A REVIEW

HEALTH AND SAFETY ASPECTS OF DEMAND RESPONSE ON ELECTRIC STORAGE WATER HEATERS: A MINI LITERATURE REVIEW

August 2018

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ABSTRACT

Reviews of current literature and recent guidelines have substantiated that, in order to stifle the culturability of legionella and colonization of the electric hot water distribution system, consistently maintaining water stored in an electric hot tank at ≥60 °C and at above 50°C across the distribution networks are no negotiable options (Canada Safety Council, 2005; WHO, 2007; Bedard et al, 2015; ABCB, 2015; ANSI/ASHRAE, 2016; Boppe et al, 2016; Dufresne, 2016). However, as exterminating legionella is a function of temperature and time (Ji, 2017), existing literature are not clear-cut on whether demand response (direct load control) operations in electric hot water tanks - which entail peak scheduling, shifting and curtailing water demand-energy loads by means of switching off the water heater - create a greater risk for legionella. In the light of this, this paper reviews what the science is today and researches any preponderance of legionella risk with direct load operations in demand response management. The findings reveal that demand response events in a thermally-stratified or stagnated electric hot water system can provide conditions for greater culturability of legionella and colonization of the water storage tank. These may be associated with two forms of legionellosis. One is an acute respiratory disease (flu-like Pontiac fever) in healthy and young people. The other is a severe pneumonia-type of illness, known as Legionnaires' disease, and predominant in at-risk populations who aspirate water containing legionella species or inhale aerosols of water droplets containing the gram-negative bacteria. [At risk populations include new-born babies, the elderly, immune-compromised individuals who have undertaken organ transplants or suffering from cancer, lung conditions, kidney diseases, diabetes including past and current smokers.]

Key Words: Legionella risk – residential hot water tanks - demand response events - temperature settings

INTRODUCTION

1. Demand Response Events

Demand response is a part of a category of demand-side management solutions, and of crucial interest to electric utilities in leveraging domestic energy loads in residential electric storage water heaters[1] by controlling the peak demand of storage water tanks (Dufresne, 2016).

In a well-insulated tank, hot water can be stored for long periods of time without any significant heat loss. This facilitates demand response management in heating water during off-peak hours and utilizing the energy storage in the hot water during peak-load periods. During the peak period, the heaters are switched off to a large number of residential houses, from a remote location, in order to cut energy demand load (Ericson, 2006). This remote control allows peak scheduling, shifting and curtailing water demand-energy loads by means of switching off the water heater (Dufresne, 2016).

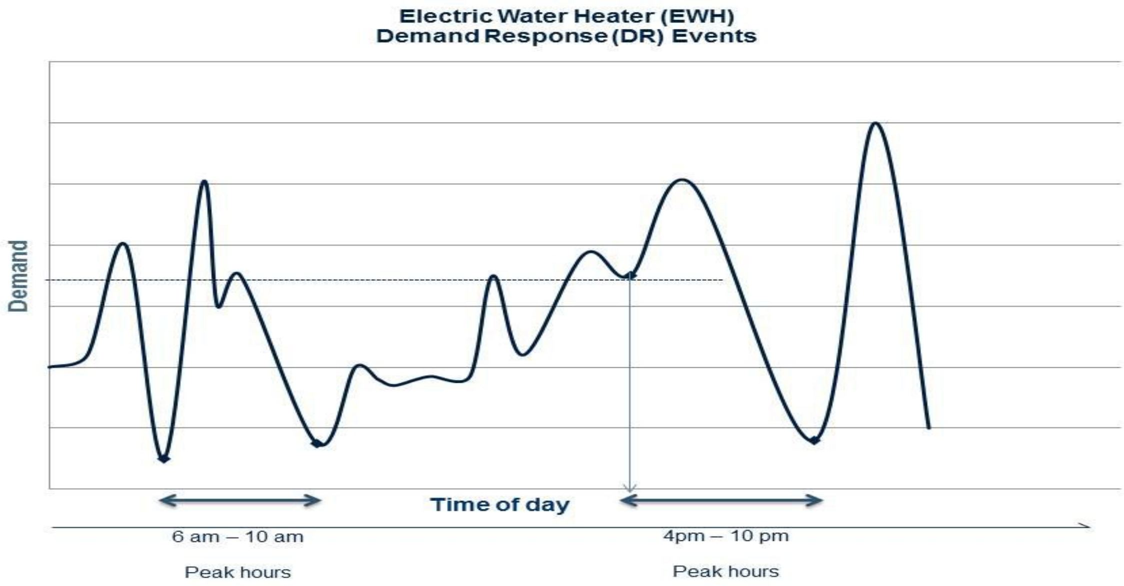

Figure 1: Demand versus Time

Demand response illustration- Intihar, C. and Onabola, C. (2018)

