Sustainability of Residential Hot Water Infrastructure: Public Health, Environmental Impacts, and Consumer Drivers

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ABSTRACT

Residential water heating is linked to the primary source of waterborne disease outbreaks in the United States, and accounts for greater energy demand than the combined water/wastewater utility sector. To date, there has been little research that can guide decision-making with regards to water heater selection and operation to minimize energy costs and the likelihood of waterborne disease.

We have outlined three types of systems that currently dominate the marketplace: 1) a standard hot water tank with no hot water recirculation (STAND), 2) a hot water tank with hot water recirculation (RECIRC), and 3) an on-demand tankless hot water system with no hot water recirculation (DEMAND).

Not only did the standard system outperform the hot water recirculation system with respect to temperature profile during flushing, but STAND also operated with 32 – 36% more energy efficiency. Although RECIRC did in fact save some water at the tap, when factoring in the energy efficiency reductions and associated water demand, RECIRC actually consumed up to 7 gpd more and cost consumers more money. DEMAND operated with virtually 100% energy efficiency, but cannot be used in many circumstances dependent on scaling and incoming water temperature, and may require expensive upgrades to home electrical systems.

RECIRC had greater volumes at risk for pathogen growth when set at the lower end of accepted temperature ranges, and lower volumes at risk when set at the higher end when compared to STAND. RECIRC also tended to have much lower levels of disinfectant residual (40 -850%), 4-6 times as much

hydrogen, and 3-20 times more sediment compared to standard tanks without recirculation. DEMAND had very small volumes of water at risk and relatively high levels of disinfection.

A comparison study of optimized RECIRC conditions was compared to the baseline modes of operation. Optimization increased energy efficiency 5.5 – 60%, could save consumers 5 – 140% and increased the disinfectant residual up to 560% higher disinfectant residual as compared to the baseline RECIRC system. STAND systems were still between 3 – 55% more energy efficient and could save consumers between $19 - $158 annual on water and electrical costs. Thus, in the context of "green" design, RECIRC systems provide a convenience to consumers in the form of nearly instant hot water, at a cost of higher capital, operating and overall energy costs.

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ORGANIZATION OF DISSERTATION

This dissertation is comprised of four chapters that represent four separate manuscripts that have been published, submitted for publication or will be submitted as shown below. The chapters have been reformatted herein to create cohesiveness to this document. All published worked has been reprinted here with permission, where applicable, from the publisher of the journal. The individual chapters and respective journals are:

- Chapter 1: A Review of the Sustainability of Residential Hot Water Infrastructure: Public Health, Environmental Impacts, and Consumer Drivers (Published in the Journal of Green Building, V6N4) reviews the current state of the knowledge on water heaters and how they relate to energy efficiency, water savings, pathogen growth and consumer issues. Key knowledge gaps are identified to support the work provided herein.

- Chapter 2: Water and Energy Savings from On-Demand and Hot Water Recirculating Systems (Submitted (in review) to the Journal of Green Building) develops a firm understanding of how two marketed "green" water heating systems perform with respect to energy efficiency as compared to a standard storage type water heater.

- Chapter 3: Role of Hot Water System Type/Design on Factors Influential to Pathogen Regrowth: Temperature, Chlorine Residual, Hydrogen Evolution and Sediment (Submitted (in review) to Water Research) provides insight into how various water heater systems and design may potential impact pathogen growth and mitigation strategies in premise plumbing. This works assesses the interplay between the many variables that exist in hot water infrastructure and identifies key areas for future study.

- Chapter 4: Optimization of Electric Hot Water Recirculation for Comfort, Energy and Public Health (to be submitted to the Journal of Green Building) evaluates the implications of optimizing hot water recirculation with respect to energy efficiency, temperature profiles, internal tank temperature and chlorine decay.

COMPLEMENTARY WORKS

In addition to the manuscripts included in this dissertation several conference presentations and posters were completed that complement the work herein:

Lieberman, R.H., A. Martin, and M.A. Edwards. Mitigation Practices and the Practical Aspects of Premise Plumbing Problems Relative to Control of Pathogens. Presented at AWWA WQTC11, Phoenix, AZ, November 17, 2011.

Lieberman, R.H. and M.A. Edwards. Poster: Residential Water Heating: The Water-Energy Nexus at Home. Presented at AEESP, Tampa, FL: July 2011.

Lieberman, R.H. and M.A. Edwards. Poster: Sustainability of Residential Hot Water Infrastructure: Public Health, Environmental Impacts, and Consumer Drivers. Presented at Engineering and Sustainability 2011, Pittsburgh, PA, April 11, 2011.

Lieberman, R.H., M. Edwards, and S. Masters. Poster: Evaluating Water Quality and Energy Efficiency of Standard and Marketed "Green" Home Water Heating Systems. Presented Poster at AWWA WQTC, Savannah, GA, November 29, 2010.

Lieberman, R.H., M. Edwards, and S. Masters. Poster: Evaluating Water Quality and Energy Efficiency of Standard and Marketed "Green" Home Water Heating Systems. Presented Poster at Energy and Water, Pittsburgh, PA, September 27, 2010.

Lieberman, R.H., M. Edwards, and S. Masters. Sustainability of Residential Hot Water Infrastructure: Public Health, Environmental Impacts, and Consumer Drivers. Presented at AWWA ACE10, Chicago, IL, June 22, 2010.

CHAPTER 1. A REVIEW OF THE SUSTAINABILITY OF RESIDENTIAL HOT WATER INFRASTRUCTURE: PUBLIC HEALTH, ENVIRONMENTAL IMPACTS, AND CONSUMER DRIVERS

1.1. BACKGROUND

Residential water heating infrastructure is tied to the primary source of waterborne disease outbreaks in the U.S. (Centers for Disease Control and Prevention (CDC) 2008c) and has a total energy demand exceeding that of the water and wastewater utility sector combined (Table 1-1) (United States Environmental Protection Agency (EPA) 2009b). Considering the high stakes, it is unfortunate that there has been little practical research that can guide rational decision-making by consumers, public health officials, regulators and legislators. In fact, the numerous scientific uncertainties associated with existing "green" advice, has the potential to create misguided policy with long-term repercussions for energy consumption and public health. This research is aimed at reducing that liability by conducting the first practical assessment of residential water heating infrastructure performance in terms of public health, environmental impacts, and consumer drivers (Figure 1-1).
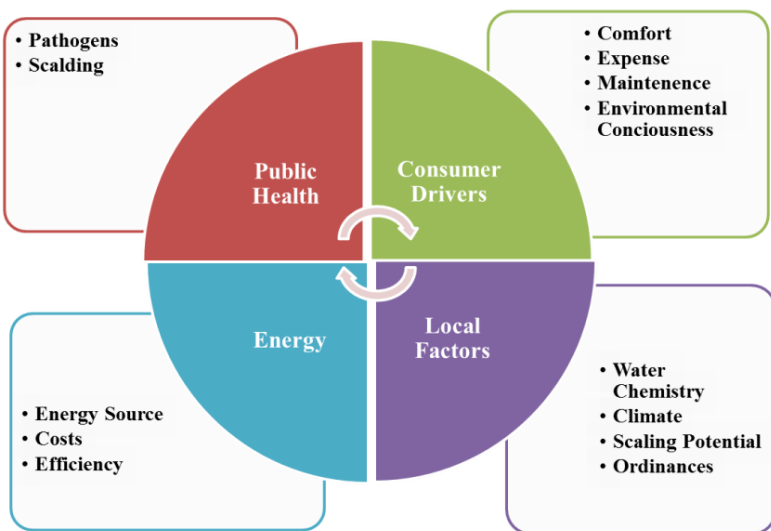
Figure 1-1 Water heater selection. *A consumer's selection of water heater infrastructure should consider public health and environmental impacts.*

To elaborate, selection of an "optimal" new or retrofit water heater

system from amongst the myriad options available, is a complex decision that often begins and ends at the consumer level by considering capital costs, comfort, reliability, maintenance, and occasionally genetic/immuno-susceptibility to waterborne disease (Figure 1-1). By outlining the various factors that should be considered with respect to water heater selection, the potential scale of complexity becomes apparent. While water heater selection is probably most driven by consumer drivers (i.e., costs, availability, and consumer comfort reports), environmental impacts, local factors, and public health (Figure 1-1) could play a larger role if more reliable, practical assessment were readily available.

Although some information regarding environmental impacts including water conservation, greenhouse gas emissions and operating costs (Table 1-2) are available through EPA web sources and EPA Energy Star ratings, such recommendations are based on extrapolation of very limited new system performance data. Home owners can upfit existing systems following specific Energy Star guidelines to be eligible for up to $1500 dollars in tax incentives for choosing certain water heaters; other systems are eligible for a 30% tax rebate with no upper limit (Energy Star (United States Department of Energy and United States Environmental Protection Agency) 2009). EPA's WaterSense program that has been developed to "help consumers identify water efficient products and programs" specifically does not include water heaters (United States Environmental Protection Agency (EPA) 2009d). Some cities, where water conservation has become a top priority, have adopted ordinances which mandate new construction to have specific, water saving, "green" plumbing designs. The Marina Coast Water District (MCWD) in California, for example, requires that any hot water fixture more than 10 linear feet from the hot water heater has a hot water recirculation system or point-of-use demand heater (Marina Coast Water District (MCWD) 2007). Although both nationwide and globally, these sustainable designs are being implemented to the supposed benefit of the environment and consumer and, in some cases by government mandate, there has been very limited research assessing the water quality, health factors, and comparative energy efficiency associated with these initiatives (Lu and Wu 2008, Wedding and Crawford-Brown 2007).

The existing recommendations can be misleading and unfounded under actual field conditions due to scaling, corrosion and climate impacts (Table 1-2). Moreover, it is believed that the type of hot water system and the quality of the water supply (i.e. nutrients and secondary disinfectant residual level) can control the occurrence of pathogens (Table 1-2). But research on this important emerging subject is only emerging, and existing data covers just a few water heater systems and water supplies. The interdisciplinary nature of the research involving plumbing, water chemistry, microbiology and human pathogen exposure has also been a barrier.
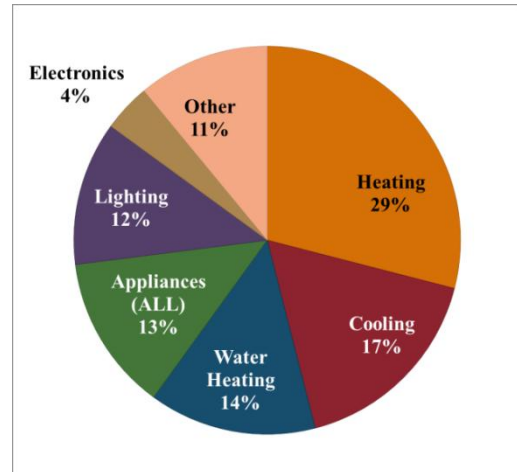
Figure 1-2 Residential water use by appliance. *2010 data for residential energy consumption.*

This paper will review various types of water heating systems and will highlight specific gaps in the literature while focusing on the mechanics, chemistry, microbiology, environmental impacts, and consumer considerations (Figure 1-1) with respect to residential hot water systems. In the sections that immediately follow, a summary of the different types of water heating infrastructure that are available, what is known about their likely environmental and public health impacts, and consideration of how local factors might dramatically alter performance are provided.
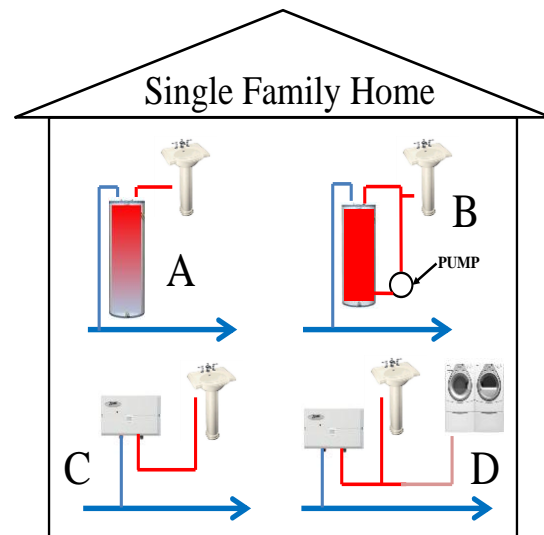
Figure 1-3 Common residential hot water heaters. *A single family residence using standard energy resources (i.e., electricity, natural gas, propane, or oil) could have several different water heater systems: A) storage tank with no recirculation, B) storage tank with hot water recirculation, C) point-of-use demand with no storage, and D) centralized demand with no storage.*

1.2. WATER HEATING SYSTEMS

1.2.1. Energy and Public Health Implications of Residential and Commercial Water Heater Infrastructure. Water heating in the United States has the largest energy consumption of any water related use. Additionally, water heating represents the second largest residential energy use (second only to heating and cooling) and uses more energy than all other home appliances combined (Figure 1-2) (Energy Star (United States Deparment of Energy and United States Environmental Protection Agency) 2010). The actual portion of the energy consumption of water heating in the home varies depending on the given year and reporting source, (Energy Information Administration (EIA) 2005, 2009a, c, Energy Star (United States Department of Energy and United States Environmental Protection Agency) 2010, United States Department of Energy (DOE) 2009c, 2011a) but the most recent data from Energy Star (Energy Star (United States Deparment of Energy and United States Environmental Protection Agency) 2010) suggests water heating accounts for 14% of residential home energy consumption (Figure 1-2). Over the past decade, between 3.3-5.5% of total U.S. energy demand is used in residential water heating, which slightly exceeds the estimated 3-4% combined energy demand of the water and wastewater utility sectors (Table 1-1) (Energy Information Administration (EIA) 2009a, United States Environmental Protection Agency (EPA) 2009b). The costs of residential water heating are high with 100 billion kWh used for electric water heating alone in 2001 at a cost of $9 billion dollars assuming average electric rates of 9 cents per kWh, which more than doubles the $4 billion estimated energy costs for the entire water and wastewater utility sector (Table 1-1) (Energy Information Administration (EIA) 2005, 2008, 2009a, b, c, Energy Star (United States Department of Energy and United States Environmental Protection Agency) 2010, United States Environmental Protection Agency (EPA) 2009b). This cost does not even include the 58 million homes that use natural gas or the remaining 8 million homes that use an alternative source of energy for water heating. With well over 100 million households in the United States using some type of water heating system, research needs to address not only the relative

energy consumption, but also the potential public health risks with regards to scalding and microbial growth, the relative economic constraints, and the water saving potentials of different choices widely available for use.

Table 1-1 Impacts of Residential Water Heating

	Total Energy Costs	% of US Energy Demand	Funded Research in Progress?
Residential Water Heating	$9 Billion[1] (Energy Information Administration (EIA) 2009c)	3 – 5% (Energy Information Administration (EIA) 2009a)	Very little
Water and Waste Water Utility Sector	$4 Billion (United States Environmental Protection Agency (EPA) 2009b)	3-4% (United States Environmental Protection Agency (EPA) 2009b)	Numerous projects

[1]Electric Water Heating Only

In terms of public health, growth of opportunistic pathogens in premise plumbing was identified as a "high priority" for research by National Research Council in 2006 (National Research Council (NRC) 2006). "Premise plumbing" refers to the portion of potable water distribution systems beyond the property line in buildings. This portion of the water distribution system water infrastructure poses unique challenges for public health and has a net present value that probably exceeds that of the main distribution system operated by water utilities (National Research Council (NRC) 2006, Rushing and Edwards 2004). The ability of premise plumbing pathogens to amplify is controlled by water temperature, residual

Figure 1-4 Electric storage heater. *A cross-section of a typical electrical hot water tank with no hot water recirculation.*

disinfectant concentrations, water nutrient levels and water age: factors directly influenced by water heating infrastructure type, design and operation. Hence, there will be inextricable direct linkages between goals of reducing energy demand and maintaining public health (Figure 1-1), both antagonistic and synergistic, which are only beginning to be appreciated and studied.

1.2.2. *Overview of Water Heater Systems.* This section provides an overview of the ongoing consumer dilemmas of choosing appropriate water heating strategies for individual residences. Water heating infrastructure can be characterized into four broad categories (Figure 1-3) including: 1) tank storage with no hot water recirculation, 2) tank storage with hot water recirculation, 3) centralized demand with no storage and no hot water recirculation, and 4) point-of-use demand with no storage and no hot water recirculation. Each of these further needs to be assessed considering key areas of local factors, energy, and public health, and consumer drivers (Figure 1-1). While there is a high degree of uncertainty in relation to defining performance for some variables, each type of infrastructure and energy source will have characteristic impacts and susceptibility to problems (Table 1-2).

The subsequent sections highlight some important inter-dependencies that are emerging in relation to design and operation of specific types of water heating infrastructure relevant to public health, energy, water conservation, and consumer considerations. Illustrative areas emphasized include storage vs. on-demand systems, concerns about scaling and scalding, electric vs. gas tanks, hot water recirculation, and "green" high efficiency heaters.

1.2.2.a. Residential Storage Water Heaters with No Hot Water Recirculation (STAND). Residential storage water heaters are the most widely used system to heat domestic water supply. While there are many different sizes and types of water heaters depending on use, a standard residential water heater storage tank as defined by this paper (Figure 1-4) consists of a steel cylindrical tank that may have a porcelain (or vitreous) enamel glass lining to limit corrosion. Ambient temperature water flows to the bottom of tank from the main water line and heating elements or gas combustion raise the water temperature to a range of 48 to 77 °C which flows out the top of the tank to the pipe system and ultimately the destination faucet. To minimize corrosion within the tank, a sacrificial anode rod made of either aluminum or magnesium alloy is placed

within the tank. Other elements that comprise the hot water storage tank are a drainage tap to remove accumulated sediment at the bottom of the tank and insulation (fiberglass or urethane) to control environmental heat loss (Klenck 1997, Lacroix 1999).

Energy efficiency of water heaters must include considerations of energy input to heat the water, energy output in terms of heated product water, and losses of heat to the ambient environment and along the pipe system (Hirst and Hoskins 1977). Standby heat losses are defined as the energy input required for maintaining hot temperatures in the storage tank when the system is not in use. On-demand water heaters virtually eliminate standby losses. Any water heater with a storage tank will have standby losses that depend on the type and quantity of insulation, surface area of the tank and hot water distribution system, differential temperature between the hot water tank and the environment (United States Department of Energy (DOE) 2009d). More complex energy equations might account for the potential benefits of the heat loss in a cold climate, in terms of reduced costs associated with heating the dwelling, or increased cost from cooling a dwelling in a hot climate.

Table 1-2 Key Characteristics of Representative Residential Water Heaters

	Energy Efficiency and Relative Energy Demand	Standby Energy Loss	Scaling Potential	Pathogen Growth Potential	Installation and Maintenance Costs	Scalding and Consumer Concerns
Electric Heater with Storage and No Recirculation (STAND)	**Energy Efficiency: HIGH** 90 – 95% (American Council for an Energy-Efficient Economy (ACEEE) 2011) **Energy Demand: BASELINE FOR COMPARISON**	**MEDIUM – HIGH** (Figure 6)	**MEDIUM** (Scaling can reduce energy efficiency but has moderate recovery after maintenance) (Isaacs and Stockton 2010)	**MEDIUM – HIGH** (Stratification in tank, AOC^2 generation, sediment accumulation; see Figure 1-4) (Lacroix 1999)	**LOW**	**Scalding Risk: LOW – MEDIUM** (Dependent on temperature setting) **Temperature Stability during Shower: HIGH**
Gas Heater with Storage and No Recirculation	**Energy Efficiency: MEDIUM** 60-65% (American Council for an Energy-Efficient Economy (ACEEE) 2011) **Energy Demand: LOWER** than STAND due to more efficient production and transportation of source energy (American Council for an Energy-Efficient Economy (ACEEE) 2011)	**MEDIUM – HIGH** (Same as STAND)	**MEDIUM – HIGH** (Scaling can increase energy demand and be irreversible) (Isaacs and Stockton 2010)	**LOW - MEDIUM** (Water heated from bottom eliminating stratification, AOC generation and sediment accumulation still probable)	**LOW- MEDIUM** (Permanent scaling effects may increase fuel costs)	**Scalding Risk: LOW – MEDIUM** (Dependent on temperature setting) **Temperature Stability during Shower: HIGH**
Electric Heater with Storage and Recirculation	**Energy Demand: HIGHER** than STAND due to increased energy consumption from pump and increased energy losses (Lieberman et al. 2010)	**HIGH** (Figure 6)	**MEDIUM** (Same as STAND)	**HIGH** (Higher Legionella incidence in and lower disinfectant residual?) (Lieberman et al. 2010, Moore et al. 2006)	**MEDIUM** (Pipe costs doubled due to return line; initial pump costs; increased fuel costs to run pump)	**Scalding Risk: MEDIUM** (Hot water arrives immediately at tap) **Temperature Stability during Shower: LOW** (Lieberman et al. 2010)
On-demand (Electric) with No Storage and No Recirculation	**Energy Efficiency: HIGH** 95-100% (Lieberman et al. 2010) **Energy Demand: 8 - 50% LOWER** energy demand than STAND (United States Department of Energy (DOE) 2009b); High energy demand during short use that may lead to grid failure (SRP Designer 2010)	**NONE**	**HIGH** (Scaling has shown to render on-demand systems inoperable with no recovery in as little as 4 months) (Thomas et al. 2006)	**LOW** (No tank for microbial growth, AOC generation or sediment accumulation)	**MEDIUM – HIGH** (Electrical upgrades may be necessary; scaling can render systems inoperable needing replacement; high energy draw during use; if point-of-use: high capital costs) (Green Energy Efficient Homes 2010, SRP Designer 2010, Thomas et al. 2006)	**Scalding Risk: HIGH** (Temperature dependent on flow rate and incoming water temperature – not setting) (Green Energy Efficient Homes 2010, United States Department of Energy (DOE) 2009b) **Temperature Stability during Shower: LOW** (Consumer issues related to inconsistent temperature and flow rate) (Green Energy

						Efficient Homes 2010, United States Department of Energy (DOE) 2009b)
On-demand (Gas) With No Storage and No Recirculation	**Energy Demand: LOWER** than electric demand due to more efficient production and transportation of source energy (American Council for an Energy-Efficient Economy (ACEEE) 2011)	**NONE**	**HIGH** (Same as above)	**LOW** (Same as above)	**MEDIUM** (Same as electrical demand; if point-of-use: high capital costs to extend gas lines throughout home; Energy Star tax rebate eligible) (Energy Star (United States Department of Energy and United States Environmental Protection Agency) 2009)	**Scalding Risk: HIGH** (Same as above) **Temperature Stability during Shower: LOW** (Same as above)
Heat Pump (Exchanger) Water Heater with Storage	**Energy Efficiency: HIGH** 2 – 3 times more energy efficient than STAND (United States Department of Energy (DOE) 2009a) **Energy Demand: LOWER** than STAND in temperate climate; may be increased demand in cold winter months	**MEDIUM – HIGH** (Same as STAND)	**MEDIUM** (Same as STAND)	**MEDIUM - HIGH** (same as STAND)	**LOW- MEDIUM** (Same as STAND but with increased energy costs in cold winter months; Energy Star tax rebate eligible) (Energy Star (United States Department of Energy and United States Environmental Protection Agency) 2009)	**Scalding Risk: LOW – MEDIUM** (Same as STAND) **Temperature Stability during Shower: HIGH**
Solar Panels with Electric Storage Backup and No Recirculation	**Energy Demand: LOWER** than STAND (dependent on regional/climate factors and type of solar heater) (United States Department of Energy (DOE) 2011b)	**MEDIUM – HIGH** (Same as STAND)	**MEDIUM** (Same as STAND)	**MEDIUM - HIGH** (same as STAND)	**HIGH** (High capital installation costs; payback potential depends on climate/region; Energy Star tax rebate eligible) (Energy Star (United States Department of Energy and United States Environmental Protection Agency) 2009)	**Scalding Risk: LOW – MEDIUM** (Same as STAND) **Temperature Stability during Shower: HIGH**
[2]**AOC = Assimilable Organic Carbon**						

1.2.2.b. Electric Versus Gas Tanks. There are certain key differences with regard to electric heating and gas heating that are critical in differentiating their performance with regards to energy efficiency, public health, environmental air quality, and cost (Figure 1-4 and Figure 1-5, respectively). First, electric water heaters typically heat the inflow water through either one or two electric components located at the top or middle of the tank whereas gas-fired storage tanks heat from the bottom (Figure 1-5). The placement of the electrical components causes vertical thermal stratification within the tank because denser, cooler water will sink to the bottom of the tank and is not directly heated by the components (Figure 1-4) (Klenck 1997, Lacroix 1999, Sole et al. 2008). Thermal stratification can be beneficial when considering a solar collector system with electric backup to improve performance and efficiency. In fact, studies have concluded that in certain systems, the greater the temperature difference, the larger the efficiency (Lacroix 1999, Sole et al. 2008). However, when considering a traditional water heater with tank storage, water stratification and relatively cool water at the bottom can lead to increased microbial contamination (Table 1-2). In fact, Legionella pneumophila, a known opportunistic pathogen that is discussed in more detail later in this review, is believed to occur in electric storage tank heaters in high numbers due to this stratification (Lacroix 1999, Sole et al. 2008).

