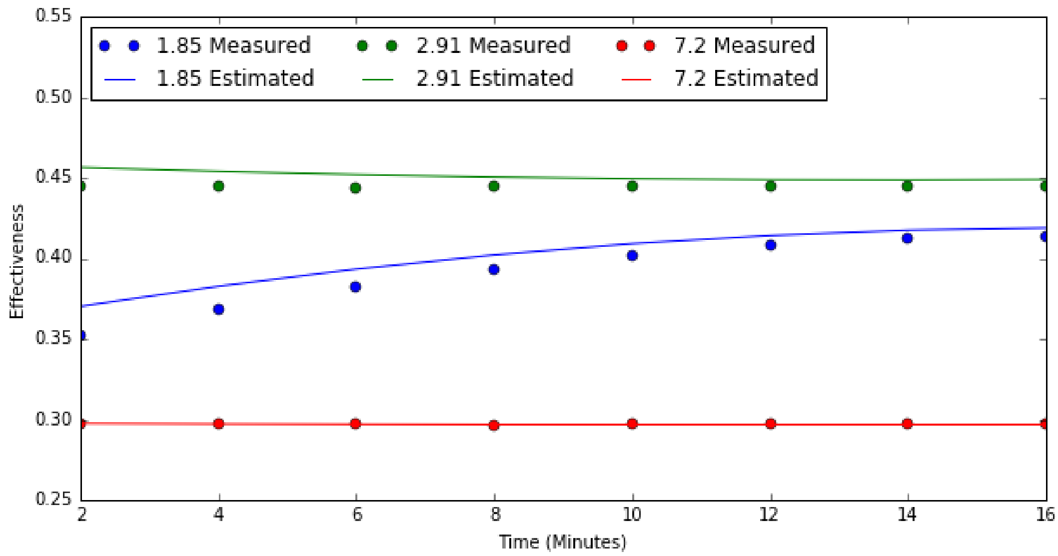

Figure 15: Predicted Average Equal Flow Effectiveness as a Function of Draw Duration for Three Flow Rates for a CSA Rated 46.6 Percent Effective Device

In Figure 15 the x-axis represents the duration of the shower event, and the y-axis states the estimated effectiveness during a shower of that length, taking into account the thermal capacitance effect of the DWHR device.

There are three important points about this data that should be discussed. They are:

1. Note that the thermal capacitance effect only has a noticeable impact in the 1.85 gpm data. This indicates that the thermal mass of the device is small, and that at higher flow rates the amount of energy recovered during the draw dominates the energy used to heat the DWHR unit. However, starting in July 2018, 1.8 gpm will be the maximum flowrate allowed for showerheads sold in California.
2. This testing was performed assuming that the DWHR device is installed in a conditioned space, and most tests began with a flush to pre-conditioned the unit to the surrounding ambient temperature. If the unit is installed in a colder space, the impact of draw duration on effectiveness will be more significant.
3. This testing was performed using the non-pre-wet test data described in Section 4.1 *Equal Flow Results.* This choice was made because the ATS lab is currently only able to flush the drain side of the heat exchanger with hot water, and the hot flush had the impact of

increasing the starting temperature of the DWHR unit. In the pre-wet tests, the effect of draw duration on total draw effectiveness was negligible even at low flow rates.

With the currently available data, the duration of a draw has a small impact on the effectiveness of the tested DWHR unit tested. While there is clearly an effect at 1.85 gpm, a typical shower flow rates and durations of 1.85 to 2 gpm and 8 to 10 minutes, the reduction in effectiveness when compared to a 16-minute shower is on the order of 1 to 2 percentage points. A deeper investigation of this topic, using data from Phase 2, may be worth considering as future versions of Title 24 will mandate lower flow rates and the impact of short draw durations will increase.

The algorithm uses a 2-stage regression. The final version is an algorithm for the effectiveness as a function of draw duration at a given flow rate. This is shown in Equation (5).

$$\boldsymbol{\varepsilon_{\dot{V}}(t) = a * t^2 + b * t + c}$$ **Equation (5)**

The a, b, and c coefficients vary as a function of flow rate. They are identified using Equations (6) – (8).

$$\boldsymbol{a(\dot{V}) = -3.3 * 10^{-5} * \dot{V}^5 + 6.7 * 10^{-4} * \dot{V}^4 - 5.18 * 10^{-3} * \dot{V}^3 + 1.88 * 10^{-2} * \dot{V}^2 - 3.17 * 10^{-2} * \dot{V} + 1.98 * 10^{-2}}$$ **Equation (6)**

$$\boldsymbol{b(\dot{V}) = 8.94 * 10^{-4} * \dot{V}^5 - 1.83 * 10^{-2} * \dot{V}^4 + 0.141 * \dot{V}^3 - 0.508 * \dot{V}^2 + 0.853 * \dot{V} - 0.528}$$ **Equation (7**

$$\boldsymbol{c(\dot{V}) = -4.89 * 10^{-3} * \dot{V}^5 + 9.66 * 10^{-2} * \dot{V}^4 - 0.704 * \dot{V}^3 + 2.32 * \dot{V}^2 - 3.39 * \dot{V} + 2.13}$$ **Equation (8)**

4.3 Unequal Flow Results

Tests in unequal flow conditions were performed across a range of flow rates. On the drain side, flow rates spanned a range from a single low-flow shower (1.45 gpm) to two simultaneous showers (3.7 gpm). On the cold side, flows ranged from 0.4 to 5.45 gpm creating a broad range of possible unequal flow combinations. The broad cold side range in flows was designed to accommodate a full range of cold water temperatures and a range of drain/cold mixing ratios at the showerhead that could occur in different California climates at different times of the year[6].