[1] "Electric storage tank water heater — an automatically controlled, thermally insulated, electrically heated water tank with a rated storage capacity of at least 50 L." Source: CSA C191-13 - Performance of electric storage tank water heaters for domestic hot water service

A typical electric hot water tank has an upper and lower thermostat with respective heating elements. Direct load control events are operated such that during off-peak hours in the night, say from about 11pm to 5am, the entire content of the tank is preheated to a temperature set point of 60°C, which is the standard thermostat setting for electric water heaters in Canada (Dufresne, 2016). By the onset of peak hours at 6am, the electric heater is turned off. During on-peak hours, hot water leaves from the top of the tank and cold water flows into the bottom of the tank. This results in stratification where the temperature at the bottom of the tank is much lower than at the top of the tank; and the overall tank system assumes a dropped temperature (Dufresne, 2016). The thermostat of the lower element will sense the drop in temperature when below a certain dead band and turns on the lower heating element.

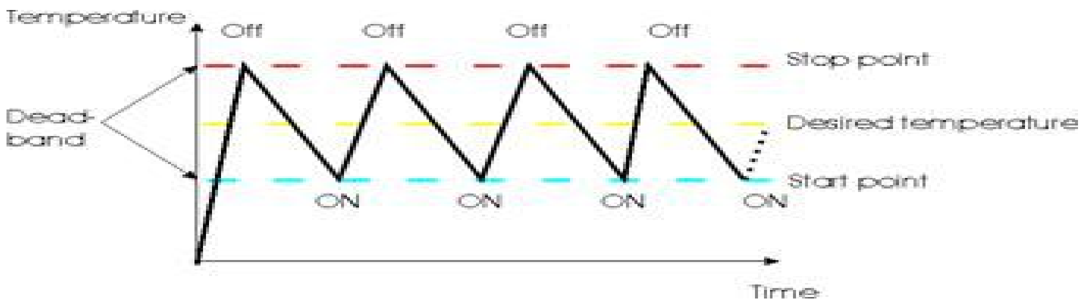

Figure 2: Dead-band (Hysteresis); Xtronics, 2017

Two phenomena associated with demand response (direct load control) operations in electric water heaters are stratification and stagnation. Loss of thermal energy (heat loss) during stagnation and stratification causes temperature fluctuations and variations in the water distribution system of an electric water heater (Dufresne, 2016). A pertinent aspect of this paper is to find out how much the water temperature drops and if the dropped temperature falls within a range susceptible for legionella proliferation and risk of legionellosis as well as what the duration of recovery is in the tank.

2. Legionellosis and Legionella

The term, 'legionellosis,' encompasses a group of diseases caused by Legionella species. Two forms of legionellosis have been identified. The milder form is a flu-like Pontiac fever, which is an acute respiratory disease which occurs in healthy and young people. Pontiac fever, including its symptoms (fever, headache, shivers, dry cough, tiredness and muscle aches) resolves on its own within a few days. It does not cause pneumonia and has no significant predisposing factors. Healthy people are susceptible to Pontiac fever, but may be more resistant to Legionnaires' disease (Erdogan and Arslan, 2016).

The second form is a severe, pneumonia-like in nature, Legionnaires' disease, which often occurs in a group of at-risk populations which include new-born babies, the elderly, immune-compromised individuals who have undertaken organ transplants or suffering from cancer, lung conditions, kidney diseases, diabetes including past and current smokers (Erdogan and Arslan, 2016). Symptoms include cough, difficulty in breathing, fever, neuromuscular pains, and headaches Erdogan and Arslan, 2016). Legionnaire's disease is now ranked among the three most common causes of bacterial community-acquired pneumonia (Centers for Disease Control and Prevention, 2016). In the USA, the disease is on the rise; and about 8000 to 18,000 people are estimated to get infected annually (Centers for Disease Control and Prevention, 2005). The recorded incidence of the disease increased by 286% between 2014 and 2016 (BC Centre for Disease Control, 2018). It is also a recurrent trigger for community-acquired pneumonia in single family residential systems, with risk factors including include old age, chronic diseases, organ transplantation, smoking, immune-compromised conditions including cancer and diabetes and poor immune functions as in newborns (WHO, 2007).