In contrast, natural gas heating in non-scaling waters tends to break up stratification typical of electric heaters due to heating from the bottom of the tank; however, in scaling waters, the internal insulating properties of thick scale may induce stratification in gas heaters by reducing heat transfer to the tank (Figure 1-5). In non-scaling waters, occurrence of *L. pneumophila* was dramatically higher in electric tanks versus natural gas as a result of stratification (Table 1-2), but with high scaling, this benefit
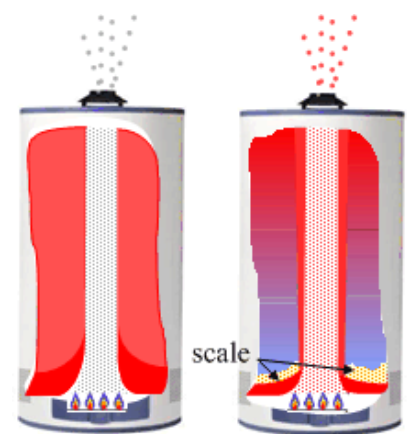
Figure 1-5 Scaling and gas water heaters. *Gas water heaters will lose efficiency as scale builds up at the bottom of the tank in hard water areas. This may cause temperature stratification and heat loss through the vent.*

might not be significant (Dewailly and Joly 1991, Lacroix 1999). Additionally, gas-fired systems typically cost less to operate than electric storage tanks if operating at full efficiency.

The California Energy Commission (CEC) estimates that a water heater using natural gas or propane as an energy source in deference to electricity will save the consumer 65% and 25% in energy costs (California Energy Commission (CEC) 2009). Calculations of lifecycle emissions and energy consumption of natural gas heaters predicts improvements of about 40-50% versus electric (California Energy Commission (CEC) 2009, Delucci 2001). However, the natural gas heaters modeled were assumed to have a high efficiency of 85%. Due to build-up of scale and other deposits (Figure 1-5), actual gas heater efficiencies can drop 27-30% in a few months and calculations based on theoretical reductions in heat transfer coefficients suggest possible reductions in heat transfer efficiency by up to 95% with an associated increase in operation costs (Table 1-2) (Glater et al. 1980, Isaacs and Stockton 2010, Thomas et al. 2006). Electric tanks tend to be less susceptible to energy loss due to scaling and can be more easily maintained because the heating element is located inside the tank and might be subject to some self-cleaning with contraction/expansion (Isaacs and Stockton 2010).

1.2.2.c. Residential Storage Water Heaters with Hot Water Recirculation. Traditionally found in multi-family homes and hotels, but gaining increasing attention for single-family residential use, a recirculation system will continuously circulate hot water from a central water heater tank so hot water is "instantaneous" at various point-of-uses throughout the buildings (Lobenstein 1993). Hot water tanks with recirculation lines eliminate the "waiting" time for hot water to reach the tap by rapidly circulating hot water via an electric pump from the water heater to each faucet that utilizes hot water (Figure 1-3). The theory behind the water saving advantages of a hot water recirculation system depends largely on behavioral patterns; a person taking a shower, for instance, no longer needs to allow water to run or "waste" until the water is at a comfortable temperature. As fresh hot water is pumped from the tank, water not utilized in the hot water line is

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cooled as it is returned the tank to be re-heated and re-circulated. Hot water recirculation tanks are dependent on the electric pump forcing flow (sometimes at high velocity) from the heater to multiple point-of-use faucets (Goldner 1999). In addition to the added energy of using a pump, recirculation systems may increase other energy losses due to increased surface area and higher temperatures, and resultant energy losses to ambient air from the hot water distribution system. (Figure 1-6). Even without operation of a pump, addition of a return line increases heat loss due to natural convection (passive recirculation) in the system via a thermosiphon.
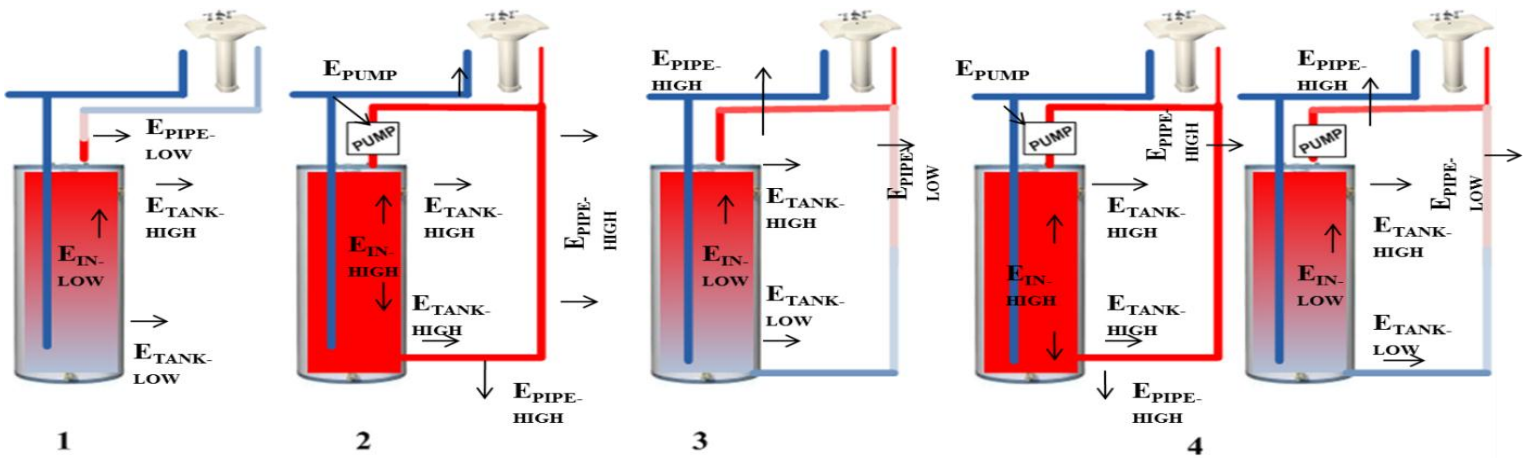
Figure 1-6 Hot water systems and energy balance. *There are four different water heater configurations for the standard and recirculation systems: 1) STAND (no recirculation), 2) RECIRC-C (hot water recirculation line, pump continuously operating), 3) RECIRC-T (no pump, thermosiphon return line to tank), and 4) RECIRC-O (optimized pump operation, hot water recirculation or thermosiphon). EIN represents the energy required to heat the tank to the desired temperature. EPUMP represents the added energy of running a pump. ETANK and EPIPE correspond to the heat loss from the tank and pipes, respectively. "HIGH" and "LOW" represent EXPECTED energy consumption/loss where "HIGH" refers to a higher temperature differential between internal (tank and pipe) water temperature and ambient (i.e., due to stratification or heat loss through the pipes, the temperature at the bottom of the tanks and pipes are cooler and thus have a lower □T between internal temperature and ambient temperature. "LOW" also represents the lower energy input expected to heat the partial tank from stratification as opposed to the entire tank (i.e., "HIGH") due to pipe recirculation. "HIGH" and "LOW" are simply expected energy inputs/losses and will be fully developed through experimentation.*

Optimization of pump operation is crucial to limiting heat loss and maximizing efficiency. Instead of running a pump continuously, the pump should be turned off during periods of low demand, and turned on via a sensor located at the point-of-use or at a specific time to meet demand. There are four system conditions (Figure 1-6) that need to be identified and analyzed for energy considerations: 1)

standard systems with no recirculation (STAND), 2) continuous recirculation via a pump (return line, pump always on, RECIRC-C), 3) recirculation via thermosiphon effect (return line, no pump, RECIRC-T), and 4) an optimized recirculation system (return line, pump not on continuously, RECIRC-O). RECIRC-O can be thought of as a combination system since it will act as a RECIRC-C during periods when the pump is operating and a RECIRC-T when the pump is off (Figure 1-6).

The Oak Ridge National Laboratory (ORNL) in conjunction with the City of Paolo Alto conducted a study examining the use of hot water recirculation (Ally and Tomlinson 2002). They estimated that nearly 1-3 gallons of potable water could be drained as a user waits for water to reach a comfortable level. While they assert that the water wastage can virtually be eliminated by hot water recirculation, it is noted several times that this is an "ideal" situation where user behavior encourages immediate use of the hot water. Water saving estimates for this study ranged from 900 – 3000 gallons per point-of-use per year. However, it should be noted that study had many limitations including small sample size, inconsistent study parameters, inconclusive results, and a narrow range of home age not comparable to current age distribution of homes in the U.S.

It was also asserted that the use of recirculation pumps would probably save energy. But The Paolo Alto study used pump systems that were consumer activated just before use, and a heat sensor was employed to turn off the pump when a desired temperature is reached (Ally and Tomlinson 2002). The assertion that the system would save energy failed to consider energy demands to run the pump and possible increased heat loss from the recirculation system (Ally and Tomlinson 2002), much less a common installation with a pump that runs continuously. It has been suggested that intermittent use of the pump consistent with reduced energy use could cause damage to the pump and system (Lobenstein 1993).

Another study in a multi-family building analyzed four different pump operations: 1) pump continuously on, 2) pump off at night (between 11:50 pm – 5:20 am), 3) pump off during "peak" use (5:45 am – 8:15 am and 5:45 pm – 9:15 pm), and 4) pump activated when return line water temperature falls below a set point (i.e., 43 °C in study) (Goldner 1999). While the study was limited in scope to one unit and short study period, they found that compared to the baseline pump operation of case 1, scenario 2 and 3 reduced of energy consumption by 5% and scenario 4 reduced energy consumption by 11%. No comparison was made to a situation without a return line. Moreover, they determined that hot water recirculation configured with a pump operating continuously consumes nearly 40% of the total fuel used to heat domestic hot water under that condition. The researchers also noted increased user complaints of decreased hot water and lower temperature water during condition 3 (Goldner 1999). It is imperative that more research be conducted on various pump use and hot water recirculation relative to consumer behavior and improved energy audits. The local code requiring recirculating systems in MCWD mentioned earlier, also required that the pump not run more than "10 minutes in any hour" (Marina Coast Water District (MCWD) 2007). While these types of recommendations may optimize system performance, there is little uniformity in recommendations and it also requires the users to maintain a regimented use schedule.

Another potential problem that arises with recirculation systems is rapid cooling due to mixing and backflow from the return line (Lieberman et al. 2010). As discussed previously, in storage type systems the cold water enters at the top of the tank and is delivered to the bottom of the tank via a closed pipe. Since recirculation systems have a return line that also enters at the bottom of the tank, fresh cold water entering the tank during flushing can "short circuit" the tank and immediately backflow through the return line to the faucet without any storage. This is likely due to the pressure differential in the tank versus atmospheric pressure at the tap. Additionally, it is hypothesized that the pump and return line create a mixing effect within the tank where colder water mixes with the heated water lowering the overall temperature of the water within the tank as opposed to the more plug flow conditions of a standard

storage tank. There have been no studies characterizing the temperature profiles within a recirculation system tank during flushing. The backflow issue can be eliminated through installation of a check valve at the end of the return line (Carter 2010, Marina Coast Water District (MCWD) 2007). Again, proper installation and optimization of this system could have dramatic effects on the overall efficiency of the design.

Other considerations with water recirculation loops include pin hole leaks and copper corrosion due to high velocity flow through copper pipes. A hotel near Lake Tahoe experienced near total water pipe failure due to a recirculation pump installed to eliminate long waits for hot water in multiple rooms. Flow-accelerated corrosion (a.k.a. erosion corrosion) is a common occurrence where flowing hot water erodes the oxide film formed by the reaction of the copper pipe and dissolved oxygen which causes a thinning of the pipe wall and overall scaling effect. This scaling effect can cause increased turbulence and increased failures (Villalobos 2007).

1.2.2.d. Tankless On-Demand Systems: Centralized and Distributed (Point-of-Use). Residential storage water heaters are the current U.S. standard. Storage type systems are prone to heat loss during stagnation (i.e., stand-by losses). On-demand tankless water heater systems have no anode, virtually no hot water storage and eliminate standby losses which can be as much as 50% of the total energy demand in storage systems (Thomas et al. 2006). The DOE estimates that use of electric centralized on-demand systems can result in energy savings between 8-34% versus electric tank storage units depending on average daily water use and using a point-of-use demand system can reduce energy use by 27-50% (Table 1-2) (United States Department of Energy (DOE) 2009b). These savings are dependent on flow rate, total water use, and the installation of low-flow devices. Additionally, the data for point-of-use heaters do not include energy savings from water use at the production phase and could potentially underestimate total energy savings. The downside of on-demand heaters include high cost, high peak energy use, limited flow potential, variable

temperatures with tap distance, and increased possibility of scalding at taps near the heater (Table 1-2) (United States Department of Energy (DOE) 2009b).

On-demand, tankless, or instantaneous water heaters eliminate storage tank heating by using heat exchange coils that raise water to a set temperature only when needed. The cold water from the distribution line passes through the unit where a gas burner or electric element heats the water to a pre-set temperature (Thomas et al. 2006). Two types of tankless water heaters will be defined in this review: located central in the building or distributed or point-of-use (Figure 1-3). While both types of on-demand systems function similarly, they have marked differences with regards to advantages, disadvantages, energy consumption, and public health considerations (Table 1-2).

In centralized systems, a large central demand system would be located somewhere in the residence and a hot water distribution system would deliver hot water to various faucets within the house (United States Department of Energy (DOE) 2009b). Water would be heated through the heat exchange coils rather than stored in a tank thus eliminating the standby losses of a storage type system; however, with this type of system, the same heat losses through the pipe network would need to be considered. The distributed or point-of-use models consist of a series of smaller tankless units installed directly at the faucet (Figure 1-3). These systems will either provide single-source use (i.e., one shower/tub) or small multiple point use (i.e., all faucets in a given bathroom including the sink and shower/tub). This type of system eliminates both standby losses from the storage tank and pipe loss through the network since the heated water does not need to "travel" to get to the tap.

There are several limitations with the use of on-demand systems (Table 1-2). Even using the largest model, gas-fired unit which should theoretically provide the most "power" for water heating, on-demand systems typically cannot provide enough hot water to supply multiple faucets and simultaneous uses at any given time (United States Department of Energy (DOE) 2009b). Additionally, the maximum

flow rate of on-demand systems are limited by several variables including the water temperature setting, cold water influent, and the heat input to the unit itself. This will lower the maximum rate at which hot water can be delivered when compared to a tank system.

Water temperature can also be inconsistent when using an on-demand system leading to consumer complaints. If a centralized demand water heater is being used, the temperature setting needs to be high enough to negate any heat loss in the pipe to the farthest faucet without causing scalding at the nearest tap. Lower temperature settings and flow rate can be more acceptable with low-flow devices, when point-of-use systems are in place, in a washing machine where comfort and scalding are not a consideration, or if the water later gets electrically heated by the appliance, as in the case of a dishwasher (Johnson and Clark 2006). While gas-fired demand water heaters provide higher flow rates than electrical demand heaters, flow rates average between 2-5 gallons per minute and still may not provide hot water to multiple locations throughout a household.

With electric systems, increased power may be an issue. Even the smallest on-demand heaters require more power (i.e., energy input) than tank systems. While standby losses are virtually eliminated, the peak energy draw during use can be a problem in neighborhoods with a taxed power grid (Green Energy Efficient Homes 2010, SRP Designer 2010), and may require the homeowner to upgrade wiring or the utility to upgrade the grid. Finally, scale buildup in the system causing damage to the unit has been noted in areas with hard water in as little as four months, leading to costly repairs and /or replacement. (Thomas et al. 2006) To combat the limitations of on-demand water heaters, consumers could consider using multiple units in parallel or point-of-source heaters that supply hot water directly to the tap used. Other solutions include installing ultralow-flow showerheads (which may lead to consumer dissatisfaction) and water softeners. Furthermore, the energy costs associated with running multiple electric *tankless water heaters simultaneously has not been reviewed.*

1.2.2.e. Alternate Energy Water Heaters. Incentive tax credits exist for solar, electric heat pump, and on-demand natural gas residential water heater infrastructure (Table 1-2). However, the practical long-term performance of these devices under scaling conditions, or in terms of pathogen control, has never been rigorously assessed. Concerns have been expressed about pathogen re-growth in solar applications although limited data available to date is inconclusive (Garnier et al. 2009, Mathys et al. 2008). In general, it might be expected that electric heat pump and solar systems would behave like electric tank systems relative to possible growth of premise plumbing pathogens, but with much higher storage volumes. However, more practical performance data must be obtained. Due to variation in temperature, climate, and weather, solar systems will typically have a back-up non-renewable energy source (i.e., electric or natural gas) and are thus susceptible to the same detriments and benefits of these systems. Since solar water heaters require maximum sun exposure to be most effective, there may be regional, climate limitations to this type of system.

1.2.3. Scaling. In certain "hard" or other waters, calcium and silica can precipitate and coat the surface of the heating elements and pipe surfaces. These deposits can cause water heater noise, increase corrosion, clog pipes, reduce heater life and dramatically reduce energy efficiency via formation of scale layers that reduce heat transfer from the energy source to the water. The reduced energy efficiency is attributed to internal insulating properties and reduced heat transfer from the scale layer to the tank. On-demand systems are especially prone to scaling problems (Table 1-2) because of the small diameter tubes required for maximum heat transfer and constant flow of water over the heating element. In some cases these devices can be rendered virtually inoperative in a matter of months due to clogging, and acidic solutions must be used to clean the scale and maintain efficiency and flow (Isaacs and Stockton 2010, Thomas et al. 2006).

The Water Quality Research Council (WQRC) in conjunction with New Mexico State University found that the effects of hard water scaling on a gas fired water heater was an increase in energy demand of 30% in just 14 days; moreover, after the scale was cleaned out, only 5% of the increase was reversed

(Table 1-) (Isaacs and Stockton 2010). Water scaling and liming (i.e., calcite precipitation) are most common in hard water, although silicates, sulfates, and waters with high total suspended solids can also form sediment or "scale" layer at the bottom of the tank for gas-fired systems and around the electrical heating components in electric water heaters. The WQTC study also showed that in a head to head comparison, scaling had a worse overall effect on energy efficiency of the gas-fired heaters than the electric water heaters by nearly 8% (Isaacs and Stockton 2010). In a recent practical study that examined this issue, efficiency of on-demand systems dropped dramatically in just a few months and some were even rendered inoperative, practical trends that might make on-demand less efficient than comparable tank systems (Thomas et al. 2006). Thus, benefits of on-demand systems will not be possible in all waters, and its use in heavily scaling waters might not save energy without frequent maintenance.

1.2.4. Overall Implications of Various Water Heating Systems. Given the multitude of variables and characteristics of the different types of water heating systems (Table 1-2), it is expected that various chemical, microbial and physical properties would differ from system to system dependent on the actual configuration of specific water heater types (i.e., Figure 1-6). There has been a noticeable lack of research that provides insights to these important issues. Future research is needed to identify how these variables are affected by altering the operation and configurations of different water heating systems.

1.3. PUBLIC HEALTH CONSIDERATIONS.

There are two serious public health concerns when it comes to water heating: pathogen growth and scalding. The former has already been described as a major area of concern for new research and the latter may become a high priority with new "green" advice in water heating systems.

1.3.1. Pathogen Growth. Traditionally, control of pathogens in water leaving the treatment plant via disinfection, coagulation, and filtration has been the paramount concern of water utilities

and the U.S. Environmental Protection Agency (U.S. EPA)—the successful mitigation of this hazard represents one of the 10 greatest engineering achievements of the 20th century (National Research Council (NRC) 2006). The CDC estimates that between 8,000-18,000 people in the United States are hospitalized each year with Legionnaires' disease (Centers for Disease Control and Prevention (CDC) 2008c). There is also a similar growing concern with non-tuberculosis mycobacterial (NTM) lung disease tied to drinking water (Centers for Disease Control and Prevention (CDC) 2008b, Falkinham et al. 2008, Marras et al. 2007). Estimates of NTM disease incidence range from 15-30 per every 100,000 persons with some 30,000 NTM infected patients in the United States (Rushing and Edwards 2004). Because susceptibility to both NTM and Legionnaire's disease increases with age and diagnosis is improving, incidence of documented waterborne disease from premise plumbing pathogens will likely continue to increase (Garcia-Fulgueiras et al. 2003, Prince et al. 1989). Representative opportunistic pathogens of concern in premise plumbing include Legionella pneumophila, Acanthamoeba, Mycobacterium avium complex and Pseudomonas aeruginosa (Table 1-3). Control of waterborne disease from these and other premise plumbing pathogens will require a noteworthy paradigm shift versus conventional water treatment practice and approaches.

Specifically, "opportunistic" pathogens do not typically cause disease in healthy persons, but can be fatal to humans with a compromised immune system such as the elderly, HIV infected persons, or hospitalized patients. Premise plumbing pathogens grow in shower heads, faucets, along pipe walls, or in water heaters, whereas conventional pathogens are naturally present in the source water from fecal contamination and do not multiply in the water itself. Finally, the primary mode of transmission and exposure is via inhalation or through wounds as opposed to ingestion (Figure 1-7).

Table 1-3 Premise Plumbing Pathogens of Concern

Pathogen	Disease(s)	Host Organism Required?	Mode of Exposure	Source
Legionella pneumophila	Legionnaires' Disease or Pontiac Fever in Children	Yes	Inhalation or Aspiration	CDC, 2008 (Centers for Disease Control and Prevention (CDC) 2008a)
Pseudomonas aeruginosa	Urinary Tract Infections, Respiratory Infections, Dermatitis, Soft Tissue Infections, Bacteremia, Bone and Joint Infections, GI Infections	No	Wound infection; other modes of transmission are unknown	Todar, K, 2008 (Todar 2008)
Mycobacterium avium	Pulmonary Disease Cervical Lymphadenitis (children)	No	Inhalation or Aspiration	CDC, 2005 (Centers for Disease Control and Prevention (CDC) 2005)
Acanthamoeba	*Acanthamoeba* keratitis	No	Wound Infection	CDC, 2008 (Centers for Disease Control and Prevention (CDC) 2008a)

Systems that maintain a consistent inflow of water from the main distribution line will tend to have continuous levels of disinfectant; however, as water remains stagnant in the system or recirculating for any length of time such as the systems found in water heaters, disinfectants will decay and water quality will decrease (Bagh et al. 2002, 2004). Chlorine decay is dependent on several variables including

pipe material, inorganic and organic material in the water, and hydraulic effects (Mutoti et al. 2007).

Since disinfectant decay over time will affect residual levels in the water, it would also be expected that disinfectant decay can be directly associated to increased biofilm production and thus decreased water quality. "Biofilm" in this paper and the research conducted by Momba, *et al.* (Momba et al. 2000) describes "a layer of microorganisms in an aquatic environment held together in a polymetric matrix attached to a substratum such as pipes." Biofilms are an integral part of microbial resistance to disinfectants (Momba et al. 2000). If disinfectant residuals drop below the normalized or designed level for any length of time, biofilm can show substantial re-growth with the new biofilm more resistant to disinfectants (Codony et al. 2005). It is important,

Figure 1-7 Pathways of pathogen exposure. *Pathogen exposure in premise plumbing systems. Acanthamoebae and other protists occur in cyst (A) and trophozoite (B) forms. Vesicles within trophozoites can harbor up to 20-1500 pathogenic bacteria such as L. pneumophila (C), which can eventually burst and lead to pathogen occurrence in tap water and shower water (D). Contact lens wearers are vulnerable to keratitis infection from Acanthamoebae (E-F). Inhaling mists containing L. pneumophila and nontuberculosis mycobacteria (NTM) can cause lung infections (G). Exposure to Acanthamoebae, P. aeruginosa and NTM through skin lesions can cause infection (H).*

therefore to understand how various water heating systems affect disinfectant decay and other chemical parameters in premise plumbing as this will have a direct effect on biofilm formation, resilience, and re-growth potential.

Certain types of water heating systems may be linked to increased incidence of *Legionella* in premise plumbing. The team of Moore, *et al.* (Moore et al. 2006) related the presence of hot water recirculation systems to increased occurrence of *Legionella* in Pinellas County, Florida. In fact, the study found that buildings that contained a recirculation system were five times more likely to have viable *Legionella* in the plumbing. This type of study has been limited in nature and pathogens such as

Mycobacterium avium and *Acanthamoeba* also may be impacted by water heater type. Thus far, there is a real, tangible gap in the research with respect to specific pathogen growth and water heating infrastructure.