All Unequal Flow testing included a drain side flush of the heat exchanger, ensuring that the DWHR unit was pre-wet.

To emulate the experimental results, a 2-D 3rd order regression was fit to the data set. This regression can be used to predict the effectiveness of a draw with any combination of flow rates within the tested range.

[6] A summer shower in Palm Springs may only have 25 percent hot water flow at the showerhead to achieve a 105°F showerhead mixed temperature due to cold water inlet temperatures approaching 90°F.

Figure 16 shows a subset of the results at drain-side flow rates of 1.45, 2.51, and 3.7 gpm.

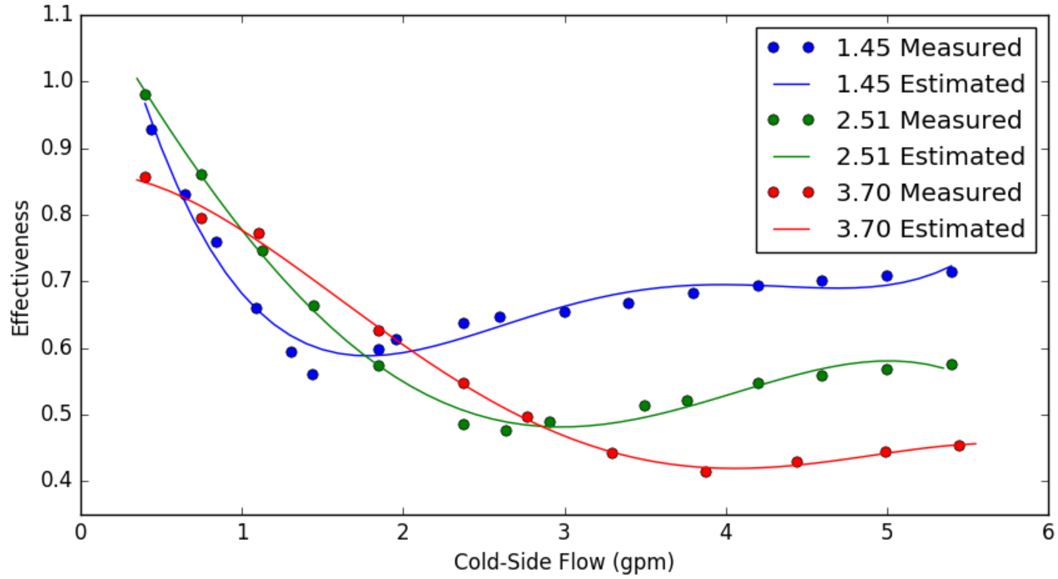

Figure 16: Effectiveness Under Unequal Flow Conditions (Drain-Side Flow: 1.45, 2.51, 3.7 gpm) for a CSA Rated 46.4 Percent Effective Device

For most points in the tested range, the regression accurately predicts the effectiveness of the draw. This is especially true for the 3.7 gpm data set. The results are slightly worse for the 1.45 gpm data set. This observation was expected; as discussed in both Equal Flow Results and the Manoucheri thesis, the results at 1.45 gpm are not as repeatable and higher variability is therefore expected. The higher variation in test results causes higher error in the regression. Even at the worst test point (Drain-Side Flow = 1.45 gpm, Cold-Side Flow = 1.44 gpm) the regression was only found to deviate from the measured data by 4 percentage points. Again, further study of the instability at low flow is recommended for the planned Phase 2 DHWR testing.

Figure 17 shows the full results of the 2-D regression. Note that, while this plot is harder to read, it displays the same trends as the subset of data in

Figure 16 as well as the predicted effectiveness values at flow rate combinations that do not match the test conditions.

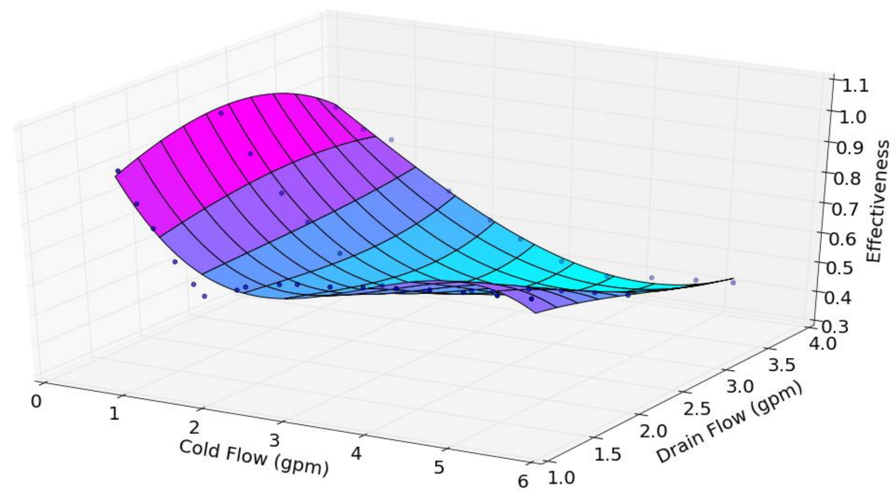

Figure 17: 2-D Curve Describing Effectiveness under Unequal Flow Conditions for a CSA Rated 46.4 Percent Effective Device