It is important to note that legionellosis is not acquired by mere presence of legionella in a hot water system or by drinking water containing the bacteria. Legionella must have entered the lungs to affect the person. The two established routes of exposure, therefore, are by inhalation of aerosols (airborne droplets) containing the bacteria and aspiration into the lungs (HSE, 2013). The risk of a person acquiring legionellosis requires the following conditions:

i. The water must contain live legionella. Ideal conditions for legionella to grow and survive include water kept at 20-50°C in the presence of tank deposits that provide nutrients for the bacteria to proliferate.
ii. Formation and spread of airborne droplets of water containing legionella.
iii. Being an at-risk person: anyone in these categories (newborn babies, the elderly, immune-compromised individuals who have undertaken organ transplants or suffering from

cancer, lung conditions, kidney diseases, diabetes including past and current smokers) who inhales or aspirates water containing colonies of bacteria into the lungs (HSE, 2013).

While there are no nationally recorded data on Legionnaire's disease in Canada (Canada Safety Council, 2005), a survey conducted in the province of Quebec reckoned that, in homes where legionella heavily colonised the storage tanks, the temperature settings of the electric heaters were significantly lower than in homes where storage tanks tested negative to legionella (Bedard et al, 2015). The thermal sensitivity of legionella and resultant colonization in residential hot water distribution system at the temperature range of 20^{o}C to 45^{o}C has been fully researched and established (WHO, 2007; Bedard et al, 2015; Klein and Tabatabaei, 2018). Legionella is not likely to become a health risk unless it begins to multiply and colonize. A residential hot water system not properly designed or maintained can facilitate such growth. Within an ideal temperature range, as stated above, legionella proliferates, and a storage water tank system can get heavily colonized in less than five days (WRAS, 2014).

Exterminating legionella is a function of temperature and time (Ji, 2017). Research has shown that at a temperature above 70°C, legionella is killed instantly. At 60°C, over 90% of the bacteria are killed in thirty two minutes whereas, at 50°C, it will take two hours to achieve the same (90%) level of elimination. Legionella multiplies the most between 20°C and 45°C and ideal conditions for proliferation being provided between 32 and 42°C. At 48-50°C, it can survive, but does not proliferate (Klein and Tabatabaei, 2018). Brazeau and Edwards (2013) provided further evidence that 46-53°C may be the upper range of growth for Legionella, and an ideal growth range existing between 30°C and 37°C.

Table 1.1. Legionella Risk and Hazard Assessment

System Type	Hazard Characteristics	Risk Level
Domestic Hot Water System	Water storage temperature exceeds 60 °C	Low
	Water storage temperature in 50-60 °C range	Medium
	Water storage temperatures below 50 °C	High
	Water distribution temperature below 50 °C	High

	Storage tank and Piping subjected to periods of prolonged water stagnation	High
	No re-circulation pump (as in a storage tank)	High
	Shower facilities (provide conducive environment for biofilms formation which are protective for legionella growth)	High

PSP Canada, 2018

METHODOLOGY

Four databases were adopted for the literature search. They were Medline Ovid, Pub Med, Google Scholar and Web of Science. The search terms were "demand response events" and "residential hot water tanks" combined with "Legionella risk," and "temperature settings." Over 30 articles published between 2003 and 2018 were reviewed and included qualitative studies, surveys, quasi-experimental studies and systematic reviews. Some grey literature through basic Google search was also included. The inclusion criteria considered the authority of the data, relevance to the topic and research question and meaningfulness of the results in practical and analytical terms.

LITERATURE REVIEW

1. **Direct Load Program in Quebec**

In a direct load control program, regulating concurrent energy demand in peak-load situations, especially, in winter seasons when peak consumptions occur, has called for a flexibility to manage demand loads and constraints within the system. This flexibility takes the form of peak shaving, load shifting and balancing in order to optimize generated energy (Ericson, 2006).