1.3.2. Scalding. System operating temperature has profound implications for control of scalding and pathogens (Figure 1-8), and different countries have different strategies. The consumer product safety commission estimates that scalding from hot tap water results in 3,800 injuries and 34 deaths annually in homes, with children at special risk (Consumer Product Safety Commission (CPSC) 2005, National SAFE KIDS Campaign (NSKC) 2004). To reduce energy costs, potential for scaling and scalding, the EPA recommends that water storage tanks be set at 49 °C (Centers for Disease Control and Prevention (CDC) 2007-2008). Unfortunately, this increases the likelihood of pathogen growth in water heaters relative to higher temperatures (Figure 8). Other countries and the World Health Organization

Figure 1-8 Pathogen growth and scalding concerns with temperature. *Higher water heater storage temperature decreases the time required for Legionella death and the time to acquire severe burns from scalding. Data for figure compiled from NRC. (National Research Council (NRC) 2006)*

(WHO) recommend setting temperatures for tanks systems above 60 °C to control pathogens, and then reduce dangers of scalding by requiring installation of mixing valves at all fixtures to maintain dispensed water below 49 °C (Centers for Disease Control and Prevention (CDC) 2007-2008, Spinks et al. 2003). A preliminary cost-benefit analysis of the higher temperature and mixing valve requirement in Canada indicated a benefit of $0.7–4.2 million in reduced scalding versus a cost of $48–119 million per year (Centers for Disease Control and Prevention (CDC) 2007-2008; however, the estimated benefit did not include costs of reduced Legionella infections and death.

1.4. CONCLUSIONS AND FUTURE WORK

There are serious long-term public health and energy implications that arise from consumer installation and operation of residential hot water heating systems. An "optimal" decision might consider individual preferences, consumer susceptibility to problems (i.e., scalding and children and immune-status for elderly), household hot water demand, climate, scaling potential, presence of nutrients in the water supply, availability of natural gas connections, and the type/concentration of residual disinfectant in the supply water. Unfortunately, due to a lack of prior research, much of the evidence is anecdotal, and head-to-head comparisons have been absent.

Most data generated on water heaters has been provided by manufacturers, plumbers, consumers, and government agencies. There has been surprisingly little practical research on head-to-head performance on water heating infrastructure despite its relevance in the water-energy nexus. Yet, municipalities and agencies are mandating certain water heaters or providing incentive for consumer selection based largely on manufacturer claims of water conservation or other "green" initiatives. Given that water heating infrastructure has important implications for green engineering, energy efficiency, water conservation, environmental microbiology, and public health, it is imperative that more research be done to quantify actual differences in these systems. The discrepancy between WHO and U.S. temperature setting recommendations has implications on energy efficiency, scalding potential, scale build-up and microbiological growth. Nevertheless, no applied direct measurements are available to understand the practical extent of the difference.

The ability of premise plumbing pathogens to amplify is controlled by water temperature, residual disinfectant concentrations, water nutrient levels and water age: factors directly influenced by water heating infrastructure type, design and operation. Hence, there will be inextricable direct linkages between goals of reducing energy demand and maintaining public health, both antagonistic and synergistic, which are only beginning to be appreciated and studied.

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CHAPTER 2. WATER AND ENERGY SAVINGS FROM ON-DEMAND AND HOT WATER RECIRCULATING SYSTEMS

2.1. BACKGROUND

2.1.1. Residential Water Heating as Part of the Water-Energy Nexus. Water heating is the second largest source of energy consumption in buildings and has a total energy demand exceeding the entire water and wastewater sector (Brazeau and Edwards 2011, Energy Information Administration (EIA) 2005, Lieberman et al. 2010). Obtaining improved performance of water heating systems in buildings (> 100 million residential households and > 14.8 million commercial structures) can yield significant benefits in terms of public health, water conservation, energy efficiency and consumer comfort (United States Environmental Protection Agency (EPA) 2009a). Some of these goals are being addressed via standards promulgated by the United States Green Building Council (USGBC), LEED and Energy Star programs, which collectively attempt to achieve certain goals of "green" design for new construction, remodeling and retrofitting. With over 100 million households in the United States using water heating systems and nearly 40% of those homes using electric water heaters, fundamental research is needed to better understand and optimize all dimensions of water heater system performance, and to inform development of sound guidance and standards for consumers (Brazeau and Edwards 2011).

2.1.2. Energy Efficiency and Conservation Programs. Energy Star, the lead rating system for appliance water/energy efficiency and sustainability, helps consumer identify products that reduce green-house gas emissions, are more energy efficient, and save the consumer money on energy use while still maintaining quality. According to Energy Star estimates, Americans reduced an equivalent of 33 million cars worth of greenhouse gas emissions and saved close to $18 billion dollars on utility bills by using Energy Star products in 2010 (Energy Star (U.S. DOE and U.S. EPA) 2011a, b, Yudelson 2008). The Energy Star program is also a basis for certain tax incentives associated with water heating systems to encourage energy efficiency (Energy Star (United States

Department of Energy and United States Environmental Protection Agency) 2009). In addition to Federal government initiatives, some cities where water conservation is a high priority due to environmental concerns, drought, cost, and other considerations, have adopted local ordinances which mandate new construction to have new, water saving, "green" plumbing designs. For example, one municipality in California has mandated that if a hot water tap is more than 10 feet from a water heater, that hot water recirculation or on-demand systems be used to reduce wasted water (Marina Coast Water District (MCWD) 2007).

2.1.3. Water Heaters and Sustainability Efforts. Certain hot water systems have been marketed "green" based on federal tax credit eligibility or municipal mandates. (Brazeau and Edwards 2011) Although these initiatives and mandates are assumed to provide net environmental benefits, there is surprisingly little scientific evidence documenting and quantifying the potential advantages. It is even possible that in many instances, there is a net energy and water loss associated with installation of certain "green" features, which can be counterproductive. For example, the hot water recirculation systems that have been mandated or otherwise encouraged in certain municipalities due to assumed reductions in energy and water use can actually be installed in a manner that has a potential to increase energy losses (Figure 2-1). The few attempts that have been made to quantify the performance of these systems have not been completely successful.

For example, in 2002, the Oak Ridge National Laboratory (ORNL) and the City of Paolo Alto conducted a study examining the use of hot water recirculation. They estimated that nearly 1-3 gallons of potable water are wasted down the drain, as a consumer waits for water to reach a comfortable level for showering. While they assert that this water wastage can be virtually eliminated by installed hot water recirculation systems, the authors correctly note numerous times that this only occurs in an "ideal" situation where residents push a button at tap starting the pump system and conveying hot water to the end use (Ally and Tomlinson 2002). Such push button type systems are not always installed in recirculation systems and there are several other systems that dominate the market (i.e., continuous

circulation, thermostat systems, timer-controlled systems, etc.) which may actually be counterproductive in terms of energy efficiency (Klein 2005).
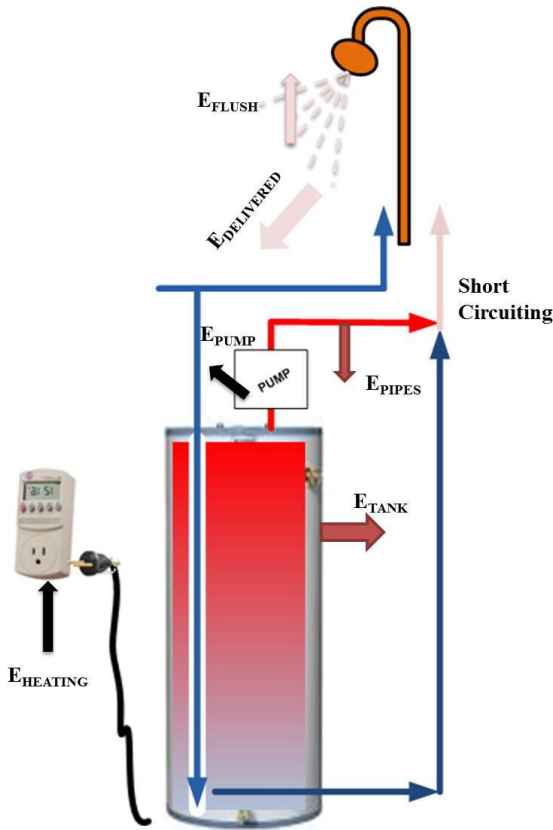
Figure 2-1 Hot water recirculation system (RECIRC). *A hot water recirculation system showing energy consumption and heat losses throughout the system. If the recirculating pump is not in use, the tank may stratify (as shown) with hotter temperatures at the top of the tank and lower temperatures at the bottom. When the pump is in use, the temperature will be nearly the same (hot) everywhere (not shown). With the installation of a check valve, short circuiting should be eliminated (not shown).*

LEGEND:

$E_{HEATING}$= Total energy consumed from general power grid (as measured by energy meter) to heat water

E_{PUMP}= Total energy consumed by pump from general power grid (as measured by energy meter)

E_{TOTAL} = Sum of all energy inputs ($E_{HEATING}$ + E_{PUMP})

E_{TANK} = Heat loss from tank to ambient during stagnation (dependent on internal tank temperature and ambient temperature)

E_{PIPES} = Energy loss per volume of hot water produced during flushing (dependent on water temperature and ambient temperature)

E_{FLUSH} = Heat loss to the environment per volume of water produced after leaving pipe and before delivery to the consumer (dependent on water temperature, air temperature, drop size and other factors)

Short Circuiting = Phenomenon where cold water can backflow out the return line at the bottom of the tank "short circuiting" the storage tank when no check valve is installed (Short Circuiting can dramatically reduce $E_{PRODUCED}$ by lowering the delivered hot water)

$E_{DELIVERED}$ = Energy actually delivered to consumer in the form of heated water

Energy Efficiency = $E_{DELIVERED}/E_{TOTAL}$

The ORNL study was a first attempt at handling the complex issues of domestic water heating and hot water recirculation, but had typical field-study limitations including small sample size, inconsistent study parameters, inconclusive results, and a narrow range of home age not comparable to current age distribution of homes in the U.S. Furthermore, the study had some fundamental problems in its variables that may cast doubt on the conclusions drawn. These problems include a failure to consider the energy use of the pump, temperature setting of the system, not considering pipe networks, materials, and configuration, and not standardizing hot water use (Ally and Tomlinson 2002).

Other possible problems for certain "green" hot water heaters are associated with consumer satisfaction. For example, on-demand instantaneous water heaters are gaining popularity in the residential sector. These types of heaters are marketed as "green" since the electric systems are virtually 100% energy efficient as there are no standby heat losses. However, these systems may require low flow fixtures, provide water with inconsistent temperature and impose other limitations (Brazeau and Edwards 2011).

2.1.4. Expected Energy Efficiency. It would be expected that the 49 °C condition would have less standby energy loss than the 60 °C condition due to lower temperature differentials between the tank and ambient room temperature. Based on a fundamental understanding of how these systems function (Figure 2-1), it is instructive to consider the likely relative performance of each system. To determine the overall efficiency of the systems, all the possible sources of energy loss must be quantified. While the temperature data can give insight to energy efficiency questions, the degree to which the efficiency is affected can only be determined through direct measurement.

2.2. RESEARCH GOAL AND OBJECTIVES

This work will provide the first head to head evaluation of electric hot water recirculation system performance compared to traditional electrical central storage system, which holistically considers: 1) relative energy efficiency data under various operating conditions, 2) overall impacts on water demand, and 3) consumer comfort and quality of energy delivery as measured by temperature profiles of delivered water.

2.3. EXPERIMENTAL DESIGN

2.3.1. Overview of Experimental Design. Three common electric water heater configurations (Figure 2) will be evaluated in the laboratory including one conventional (system 1) and two systems reported to be "green" by specific ordinance requirements, federal tax credit eligibility and/or Energy Star rated (Energy Star (United States Deparment of Energy and United States Environmental Protection Agency) 2010, Energy Star (United States Department of Energy and United States Environmental Protection Agency) 2009, Marina Coast Water District (MCWD) 2007) (systems 2-3):

1) Storage tank with no hot water recirculation (**STAND**);

2) Storage tank with hot water recirculation (**RECIRC**); and

3) Point-of-use on-demand with no storage and no hot water recirculation (**DEMAND**)

Each system was operated with an identical water supply, delivered water volume and flow rate, target temperature setting, and usage pattern (controlled with a timer). All electrical inputs were quantified (ASHRAE 2006, United States Department of Energy (DOE) 2000, 2001). The STAND and RECIRC systems were identical 20 gallon electric tanks with manufacturer equipped anode rods. The RECIRC system was equipped with a 25 Watt hot water recirculation pump and return line. All systems

were fitted with 30 feet of ¾" copper pipe coils to the laboratory tap, and the RECIRC system with an additional 30 feet of ¾" copper coil as the return line. All taps, valves, connections, and adapters are copper or brass. Upstream of the water heating systems, a waste line was installed so municipal tap water could be flushed for at least 10 minutes prior to demand from the experimental apparatus, which was revealed to ensure delivery of water with constant temperature and chemistry.

The tap water is relatively soft, chloraminated water from the Town of Blacksburg. Prior to installation, both tanks were rinsed and spiked with 20 mg/L hypochlorite and total chlorine decay was measured over a 3-day period to quantify any differences in decay rates from the equipment (i.e., tank) alone. Moreover, at the start of the experiment, both tank systems were operated under a similar set of conditions (i.e., return line closed via a valve and the pump shut off in RECIRC system), and energy consumption of the tanks was identical.
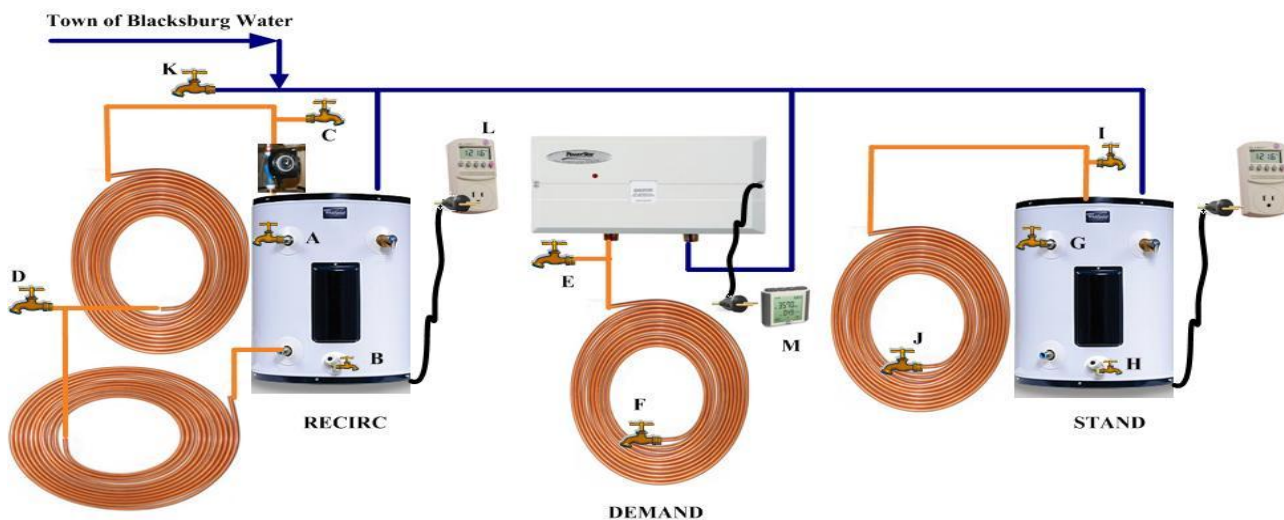
Figure 2-2 Experimental design. *Experimental design of head-to-head water heaters: A-J) Sample Taps, K) Flush/Waste line, L) 120 V energy meter, and M) 220 V Energy meter. For experiments described in this paper, all copper tube was insulated.*

2.3.2. Water Consumption Profiles. Research was conducted using four different water use patterns: high use, low use, high temperature and low temperature. The high use pattern was determined based on a comprehensive study conducted by Goldner of water heater use patterns in

New York. The study showed a high average use was 54 gal/person/day (Goldner 1994). According to the 2000 census, an average family size is 3.14 which would equate to a total volume of 170 gal/day. If we figure a nominal water heater tank stores about 50 gallons, this would mean that the tank fully empties at least 3 times. Based on these calculations, high use was defined as a system with complete volume turnover 3-times daily with 8-hour stagnation events between events (United States Census Bureau 2000). Low use represented a situation in which demand was 1/6 of high use with a 25% tank turnover every 12 hours. The high temperature setting is based on the World Health Organization (WHO) recommended operating temperature of 60 °C designed to limit microbial growth (Bartram et al. 2007), while the low temperature setting is based on the United States recommended temperature of 49 °C to conserve energy and minimize scalding potential (United States Environmental Protection Agency (EPA) 2009c). All pipes were initially insulated with standard self-sealing foam insulation (R = 2) to represent a "best case" for energy efficiency and the pump in the RECIRC system was run continuously to ensure a stable, constant temperature in the pipe network.

2.3.3. Temperature and Energy Measurements. Total energy ($E_{HEATING}$; Figure 2-1) measurements were determined using an electric watt meter that measured alternating current (AC) directly and gives cumulative kWh values for the RECIRC and STAND systems as well as the RECIRC pump. To measure the 220 V DEMAND system, a wireless energy meter captures the watt-hours via sensors on each of the circuits. The energy delivered ($E_{DELIVERED}$) was defined in terms of hot water yielded (i.e., $q = mc\Delta T$, where q = energy in terms of heat transfer to water, m = mass, c = specific heat capacity of water, and ΔT = change in temperature; Figure 2-1). Temperature was measured as follows: 1) 4 gallon cumulative buckets of water from the laboratory tap (as used for energy calculations) was measured using digital thermometers, and 2) flushing temperature profiles were measured using automatic loggers and thermocouples that measured temperature every 10 seconds.

Table 2-1 Expected Energy Consumption and Loss

System	Condition	E_{TANK}	E_{PIPES}	E_{FLUSH}	$E_{SHORT\ CIRCUITING}$	Total Energy Loss	Expected $E_{PRODUCED}$	E_{PUMP}[c]	$E_{HEATING}$	E_{TOTAL}	Expected Energy Efficiency[d]
Standard Tank with No Recirculation	49 °C High Use[a]	Low	Low	Low	N/A	Low	Medium-High	N/A	Low-Medium	Low-Medium	High
	49 °C Low Use[b]	Low-Medium	Low-Medium	Low-Medium	N/A	Low-Medium	Medium	N/A	Low	Low	High
	60 °C High Use	Medium	Medium	Medium	N/A	Medium	High	N/A	Medium-High	Medium-High	Medium-High
	60 °C Low Use	Medium-High	Medium-High	Medium-High	N/A	Medium-High	Medium-High	N/A	Medium	Medium	Medium-High
Tank with Recirculation and No Check Valve	49 °C High Use	Low-Medium	Low-Medium	Low-Medium	Medium	Low-Medium	Low-Medium	Medium	Medium	Medium-High	Medium- High
	49 °C Low Use	Medium	Medium	Medium	Medium	Medium	Low	Medium	Low-Medium	Medium	Medium-High
	60 °C High Use	Medium-High	Medium-High	Medium-High	High	Medium-High	Low-Medium	Medium	High	High	Medium
	60 °C Low Use	High	High	High	High	High	Low	Medium	Medium-High	High	Medium
Demand	Low Setting	N/A	Low	Low	N/A	Low	Medium-High	N/A	Low	Low	Very High
	High Setting	N/A	Low-Medium	Low-Medium	N/A	Low-Medium	High	N/A	Low-Medium	Low-Medium	Very High

[a]During high use, the temperature of water produced fluctuates from hot-cold as the tank empties (i.e., as the tank flushes, the ΔT between water temperature and ambient lessens)

[b]During low use, the temperature of water produced is a small volume at maximum temperature (i.e., ΔT between water temperature and ambient is maximized)

[c]In recirculation systems, the pump is assumed to run constantly (24/7)

[d]Energy Efficiency = Energy Produced/Total Energy

2.4. RESULTS AND DISCUSSION

After describing characteristic temperature profiles of water flow from each system, and within the storage tanks when present, the overall energy efficiency of each system is quantified. A final section describes the factors affecting the practical performance of on-demand electric heaters.

2.4.1. Temperature during System Flushing. During flushing, the RECIRC system had less temperature stability during flushing than did the STAND configuration. In all cases the RECIRC systems had a short period of stable high temperature, followed by a continuous decrease in temperature (Figures 2-3 and 2-4). The decrease in temperature was more rapid in the winter months. In contrast, the STAND system was characterized by a brief period in which water temperature rapidly rose as cooled water in the pipes was replaced with the hot water from the tank. Thereafter, the temperature remained stable until the hot water in the tank was completely displaced with cold water. The DEMAND system showed similar pattern to STAND with two key differences: 1) the hot water never "ran out" and was continuous until flushing ended, and 2) the maximum temperature never rose above 37 °C or 27 °C in the maximum energy and minimum energy settings, respectively. Clearly, from a consumer comfort standpoint, factors such as the length of the time for the hot water to reach the tap, the stability of the water temperature during flushing, and the maximum temperature are going to be important considerations for water heater selection. For example, using the STAND system as a baseline for comparison, both of the "green" models (i.e., RECIRC and DEMAND) had lower delivered water temperatures after 1-2 minutes of flushing. The main concern with the DEMAND system was the limited ability to achieve temperature targets for a comfortable shower. To achieve a temperature of 37 °C (warm enough for showering), the flow rate had to be dropped to the minimum flow rate possible (approximately 0.80 gpm). Lower flow rates automatically shut off the heating elements as a safety feature to prevent

scalding.   Operating the system at the low energy setting was the least desirable condition for a
consumer comfort standpoint. Although, this setting uses less energy to run and may be better from
a total energy perspective, it does not provide enough power to actually provide hot water (Figure 2-
3).
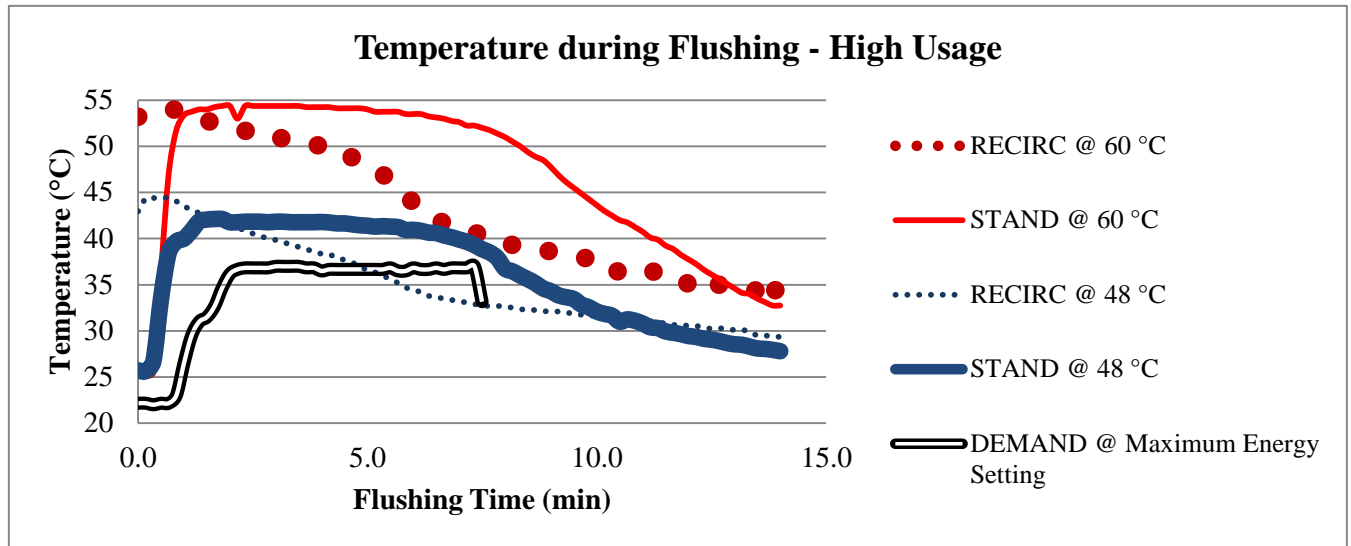
Figure 2-3 Temperature profile during flushing for the low use condition.
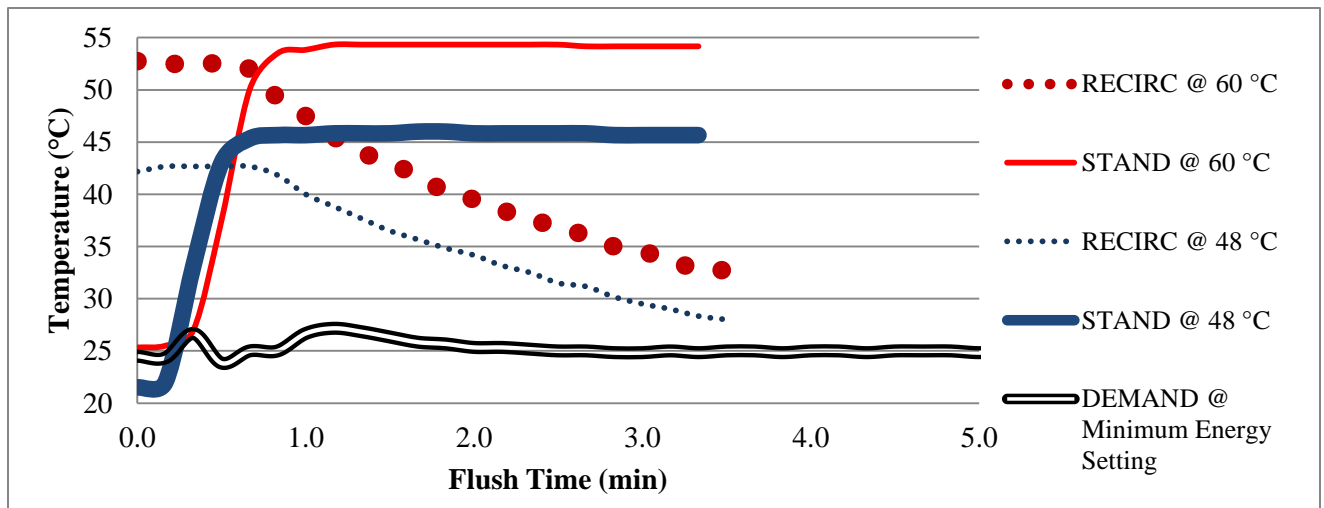
Figure 2-4 Temperature profile during flushing for the high use condition.