The 2-D 3rd order regression is shown in Equation (9).

$$\boldsymbol{\varepsilon} = 0.617 - 0.296 * \dot{V}_C + 0.137 * \dot{V}_C^{\,2} - 0.016 * \dot{V}_C^{\,3} + 0.435 * \dot{V}_D - 0.224 * \dot{V}_D * \dot{V}_C + 0.088 * \dot{V}_D * \dot{V}_C^{\,2} - 0.009 * \dot{V}_D * \dot{V}_C^{\,3} - 0.047 * \dot{V}_D^{\,2} - 0.012 * \dot{V}_D^{\,2} * \dot{V}_C - 0.031 * \dot{V}_D^{\,2} * \dot{V}_C^{\,2} + 0.005 * \dot{V}_D^{\,2} * \dot{V}_C^{\,3} - 0.013 * \dot{V}_D^{\,3} + 0.022 * \dot{V}_D^{\,3} * \dot{V}_C - 9.44 * 10^{-4} * \dot{V}_D^{\,3} * \dot{V}_C^{\,2} - 3.63 * 10^{-4} * \dot{V}_D^{\,3} * \dot{V}_C^{\,2}$$

Equation (9)

4.4 Cold-Side Inlet Temperature Results

Tests similar to the CSA protocol were used to study the impact of changing cold-side inlet temperature on draw effectiveness. These were performed with a cold-side inlet temperature of 50°F, 70°F, and 90°F to reflect the full range of temperatures expected in California for various climates and seasons. Figure 18 shows the results comparing the three data sets. One should note that not all cases were run for each cold-side inlet temperature, and the DWHR unit was pre-wet in all tests.

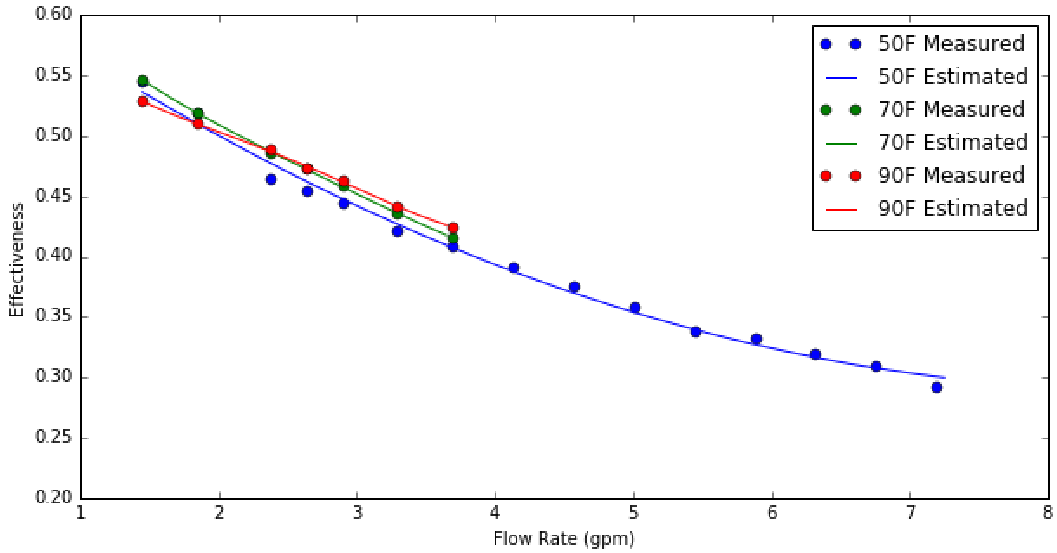

Figure 18: Draw Effectiveness as a Function of Flow-Rate and Cold-Side Inlet Temperature (Equal Flow) for a CSA Rated 46.4 Percent Effective Device

A very slight increase in effectiveness with increasing cold-side inlet temperature was observed. This effect was emulated using the regression presented in Equation (10).

$$\varepsilon = -3.06 * 10^{-5} * T_{C,I} + 4.96 * 10^{-3} * T_{C,I} + 0.281 \quad \textbf{Equation (10)}$$

4.5 Drain-Side Inlet Temperature Results

Similarly, to the cold-side inlet temperature, a series of tests were used to determine the impact of changes in the drain-side inlet water temperature. Tests were performed under equal flow conditions at flow rates similar to the CSA tests, and unequal flow conditions with a drain-side flow rate of 1.8 gpm. In all cases, the DWHR unit was pre-wet. The tests used drain-side inlet temperatures of 100.4°F and 90°F, and the draw effectiveness was compared under all conditions. The results are shown in Figures 19 and 20.