In a bid to ensure that energy supply meets demand, particularly, in winter when residential demand often exceeds the generating capacities of utilities, Hydro Quebec has launched direct load control programs in the residential sector using advanced metering infrastructure that incorporates smart residential meters, advanced communication systems, data procurement and treatment software (Dufresne, 2016).

2. Heat Loss in a Stagnating Pre-heated Water and Legionella Risk

Typical residential water heaters in Quebec are a 270-litre (60 gallons) tank with a rated heating element capacity of 4.5kW or a 180-litre (40 gallons) tank with heating power of 3kW. Heat loss occurs even in a well-insulated tank (Schneyer, 2011), and the rate of thermal energy loss in a stagnating tank (with unused hot water) is one factor in Legionella propagation. For example, a 180L electric water heater may lose 50 to 70 watts of heat per hour while a 270L water heater may lose heat at 75 to 95 watts/hour (Wong et al, 2013). Aside the volume of a storage tank, thermal energy loss is a function of other factors which include the average temperature of hot water in the tank, the ambient air temperature and the size of the tank (Ericson, 2006). Heat losses are greater in cooler ambient air temperatures (winter periods) (Dufresne, 2016). Higher temperatures of stored water have been shown to give way to greater heat losses (Dufresne, 2016). Bigger sized tanks also have greater heat losses. The heat loss from a fairly well-insulated 270L tank is approximately 135W/h at a temperature of 75°C (HiO, 2005).

Schneyer (2011) and Bedard et al (2015) reckoned that insulation does not protect against heat losses and cannot guarantee a maintained high temperature over a long period of stagnation. To maintain water at a minimum safe temperature and prevent legionella proliferation and colonization of the storage tank, as pre-heated water waits to be used (stagnation), Bedard et al (2015) recommended maintaining a less than 5°C system heat loss and a minimum temperature of 50-55 °C at the water outlet.

In Canada, thermostats often have a dead-band range of approximately 10°C (Dufresne, 2016), This means that the heating element goes into operation only when temperature falls below 50°C and stops when the temperature goes beyond 60°C. Based on the thermostat's dead-band, a pre-heated tank in stand-by mode (water waiting to be used) may take an approximate of nine hours for the thermostat to activate the heating element as a result of heat loss (Ericsson, 2006). This, when juxtaposed against a recommendation by the Water Regulations and Advisory Scheme (WRAS, 2011), that water in residential storage tanks should be preheated for a period of 8 hours over a 24hr-period in order to preclude legionella from the hot tank system, brings on a call-to-action. This is to establish a continuous temperature monitoring and a move away from traditional control of electric hot water tanks which maintains the heater at a constant temperature set-point or pre-heats the water during off-peak hours for only a couple of minutes.

Gelazanskas and Gamage (2015) proffered an avenue to preventing stagnation and delay in use of pre-heated water through hot water demand forecasting and advanced control techniques. These techniques help profile patterns of hot water usage and make allowance for reduction in heat loss. Forecasting hot water consumption, Popescu and Seban (2008) demonstrated that an aggregate of the total thermal power demand for different days in a week can be forecasted using time series model. Gelazanskas and Gamage (2015) buttresses that energy load (electricity) demand, thermal demand and demand response can be predicted using simulation models and artificial intelligence.

Hot water demand forecasting will help to know when individual residential houses will need hot water and allow for reduced temperature settings during times of no-use. As demand response management entails load shifting and balancing operations, it is possible to perform these load shifting operations within a varied range of temperatures such that the energy loads of individual residential houses vary with time to enable a system balance. It is important that the range of temperature is wide and comfortable to preventing legionella growth. This affords the hot water heater and tanks more flexibility and a margin of safety in keeping Legionella from the tank while balancing peak and off-peak loads (Gelazanskas and Gamage, 2015).

Bakker et al (2008) also emphasized forecasting domestic heat (thermal) demand 24 hours ahead which was predicted by deploying Artificial Neural Networks (ANN) combined with the thermal profiles of the previous day and previous week as well as current weather information. Designing and operating domestic hot water tanks in this manner is crucial to preventing stagnation, extensive heat loss and a drop in temperature and ultimately for legionella control . Where system design and operations cannot preclude stagnation, installation of automatic flushing of the tank system in a periodical manner is recommended (Bakker et al, 2008).