While the RECIRC system avoided the 50 – 60 second initial temperature rise in the STAND system, the delivered water temperature declined steadily after the first minutes of flushing. Two possible explanations for this rapid cooling were identified: 1) cold water from the distribution system was instantly mixing in the hot water tank causing a drop in internal temperature throughout the volume, or 2) cold water from the distribution system was short circuiting the tank by back-flowing out of the return line mixing at a junction upstream of the tap (Figure 2-1).

A tracer study using a 170 g slug of KCl (39 g as K+) added to the cold water influent pipe before the tank, was conducted in the RECIRC system as designed and then again with the installation of a check valve to prevent backflow through the return line (Figure 2-5). K+ was measured in the effluent water (in a well mixed 4 gallon capture).
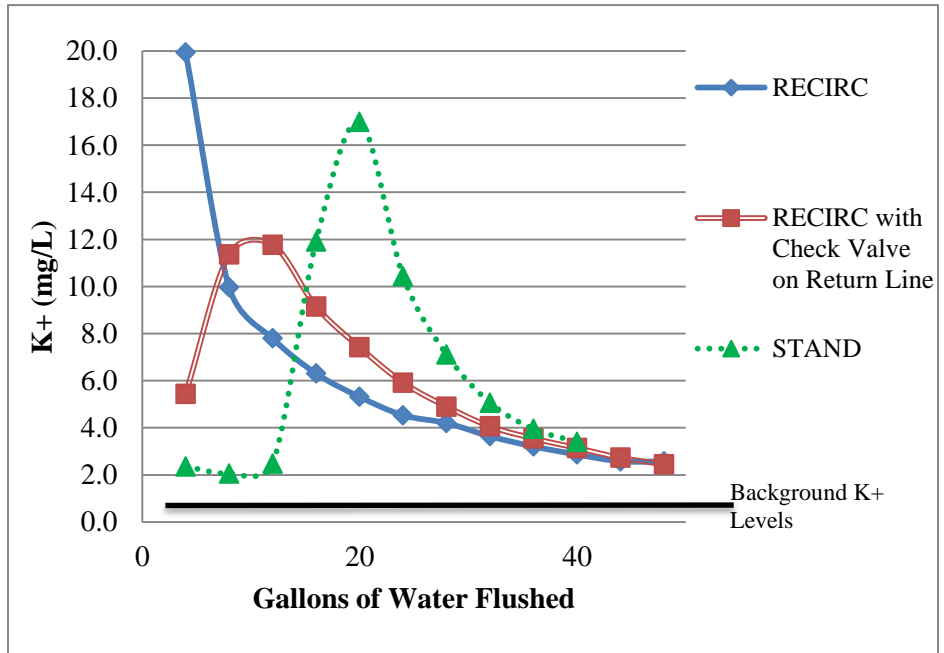
Figure 2-5 KCl tracer study. *A slug of KCl was fed into the reactor and K+ was measured in the effluent water to determine how and if mixing was occurring in the recirculation system.*

The extent to which K+ appeared in the delivered water from the tank unambiguously indicates the extent of short-circuiting of cold water that was initially outside the tank. When the check valve was installed, only 9% of the first 4 gallon effluent water was derived from cold influent water initially held outside the tank and that had never been heated (Figure 5), indicating limited mixing of cold water with the hot water stored in the tank in the early phases of showering. In contrast, when the check valve was removed, 4 times more K+ was present in the 4 gallon effluent, indicating 4 times more cold water was present in the delivered water, and confirming that cold water was essentially by-passing the tank via

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reverse flow through the recirculation return line if the check valve is absent. This issue has important implications for the overall energy efficiency and operation of hot water recirculating systems. The STAND system operated closer to a plug flow system, as expected (Figure 5).

2.4.2. Storage Tank Temperature during Stagnation. The internal temperature of the tanks during stagnation gives insight to the expected energy efficiency of the systems. Standby losses have been cited as being responsible for as much as 50% of the energy demand of storage type water heating systems (Thomas et al. 2006). These losses are dependent on several factors including the internal temperature and volume of the storage water, the ambient temperature, and the type and amount of installation.

Due to mixing from the pump, the RECIRC system has a consistent, high temperature throughout the entire volume of the storage tank. Temperature recovery from high water demand was essentially complete by 45 minutes after the event throughout the entire volume of the tank. In contrast, the recovery of stable temperature profiles, especially at the bottom of the STAND system for high user pattern, did not occur over the 8 hours of testing. In the low use condition where only 25% of the tank volume turns over each use (50% turn-over per day) the bottom 20% of the STAND storage tank was approximately 12 – 15 °C lower than the top 80% due to temperature stratification within the tank.

The temperature stratification is even larger in the high use STAND condition. Since one tank volume was displaced, 60% of the storage volume was at 10 – 12 °C lower than the temperature setting. This has many implications on standby losses. As previously stated, standby losses are controlled by the temperature differential versus ambient air. The average surface temperature of the tank decreased: RECIRC low use > RECIRC high use > STAND low use > STAND high use. Thus, it would be expected that the RECIRC tank has a greater standby losses than the STAND system in all cases, and low use would always have greater standby losses than high use patterns. More specific graphical representation of the internal tank temperatures is shown in Chapter 3.

2.4.3. Energy Efficiency. In all cases, the RECIRC had lower energy efficiency compared to the STAND and DEMAND systems (Table 2-2). Not only is there added energy consumption for hot water recirculation from the pump (25% net energy increase), but the tank itself requires nearly double the energy to heat water as compared to the standard hot water system due to increased standby heat losses from the pipe system and the loss of natural stratification within the tank.

Table 2-2 Energy Efficiency

Condition	Total Energy Consumption (kWh/Day)				Energy Out (kWh/Day)		Energy Efficiency (%)	
	STAND	RECIRC - TANK	RECIRC - PUMP	RECIRC - TOTAL	STAND	RECIRC	STAND	RECIRC
60 °C, High Use	8.1	9.9	0.61	10.5	7.04	5.82	86.9	55.4
49 °C, High Use	4.8	6.9	0.61	7.5	4.27	4.12	88.3	55.0
60 °C, Low Use	3.2	7.3	0.61	7.9	1.68	1.50	52.2	19.0
49 °C, Low Use	2.7	4.9	0.61	5.5	1.47	1.25	55.1	22.7

2.4.4. Normalized Energy Efficiency and Consumer Use. The total energy demand of the systems (Table 2-2) appears to indicate that operating at 49 °C expends 12-40% less energy than operating at 60 °C for the same use pattern, but this is misleading. In the tested scenario, the total energy and output energy of delivered water were calculated without using a mixing valve to temper the hot water with cold water. A higher percentage of cold water would be mixed with water at the 60 °C set point to provide a comfortable shower and to prevent scalding. The temperature of a comfortable shower is typically in the range of 32 – 43 °C (Delta Faucet 2011).

If the data are normalized for consumer mixing of hot water with cold to hit a target temperature of 37 °C, the total extra energy of operating at 60 °C versus 49 °C is 1-15% higher (Table 2-3). Thus, while lower temperatures might be necessary and desirable to reduce scaling and scalding potential, in the absence of these considerations overall energy savings from operating at 12 °C lower temperature are

modest, and the difference is due to reduced standby losses. In situations with water of higher scaling propensity, over the long term the relative performance advantage of operating at 49 °C might increase.

From another perspective the relative energy savings of 49 °C vs. 60 °C might be eliminated or even reversed if a smaller water heater was operated at the higher temperature. If the size of the water heater was optimized to provide the same volume of delivered tempered water (e.g. 30 gallons of 37 °C tempered water), then less hot water volume would be needed from a system operated at 60 °C system (Table 2-3). Assuming that the surface area of the tank is proportional to standby heat losses, using the example of a target demand of 30 gallons of 37 °C delivered tempered water, operation of a water heater at 49 °C would require a 20 gallon hot water tank, whereas the same volume of delivered was for a system at 60 °C would only require a 14.5 gallon tank with a 17% reduction in surface area. It is conceivable, then, that if water heaters are optimized to minimize tank volume at higher temperature settings that the benefits of minimizing standby losses would outweigh any increased energy consumption from operating at a higher temperature in non-scaling waters.

Overall, under conditions tested herein, the RECIRC system is still far less energy efficient than the STAND systems. While the RECIRC system will undoubtedly save water at the tap given perfect user conditions (Figures 2-4 and 2-5), there is an increased energy consumption of 4-5 kWh and 6 – kWh per day compared to STAND and DEMAND, respectively. In the model systems, it takes between 45 seconds and 1 minute for the STAND system to run all the cool water to waste (Figures 2-4 and 2-5) This equates to approximately 1.2 – 1.5 gallons conserved in RECIRC as compared to STAND for each flushing event. Given that it typically takes 2 gallons of water to produce 1 kWh at the energy production phase, the total net water use can actually favor STAND (Table 2-3) (Torcellini et al. 2003). Thus, this marketed and sometimes mandated "green" system is actually less energy efficient, and is probably less water efficient overall, than the standard system it replaced. When these tradeoffs are compared on the basis of overall consumer costs, a consumer would potentially spend 50 – 300% more per year to heat

water using a RECIRC system as compared to a STAND type heater. To verify this important conclusion for one set of actual operating conditions, the outflow volume of the STAND and RECIRC system operated at 60 °C and low use was operated to provide the same amount of useful product (i.e., 10 gallons/day averaging 1.44 kWh/day for STAND versus 4 gallons/day averaging 1.37 kWh for RECIRC). The measured difference in energy costs was 287% higher for the RECIRC system versus the calculated estimate of 306% in Table 2-3.

2.4.5. Point-of-Use DEMAND Water Heaters. Despite achieving nearly 100% energy efficiency the point-of-use DEMAND systems are not always a viable alternative to the STAND system. Specifically, the output temperature is a strong function of the input temperature and flow rate (Figure 2-7). The net result is that there is a limited range of flow rates at which the system will achieve reasonable temperatures of 32 – 43 °C for the delivered water even when no cold water is used. On average, a "reasonable" shower is in the range of slightly below or above average human body temperature (i.e., 37 °C). Not all DEMAND water heaters can meet this minimum temperature. According to the manufacturer specifications for the DEMAND heater used in this experiment, there is a fixed rise in temperature for a given flow rate at the high and low energy settings, respectively (Figure 2-7). Based on these guidelines, in the winter months in Blacksburg, VA where the influent water is below 10 °C, using the high energy setting, a consumer would have to lower the flow rate of the shower to below 1.25 gpm to achieve even a minimum acceptable temperature for showering (note: the minimum temperature defined in this paper is 32 °C which may not be adequate for many users). Over 50% of the continental United States (from as far south as North Carolina and parts of Texas and Arizona) has seasonal low temperatures below 10 °C, which implies that a substantial fraction of homeowners in these states would need to install low-flow fixtures and/or preheat the influent water to utilize typical electric on-demand systems (NOAA 2004) On the low energy setting, there is no flow rate that would provide water hot enough for a

shower, except if the influent water was above 26 °C and a low-flow showerhead with flow rate

below 2 gpm is used (Figure 2-6).

Table 2-3 Net Water Consumption and User Costs for Normalized Energy Efficiency

	60 °C, High Use		49 °C, High Use		60 °C, Low Use		49 °C, Low Use	
	STAND	**RECIRC**	**STAND**	**RECIRC**	**STAND**	**RECIRC**	**STAND**	**RECIRC**
Total Energy (kWh/Day)	8.1	10.5	2.7	5.5	3.2	7.9	2.7	5.5
Normalized Total Energy (kWh/Day)	5.8	10.2	5.7	10.3	1.6	5.1	1.5	4.3
Water Consumed for Energy Production (Gal/Day)[e]	11.6	20.4	11.4	20.6	3.2	10.2	3.0	8.6
Water Wasted at Tap (Gal/Day)[f]	4.5	0	4.5	0	3	0	3	0
Net Water Consumption (Gal/Day)	**16.1**	**20.4**	**9.9**	**11.0**	**6.2**	**10.2**	**6.0**	**8.6**
Annual Consumer Electricity Bill[g]	$233	$410	$229	$414	$64	$205	$60	$173
Additional Costs of Water Due to Waste[h]	$4	$0	$4	$0	$3	$0	$3	$0
Total Cost to Consumer for Water Heating	**$237**	**$410**	**$233**	**$414**	**$67**	**$205**	**$63**	**$173**

[e] 1 kWh energy produced = 2 gal of water consumed at energy production phase
[f] From Figures 4 and 5 given a flow rate = 1.5 gpm
[g] Given Average Electricity Rate: 1 kWh = $0.11
[h] Given Average Water Rate: 1 gal = $0.0025

Furthermore, even the smallest DEMAND system available required 220 V electrical connections,

and we had to install an $200 voltage booster to upgrade our laboratory's 208 V to 230 V enable the

system to heat the water above room temperature during the coldest months. Even with a voltage booster

and running at the highest setting, DEMAND only was able to heat the influent water to about 37 °C and

was lower than the expected manufacturer specs due to a voltage drop when the system is in use (Figure

2-4 and Figure 2-6). Furthermore, this temperature was only achieved by reducing the flow rate to the

lowest possible flow rate of 0.75 gpm. Without the installation of low-flow fixtures at the tap (and even with lower flow fixtures) this flow rate may not be desirable to consumer the coldest winter months and using the low setting, the temperature barely rose above 25 °C (Figure 2-4).
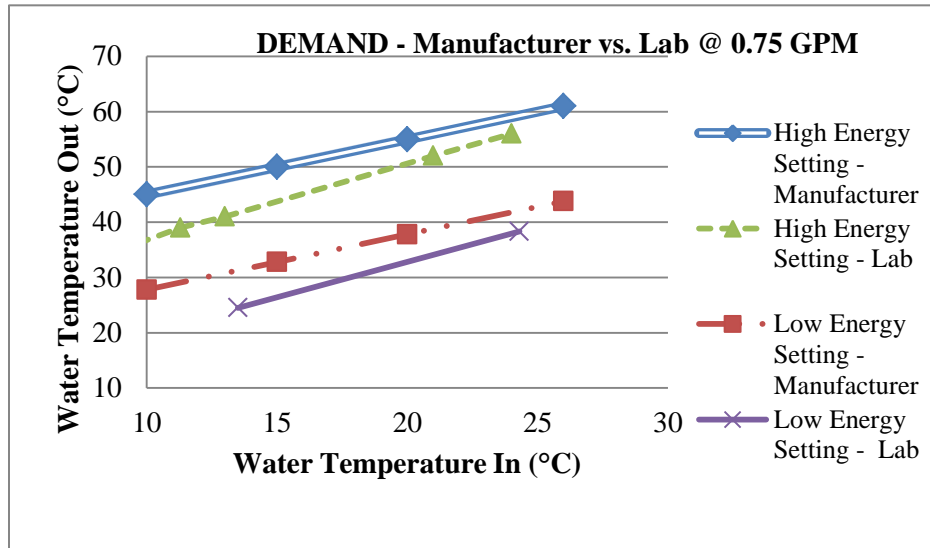
Figure 2-6 Manufacture specs versus laboratory measurements for DEMAND system at 0.75 gpm.
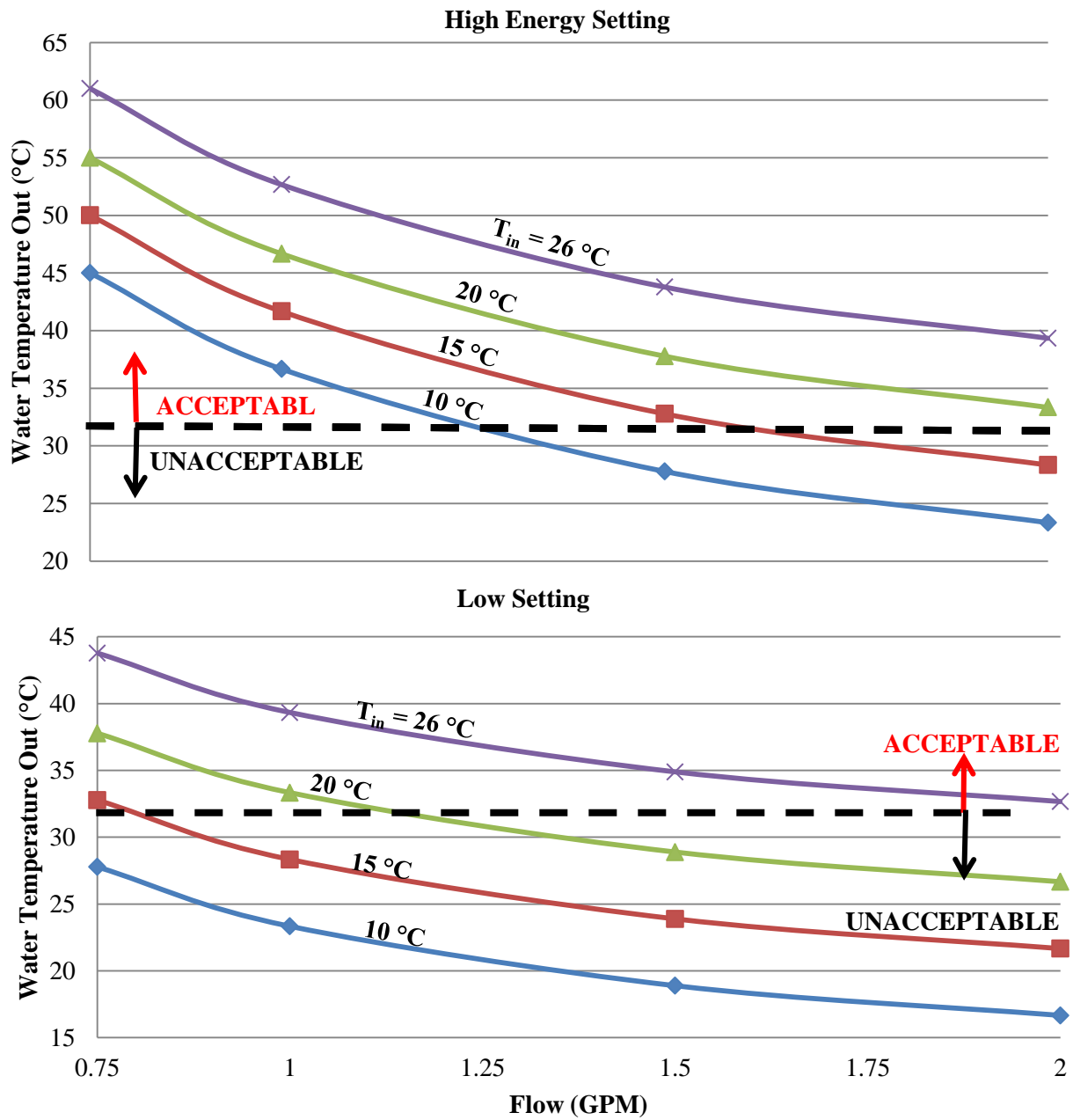
Figure 2-7 Expected output temperatures based on incoming temperature and flow rate from manufacturer specs for the high and low energy settings of the DEMAND system, respectively

2.5. CONCLUSIONS

The results of this research provided numerous insights which run contrary to the conventional wisdom and raise significant concerns as to whether certain "green" water heater installations are actually achieving their targeted objectives. From a temperature and energy perspective, the goal of reducing energy demand seems to be in direct conflict with the outcome. The RECIRC system, although mandated by certain municipalities and marketed "green" by manufacture claims, is in fact more detrimental to conservation aims as compared to other systems. The DEMAND system is in fact the most energy efficient, but has issues such as increased power draw during use and inconsistent and undesirable temperature and flow rate. Although additional research is necessary to better understand water heating in the context of the water-energy nexus, this research provides a first step for rational decision making by regulators, public health officials, manufacturers and consumers.

CHAPTER 3. ROLE OF HOT WATER SYSTEM TYPE/DESIGN ON FACTORS INFLUENTIAL TO PATHOGEN REGROWTH: TEMPERATURE, CHLORINE RESIDUAL, HYDROGEN EVOLUTION AND SEDIMENT

3.1. INTRODUCTION

Successful control of waterborne disease from fecal-derived pathogens has been achieved from source water protection, primary disinfection and removal of particulates before distribution of water to homes (National Research Council (NRC) 2006). Mitigating emerging problems with human pathogens that colonize premise plumbing systems will require new control paradigms, which include an improved understanding of how selection and operation of building water systems can either increase or decrease the risk of pathogen amplification (Centers for Disease Control and Prevention (CDC) 2008b, c, Liu et al. 2006, Pryor et al. 2004). For instance, use of home filtration devices that remove chlorine disinfectants, certain metered faucets and lowering water heater temperatures to < 49 °C (for energy savings and reduce likelihood of scalding) can sometimes encourage pathogen growth, but increasing water heater temperatures to > 60° C may decrease pathogen growth (Berry et al. 2006, Brazeau and Edwards 2011, Centers for Disease Control and Prevention (CDC) 2008c, Mauchline et al. 1992, Moore et al. 2006, Pryor et al. 2004). Two studies found higher incidence of *Legionella* in buildings with hot water recirculation systems or when continuous flow conditions were present -- a potentially worrisome development given that certain municipalities require installation of such systems for water conservation and perceived energy efficiencies (Liu et al. 2006, Pryor et al. 2004).

The concern over public health implications of premise plumbing pathogens is current increasing. The Centers for Disease Control and Prevention (CDC) estimates that between 8,000-18,000 people in the United States are hospitalized each year with Legionnaires' disease due to infection by *Legionella*, *Legionellosis* is responsible for the most cases of waterborne disease and deaths associated with potable water (Centers for Disease Control and Prevention (CDC) 2008c). Other pathogens of concern such as

Acanthamoeba, Mycobacterium avium complex and *Pseudomonas aeruginosa* can also grow within water heating systems and cause thousands of cases of infection annually (Aumeran et al. 2007, Brazeau and Edwards 2011, Centers for Disease Control and Prevention (CDC) 2008b, c, Falkinham et al. 2008, Lyytikainen et al. 2001, Marras et al. 2007, Marras et al. 2005).

This research is aimed at providing fundamental insights into the role of water heater system design and operation, in creation of microclimates suitable for pathogen growth. That is, growth of premise plumbing pathogens can be strongly influenced by temperature, chloramine/chlorine residual, hydrogen availability, dissolved oxygen, chlorine, and sediment-- this is the first study to conduct a head-to-head performance evaluation for representative systems found in buildings (Table 3-1). Results will help formulate rational decision-making relative to the important, yet sometimes synergistic and sometimes antagonistic goals, of water conservation, energy conservation and public health.