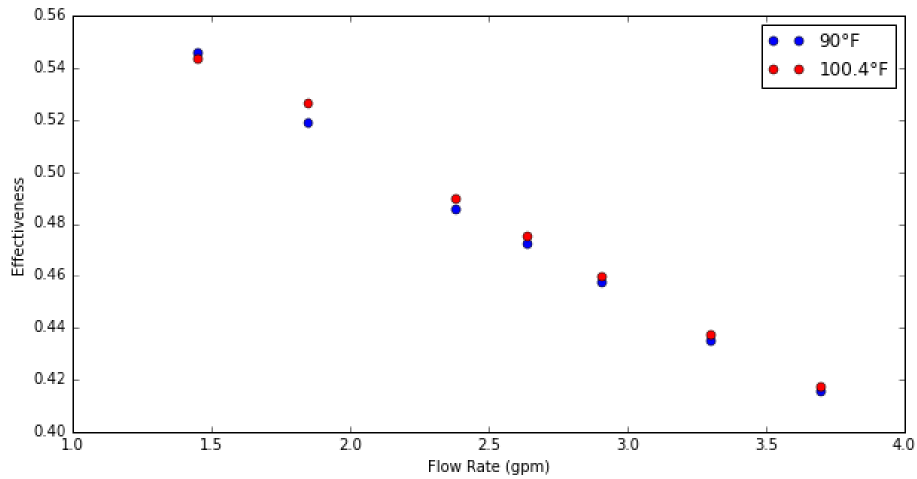

Figure 19: Draw Effectiveness with Varying Drain-Side Inlet Temperature (Equal Flow)

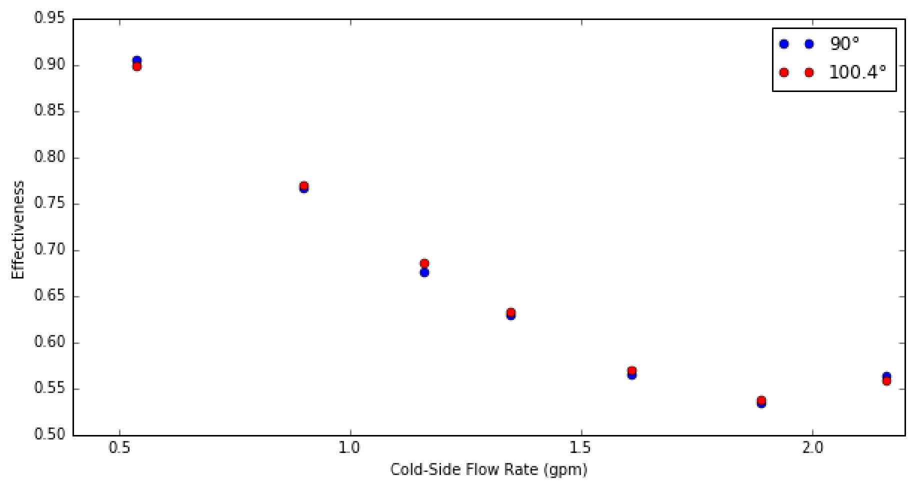

Figure 20: Draw Effectiveness with Varying Drain-Side Inlet Temperature (Unequal Flow)

Both Figures 19 and 20 show a very small difference in effectiveness between the 100.4°F and 90°F data sets. In each case the difference is smaller than the measurement uncertainty in the test. In response to this data, no algorithm was created for changes in drain-side inlet temperature.

5. ALGORITHM DEVELOPMENT

The preceding sections described regressions used to identify the effectiveness of the lab-tested DWHR device in a broad range of situations. The final task was to convert these regressions to an algorithm which could be incorporated into the CBECC-Res Title 24 compliance software, allowing modeling of DWHR performance for other non-tested devices as a function of flow and temperature. To develop this algorithm, two modifications were made:

1. The regressions for effectiveness for the lab-tested device as a function of flow-rate and/or inlet temperature were used to create effectiveness correction factors. These correction factors can then be used as multipliers to estimate the effectiveness of a different device under the same flow and temperature conditions. The correction factor is equal to the estimated effectiveness of the lab-tested device at the current flow/temperature conditions divided by the estimated CSA rating of the lab-tested device.
2. Equations were added to identify the average pre-heated water temperature for a given draw. This output was requested by Jim Lutz[7] as it allows calculations in CBECC for the flow-rate of hot water from the water heater to the shower.

Two separate algorithms were created, one for equal flow configurations and a second for unequal flow. This choice was made because combining the two data sets resulted in some calculation instability within the regression. Both equations are of the same form, which is presented in Equation (11).

$$\boldsymbol{\varepsilon_{Draw} = \varepsilon_{CSA} * f_{Dur} * f_{T,C,I} * f_{\dot{V}}}$$ **Equation (11)**

The factor for changes in flow rate can represent either equal flow or unequal flow configurations. It should be calculated using the corresponding regression equation, and dividing by the estimated effectiveness of the tested unit (0.454). Equal flow installations should use Equation (4), and unequal flow installations should use Equation (9).

Several tests were used to validate the resulting algorithm. The results of the validation process are shown in Table 4.