3. Legionella Risk in a Thermally Stratified Water Tank

Two parallel drivers of heat loss during withdrawal events (on-peak periods) are household hot water usage and the water inlet temperature. In winter, the water inlet temperature is as low as 1.5^{o}C and has been recorded as high as 23^{o}C in summer (Laperrière, 2008; Wong et al., 2013). This accounts for the higher temperature gradient (stratification) in winter compared to summer. Dufresne (2016) reckons that temperature stratification, occurring from hot water at the top, near the outlet of an electric hot tank, and cold water at the bottom, is a storehouse of energy and a desirable phenomenon by hot tanks manufacturers.

However, thermally stratified hot water tanks during winter and summer give rise to seasonal temperature gradients that increase the proneness of various regions of the hot tanks to legionella colonization. Dufresne (2016) submitted that in winter, there is a 23°C temperature gradient as the average water temperature in tank is at 27°C, and the outlet of the tank at 50°C. Whereas, in summer, a 17°C gradient leaves the average water temperature in tank at 33°C, and the outlet of the tank at 50°C. This gives way to two thoughts. First, the average water temperatures of 27°C and 33°C in the tank, in both winter and summer, respectively, are within the range of temperatures that legionella can colonize a hot tank system, and in contradiction with the recommendation by Canada Safety Council that water should be stored and maintained in the tank at 60 °C or higher (Canada Safety Council, 2005). Second is that the temperature of water leaving the outlet at 50°C does not also align with recommendations from the Canada Safety Council (2005) that water leaving the outlet of the tank should be no lower than a temperature of 54°C.

Moreover, each withdrawal event from the tank results in heat loss (Dufresne, 2016), and as the thermostats' dead band length is approximately 10°C, the heating element will not be turned on until the thermostat senses that temperature reads below the dead band at 50°C. This leaves the tank system in a range where it is prone to legionella propagation.

Legionella can withstand temperatures of up to 50°C for several hours, but destroyed within a few minutes at 60°C (WHO, 2007). Temperature of water between 20 and 50°C are supportive to legionella growth and survival with an ideal growth temperature between 32-42°C. Therefore the most effective way to prevent legionella colonization in an electric hot water tank is to maintain temperatures outside the range of 20-50°C (WHO, 2007). It is, particularly, important that demand response events account for stratification by ensuring that direct load programs can influence the outlet temperature and the average temperature of the tank in a way that precludes legionella proliferation.

4. Recovery Time and Margin for Legionella Risk

Electric water heaters are designed such that the rate of heat loss (thermal energy) from each withdrawal event from the tank per time is greater than the capacity of the heating elements to heat up water faster and make up for the heat lost. That is, the time it takes to restore a previous level of thermal energy to the tank is longer than the time it took to lose or remove the heat initially (Dufresne, 2016). This lag between each water withdrawal event and restoration of the energy level previously stored in the tank accounts for longer recovery time. Dufresne (2016) demonstrated this in a thermodynamic modelling to study water usage patterns in Quebec. He found out that while the tank heating element gets turned on based on the thermostat setting, the rate of recovery is limited by a number of factors which include hot water consumption pattern, timing of household water consumption, the length of peak hours (that is time between disconnection and reconnection of water heaters), temperature of the inlet water, power rating of the heating element and water outlet temperature.

During periods of large withdrawals and when households have depleted hot water (lacking hot water), the outlet water temperature is below the dead band of the electric water heater (Dufresne, 2016) This is, most of the time, below a temperature of 50°C. This points to concerns for legionella risk as the temperature falls within an upper range of growth for legionella coupled with the fact that thermal energy recovery may take a couple of hours within which Legionella can proliferate a great deal.

An optimal demand response event is, therefore, one which, while maximizing electric water heater load curtailment, ensures optimal recovery time such that electric water heaters are switched back on in time so that the users never lack hot water.