3.2. EXPERIMENTAL METHODS.

Three hot water systems were constructed and operated in parallel to facilitate a "head-to-head" comparison of a standard water heating system with storage (STAND) to two so-called "green" water heating systems including: 1) a storage system with a pump and hot water recirculation system (RECIRC) and 2) and on-demand system with no storage and no recirculation line (DEMAND) (Figure 3-1). These systems were designed to operate under four representative consumer use conditions: 1) high temperature (60 °C) and high use (tank completely turns over 3 times daily with 8 hour stagnation in between flushing), 2) high temperature and low use (only ¼ of the tank volume turns over twice daily with 12 hour stagnation), 3) low temperature (49 °C) and high use, and 4) low temperature and low use. The high use was selected to represent a high average use (i.e., 54 gal/person/day) as defined by a comprehensive study of New York homes (Goldner 1994). Given an average family size of 3.14 (United States Census Bureau 2000) and a nominal water heater size of 50 gallons, this equates to a use patter where the tank fully empties at least 3 times. Based on these calculations, high use was defined as a system with complete.

Table 3-1 Overview of Physical Water System Variables for Representative Pathogens.

	Temperature	Total Chloramine Residual	Hydrogen Evolution	Dissolved Oxygen (DO)	Copper	Sediment	References
Issue	Controls volume of system in which pathogen growth and death occurs	Controls many pathogens but can select for others.	Potential nutrient and AOC source	Requirement, but if too high may inhibit growth	In soluble form, may be toxic to pathogens	Provides surface for detachment, biofilms	
Legionella	Ideal Growth Range: 30 - 37 °C\n\nGrowth Impeded: > 46 °C	High chloramine seems to control problem	Unknown Effects	Microaerophile – higher growth rate in lower oxygen environment	Suspected to inhibit growth above 50 ppb; Can increase disinfectant decay rate	Suspected to assist growth	(Berry et al. 2006, Borella et al. 2004, Buse and Ashbolt 2011, Dewailly and Joly 1991, Leoni et al. 2005, Liu et al. 2006, Mauchline et al. 1992, Moore et al. 2006, Pryor et al. 2004, Zacheus and Martikainen 1994)
Mycobacteria Avium Complex (MAC)	Growth Range: 15 - 45 °C\n\nGrowth Impeded: > 53 °C	High chloramine does not control and may increase	Some MAC are Hydrogen Oxidizing	Microaerophile – higher growth rate in lower oxygen environment	Much more resistant to copper than *Legionella*	Suspected to assist growth	(Berry et al. 2006, Falkinham et al. 2001, Gomila et al. 2008, Kirschner et al. 1992, Lin et al. 1998, Momba et al. 2000, Moore et al. 2006, Norton et al. 2004, Pryor et al. 2004)

volume turnover 3-times daily with 8-hour stagnation events between events. Low use represented a situation in which demand was 1/6 of high use with a 25% tank turnover every 12 hours. The high temperature setting is based on the World Health Organization (WHO) recommended operating temperature of 60 °C designed to limit microbial growth (Bartram et al. 2007), while the low temperature setting is based on the United States recommended temperature of 49 °C to conserve energy and minimize scalding potential (especially in children) of typical consumer daily hot water demand. The US EPA currently recommends a hot water system temperature of 49° C whereas Canada, Australia and the WHO recommend 60 °C (Levesque et al. 2004).

The influent water was unaltered Town of Blacksburg water which is a soft water treated with chloramine disinfectant. The influent water was flushed for a period of 15 minutes prior to entering the water systems to eliminate water age in the building as a variable. For QA/QC, the

Figure 3-1 Experimental design. Experimental design of head-to-head water heaters: A-J) sample taps, K) flush/waste line, L) 120 V energy meter, and M) 220 V energy meter. For experiments described in this paper, all copper tube was insulated (Picture to be published in Brazeau and Edwards, 2012)

flushing order of the systems was varied occasionally throughout the experiment with no significant impact on the results presented herein. Additional details regarding operation and energy efficiency during testing are presented elsewhere (Brazeau and Edwards 2012b).

Water quality parameters (i.e., total chlorine, dissolved oxygen, and metal concentrations) were measured in accordance with Standard Methods. Samples were collected (unless otherwise indicated) from the bulk water at the top and bottom of the tanks and the outflow of the DEMAND system (sample taps A, B, E, G and H; Figure 3-1). The test waters were analyzed for metals concentrations using a Thermo Electron X-Series inductively coupled plasma with mass spectrometer (ICP-MS) per Standard Method 3125-B (APHA; AWWA; and WEF (American Public Health Association; American Water Works Association; and Water Environment Federation) 1998). Samples and calibration standards were prepared in a matrix of 2% nitric acid by volume. Total chlorine concentrations were determined via colorimetric methods using a HACH pocket chlorimeter. 500 mL bulk water samples were collected with minimal headspace and tested immediately for dissolved oxygen concentrations using a YSI Model 58 Dissolved Oxygen Meter. Internal tank temperature was measured using a series of wireless data logger temperature probes that were inserted in the tank at various depths and temperature was automatically recorded every 30 minutes (Figure 3-2). Hydrogen was measured using a residual gas analyzer type gas chromatograph. Samples for GC analysis were collected at sample taps C, E and I (Figure 3-1) in glass vials using a 50% air and 50% water volume with an airtight septum for head space sampling immediately after collection. Henry's Law was used to back calculate aqueous total dissolved hydrogen concentrations that were present in water sample.
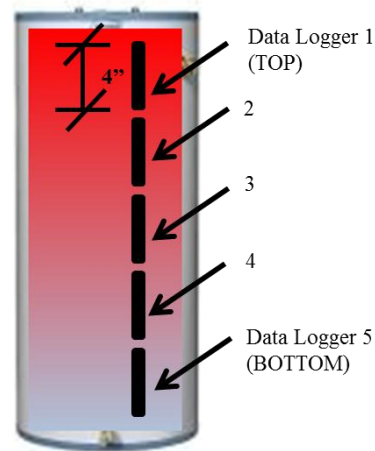
Figure 3-2 Tank data loggers. *To measure the internal temperature of the tanks, data loggers (1-5) were installed that automatically measured temperature every 30 minutes.*

3.3. RESULTS

After describing characteristic temperature profiles of internal tank temperatures within the STAND and RECIRC systems, the impacts of water heater type and operation on disinfectant residual (i.e., total chlorine) is quantified. The impacts of each system on other water quality parameters including DO, metal concentrations, hydrogen and sacrificial anode rod depletion are analyzed, along with some

bench scale testing to identify important mechanisms of chloramine decay. A final section compares performance to the DEMAND systems.

3.3.1. Storage Tank Temperature during Stagnation. The profiles of internal temperature within each tank during stagnation (Figures 3-6) reveals the complexities of controlling pathogens by temperature alone, and the over-simplification of characterizing system temperature using the water heater setting. A weighted average was calculated to compare the relative volume of each tank below identified temperature thresholds (Table 3-2). For example, in the case of 60 °C low use, to calculate the percentage volume at risk due to temperatures below 46 °C, it was estimated that 8 gallons of water was below 46 °C for 1.25 hours and 4 gallons were below the trigger temperature for 6 hours during each 12 hour cycle (Figure 3-3). This translates to a weighted average of 2.8 gallons per day below the threshold of 46 °C, which in a 20 gallon tank is equal to 14% of the tank per day (i.e.,

$$\frac{(8\ gallons*1.25\ hour+4\ gallons*6\ hours)}{24\frac{hour}{day}} * \frac{2\ turnovers}{day} = 2.8\ total\frac{gallons}{day}; \frac{2.8\ gallons*100}{20\ gallons} * 100 = 14\%).$$

The same calculation was repeated for all conditions at 46 °C and 37 °C (Table 3-2).

In both the high use and low use conditions, due to constant mixing, the RECIRC system had a relative consistent, high temperature throughout the entire volume of the storage tank. Temperature recovery from high water demand events was essentially complete within 45 minutes throughout the entire volume of the tank. In contrast, due to stratification, a consistent temperature profile with depth was never achieved in the STAND system, especially under high use conditions, over the 8 hours of testing. The DEMAND system has minimal storage volume (~0.03 gallons) which during no-flow events cools to ambient. There is evidence to suggest that 46 - 53 °C may be the upper range of growth for key pathogens such as Legionella and MAC, respectively with upwards of 60 °C needed to kill the bacteria and the ideal growth range being somewhere below 37 °C (Table 3-1).

Applying a threshold of 46 °C as a temperature cutoff that would allow *Legionella* amplification (Table 3-1), a target EPA-recommended temperature setting of 49 °C results in large volumes of water suitable for pathogen growth under the two different operating regimes. (Table 3-2, Figures 3-4 and 3-6). In fact, as compared to the STAND system, the RECIRC system had nearly 30% more storage volume below 46 °C in the high use condition and 130% more in the low use condition. From this perspective, the STAND system would seem to be more conducive to *Legionella* inactivation. However when considering the volume of water in the ideal growth range using a 37 °C criteria, the RECIRC system has very little suitable volume (2.5% in high and 0% in low use) whereas the STAND system has up to 25 times greater volume (62% in high and 13% in low use). Ultimately, a much better understanding of microbial ecology, pathogen growth and inactivation rates would be needed to determine which of these systems would be more conducive to pathogen problems. Clearly, the two systems are very different in terms of water volumes in the temperature ranges causing growth and inactivation.

Using a temperature setting of 60 °C yields dramatic improvements for both systems (Table 3-2, Figures 3-3 and 3-5); however, even in the best case scenario of high temperature and low use, 14% of the STAND volume still remains below the critical temperature required for inactivation over a 24 hour period (Figure 3-5). At 60 °C the RECIRC system outperforms the STAND system, in terms of minimizing water volume below 37 °C and maximizing water volume above 46 °C. At low use the entire volume of the RECIRC tank is above 46 °C while only 86% of the STAND tank is above this mark. For high use both tanks have volume below 46 °C during the 24-hour period, but there is still 40% less volume below 45° C in RECIRC than in the STAND tank (Table 3-2). Hence, if temperature alone is considered, a RECIRC system would appear to be the better choice for pathogen control at 60° C from the perspective of temperature alone.
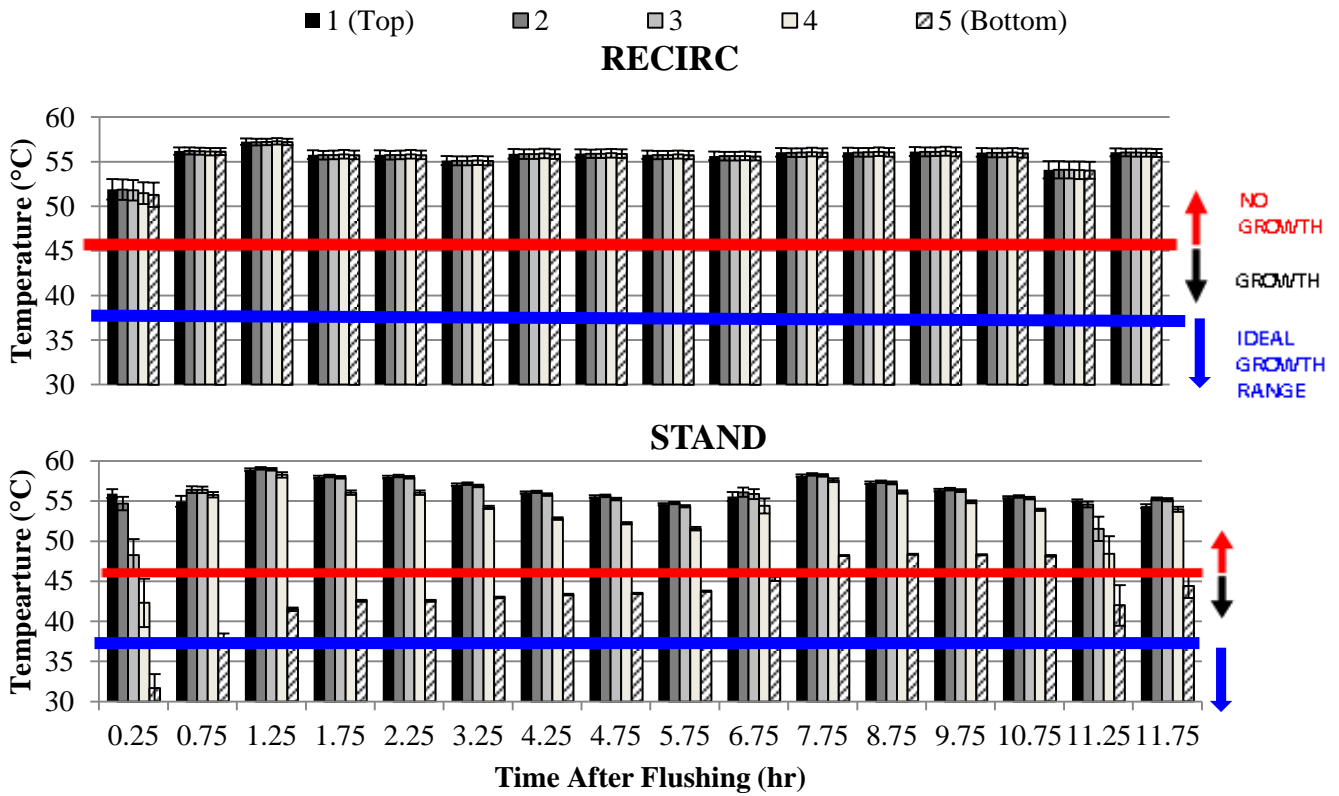
Figure 3-3 Internal tank temperature with depth for RECIRC and STAND systems at 60 °C and low volume use.
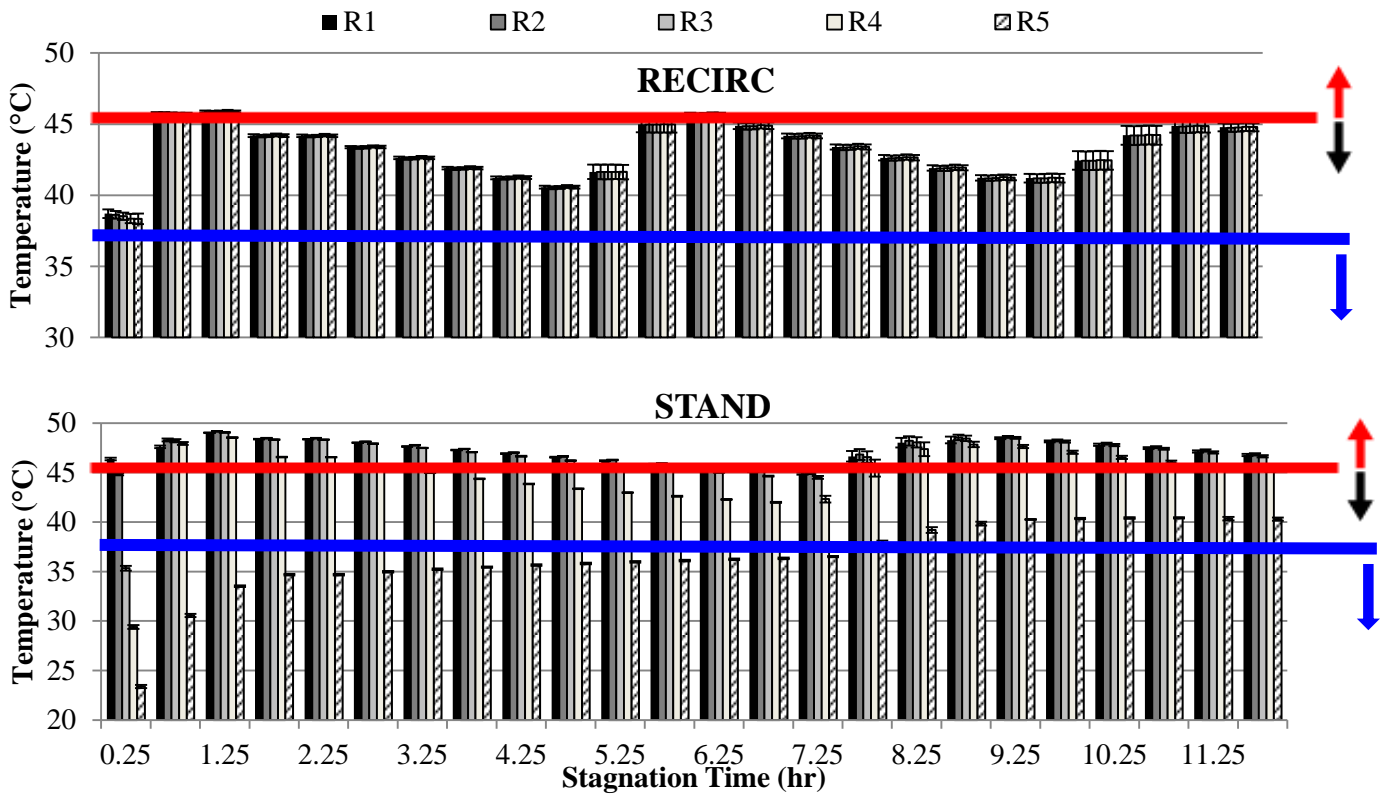
Figure 3-4 Internal tank temperature with depth for RECIRC and STAND systems at 49 °C and low user pattern.
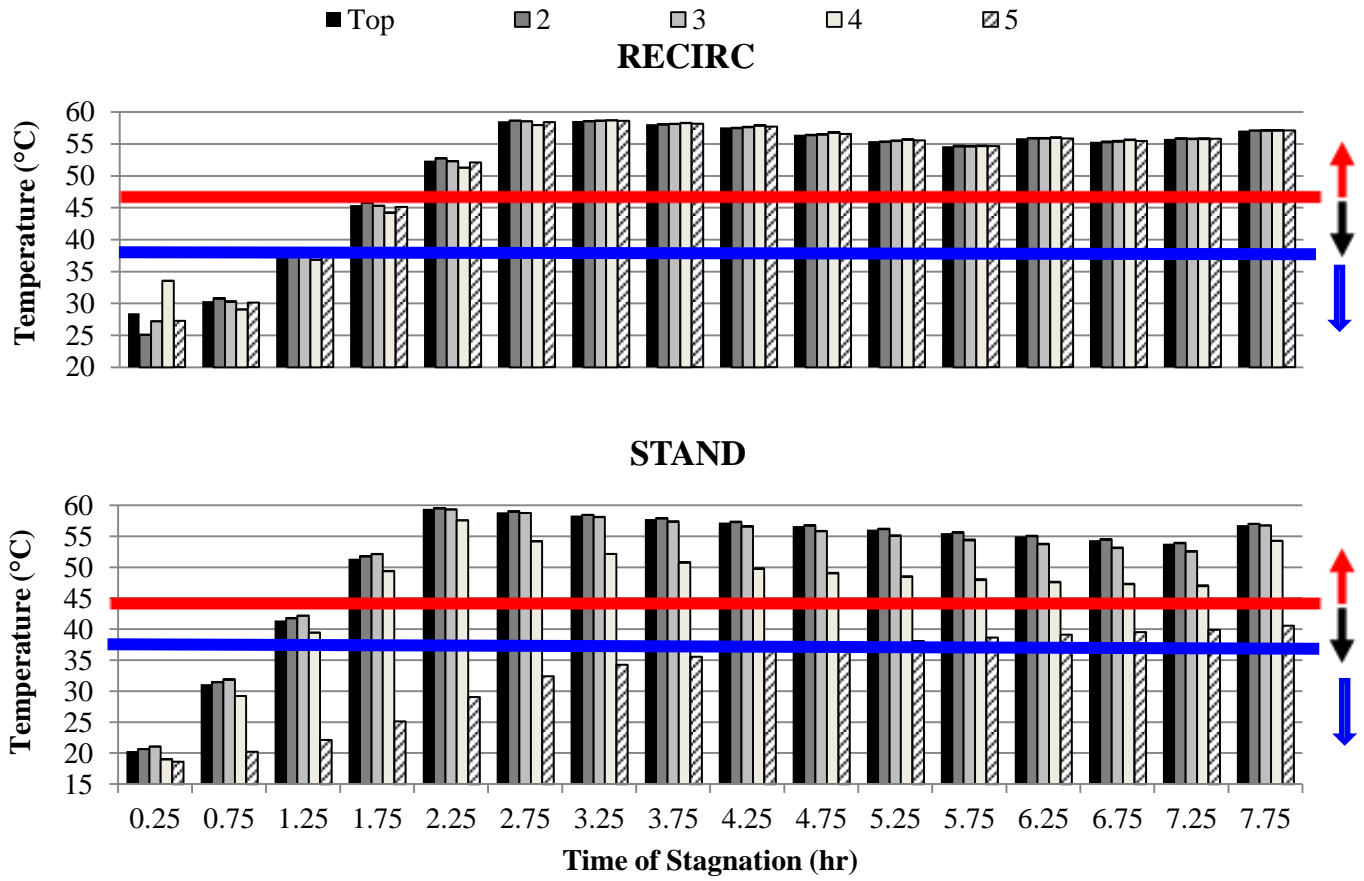
Figure 3-5 Internal tank temperature for RECIRC and STAND systems at 60 °C and high user pattern
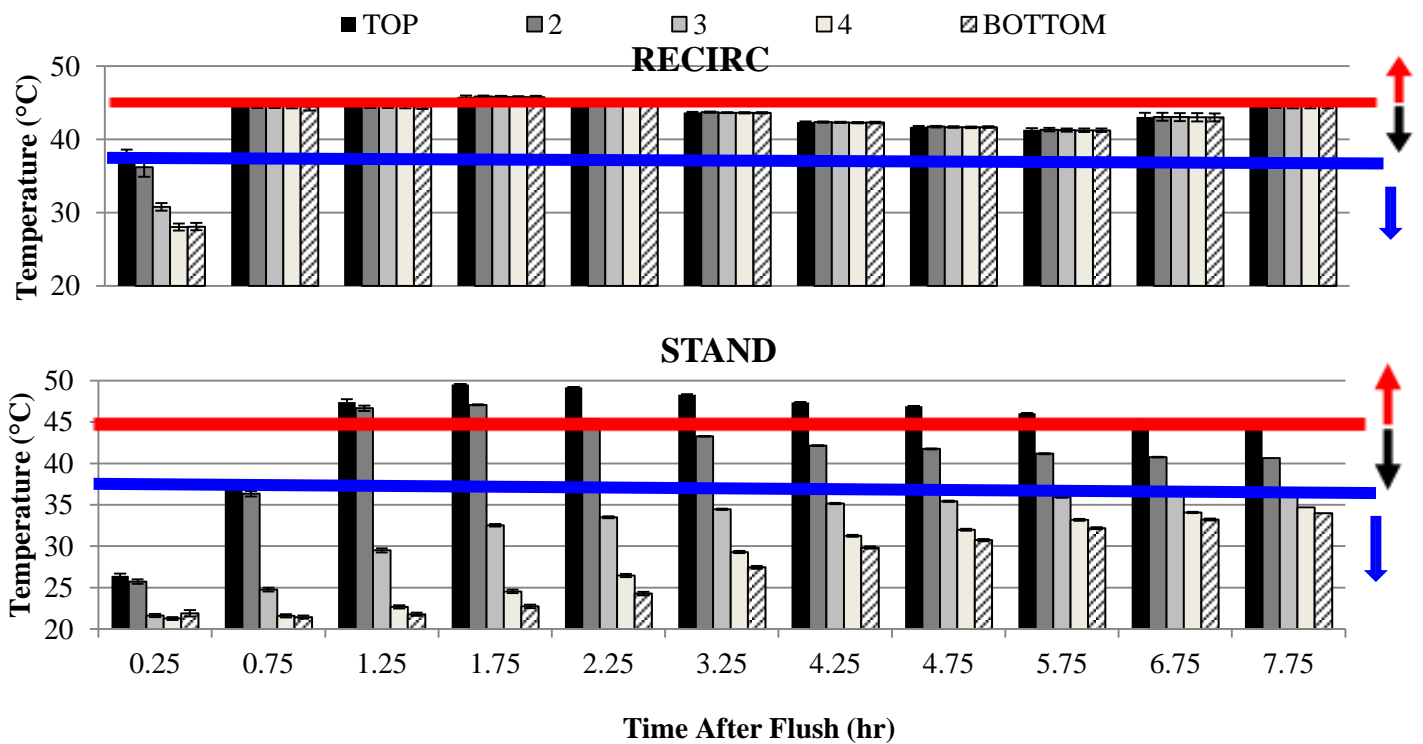
Figure 3-6 Internal tank temperature for RECIRC and STAND systems at 49 °C and high user pattern.

Table 3-2 Average Percent of Tank Volume below Key Temperatures during a 24-hour period under the Various Test Conditions.