Table 4: Algorithm Validation Results

$\dot{V}_C$ (gpm)	$\dot{V}_H$ (gpm)	$T_{C,I}$(°F)	ε_{Mea} (%)	ε_{Draw} (%)	Error (%)
2.51	2.51	50.63	47.1	45.4	-3.85
4.49	1.99	53.33	62.0	64.5	3.83
2.17	3.59	69.33	58.2	57.5	-1.18
0.92	1.80	87.72	74.8	73.7	2.62
1.13	1.99	52.63	71.7	71.0	-1.02

7 Supporting Bruce Wilcox and team on ACM water heating work

Two equations were used to identify the average pre-heated water temperature over the course of a draw. The first equation identifies the average rate of heat transfer to the water on the cold side, while the second equation converts that average heat transfer rate to the average outlet temperature. They are shown in Equations (12) and (13).

$$\dot{Q}_{Avg} = \varepsilon_{Draw} * \min(\dot{V}_C, \dot{V}_H) * \rho * C_P * (T_{H,I} - T_{C,I}) * 60 \qquad \textbf{Equation (12)}$$

$$T_{C,O} = \frac{\dot{Q}_{Avg}}{\dot{V}_C * \rho * C_P * 60} + T_{C,I} \qquad \textbf{Equation (13)}$$

In both Equations (12) and (13) the 60 represents a unit conversion from gpm to gal/hr.

The easiest way to implement this algorithm in CSE is to use Equation (12) to estimate the average heat transfer rate, and multiplying by the draw duration to identify the total amount of energy saved during the shower. The recovery load on the water heater would then be reduced by the amount of energy saved by the DWHR device.

The cold-side outlet water temperature output is available in case CSE is modified to employ more complex residential hot water simulation techniques. Lutz has expressed interest in modifying CSE to determine water flow rates based on cold, preheated, and hot water flow rates. This may be necessary in Unequal – Flow to the Shower configurations, as the cold-side flow rate (A necessary input for the DWHR algorithm) will be a function of the pre-heated water temperature at the shower.

Note that all equations used in the algorithm assume a constant water flow rate, on both the cold and drain side, for the duration of the shower. The model will not be able to adapt to changes in flow rate during a draw, and all simulation flow rates must be constant, which is consistent with the currently planned ACM assumption. This could raise an issue in Unequal Flow – Fixture installations. If CSE attempts to model the change in cold water flow at the fixture in response to changes in cold water temperature, that must be done before sending an average flow rate to the DWHR algorithm. This limitation may result in iterative solutions, which would increase the simulation time.

6. Proposed CBECC Implementation

Integration of the DWHR device into CBECC requires inclusion of both a pre-requisite condition, and several inputs to the algorithm.

Connecting the master bath shower to the DWHR device should be considered a pre-requisite. It is believed that most showers are taken in the master bathroom, and that installations not connected to that shower stall will rarely be cost-effective.

The DWHR algorithm requires several inputs in order to predict the annual energy savings. These inputs can be broken into the two categories 1) Inputs describing the draw, and 2) Inputs describing the installation. The inputs describing the draw are the hot and cold side flow rates and temperatures, all of which are outputs from other CSE algorithms. As these inputs do not impact the CBECC interface, they are not discussed here. The inputs describing the installation are specific to each building, and it is recommended that the CBECC interface be modified to include the following items:

1. **CSA-rating of the installed device:** The CSA rating is a published effectiveness for each DWR device, and the basis of the proposed algorithm, as such, the user needs to input the rated effectiveness of the device they intend to install.
2. **Installation configuration:** This input allows the user to specify the installation configuration: either a) Equal Flow, b) Unequal – Flow to the Water Heater, or c) Unequal – Flow to the Shower. As demonstrated in the Results Chapter, the effectiveness of the unit, and thus the energy saved, is very sensitive to the drain and cold water flow rates. These flow rates are determined by the installation configuration, making it a necessary input.
3. **Percentage of shower stalls connected to the device:** It is entirely likely that not all shower stalls will be connected to the DWHR device in some applications. In these cases, some showers will not provide a hot water resource to the DWHR unit. This input will allow CSE to reduce the input shower water volume to the DWHR unit accordingly, and avoid giving the DWHR device more credit than is appropriate.

CSE will use these inputs to identify the savings from a DWHR unit using the algorithm proposed in Algorithm Development. The algorithm must be applied to find the savings from each shower event individually. The first step is identifying the effectiveness of each draw using Equation (11). Each of the terms in Equation (11) are as follows:

- $\boldsymbol{\varepsilon_{CSA}}$**:** This is the CSA-rating of the installed device input by the user.
- $\boldsymbol{f_{Dur}}$**:** This factor represents the impact of the draw duration, and is calculated as a function of flow rate and duration using Equations (5) through (8). The flow rate and draw duration inputs must be supplied by CBECC.
- $\boldsymbol{f_{T,C,I}}$**:** This term is used to estimate the impact of changes in the cold side inlet temperature. It is calculated by evaluating Equation (10), and dividing the result by 0.454[8]. The cold side inlet temperature must be supplied by CBECC.
- $\boldsymbol{f_{\dot{V}}}$**:** This factor is used to represent the effect of flow rate on DWHR performance. In Equal Flow installations it is calculated by evaluating Equation (4) and dividing by 0.454. In Unequal Flow installations, use Equation (5) and divide by 0.454. The drain and cold side flow rates must be supplied by CBECC.

To identify the average rate of heat recovery during a shower use Equation (12). The result can be multiplied by the duration of the draw (in hours) to identify the total heat recovered during a shower.

The average cold side outlet temperature can be calculated using Equation (13). This will be necessary to identify the cold side flow rate in Unequal – Flow to the Shower installations.