RECOMMENDATION

There is an ample of health and safety recommendations in Canada and other jurisdictions that substantiate that in order to stifle the culturability of Legionella and colonization of the hot water distribution system, consistently maintaining water stored in an electric hot tank at ≥60 °C and at above 50°C across the distribution networks are no negotiable options (Canada Safety Council, 2005; WHO, 2007; Bedard et al, 2015; ABCB, 2015; ANSI/ASHRAE, 2016; Boppe et al, 2016; Dufresne, 2016). This will make up for heat loss and longer recovery time as well preclude the risk for legionella. This, however, has engendered concerns for scalding as constituted in many water regulations, but best practices entail the use of point-of-use temperature tempering devices at the tap. This ensures that water gets stored at ≥60 °C, and comes out of the tank outlet at a minimum of 55°C, and moving through the pipe distribution system and delivered at the tap at above 50°C (Bedard, 2015; HSE, 2013). Point-of-use temperature tempering devices are recommended for use at the tap (Bedard et al, 2015; ANSI/ASHRAE, 2016).

Regarding discrepancies in current literature, especially, as some regulations discourage thermostat setting set at a minimum of 60°C , Bedard et al (2015) reckoned that Legionella Pneumophila colonies are found present in hot water tank system even at a water heater temperature as high as 60°C. Evidence from Europe and United States also reported that 10% - 50% hot water samples operated at 60°C tested positive for legionella (Bedard et al, 2015). This relates back to the school of thought that exterminating legionella from an electric storage tank system is a function of time, temperature and extent of colonization of the system (Ji, 2017). For a hot tank heavily colonized with 100,000 [2]cfu/l Legionella, a 60°C temperature in the tank will only reduce the count by a factor of 10 in 3.2 minutes from 100,000 to 10,000 cfu/l Legionella. To reach an acceptable level of 100 cfu/l, a couple of exposures at 60°C is required (WRAS, 2011). This explains why electric heater setting to a high temperature, say 60°C, may not translate into a safe temperature of water at the distal outlets (Rhoads et al, 2015).

CONCLUSION

This review substantiates that demand response (DR) events carry a greater risk for legionella than if there were no demand response management. The findings reveal that DR events in a thermally-stratified or stagnated electric hot water system can provide conditions for greater culturability of legionella and colonization of the water storage tank. This creates undue health risks associated with two forms of legionellosis - an acute respiratory disease (flu-like Pontiac fever) in healthy and young people and a severe pneumonia-type of illness known as Legionnaires' disease in at-risk populations (which include new-born babies, the elderly, immune-compromised individuals who have undertaken organ transplants or suffering from cancer, lung conditions, kidney diseases, diabetes including past and current smokers), who aspirate water containing legionella species or inhale aerosols of water droplets containing the gram-negative bacteria.

[2] cfu/l — Colony-forming units per litre. Source: Biotech Laboratories, Statistical Data.

An important deduction from the literature reviewed is that while the risk of legionella is directly a function of the thermostat setting of the heating element, the extent of legionella colonization is indirectly a function of other factors such as the rate and duration of heat loss, how much the water temperature drops, the length of recovery time and extent of water withdrawal, inlet water temperature (which varies on a seasonal basis), ambient temperature of indoor air, and technical characteristics of the electric water heater such as tank volume, power rating of the heating element, thermal insulation, and dead band length.

As energy consumption compensating for heat loss is greater than energy for hot water usage, it is important that demand response management focuses on measures to minimize heat loss through advanced techniques. Managing energy load, while simultaneously closing down on the risk for legionella, warrants new demand response and load balancing tools, techniques for reducing heat losses, efficient use of water, and achieving hotter water temperature at the top of the tank (higher water outlet temperature). It is particularly important that electric water heaters are appropriately designed and installed to ascertain that minimum safe temperatures are preserved throughout the electric hot water tank and distribution system.

In addition, there are forecasting techniques to predict 4-hour-ahead household hot water consumptions or demands using exponential smoothing, autoregressive integrated moving average (ARIMA) models, seasonal decomposition models and a host of simulation and forecasting techniques. This shows that prediction methods combined with advanced control techniques can be applied to control hot water consumption without compromising safety or increasing health hazards on consumers (Gelazanskas & Gamage, 2015).

For further readings on advanced control techniques in operating residential electric water heating, some pertinent papers have been cited in the ‘additional reference’ section below.

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