Water Heater Type	Storage Volume (Tank) Below 46 °C Per Day High Use (% Tank)		Storage Volume (Tank) Below 46 °C Per Day Low Use (% Tank)		Storage Volume (Tank) Below 37 °C Per Day High Use (% Tank)		Storage Volume (Tank) Below 37 °C Per Day Low Use (% Tank)	
Tank setting	**60 °C**	**49 °C**	**60 °C**	**49 °C**	**60 °C**	**49 °C**	**60 °C**	**49 °C**
STAND	31	78	14	38	21	62	0.13	13
RECIRC	22	100	0	88	16	2.5	0	0

3.3.2. Water quality parameters: oxygen, sediment, metals, and hydrogen. In addition to temperature, other water quality parameters were measured including dissolved oxygen (DO) (Figure 3-7), soluble and total metal concentrations, and hydrogen gas in the bulk water (Figure 3-8; Table 3-4). The pH of the water was monitored throughout the experiment and remained fairly consistent in the 7.7 – 8.0 range. Typical influent values over the duration of the study were recorded (Table 3-3) and were generally very similar to values observed in the demand system which had no storage or anode rod (Table 3-4).

Table 3-3 Influent Water Parameters (Town of Blacksburg Water)

Season	Temperature °C	pH	DO (mg/L)	H_2 (ppb)	Al (ppb)	Cu (ppb)	Total Cl (mg/L)
Summer	26	7.4	10.7	1500	45	15	2.50
Winter	13	7.4	12.5	2750	25	6.5	2.40

With respect to DO, the RECIRC system and the top of the STAND system were similar with medians between 4.9 – 5.5 mg/L (Figure 3-7 and Table 3-4). The RECIRC system also showed the most

homogeneity with the lowest measured DO (4.9 mg/L) at both the top and bottom of the tank. The STAND system, however, showed heterogeneity with the top of the tank at 5.5 mg/L DO and 8.1 mg/L at the bottom of the tank where the temperatures were cooler. The DEMAND system had the highest level of DO with a median twice that of the higher temperature STAND and RECIRC systems (Table 3-3).

Both the STAND and the RECIRC system had suspended sediment in the bulk water, and it was visually obvious that the RECIRC system had more turbidity in the bulk samples compared to the STAND system. Samples were acidified to dissolve the suspended sediment and analyzed on ICP-Mass Spec. Samples were also filtered to determine the contribution of particulate versus dissolved concentrations.
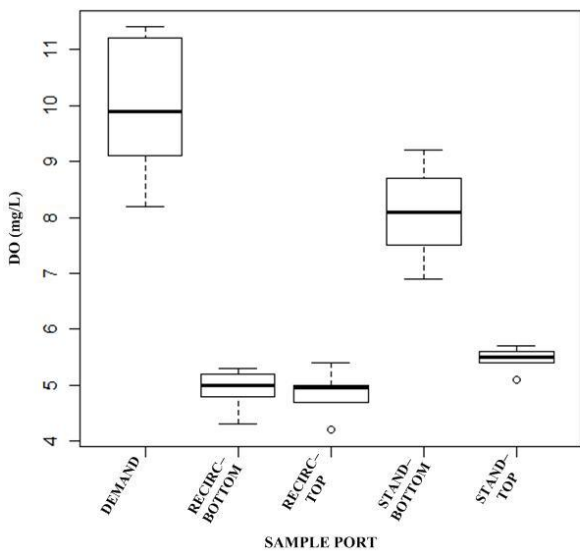
Figure 3-7 Dissolved Oxygen (DO) concentrations at various sample ports (Figure 1) in the bulk water of the systems taken at 60 °C and high use.

In the RECIRC system, between 8-23% of the total metal concentration was dissolved, these was 2 – 3 times higher aluminum and 2 – 4.5 times more copper particulates than in the standard system. It has been suggested that copper levels above about 100 pbb may inhibit pathogen growth, and in this study total copper was much higher than these levels but soluble copper was much lower (Lin et al. 1998, Zacheus and Martikainen 1994, Zhang et al. 2009). Future research needs to distinguish which forms of copper may control pathogens, since the active form of metal has been identified as soluble Cu^{+2} in prior research for microbes such as nitrifiers (e.g., Zhang et al., 2009). There was no clear trend in soluble copper levels with higher temperature, although total copper was much higher at 60° C than at 49 °C (Table 3-4).

The primary source of aluminum in the water was the sacrificial anode rode (Table 3-3), and consistent with expectations based on measurements in Figure 8, at the end of the experiment the

RECIRC anode rod was much more corroded as evidenced by higher weight loss (Table 3-4). Over the 19 month duration of this experiment, 24% of the RECIRC anode disappeared versus 13% of the STAND anode, raising the possibility that a water heater would have a shorter service life if used in a recirculation mode if the anode is not changed more frequently. Moreover, since anode rod corrosion can cause hydrogen evolution, it was not surprising that the RECIRC system had 4 – 6 times higher ambient H_2 than the STAND system (Table 3-4). Aside from rare cases in which H_2 evolved from potable water heating systems led to series explosions, higher levels of H2 might fuel microbial regrowth (WSOCTV 2007).

Table 3-4 Quantitative results for water quality parameters.

Water Heater Type	DO (mg/L)[1]		Al (ppb)[2] (Total)		Al (ppb)[2] (Soluble)		Cu (ppb)[2]		Cu (ppb)[2] (Soluble)		H_2 (ppm)		Anode Rod
Temperature, Use, or Location	Top of Tank	Bottom of Tank	60 °C	49 °C	60 °C	49 °C	60 °C	49 °C	60 °C	49 °C	High Use	Low Use	Weight Loss (%)
STAND	5.5	8.1	1034	126	36	80	130	24	14	12	210	580	13%
RECIRC	4.9	4.9	3467	2676	174	294	751	310	32	56	1240	2360	24%
DEMAND[3]	N/A	10	20	38	18	38	170	20	62	12	80	0.7	N/A

[1]**DEMAND dissolved oxygen (DO) data taken from just below heating system**
[2]**Value represents an average of the concentration in the top and bottom of the tank (Figure 3-1)**
[3]**For DEMAND system: 60 °C = High Setting; 49 °C = Low Setting**
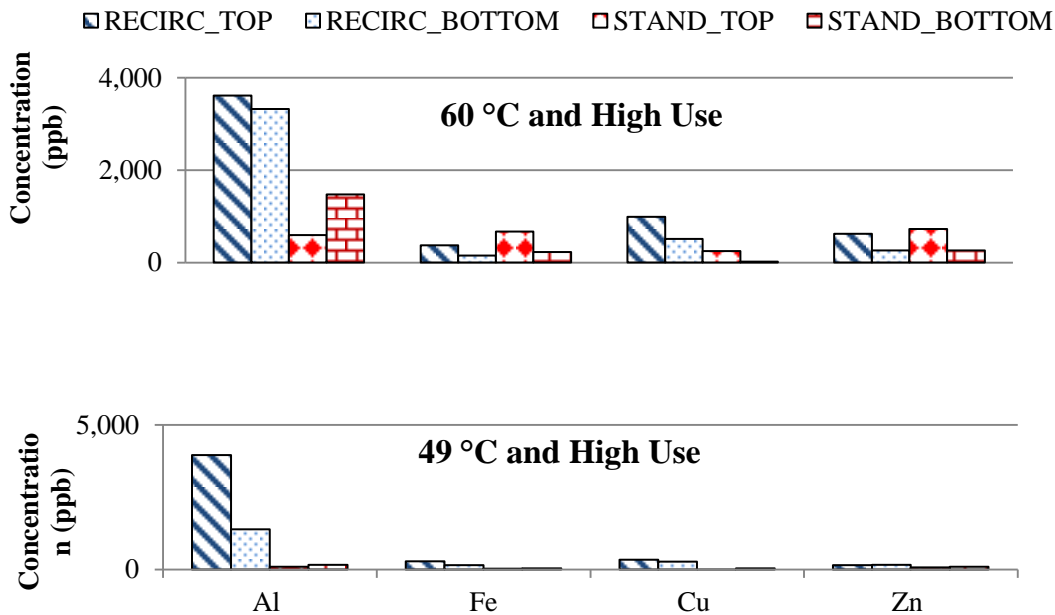
Figure 3-8 Total metal concentrations in bulk water samples for the RECIRC and STAND systems.

3.3.3. Disinfectant Residual. Low disinfectant residuals in water systems have been linked to higher incidence of Legionella and lower incidence of MAC (Falkinham et al. 2001, Moore et al. 2006, Pryor et al. 2004). To monitor total chlorine levels in the water heating systems, samples were taken from the top and bottom of the storage tanks during stagnation and at the tap during flushing. Each hot water configuration and operating condition differed markedly in profiles of chlorine residual during operation. In all conditions, the total chlorine residual was 1.5 – 10 times higher in the STAND system as compared to the RECIRC system (Figure 3-9 and Table 3-5). Since each tank received identical inputs of total chlorine, it is clear that there is much more chlorine decay in the RECIRC than in the STAND system.
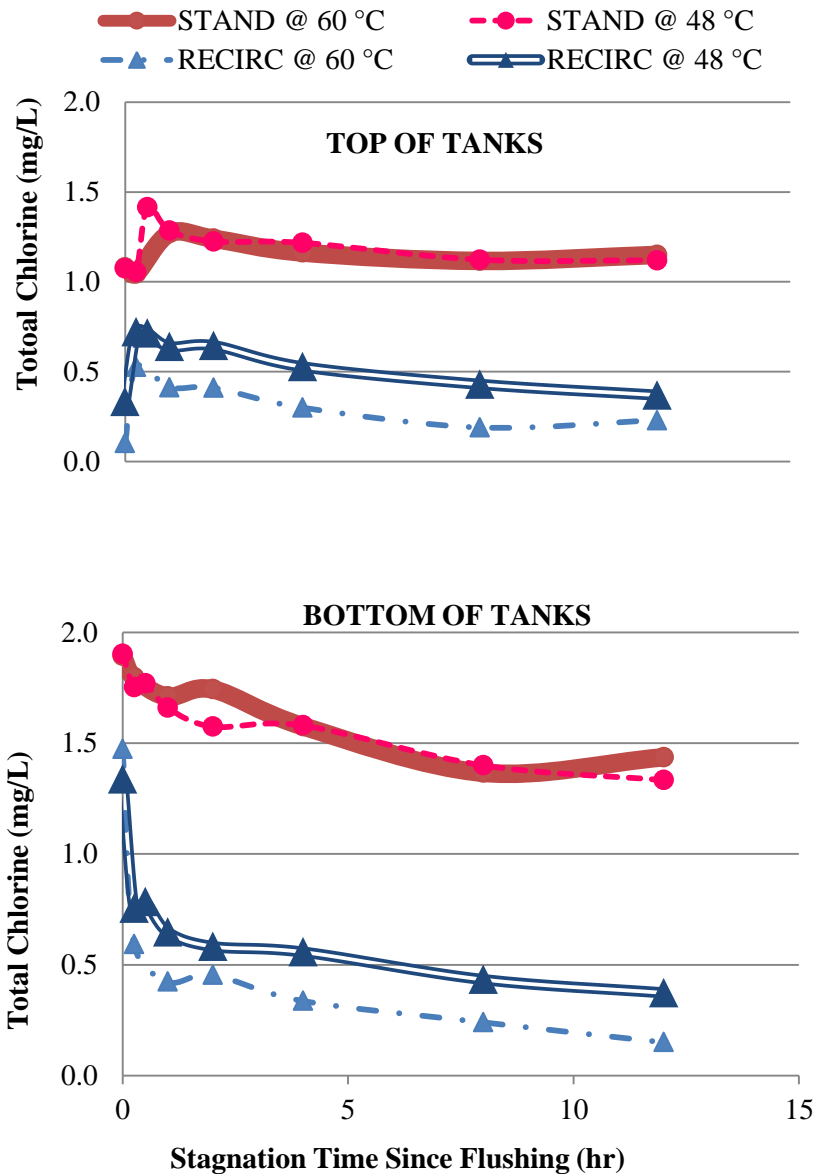
Figure 3-9 Total chlorine decay during stagnation for the low use conditions

Table 3-5 Chlorine Residual after Stagnation

Water Heater Type	Disinfectant Residual After 8 hour Stagnation High Use – Top of Tank (mg/L)		Disinfectant Residual After 8 hour Stagnation High Use – Bottom of Tank (mg/L)		Disinfectant Residual After 12 hour Stagnation Low Use – Top of Tank (mg/L)		Disinfectant Residual After 12 hour Stagnation Low Use – Bottom of Tank (mg/L)	
	60 °C	49 °C	60 °C	49 °C	60 °C	49 °C	60 °C	49 °C
STAND	1.42	2.09	1.69	2.21	1.15	1.12	1.44	1.33
RECIRC	0.55	1.45	0.47	1.40	0.23	0.37	0.15	0.37

3.3.4. Bench-Top Chlorine Decay Tests. There were many potential factors that could increase the chlorine decay rate in the RECIRC system including higher overall temperatures and continuous contact of water with metals (i.e., aluminum sediment, copper pipes, anode, tank wall, etc.). To help quantify the amount of decay due to these factors, a series of bench top studies were conducted.
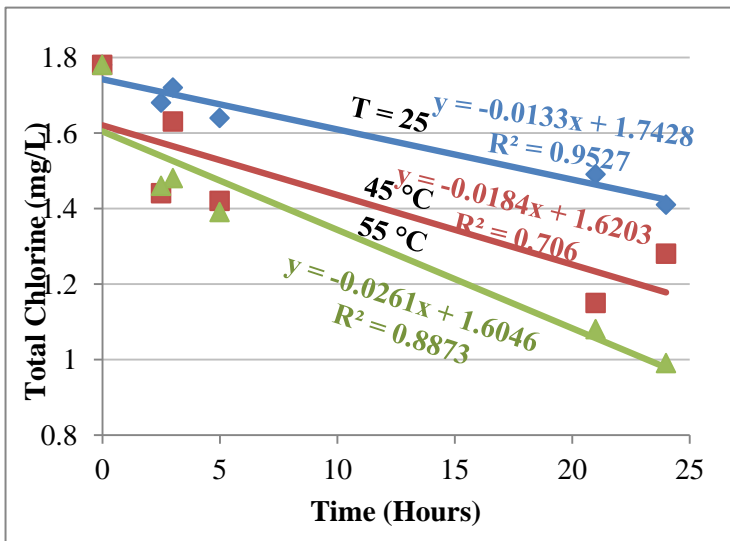
Figure 3-10 Bench-top experiment results determining chlorine decay at various temperatures.

First, since it deemed possible that the higher overall temperatures in the recirculation tank could cause more rapid chlorine decay, Town of Blacksburg tap water was put into glass containers at target temperatures and chlorine was monitored for 24 hours. Glass was chosen since it is highly inert and was considered representative of ceramic glass hot water tank liners. The results of the temperature decay test (Figure 3-10) indicated that chloramine at 55°C disappeared 1.5 and 2 times faster than at 45° and 25° C, respectively. The lower temperatures in

the standard vs. recirculation tank are therefore consistent with the expected trend in total chlorine, but calculations indicate that it could only account for up to 20% of the observed difference. This prompted additional testing to identify other sources of chloramine demand including reactions with sediment, aluminum anode rod, and copper pipe.

To test the role of sediment, samples of bulk water from the bottom of the tanks where turbidity was observed to be the highest were collected and solids were sampled and centrifuged. The solids collected were dissolved in tap water and placed in a 55 °C water bath. Over time, the chlorine was measured and it was determined that the sediment did not affect the rate of chlorine decay as compared to the control sample without any sediment added. Similar testing using a piece of aluminum anode rod selected to achieve the same surface area (SA):volume ratio present in the water heater also illustrated no significant chloramine demand versus a control.

The final test attempted to examine the implications of continuous water flow through the 9 meters of 3/4" copper tubing in the recirculation line (Figure 3-1). Glass beaker testing was conducted with new copper pipe at a copper SA:water volume identical to that present in the
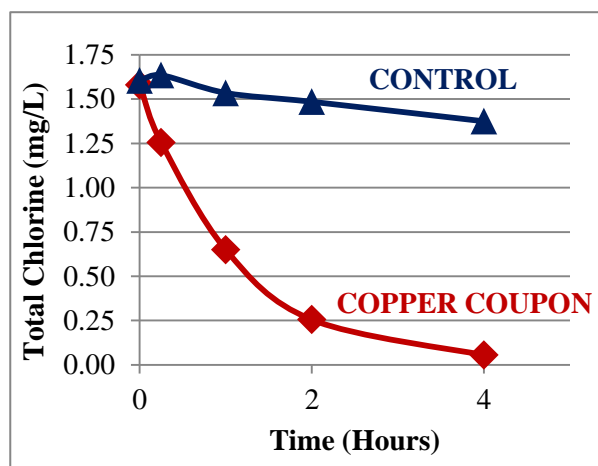
Figure 3-11 Bench-top experiment results determining chlorine decay when mixed with a copper coupon.

RECIRC system at 55 °C, while stirring with a magnetic stir rod at a moderate rate to ensure complete mixing of the reactor. In 4 hours, the sample with the new copper coupon had undetectable chlorine, whereas the control without copper only decayed slightly (Figure 3-11). Nguyen et al. observed this mechanism for chloramine decay in cold water, and determined that new copper showed a chlorine decay rate much higher than older copper (Nguyen et al. 2012). Thus, the aged copper is probably why some chloramine residual was present in the pilot test apparatus versus the undetectable chlorine after a few hours in the bench test with new copper.

3.4. DISCUSSION: IMPLICATONS FOR PATHOGEN CONTROL

There are numerous important implications of this research for forensic evaluations of opportunistic premise plumbing pathogen growth in field and laboratory rigs, projected comparisons of water heater system performance relative to microbial growth, and for considering interventions that might be used to control pathogens in buildings/hospitals. At present, the data is insufficient to draw definitive conclusions, but it is nonetheless useful to highlight the likelihood that there would sometimes be profound differences between pathogen growth in STAND versus RECIRC and DEMAND systems. Given variations expected with water chemistry and operation conditions, the differences between STAND and RECIRC do not always unambiguously favor one system or another in terms of pathogen regrowth. Discussion below is framed in terms of draft proposed ASHRAE standards for Legionella control through: 1) temperature control (> 60 °C) and 2) maintaining a disinfectant residual (> 0.5 mg/L Cl) (ASHRAE 2011). The possibility of trying to use partial approaches of each, using EPA standard temperature settings of 49 °C and secondary disinfectant residual from the treatment plant is also considered.

3.4.1. DEMAND Systems and Pathogen Control. Since the DEMAND system has nearly no storage volume and has negligible disinfectant decay, it has major advantages relative to STAND or RECIRC systems. But for the device tested, in winter the DEMAND system never heated the water above the 25 – 30 °C (Brazeau and Edwards 2012b) threshold necessary for consumer comfort, much less thresholds necessary for thermal disinfection of pathogens (> 70 °C) which were never achieved anywhere in the system. To address the comfort issue consumers have been instructed by manufacturers to purchase a STAND system to preheat the water, in which case the temperature setting of that tank preheater is likely to be important. In sum, given that the electric DEMAND systems could not supply hot water in quantity sufficient for consumers, it is not clear if the obvious benefits of such systems in terms of public health would be realized.

3.4.2. STAND vs. RECIRC Systems. In the subsequent sections, the effects of the various metrics measured in this study will be discussed with respect to pathogen growth and mitigation in the STAND system as compared to RECIRC.

3.4.2.a. ASHRAE Temperature Standards for Pathogen Control vs. Standard EPA Temperature Recommendations. The new ASHRAE draft standards propose a minimum outflow temperature of 60 °C from the water heater as well as maintaining 51 °C through the entire tank and pipe infrastructure. This is very different from the current EPA recommended tank temperature setting of 49 °C for increased energy efficiency and controlling scalding potential. From the perspective of a temperature set point of 60° C and maintain high temperatures throughout the hot water system, the conventional wisdom that RECIRC systems would be expected to have a lesser likelihood for pathogens such as L. Pneumophila than stratified tank electric water heaters was validated in this work (Lacroix 1999). But if temperature settings are at or below 49 °C, the opposite trend seems to be true, since STAND had somewhat less volume susceptible to regrowth than RECIRC.

3.4.2.b. **Flow Characteristics.** Without the installation of a check valve on the RECIRC system, water actually short circuited the tank during flushing causing a reversal of flow in the return line that can might cause problematic shearing of biofilm from pipes (Brazeau and Edwards 2012b).

There is also uncertainty as to whether continuous flow conditions actually inhibit or support pathogen growth. For example continuous flow transports nutrients directly to the biofilm along the pipe walls, but would also increase transport of disinfectant to the biofilms. A recent study also demonstrated that under some conditions, continuous flow conditions increased biofilm formation and Legionella growth (Liu et al. 2006). Overall, the direct effects of flow on pathogen control require additional study.

3.4.2.c. Water Quality Parameters Potentially Influential in Pathogen Growth. There are a host of water quality parameters that could influence pathogen growth positively or negatively.

Increased levels of metals could act as a nutrient source or toxin for bacteria (Table 3-1). The extent to which soluble metals such as Cu^{+2} are toxic to pathogens needs to be explored more fully, along with possible differences in soluble and total metal concentrations in STAND and RECIRC systems, given that temperature varied slightly and total metal concentrations varied markedly (Table 3-2). DO has also been implicated as an important factor in bacteria growth, in that both Legionella and MAC have been described as a microaerophile suggesting that the lower levels of DO found in the entire storage volume of the RECIRC tank may be more supportive of growth (Tables 3-1 and 3-6, Figure 3-7).

Recently, there has been discussion of controlling pathogens by removing AOC at the treatment plant and limiting the potential for microbial growth. While it is known that humic substances and organic carbon are essential for heterotrophic bacteria to grow (Camper 2004), unfortunately there are a variety of mechanisms by which AOC can be created in premise plumbing. For example, it has been suggested by Morton, et al. that carbon can actually generate in water heaters from hydrogen evolution due to decay of the anode rods at a rate of 0.2 mg C/mg H_2 and other work has demonstrated that sorption of humic substances to rust sediment might increase fractions of bioavailable carbon (Butterfield et al. 2002, Lieberman et al. 2011, Morton et al. 2005). The RECIRC system had more corrosion of the anode rod and also much higher concentrations (4-6 times) of H_2 in the tank (Table 3-3), which could ultimately lead to more AOC generation or available nutrients within the RECIRC system as compared to the STAND system (Table 3-6), since certain species of MAC may be able to utilize H_2 directly as a nutrient source leading to potential increased pathogen growth from anode decay products directly (Gomila et al. 2008). However, once the anode rod disappears, AOC generation from anode decay would cease, and this would occur more quickly in the RECIRC tank. Thus, while the RECIRC may have more hydrogen in the short term, the STAND system has potential to produce hydrogen over longer period of the tank life.

Table 3-6 Summary of Key Differences between Physical Parameters which may Influence Pathogen Propagation.

SYSTEM	Temperature	Total Chloramine Residual	Hydrogen, Sediment	DO	Total Copper	Flow Reversal, Mass Transport to Biofilm
STAND	**Tank:** Stratifies; Bottom as much as 25 °C cooler than top **Pipes:** Cool to ambient (25 °C)	Up to 860% higher than RECIRC in bulk water	H$_2$ lower than RECIRC	Overall higher than RECIRC	5.5 – 13 times lower than RECIRC	None, Low transport
RECIRC	**Tank:** Homogenous **Pipes:** Heated to tank temperature	Improved delivery of disinfectant to biofilm	Circulation delivers H$_2$ directly to pipe biofilm	Lower DO leads to increased growth of microaerophile	310 - 750 ppb	Flow reversal in pipes, high transport
DEMAND	**Tank:** N/A **Pipes:** Cool to ambient (25 °C)	Virtually no decay from distribution system levels	Extremely low H$_2$; No sediment accumulation	Highest levels of DO	Similar to STAND	None

3.4.2.d. **Pathogen Growth Potential for 3 Proposed Conditions Derived from ASHRAE Standard and EPA recommendations**. To examine the implications of these controls with respects to the water heaters systems, three different scenarios are considered: 1) using temperature alone as the control strategy, 2) relying on secondary treatment disinfectant residuals from the water treatment plants at "energy efficient" temperatures (i.e., 49 °C), and 3) applying disinfectants in buildings while using "energy efficient" temperatures (i.e., 49 °C).

3.4.2.d.1 Condition 1: Temperature as a Control. In the case of 60 °C temperature control, the RECIRC system is favored (Table 3-2) given that no storage volume (pipes included) is below 46 °C. The requirement that no area in the system (pipes and tank) can be below 51 °C likely means that RECIRC systems are required without any significant branching,

since in the STAND system a portion of the storage volume is always below the set temperature due to pipe cooling and stratification. It is unclear how it would be possible to maintain branches of recirculation lines above 51 °C. Moreover, since Legionella grow better in temperatures above ambient room temperature (i.e., increased growth was observed by Buse and Ashbolt in the 30 – 37 °C range as compared to 24 °C), the recirculation of warm water through the main pipes may cause dead-end lines with low disinfectant residual to be warmed to some temperature above 25 °C and below 45 °C (Buse and Ashbolt 2011). At these dead-end sections, there is tremendous potential for pathogen growth and thus, recirculation in this instance may be detrimental to the goals of pathogen mitigation.