The total annual energy savings can be identified by summing the savings from each individual shower over the course of the year. An additional factor, based on the percentage of shower stalls connected to the device input by the user, will need to be integrated into the algorithm;

[8] The estimated CSA rating of the tested device, which was used to create the correction factors.

however, without a clearly defined shower location allocation strategy, the implementation for this is not currently clear.

7. DISCUSSION

This chapter provides additional discussion on several topics. They are 1) Partial wetting on the drain side of the DWHR device at low flow, and how that impacts energy savings, 2) Losses between the DWHR device and the connection to the shower and/or water heater are not currently modeled, and their impact on DWHR savings have not been thoroughly studied, 3) Comparisons between CA savings estimates, based on local conditions and this algorithm, and Canadian estimates based on the CSA model and Canadian conditions, 4) Estimates of potential energy savings in California, as well as recommendations to improve the estimates, and 5) Additional items concerning the differences between laboratory data and DWHR operation in real buildings, which may impact the potential savings.

7.1 Partial Wetting at Low Flow

As was discussed in in Section 4.1 *Equal Flow Results*, partial wetting was observed in some tests with a drain side flow of less than 2 gpm. During some low flow tests, this issue was overcome by pre-wetting the drain side of the heat exchanger. However, the question of how this impacts real draws in California buildings remains. It is highly likely that some low-flow draws will result in partial wetting with low effectiveness, while other draws will more closely resemble the pre-wet, high effectiveness results.

Four factors which likely impact this behavior include 1) The draw profile, 2) The length of straight drain pipe before the DWHR inlet, 3) The diameter of the DWHR unit, and 4) The effect of soap in the drain water. If another draw, particularly one at high flow, occurred shortly before a shower, then the drain side of the DWHR device will likely be pre-wet resulting in high effectiveness. If there was a long delay after the prior draw, the drain side will be dry increasing the chances of low effectiveness. Additionally, installations with short sections of drain pipe leading to the inlet of the DWHR device do not provide much opportunity for the falling film to develop before entering the heat exchanger. Installations with long segments of drain pipe preceding the DWHR unit may allow the falling film to develop and avoid this issue. This effect may be reduced by installing a low-diameter DWHR unit, and proper sizing of the unit may be critical. Finally, it′s possible that adding soap to the water impacts the flow significantly enough to avoid this issue.

These concepts were identified during this initial study, but the project timeline did not allow for an in-depth study. Further research determining how these effects impact DWHR effectiveness in real California buildings should be pursued in future Phase 2 testing. Future research should include methods to evaluate this.

7.2 Horizontal DWHR Units

This study focused solely on vertical DWHR units; however, horizontal DWHR units should potentially be considered for the California market. These units are installed in the bottom of a shower stall, and can thus be used in showers on the first floor. This ability allows them to be used, and save energy, in applications where vertical DWHR units are not applicable, a feature that would be beneficial for many California slab on grade homes. Phase 2 could include a study of horizontal DWHR units. Potential items to study include:

1. Effectiveness of the DWHR device as a function of the same conditions addressed in this report.
2. Maintenance required for horizontal DWHR devices, and the associated effect on the persistence of savings. As a horizontal heat exchanger, there is increased risk of the heat exchanger clogging and the effectiveness decaying over time.
3. Differences in installed cost, both in new construction and retrofit applications. As part of the floor of the shower stall, it is not certain that the installed cost will be similar to vertical DWHR units, nor is it safe to assume that a retrofit installation will be as simple.

7.3 Preheated Water Distribution Losses

This initial study focused specifically on the DWHR unit; however, as part of a whole-building hot water system, the energy recovered by the DWHR unit will be reduced by losses in the piping distributing the pre-heated water to the shower and/or water heater. These losses will be caused by 1) Heat loss through the pipes during a draw, and 2) Energy in the water remaining in the pipes after a draw. As part of this effort, a brief simulation study was performed[9]. The results indicated that the lost energy may be on the order of 1 to 3 percent of the recovered energy; however, the study used many assumptions which may or may not be accurate. It is recommended that Phase 2 include surveying installers to understand more about how DWHR units are installed, and repeating the study with more detailed information. Particularly useful information includes:

1. The length of pipe connecting the DWHR cold side outlet to the water heater and/or the shower.
2. The diameter of the pipe leaving the cold side outlet of the DWHR unit.
3. Insulation R-value, if the pipe is insulated.
4. The typical delay between a shower and the following draw.

This information would allow either simulations or theoretical calculations to more accurately estimate the amount of recovered heat lost in the distribution.

7.4 Comparison to CSA Implementation

Several alterations based on the differences between Canada and California, as well as improvements to the base algorithm, were made to the CSA protocol as part of this work. These changes cause differences in savings, as would be expected when applying the DWHR technology to a different climate and regulatory environment.

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[9] Assuming 10 ft. of uninsulated ¾″ PEX pipe between the DWHR unit and the water heater.

The alterations to adopt the algorithm to Californian conditions consisted of two main changes. They were:

1. Using the regression to estimate the effectiveness at lower flow rates: Because California showerhead regulations are limited to 2 gpm and will drop to 1.8 gpm in 2018, the 2.51 gpm rating from the CSA protocol is too high for California applications. The implemented algorithm is designed to identify the effectiveness as a function of flow rate, at flow rates appropriate for California.
2. California also has significantly warmer mains water temperatures than Canada: While the CSA protocol uses a cold side inlet temperature of 50°F, the inlet temperatures in California can reach as high as 90°F. To accommodate this difference, a regression for changes in cold side inlet water temperature was developed and added.

Additionally, some improvements enhancing the ability of the algorithm to predict effectiveness in all applicable situations were made. These improvements include:

1. Developed an algorithm predicting the effectiveness as a function of shower duration. This algorithm takes into account the thermal mass effects of the DWHR unit, while the CSA protocol identifies the steady state effectiveness.
2. Added testing, and created a 2-D regression identifying effectiveness in unequal flow installations. This allows more accurate predictions of savings during unequal flow installations than other implementations, such as RESNET.
3. All tests in the CSA protocol use a pre-wetted heat exchanger, which predicts a higher effectiveness than will likely be seen in real applications. This effort provided a preliminary study, and demonstrated the potential for incomplete wetting to reduce the effectiveness of the DWHR unit at typical shower flow rates.

These changes have a significant impact on the predicted savings. To demonstrate the impact of these changes, two cases are studied. They are 1) The impact of a Canadian 50°F mains inlet temperature, compared to a 70°F common Californian inlet temperature, and 2) The reduction in effectiveness caused by incomplete wetting at low flow rates, by comparing a two gpm shower using the pre-wet and the non-pre-wet effectiveness values.

1. Case 1: Energy savings comparison for 50°F vs. 70°F inlet water temperature - Both the draw effectiveness and total energy saved are affected. As demonstrated in Cold-Side Inlet Temperature Results, the effectiveness of the tested unit increased with increases in cold side inlet temperature. In this example simulation, the effectiveness rose from 46.4 percent at 50°F inlet temperature, to 49.1 percent at 70°F inlet temperature. However, the higher inlet temperature caused a lower temperature difference across the DHWR device, and reduced energy savings. Despite having a higher effectiveness, the Californian installation is expected to save 3,107 Btu compared to 4,872 in Canada (36 percent reduction), assuming a 10 minute, 2.51 gpm shower.
2. Case 2: Impact of dry vs wet DWHR start up condition – The savings for the pre-wet case were predicted using the effectiveness regression shown in Figure 14, while the dry case used the effectiveness data shown in Figure 13. The resulting effectiveness for the pre-wet case was 50.9 percent, and for the dry case was 45.0 percent. This decrease in

effectiveness translated to an 11.5 percent reduction in energy savings from 2,570 Btu in the pre-wet case to 2,273 Btu in the dry case for a 10 minute, 2 gpm shower[10].

Table 5: Comparison Between Pre-Wet and Dry Performance

Initial Condition	ε_{Draw} (%)	Savings (Btu)
Pre-Wet	50.9	2,570
Dry	45.0	2,273

The savings estimate for dry initial conditions is 11.5 percent, or 297 Btu, lower per shower[11]. Note that this discrepancy will become more drastic as California shower flow regulations are lowered.

7.5 Estimated Annual California Home Savings

To provide a rough estimate of the potential savings from DWHR units in California homes, simulations estimating the expected annual savings in four test cases were performed. The four test cases were:

1. A single DHWR-connected shower per day, with 65°F average cold water inlet temperature,
2. A single shower per day, with 75°F average cold inlet water temperature,
3. Two showers each day, with 65°F water temperature, and
4. Two showers each day, with 75°F water temperature.

All simulations were performed assuming a 10 minute, 2 gpm shower. The DWHR device was assumed to be 46.6 percent effective (The CSA rating for the tested Power Pipe). The annual reduction in recovery load was calculated assuming that the house uses a tankless water heater with an energy factor of 0.82 (Times a 0.92 derating factor, as per current Title 24 calculations). Note that these estimated savings are based on a theoretical, simplified draw profile. These calculations should be redone using the 2016 ACM draw profile, when it is available, to more accurately estimate the potential savings in various buildings and scenarios.

In order to compare the savings in Equal Flow and Unequal Flow installations, the simulations were performed for Equal flow, Unequal – Flow to the Water Heater, and Unequal – Flow to the Shower configurations. The cold side flow rate was calculated differently to mimic the different installation cases. It was calculated in the following three ways:

- Equal Flow: The cold side flow matched the shower flow rate of two gpm.

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[10] Identifying this difference was not possible in the CSA protocol, as all of their tests use a pre-wetted heat exchanger.

[11] Assuming a 10 minute, 2 gpm shower with 105 °F shower water temperature, 120 °F water heater set point, and 70 °F mains water temperature.

- Unequal – Flow to the Water Heater: The cold side flow was calculated using a heat balance on the mixing valve at the shower[12].
- Unequal – Flow to the Shower: The cold flow was again calculated using a heat balance on the mixing valve at the shower. In this case, the cold flow and cold water temperature were functions of each other, and the equation was solved iteratively.

The results for Equal Flow installations are shown in Table 6. Note that many installations will use unequal flow configurations.