3.4.2.d.2 Disinfectant Residual from Secondary Treatment at Water Treatment Plant. Due to increased contact with copper pipes and higher temperatures (Figures 3-10 and 3-11) the RECIRC system had much less disinfectant residual throughout the system volume compared to the STAND (Table 3-5) and was frequently well below 0.5 ppm total chlorine. If the biofilm was nutrient limited, greater rates of mass transport in RECIRC systems might also be expected to enhance microbial growth from AOC, H_2, and nutrient transport to the biofilm. On the other hand, even though the bulk water has a much lower residual, the biofilm along the pipe wall might be better controlled by enhanced and continuous delivery of the low level disinfectant in the RECIRC system (Table 3-6). Overall, relative performance of STAND vs. RECIRC is likely to be a function of actual differences in chlorine residual in a given water system, trophic status (i.e., nutrient levels) in the hot water system, effectiveness of low level disinfection at continuous flow, and types of plumbing materials present. Further study on the effect of chlorine decay with recirculation through PEX and copper pipes, and detailed biofilm studies, is needed to better understand these tradeoffs.

3.4.2.d.3 On-site Disinfection. If high enough levels of disinfectant were maintained to outweigh detriments of water volumes at lower temperatures, the RECIRC system would appear to have the edge on the STAND system.   Furthermore, as discussed previously, there is some evidence to suggest that flow through pipes that delivers nutrients to the biofilm source may in fact lead to increased pathogen growth (Liu et al. 2006). From these perspectives the STAND system may be better at controlling pathogen growth. On the other hand, if copper pipe is present, higher levels of total copper may be in the water, which might control pathogens to some extent. The soluble copper levels were 2-3 times higher in RECIRC vs. STAND systems, and in some situations such as lower pH the levels might rise above the 100 ppb level needed to assist in control of biofilms.

3.5. CONCLUSIONS

In a controlled head to head study in a system with copper plumbing, hot water recirculation caused much lower levels of disinfectant residual. The standard systems without hot water recirculation had 40 -850% higher concentrations of total chlorine in the tank. There was no instance when the bulk water in the standard tank dropped below a disinfectant residual of 1 mg/L, whereas levels below 0.5 mg/L were not uncommon in the recirculating system. Systems with hot water recirculation also had 4-6 times higher hydrogen and 3-20 times more suspended metal hydroxide sediment compared to standard tanks without recirculation. On demand tankless systems had very small volumes (~0.03 gallons) of water at risk and relatively high levels of disinfection. When run at a temperature of 49 °C the water volume at risk for *Legionella* growth was up to 130% higher for recirculating tanks vs. standard tanks, but run at a temperature of 60 °C the volume of water at risk in the recirculation system was 0% as compared to 14% in the standard tank.

CHAPTER 4. OPTIMIZATION OF ELECTRIC HOT WATER RECIRCULATION SYSTEMS FOR COMFORT, ENERGY AND PUBLIC HEALTH

4.1. INTRODUCTION

Potable hot water systems in buildings are a critical part of the water-energy nexus, as water heaters account for the single largest water-related energy consumption in the United States (Brazeau and Edwards 2011). More recently, hot water recirculation systems have become more common in large single family homes, multi-family structures, hotels and large commercial buildings. These systems are marketed as water-saving, energy efficient, and are mandated in certain municipalities (Ally and Tomlinson 2002, Brazeau and Edwards 2011, Marina Coast Water District (MCWD) 2007). However, a recent head-to-head comparison has demonstrated that these systems actually use more net energy and water than traditional standard water heaters without recirculation. (Brazeau and Edwards 2012b) There is also emerging concern that recirculation systems will sometimes increase the occurrence of *Legionella* (Brazeau and Edwards 2012a, Moore et al. 2006).

This research follows up on work by Brazeau and Edwards (Brazeau and Edwards 2012a, b) which identified several problems associated with continuously operated recirculation systems including reduced energy efficiency, reduced consumer comfort (i.e., temperature of produced water) and reduced levels of disinfectant (Table 4-1) It was considered likely that some of these
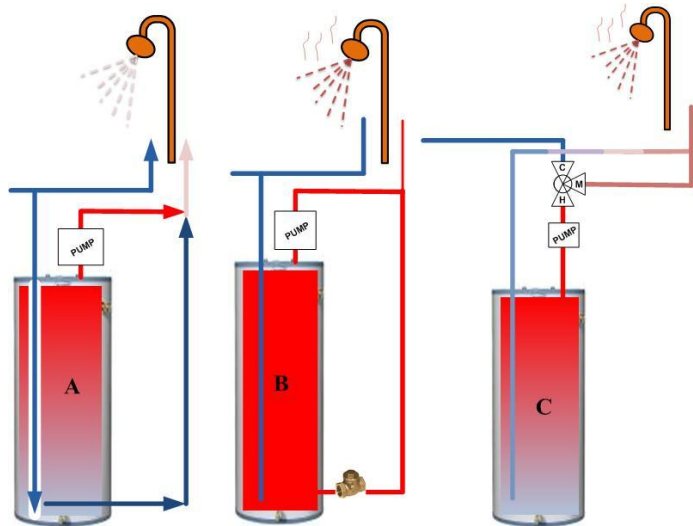
Figure 4-1 Various hot water recirculation (RECIRC) systems. *A) Dedicated recirculation line with no check valve installed at pipe return, B) Dedicated recirculation line with installation of a check valve, and C)Retro-fit: recirculation line tied into existing cold water line with mixing valve at outlet of storage tank (not tested in this study).*

concerns could be reduced by operating the pump only for short time periods by the following approaches: 1) turning on the recirculation pump only for a short period with a timer, 2) use of a temperature sensor to turn on the pump when pipes cool below a set point, 3) combination of #1 and #2, or 4) a switch that turns on the pump just before hot water is needed (Klein 2005). It is also possible to install systems with a check valve (Figure 4-1) or placing the pump at the bottom of the heater (always on), which might prevent cold water from short circuiting the hot water tank and passing directly to the shower, a factor which was found to decrease consumer comfort and energy efficiency in prior work. This research will evaluate the potential for optimization of recirculating systems, in order to guide improved future design/installation and possible retrofits to improve performance of existing systems (Table 4-2).

4.2. METHODS

Three hot water systems were constructed and operated in parallel to facilitate a "head-to-head" comparison of 1) a standard water heating system with storage (STAND), 2) a "green" water heating storage system with a pump and dedicated hot water recirculation line (RECIRC), and 3) a tankless on-demand system. The "baseline" RECIRC installation operated the recirculation pump continuously and had no check valve on the return line. All pipes were insulated with standard self-sealing foam insulation (R = 2). Additional details on the apparatus design and operation are provided elsewhere (Brazeau and Edwards 2012a, b).

The systems were operated under various conditions including high use, low use, high temperature and low temperature to examine practical extremes encountered in practice. High temperature is 60°C, lower temperature is 48°C, high use involved drawing 100% of the tank volume every 8 hours (3x per day), and low use was a draw of 25% of the tank volume twice daily (Brazeau and Edwards 2012a, b, Goldner 1994).

In this research, the baseline conditions (RECIRC-Baseline and STAND) were compared to three "optimized" modes of operation including: 1) Pump Optimized – pump operates on a timer set to turn on 15 minutes just prior to flushing, 2) Check Valve – a check valve was installed at the return line to prevent short circuiting and 3) Pump Optimized-Check Valve – a combination of the two strategies. To compare energy efficiency and consumer comfort, temperature profiles of water heater output and disinfectant decay, "worst" case conditions derived from prior research were selected (Table 4-1). Since both energy efficiency and chloramine decay were worst in recirculation systems at 60 °C, this temperature setting was chosen for evaluation.

Energy efficiency was derived by methods described in Brazeau and Edwards 2012 (Brazeau and Edwards 2012b) where energy efficiency = total energy delivered in hot water to the tap/total energy consumption. Total energy was determined using an electric watt meter that measured alternating current (AC) consumption directly and provides cumulative kWh values for the RECIRC and STAND systems as well as the RECIRC pump. The energy delivered in hot water to the tap was based on temperature increase of water from the heater (Figure 4-1):

$$q = mc\Delta T$$

where q = energy in terms of heat transfer to water

m = mass

c = specific heat capacity of water

ΔT = change in temperature

ΔT was determined by measuring the initial temperature of influent cold water in 4 gallon buckets of water from the laboratory tap using a digital thermometer. Additional information on temperature profiles within the tank was obtained using a data logger and temperature probes inserted in the tank with every 4" depth, and used to determine the volume of water potentially susceptible to regrowth of pathogens (Brazeau and Edwards 2012a, b).

The "worst" case condition for disinfectant residual for the RECIRC system was during the 60 °C and low use condition (Table 4-1) (Brazeau and Edwards 2012a). Since chlorine decays with both time and temperature, the longer stagnation period, low volume of water turnover, and higher temperature of this condition makes it the most vulnerable to increased disinfectant decay. Therefore, for the purposes of disinfectant residual, this operation mode was replicated for the "optimized" conditions to analyze chloramine decay. Chloramine residual was analyzed identically to the previous study (Brazeau and Edwards 2012a) for continuity using colorimetric methods via a HACH pocket chlorimeter.

Table 4-1 Key Results from Previous Studies to Draw Baseline Comparisons to Optimized Study.

Water Heater Type	Energy Efficiency – High Use		Energy Efficiency– Low Use		Disinfectant Residual – High Use (mg/L)		Disinfectant Residual – Low Use (mg/L)		User Comfort for Shower at 37 °C
	60 °C	49 °C	60 °C	49 °C	60 °C	49 °C	60 °C	49 °C	Figure 4-2
STAND	90%	88%	52%	55%	1.55	2.15	1.30	1.22	Remains above 37 °C for length of flush (13.5 minutes)
RECIRC	55%	55%	19%	23%	0.51	1.42	0.19	0.37	Immediately rises above 37 °C; but drops below 37 °C after 5.5 minutes

4.3. RESULTS

After examining the impacts of optimization on temperature of water delivered to the tap and energy efficiency, effects on internal tank temperature and disinfectant residuals (i.e., total chlorine) are quantified.

4.3.1. Temperature Profiles during System Flushing. During the baseline mode of operation (60 °C and high use), the hot water delivered to the tap from the RECIRC system cooled rapidly after 2 minutes of flushing (Figure 4-2), whereas the STAND tank remained at a high constant temperature for 8 minutes (i.e., nearly 50% of the flushing time).

Table 4-2 Various Modes of Operation and Installation for Hot Water Recirculation Systems.

ISSUE	Various Pump Operations/Modes					Other Installation Considerations			
	Continuous Pump (Baseline)[1] Pump installed either at top of tank or bottom of tank and runs continuously	**Timer Controlled Pump[1,2]** Pump only operates at pre-determined times (highly variable) (Klein 2005)	**Thermostat-Controlled Pump** Pump is triggered on when thermostat in pipes drops below a pre-determined temperature	**Demand Pump[1,2]** Pump is controlled by push-button that is triggered by user	**Thermosiphon** No pump – recirculation is controlled by thermal changes and gravity through a return line	**Check Valve[1]** Installed on return line to prevent backflow from water heater	**Pump Location** Can either be installed at top of tank or bottom of tank	**Recirculation Pipes** **New Construction:** Dedicated Return line **Retrofit:** Can tie into existing cold water line (Figure 1)	**Pipe Insulation** **New Construction:** Pipes typically insulated **Retrofit:** Pipes may not have any insulation
Energy Implications	Increased heat loss due to loss of stratification and through pipes; pump requires energy (Brazeau and Edwards 2012b)	Less energy than baseline; Highly dependent on timer set-up	Expected to have greater energy efficiency than continuous pump	Recirculation and pump energy minimized	Much less energy loss than baseline	If not installed: short circuiting of cold water reducing delivered energy (Brazeau and Edwards 2012b)	If installed at bottom – similar to check valve	No dedicated cold water line – all water consumption uses some heated water	Tremendous heat loss potential during circulation through pipes
Flushing Temperature Implications	Instant hot water at tap, mixing due to pump may cause rapid cooling (Brazeau and Edwards 2012b)	If pump is off during flushing, cooling effects from pump eliminated?	If pump is off during flushing, cooling effects from pump mixing eliminated?	If pump is off during flushing, cooling effects from pump mixing eliminated?	Same as baseline?	If not installed: short circuiting of cold water causing rapid cooling (Brazeau and Edwards 2012b)	If installed at bottom – similar to check valve?	Water always warm? No cold water? Water not hot enough?	Same as baseline?
Pathogen Growth Potential	Low disinfectant residual due to pipe contact; nutrients, toxins and disinfectant delivered to biofilm; increased H_2 (Brazeau and Edwards 2012a)	Little difference from STAND?	Little difference from STAND?	Little difference from STAND?	Same as baseline?	If not installed: potential reverse flow in pipes (Brazeau and Edwards 2012a)	If installed at bottom – similar to check valve?	Cold water line eliminated – warm water through pipes increases pathogen growth?	Same as baseline?

[1]**Tested herein**
[2]**Timer was reduced to lowest possible to represent "best case" for timer controlled and/or a demand controlled pump**

It was hypothesized that the rapid decrease in temperature of water flowing from the RECIRC system was due to cold water mixing within the tank due to action of the pump, and and/or cold water back flowing (i.e., short circuiting) out of the bottom of the tank (reverse flow through the return line). The existence of a short circuiting effect was unambiguously demonstrated previously through a tracer study (Brazeau and Edwards 2012b). Short circuiting through the return line is not possible in the STAND system because there is no return line. Three different modes of operating the RECIRC system were tested to examine optimization approaches to mitigate the drop in temperature.

The RECIRC-Pump Optimized condition, which runs the pump for just 15 minutes before use and then turns the pump off when hot water is drawn from the tank, had no impact on the cooling trend (Figure 4-2). Clearly, the mixing of hot water with cold is not due to the pump. In contrast, the installation of a check valve and leaving the pump operating continuously, eliminated the cooling problems for water drawn from the tank and operated nearly identical to the STAND system. Likewise, the combination strategy (RECIRC-Pump Optimized-Check Valve) also made the RECIRC system behave nearly like the STAND system in terms of stable, consistent hot water flow (Figure 4-2). Overall, these results demonstrate that use of a check valve eliminates undesired dropping water temperature during use of a recirculation system.
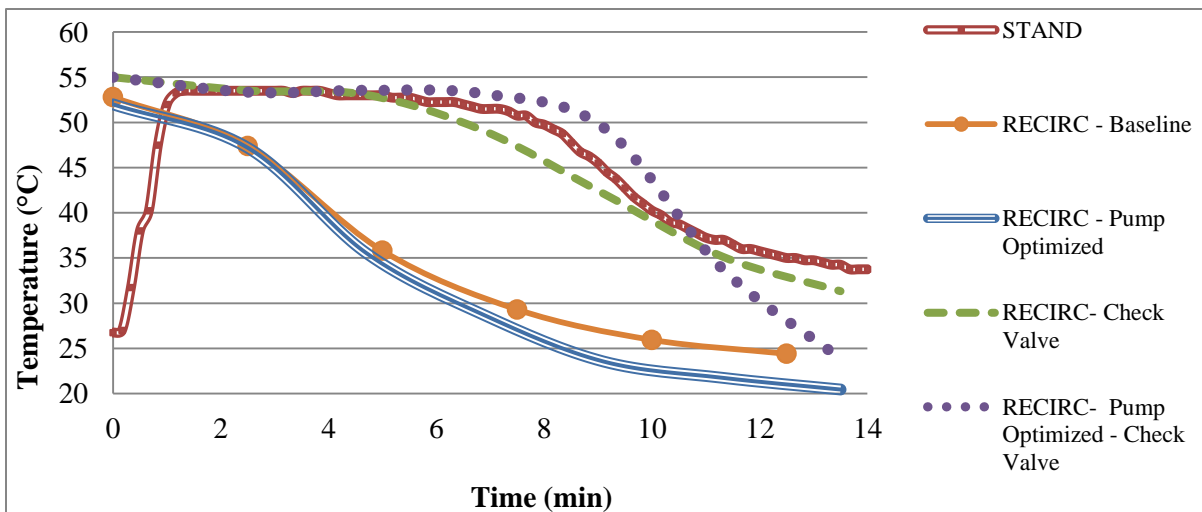

Figure 4-2 Temperature profiles during flushing.

4.3.2. Energy Efficiency. Heat losses through the walls of pipes and tanks for the different hot water systems were discussed in detail previously (Brazeau and Edwards 2012b). Losses are exacerbated by continual recirculation of hot water and the electricity consumed by the pump is also significant. Short circuiting, as defined previously in RECIRC systems without a check valve installed, also tends to reduce energy delivery in the form of hot water, reduce daily energy demand, and lower the overall energy efficiency.

Installation of a check valve alone with continuous pump operation, markedly improved the delivery of hot water, but only improved energy efficiency by about 3% (Table 4-3). Restricting use of the pump to just 15 minutes immediately before water demand events dramatically reduces extra energy losses of RECIRC vs. STAND systems. When the RECIRC-Baseline condition was compared to the RECIRC pump optimized conditions at high use and low use, the energy efficiency improved by 25.8% and 53.1%, respectively. But even with the pump turned off 98% of the day at low and high use, energy efficiency of the RECIRC was still 20 - 40% lower than the STAND condition. When both check valves and reduced pump demand were used in RECIRC systems, the comparable STAND system was still 5% more efficient than the RECIRC-Pump Optimized-Check Valve system (Table 4-3).

4.3.3. Internal Tank Temperature. A recommended minimum temperature of 60 °C is proposed for pathogen control by the World Health Organization, ASHRAE and others (ASHRAE 2011, Levesque et al. 2004, World Health Organization (WHO) 2007). But the tank setting only influences, and does not control, the temperature of the volume of water in pipes and at the bottom of water heaters. If 46 °C is considered as a threshold for the termination of Legionella and MAC growth and 30 – 37 °C is an ideal growth range, then weighted daily average volumes of water in each storage tank at risk for potential pathogen growth can be determined using the equation described in Brazeau and Edwards, 2012 (Figure 4-3, Table 4-4) (Brazeau and Edwards 2012a, Buse and Ashbolt 2011, Norton et al. 2004).

Table 4-3 Energy Efficiency Results

Condition	Total Energy Consumption (kWh/Day)				Energy Out (kWh/Day)		Energy Efficiency (%)	
	STAND	RECIRC - TANK	RECIRC - PUMP	RECIRC - TOTAL	STAND	RECIRC	STAND	RECIRC
Pump On Continuously								
60 °C, High Use	8.1	9.9	0.61	10.5	7.04	5.82	86.9	55.4
60 °C, Low Use	3.2	7.3	0.61	7.9	1.68	1.50	52.2	19.0
60 °C, High Use - Check Valve	9.7	14.3	0.63	14.9	8.60	8.70	89.1	58.3
Pump Optimized - On 15 Minutes Prior to Flushing								
60 °C, High Use	10.6	7.5	0.03	7.6	9.44	5.27	88.8	69.7
60 °C, Low Use	3.3	4.0	0.01	4.0	1.68	1.60	51.2	40.5
60 °C, High Use - Check Valve	9.7	11.6	0.03	11.7	8.85	10.22	91.7	87.6

In every condition the STAND system had 30 – 430% more volume at risk than the RECIRC systems when applying the 46 °C threshold for controlling pathogen growth (Table 4-3). Moreover, the STAND system had 24 – 577% more volume in the ideal growth range during a 24-hour period. The addition of the check valve to the baseline condition (RECIRC – Check Valve) had nearly 2.5 times less water at risk as compared to the RECIRC-Baseline and represents a "best case" scenario from a temperature perspective on pathogen growth. When the pump was continuously on (Baseline and RECIRC-Check Valve conditions), the RECIRC systems had a high, stable temperature throughout the tank which eliminated stratification (Figure 4-3). When the pump was optimized (RECIRC-Pump Optimized and RECIRC-Pump Optimized-Check Valve), there was stratification during stagnation which was broken up just prior to flushing. Since the entire volume of the tanks and pipes were heated prior to flushing (due to recirculation), the RECIRC-Pump Optimized conditions heated faster than the STAND system (Figure 4-3).
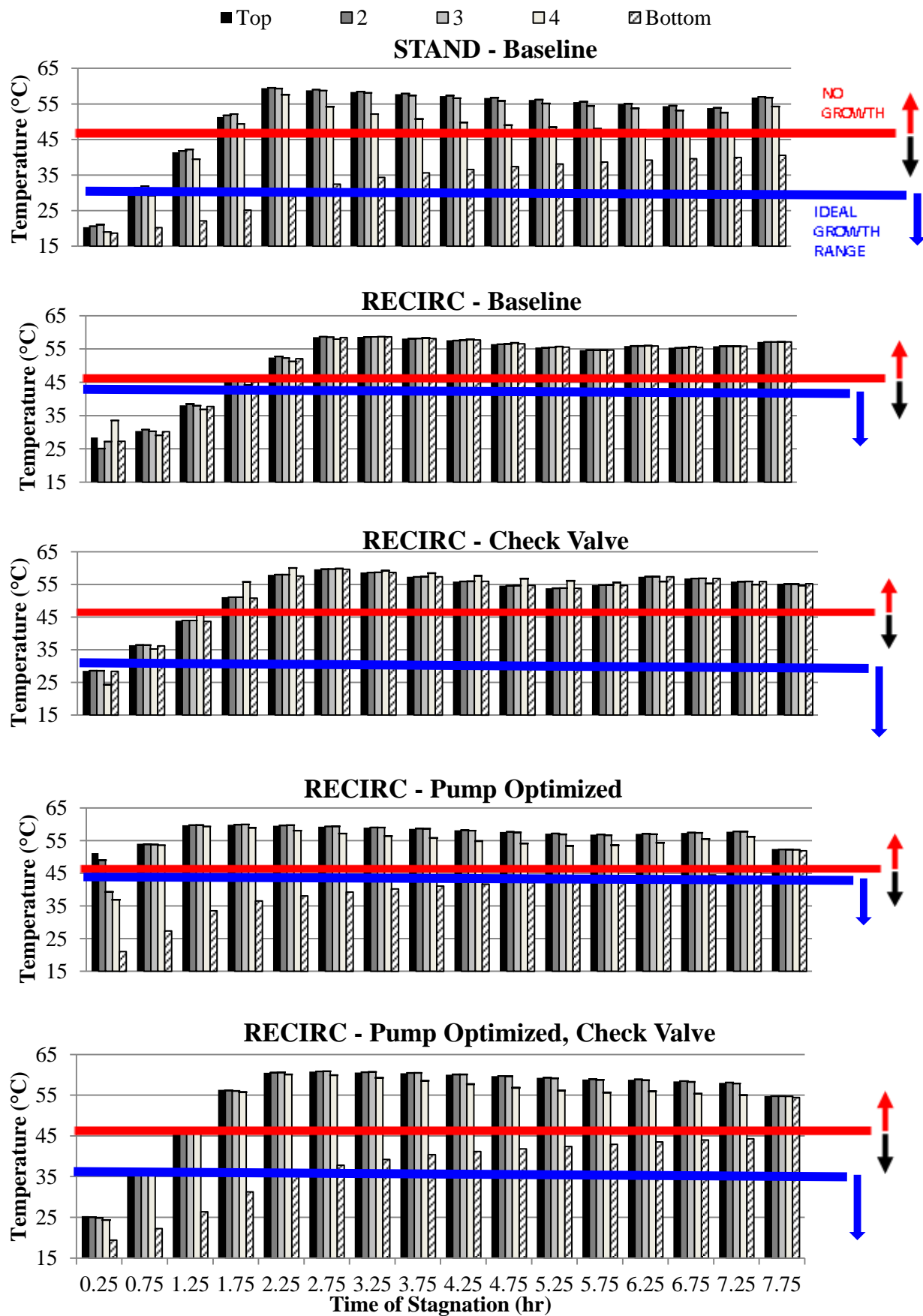
Figure 4-3 Internal tank temperatures for baseline and optimized conditions at 60 °C and a high user pattern. *Data loggers were inserted the length of the tank as described in Brazeau and Edwards, 2012 (Brazeau and Edwards 2012a) with each data logger (Top, 2, 3, 4, and Bottom) being 4" in length.*

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Table 4-4 The average percent of tank volume below key temperatures during a 24-hour period of the baseline conditions as compared to the optimized conditions.