Table 6: Estimated Annual Reductions in Recovery Load in Four Equal Flow Test Cases

	TC,I = 65°F	TC,I = 75°F
1 shower/day	12.70 therms	9.24 therms
2 showers/day	25.40 therms	18.48 therms

The results in Table 6 show that moving from a colder California climate (65°F average annual inlet) to a warmer southern California climate (75°F) is expected to reduce savings by ~27 percent. DWHR units are also expected to be more cost-effective in dwellings with more occupants (And, thus, more showers). Note that the anticipated savings increases linearly with number of showers..

Table 7 states the predicted savings in unequal flow configuration, assuming one shower each day, both as a percentage of the Equal Flow savings and in terms of therms/yr.

Table 7: Predicted Savings as a Percent of Equal Flow Savings[13]

	$T_{C,I}$ = 65°F (% of Equal Flow)	TC,I = 65°F (therm/yr)	$T_{C,I}$ = 75°F (% of Equal Flow)	$T_{C,I}$ = 75°F (therm/yr)
Unequal – Water Heater	59%	7.49	70%	6.47
Unequal - Shower	77%	9.78	89%	8.22

The predicted savings in .

Table 7 range from 59 percent to 89 percent of the savings in an Equal Flow installation. Note that this shows more diversity than the 77.7 percent derating factor in the RESNET implementation.

7.6 Additional Concerns

This work is based on laboratory results for a single, new device. Additional studies reflecting installations in real building would increase confidence when extrapolating these results. Specifically, three items should be studied:

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[12] Assuming a 105 °F shower temperature, and 120 °F heater set point.

[13] The cold side flow rates in unequal flow simulations ranged from 0.545 gpm to 1.123 gpm. The $T_{C,I}$ = 65 °F tests has the two lowest flow rates. The Unequal – Flow to the Shower configuration also had a higher flow than the Unequal – Flow to the Water Heater configuration.

1. **Fouling:** Tests should be performed comparing an old, used DWHR device to a brand new one. In this way the longevity of savings, which has a significant impact on the life cycle cost, can be determined.
2. **Field studies:** Studying installations of DWHR units could indicate that they perform differently in the field than laboratory tests indicate. Some potential differences include the quality of the installation, or the impacts of the draw profile. Studying these topics in more detail will allow a better estimate of how actual savings compare to the savings estimates presented here.
3. **Other manufacturers:** DWHR performance may vary depending on the design of the unit. Devices from other manufacturers should be studied to ensure that the algorithm can be used to extrapolate the results to units other than the one tested. If not, the algorithm should be modified to account for these differences.

7.7 Next Steps

SoCal Gas, NegaWatt, ATS, and DEG are currently defining the scope of Phase 2 research efforts. It will include laboratory testing, data analysis, economic analysis, and manufacturer surveys. The testing and data analysis will drive improvements to the algorithm. Input from the manufacturer surveys will be combined with the test results to determine eligibility criteria and best practices.

Specific topics to be studied include:

1. Comparing test results between multiple units, and validating the algorithm,
2. Studying how real world conditions, such as soapy water or tilted installations, impact DWHR performance,
3. A detailed economic analysis of DWHR units in single and multi-family residential buildings.

8. CONCLUSIONS

Domestic hot water currently represents 49 percent of residential natural gas consumption in typical California households, suggesting that reductions in water heating energy use are possible as part of high efficiency homes. Previous DHWR studies have shown that there is potential for savings through installation of drain water heat recovery devices, although most of the evaluations have been completed in cold climates.

The goal of this study was to complete a detailed laboratory based performance evaluation of a single DWHR device in the PG&E ATS testing facility and evaluate the resulting data to generate an algorithm appropriate for integration into the CBECC Title 24-2016 compliance software. The algorithm developed includes correlations for device effectiveness as a function of installation configuration, flow rate, draw duration, and inlet temperature. Validation results showed that, under the tested conditions, the model was accurate within ± 4 percent, which is less than the uncertainty in the measured data.

Recommendations for integrating this algorithm into Title 24 and CBECC are provided.

Several items addressed in this evaluation warrant further study. They are:

1. **Partial wetting:** The causes and impacts of partial wetting have only been briefly studied. Further research should determine when it is likely to occur, how the selection of DWHR unit and installation design impact this effect, and the extent to which it impacts the potential savings.
2. **Distribution losses:** The heat lost in the distribution pipes after being recovered by the DWHR unit was not thoroughly studied. Further efforts should be made to identify how the units are typically installed, and how much heat is still in the pipe after the draw.
3. **Cost-effectiveness estimates:** The estimates of savings should be repeated using the draw patterns for the 2016 version of CBECC. Doing so will provide a more accurate estimate of savings, and determine whether or not future research is warranted. Additionally, more cost effective applications (multi-family shared shower drains, dormitories, hotel/motel, etc.) have more complicated installation variations that should ideally be evaluated in the lab.
4. **Comparison to field installations:** It is possible that, through a combination of fouling, different installations, draw profiles, and differences between manufacturers, the lab results do not match the results in field installations. Testing on a used DWHR device, units from different manufacturers, and field studies should be performed to ensure that these results can be extrapolated or the algorithm can be modified to account for these differences.
5. **Horizontal:** Only vertical DWHR units were studied while horizontal, unlike vertical, DWHR units could be used in first floor shower stalls. Performing testing on those units would allow for the inclusion of these devices in the algorithm.

9. References and Other Research

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