Water Heater Type	Storage Volume (Tank) Below 46 °C Per Day High Use (% Tank)	Storage Volume (Tank) Below 37 °C Per Day High Use (% Tank)
STAND	31	21
RECIRC	22	16
RECIRC – Check Valve	16	9.4
RECIRC – Pump Optimized	18	6.9
RECIRC – Pump Optimized – Check Valve	24	14

      4.3.4. Disinfectant Residual. The STAND system had up to 850% more chlorine residual in the bottom of the tank as compared to the RECIRC-Baseline condition (Figure 4-4) (Brazeau and Edwards 2012a). The optimized RECIRC systems also always had less disinfectant residual than the STAND system (Figure 4-4). While adding a check valve increased the total disinfectant residual at the end of stagnation as compared to the baseline condition, the STAND system still had up to 260% more residual as compared to this optimized RECIRC condition. This shows that while short circuiting and dilution may be responsible for some of the decrease in total chlorine, even short term pump operation and associated contact additional with premise plumbing is a dominant factor in increased chlorine decay (Brazeau and Edwards 2012a, Nguyen 2005).

      When the pump operation time was minimized, there was 4.5 – 5.5 times more chlorine residual at the end of stagnation as compared to RECIRC-Baseline (Figure 4-4). Furthermore, since the system is not completely mixed throughout the stagnation period, there is 1.5 times more chlorine residual at the

bottom of the tank, where increased sediment and lower temperatures could facilitate a greater likelihood of biofilm and pathogen growth as compared to the top of the tanks. In the continuously pumped systems, the total chlorine is the same at the top and bottoms of the tank.
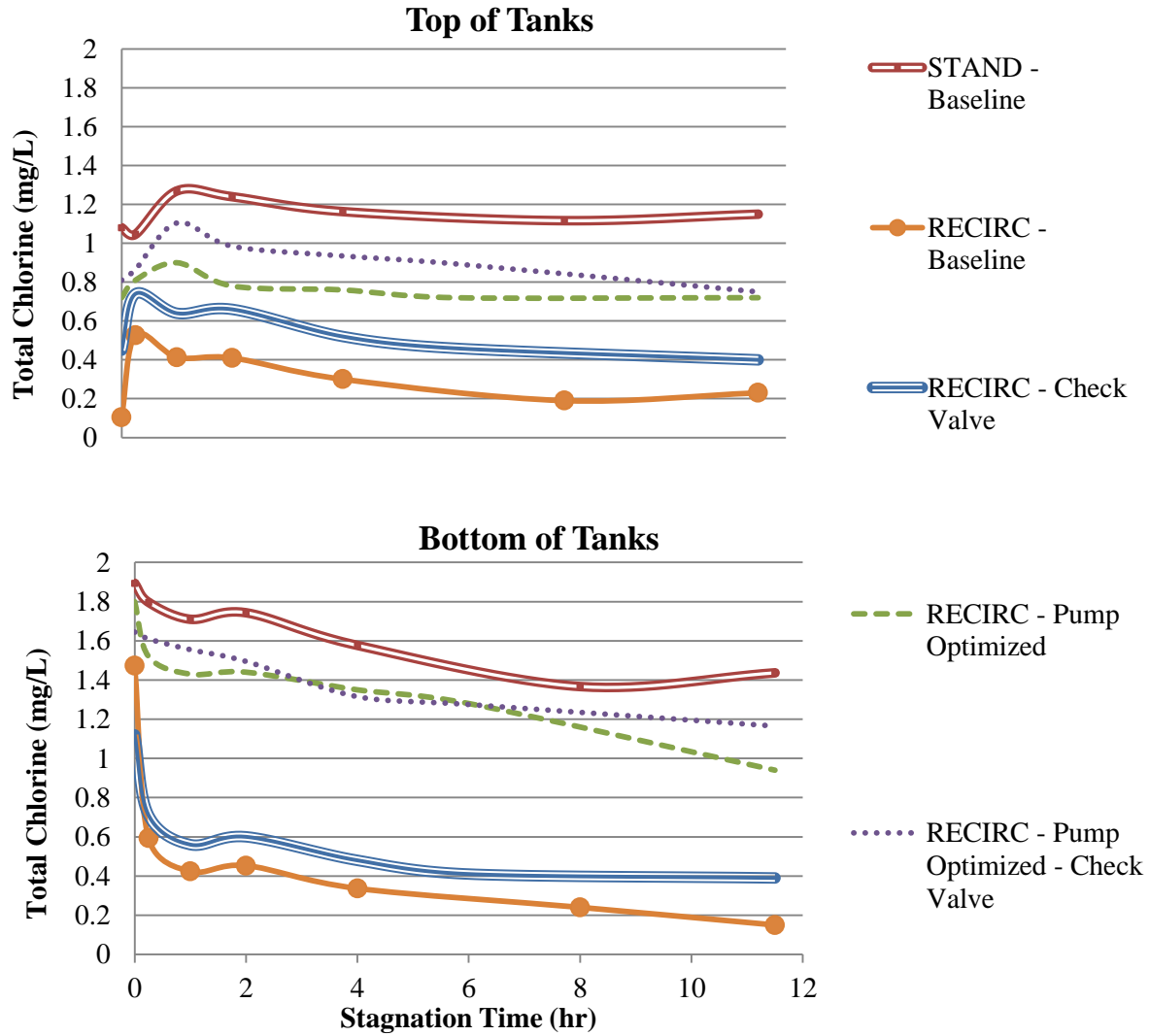

Figure 4-4 Total chlorine residual in storage tanks for various operation modes at 60 °C and a low user pattern.

4.4. DISCUSSION

4.4.1. Energy Efficiency, Water Savings, Costs, and Consumer Concerns. Hot water recirculation is marketed as water and energy saving (Ally and Tomlinson 2002, TACO - Residential and Commercial Hydronic Systems 2006) and while it does in fact save some water at the tap in the consumers home, it inevitably does so at the expense of increased energy use. Under the best scenario optimized RECIRC had 20% more energy consumption and was 3% less energy efficient. Under the worst scenario, RECIRC used 145% more energy than STAND and was 56% less energy efficient (Table 4-3). A more representative analysis from the perspective of a consumer needs to consider that hot water alone is not used, but that hot water will be tempered with cold water to achieve a consistent shower or bath temperature.

4.4.1.a. Normalized Energy Efficiency. Since the temperature and total hot water delivered varies markedly from system to system, calculations were made to estimate energy efficiency if the consumer mixed the hot water with cold water to achieve a fixed volume of water at 37 ° C (Table 4-3) (Delta Faucet 2011). This would reflect the total energy demand on each system if consumers adjusted cold water continuously while showering to maintain 37 °C, if a mixing valve made such adjustments automatically, or if volumes of water were drawn for a bath at a constant final temperature (Table 4-3). Prior work demonstrated that the estimates obtained using calculations had minimal error, when compared to confirmation experiments conducted when systems were actually operated to deliver identical quantities of heat (e.g., a fixed volume of water raised to the same temperature) (Brazeau and Edwards 2012b).

Using this normalized result, net water consumption and total annual costs associated with the defined use patterns for each system were compared to the baseline conditions (Table 4-5, Figure 4-5, and Figure 4-6). In all cases, the overall costs associated with the optimized RECIRC systems were 8.5 – 66% higher than the baseline STAND system. While this seriously calls into question the "green" designation for such systems, the use of an optimized recirculation does improve markedly on conditions in previous

work, for which RECIRC costs were up to 200% higher than STAND (Brazeau and Edwards 2012b). In other words, the RECIRC system reduces the consumer wait time for hot water at that tap at the expense of higher energy use and consumer costs between 8-200% more, dependent on use patterns, system design and operation (Table 4-5).

4.4.1.b. Net Annual Water Consumption.   While the RECIRC system is not energy saving as compared to the STAND system in any scenario, there are probably some net annual water savings accrued from operation of the hot water system that are projected only if the pump is optimized (Figure 4-6). These projections require an extreme assumption that all water in STAND systems is wasted down the drain until the temperature of the hot water reaches 37°C and that no water at all is wasted by consumers in the RECIRC system. This extreme assumption is probably close to reality for shower use, but not if a consumer captured all water for bathing and tempered it to a final target temperature. Under this extreme scenario, two of the systems with the RECIRC pump optimized (low use and high use with a check valve) have a projected net water savings of 2 gallons per day compared to the comparative STAND system (Figure 4-5, Table 4-5).

4.4.1.c. Consumer Costs. RECIRC systems always cost more than STAND systems (Figure 4-5). Even under the best case scenario RECIRC costs 8.5% more to operate than STAND. While this tradeoff obviously depends on the relative cost of water and energy (i.e., in this work $0.11/kWh and $0.0025/gal of water) it is difficult to imagine a scenario when RECIRC would actually save consumers in operating costs. The extra cost of operating a RECIRC system was reduced dramatically by optimizing the pump operation (Figure 4-6). Installation of the check valve alone reduced operating costs by 4%, whereas optimization of pump operation decreased annual costs by 37% and 45% for the high use and low use conditions, respectively (Table 4-5). As discussed in Section 3.2, the energy efficiency of installing a check valve was very similar to the baseline condition and thus had an almost negligible effect on total costs when normalized (Table 4-4).

Table 4-5 Net Water Consumption and User Costs for Normalized Energy Efficiency at 60 °C for Various Operation Modes

	High Use		Low Use		High Use- Check Valve		High Use		Low Use		High Use - Check Valve	
	Pump On Continuously						Pump Optimized - On 15 Minutes Prior to Flushing					
	STAND	RECIRC	STAND	RECIRC	STAND	RECIRC	STAND	RECIRC	STAND	RECIRC	STAND	RECIRC
Total Energy (kWh/Day)	8.1	10.5	3.2	7.9	9.7	14.9	10.6	7.6	3.3	4.0	9.7	11.7
Normalized Total Energy (kWh/Day)	5.8	10.2	1.6	5.1	5.7	9.7	5.7	7.9	1.6	2.1	5.5	6.1
Water Consumed for Energy Production (Gal/Day)*	11.7	20.3	3.1	10.1	11.4	19.4	11.4	15.7	3.2	4.2	11.1	12.2
Water Wasted at Tap (Gal/Day)**	4.5	0	4.5	0	4.5	0	4.5	0	3	0	3	0
Net Water Consumption (Gal/Day)	**16.2**	**20.3**	**7.6**	**10.1**	**15.9**	**19.4**	**15.9**	**15.7**	**6.2**	**4.2**	**14.1**	**12.2**
Annual Consumer Electricity Bill***	$234	$409	$63	$203	$228	$390	$229	$315	$64	$85	$222	$244
Additional Costs of Water Due to Waste****	$4	$0	$4	$0	$4	$0	$4	$0	$3	$0	$3	$0
Total Cost to Consumer for Water Heating	**$238**	**$409**	**$67**	**$203**	**$232**	**$390**	**$233**	**$315**	**$67**	**$85**	**$225**	**$244**

* 1 kWh energy produced = 2 gal of water consumed at energy production phase

**Given a flow rate = 1.5 gpm

***Given Average Electricity Rate: 1 kWh = $0.11

****Given Average Water Rate: 1 gal = $0.0025
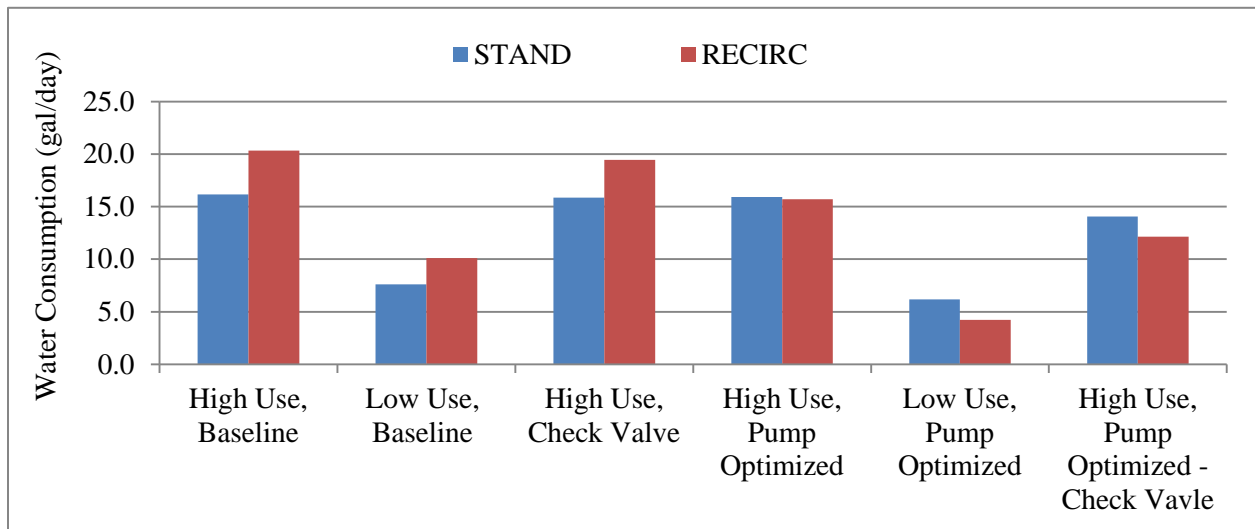
Figure 4-5 Relative daily water consumption of operating the various water heater systems under the "optimized" conditions at a temperature setting of 60 °C. *Note: Water consumption includes water used for energy production (Table 4-4).*
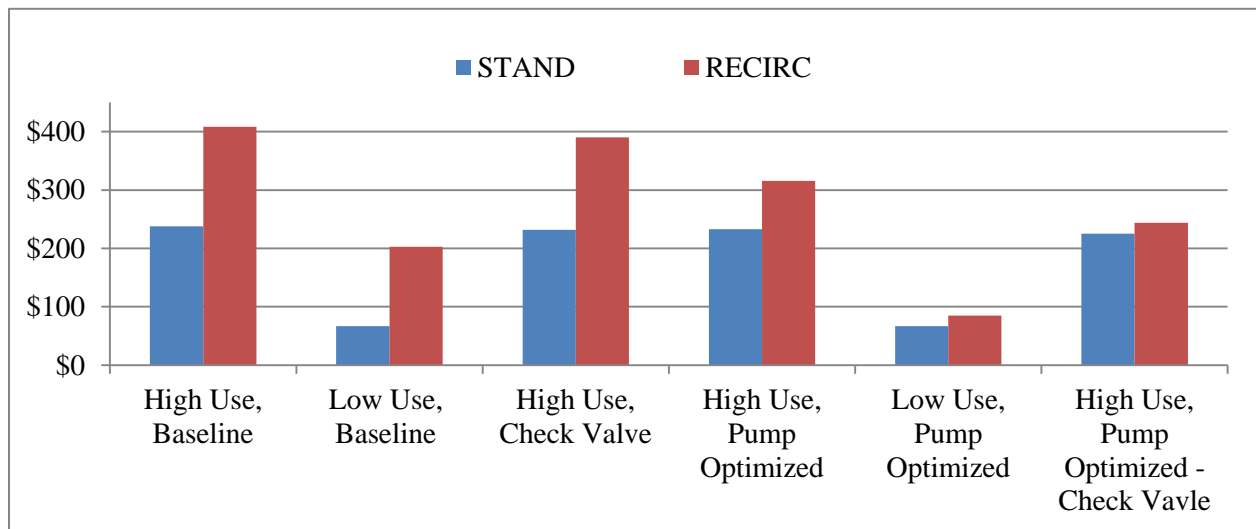
Figure 4-6 Relative annual costs of operating the various water heater systems under the "optimized" conditions at a temperature setting of 60 °C.

There are other potential concerns and costs associated with RECIRC systems. First, as noted previously, any cold water mixing due to short circuiting or pump circulation may cause a noticeable difference in user comfort (Figure 4-2). If a comfortable shower temperature is defined as 37 °C, then the STAND system has a capability for 9 – 260% longer shower times as compared to the various RECIRC systems (Figure 4-2). In the worst-case baseline condition, the comfortable shower time for RECIRC

draws only 20% of the tank volume. Extrapolated to a standard water heater size of 40 gallons and a flow rate of 1.5 gpm, this would equate to a 5.4 minute shower assuming the user steps in immediately after turning on the tap and there is no cold water mixing. If the tank temperature setting was 49 °C as recommended by the EPA, this effect would likely be even more noticeable (United States Environmental Protection Agency (EPA) 2009c). It is possible, even likely, that a consumer in such situations might terminate their showering more quickly due to discomfort, resulting in actual water and energy savings. Such human behavioral analysis is beyond the scope of the work presented herein.

4.4.2. Potential Implications on Pathogen Growth in Premise Plumbing. Similarly to the baseline study (Brazeau and Edwards 2012a), analysis of factors that might influence pathogen growth are framed in terms of draft proposed ASHRAE standards for Legionella control through: 1) temperature control (> 60 °C) and 2) maintaining a disinfectant residual (> 0.5 mg/L Cl) (ASHRAE 2011).

4.4.2.a. Pathogen Mitigation through Temperature Inactivation Strategies. From the perspective of temperature control, all of the RECIRC systems outperformed the STAND system with respect to minimizing storage volume at risk for pathogen growth. The RECIRC-Check Valve system shows the greatest potential for pathogen control with the smallest volume at risk (Table 4-4). The key point is that with recirculation, the internal tank temperature and pipes in the loop are at a constant and high temperature everywhere, which is potentially beneficial in terms of reducing pathogen amplification.

When the pump is optimized and only runs for 15 minutes prior to flushing, stratification occurs during stagnation making these systems more like the STAND system. However, since there is some recirculation prior to flushing which heats the entire volume of the water including near the bottom of the tank, the "recovery time" (i.e., the time it takes for the fresh, cold water to heat to the temperature setting, Figure 4-3) for the RECIRC-Pump Optimized system is less than both the RECIRC-Pump Optimized-Check Valve and the STAND system given that some volume of cold water short circuits the tank.

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The bottoms of water tanks may have a great potential for pathogen growth due to sediment accumulation and temperature stratification in some systems. Both of the continuous pumping conditions (RECIRC-Baseline and RECIRC-Check Valve) have the hottest temperature at the bottom of the tanks, with an average and maximum temperatures well above 46 °C (Figure 4-9). Both of the pump optimized conditions have average temperatures at the bottom of the tank below 40 °C which is suitable for pathogen growth. However, the maximum temperature of these systems is above 50 °C which can conceivably stop pathogen growth each time the pump mixes the tank. In contrast, the bottom of the STAND system never rises above 40 °C, possibly creating conditions suited to sustained pathogen amplification (Figure 4-9).
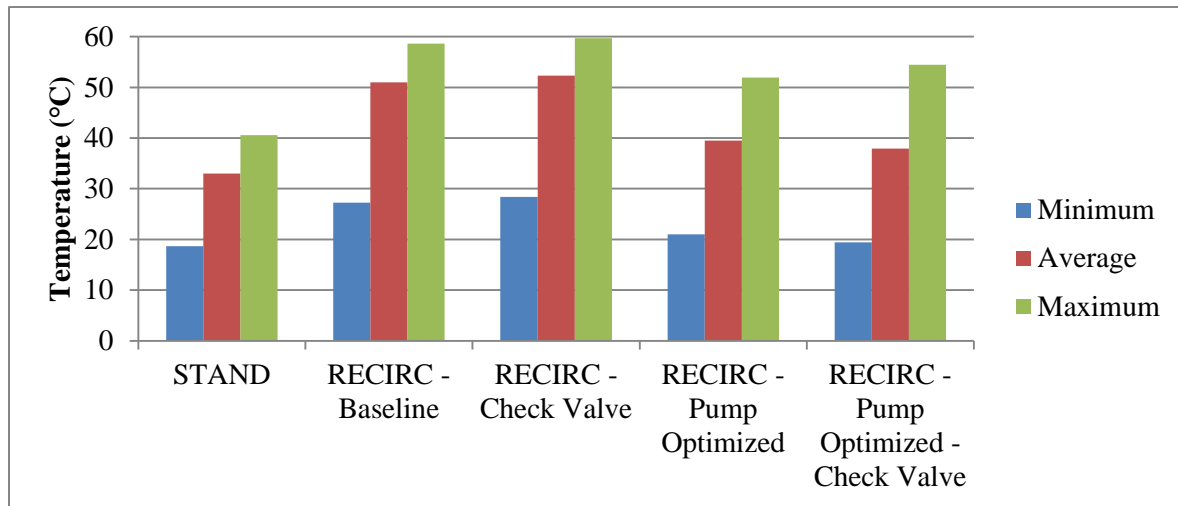
Figure 4-7. Minimum, average and maximum temperatures at bottoms of tanks during 8-hour stagnation period.

4.4.2.b. Pathogen Mitigation and Disinfectant Residual. Comparing RECIRC to STAND systems, all of the RECIRC systems have less chlorine residual than STAND at all times in the tank (Figure 4-4). However, it is possible that enhanced transport of chlorine to the biofilm along the tank and pipe walls during the 15 minutes that the pump is on, might be beneficial for biofilm control despite the lower overall disinfectant residual. That is, the extra delivery of disinfectant to the pipe walls during recirculation and resulting benefits in control of biofilm, could outweigh detriments associated with less chlorine in the RECIRC systems.

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When comparing one RECIRC system to another, the RECIRC-Pump Optimized conditions had up to 560% more chlorine residual than the RECIRC-Baseline condition (Table 4-6). The RECIRC-Check Valve system had up to 122% more disinfectant residual than the RECIRC-Baseline condition, but still had far less chlorine residual than the RECIRC-Pump Optimized conditions. Finally, the installation of a check valve prevents short circuiting and any biofilm shearing from reverse flow along the pipe return line. This is another added benefit of installing a check valve on the return line (Table 4-6).

4.5. CONCLUSIONS

4.5.1. Comparison of RECIRC-Baseline to the Optimized RECIRC Systems. In a head to head study evaluating how optimized electric RECIRC systems compared to those without a check valve and continuous pump operation (baseline RECIRC), optimization could increase energy efficiency 5.5 – 60%. This equates to 5 – 140% cost savings for heating water compared to the typical installation of RECIRC systems. The optimized condition also produced a 560% higher disinfectant residual at the bottom of the tank at the end of the 12-hour stagnation period.

4.5.2. Comparison of RECIRC systems to STAND. Despite claims of water savings, the baseline RECIRC systems had a net water consumption of 2.5 – 4.0 gallons per day more than the STAND system. However, when the pump was optimized, under fairly extreme assumptions of consumer waste of water down the drain while temperature rose in a STAND system, the RECIRC system saved up to 2 net gallons per day versus STAND. The STAND system had 30 – 230% more volume at risk for pathogen growth as compared to any of the optimized RECIRC systems. The continuous pump operation RECIRC with a Check Valve system had the least amount of volume at risk.

Table 4-6 Summary of Key Results.

SYSTEM	Stagnation Temperature		Energy Efficiency (High Use)	Annual Water Consumption for High Use (gal/yr)	Annual Consumer Cost for Water and Energy for High Use	Volume of Water at Risk for Pathogen Growth (per day)	Total Chloramine Residual	Flow Reversal, Mass Transport to Biofilm
STAND	**Tank:** Stratifies; Bottom as much as 25 °C cooler than top		90%	5700	$230	31%	Up to 860% higher than RECIRC-Baseline in bulk water	None, Low transport
	Pipes: Cool to ambient (25 °C)							
RECIRC -- Baseline	**Tank:** Homogenous		55%	7410	$409	22%	Improved delivery of disinfectant to biofilm	Flow reversal in pipes, high transport
	Pipes: Heated to tank temperature							
RECIRC -- Check Valve	**Tank:** Homogenous		58%	7080	$390	9.4%	Up to 122% higher than RECIRC-Baseline; Delivery to biofilm	None, High transport
	Pipes: Heated to tank temperature							
RECIRC -- Pump Optimized	**Tank:** Stratifies; Bottom as much as 25 °C cooler than top; Homogenous 15 minutes prior to flushing		70%	5730	$315	18%	Up to 400% higher than RECIRC-Baseline; Low delivery to biofilm,	Flow reversal in pipes, low transport
	Pipes: Cool to ambient (25 °C)							
RECIRC – Pump Optimized - Check Valve	**Tank:** Stratifies; Bottom as much as 25 °C cooler than top; Homogenous 15 minutes prior to flushing		88%	4450	$244	24%	Up to 560% higher than RECIRC-Baseline; Low delivery to biofilm	None, low transport
	Pipes: Cool to ambient (25 °C)							

While optimizing the RECIRC system improved total chlorine residuals, the STAND system still had 25 – 250% more total chlorine residual than the optimized RECIRC systems. STAND systems were between 3 – 55% more energy efficient and were projected to save consumers between $19 - $158 annual on water and electrical costs when compared to any of the RECIRC systems. Thus, in the context of "green" design, RECIRC systems provide a convenience to consumers in the form of nearly instant hot water, at a cost of higher capital, operating and overall energy costs.

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