Energy Efficiency Potential of Gas-Fired Water Heating Systems in a Quick Service Restaurant

An Emerging Technology Field Monitoring Study

FSTC Report 5011.07.19

Food Service Technology Center
October 2007

Prepared by:

Angelo Karas
Don Fisher

Contributor:
Charles Wallace

Fisher-Nickel, inc.
12949 Alcosta Blvd., Suite 101
San Ramon, CA 94583
www.fishnick.com

Prepared for:

Pacific Gas & Electric Company
Customer Energy Efficiency Programs
PO Box 770000
San Francisco, California 94177

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Acknowledgments

The PG&E Food Service Technology Center (FSTC) acknowledges the support provided by suppliers of the water heating equipment for this field study.

The FSTC recognizes the commitment of the participating restaurant chain to increasing the energy efficiency of its facilities and eagerness to support this emerging technology initiative. The willingness of the restaurant staff to accommodate our on-site visits and needs was appreciated.

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The hot water load represents a significant portion of the energy and water consumed in a commercial food service operation. The objective of this field study was to characterize the hot water demand and associated energy use of a high efficiency (condensing) gas-fired tank-type (storage) water, a standard-efficiency gas-fired tankless (i.e., instantaneous) water heater and a high efficiency gas-fired tankless gas water heater installed and monitored sequentially in a quick-service restaurant. All work was done under the auspices of the Pacific Gas and Electric (PG&E) Company within the scope of its Emerging Technologies (ET) Program.

The study was conducted at a multi-unit (chain) quick-service restaurant with a hamburger-theme menu located in Pleasant Hill, California. From the perspective of the restaurant design team, a key motive to participate in this study was to determine if there would be an energy cost saving benefit to specifying an instantaneous water heater over their current high efficiency, tank-type heater specification. The water heating system in this restaurant was designed with a 125,000 Btu/h, 60-gallon high efficiency water heater (GAMA reported[1] Thermal Efficiency of 95% with Standby Loss of 560 Btu/h). The FSTC contracted to have a standard-efficiency 236,000 Btu/h tankless water heater (Thermal Efficiency of 82% calculated using the manufacturer's input rate and capacity specifications) installed alongside the existing heater. Subsequently, a high efficiency tankless heater with an input rate of 199,000 Btu/h (Thermal Efficiency of 91.7% from manufacturer's specification sheet) was installed in place of the standard-efficiency tankless heater. The plumbing was arranged so that either the tank-type or tankless water heater could be "valved" in or out and operated independently. All pertinent data was logged at one-minute intervals. The parameters of interest were temperature of the incoming cold water, temperature of outgoing hot water, water flow through the heaters, and gas consumption of the heaters.

The daily hot water consumption in this restaurant averaged close to 500 gallons per day, nominally ranging from 200 gallons to 900 gallons per day over the monitoring period. With the high efficiency tank heater, a peak flow (based on the average over a 1-minute period) of ten gal/min (10 gpm) was recorded. Inherent in its design, at full capacity, a tankless heater typically will restrict the flow of hot water to maintain a constant [setpoint] outlet temperature. Thus, the measured peak flow with the tankless heaters in operation was approximately five gal/min (5 gpm). Since this restaurant did not have any flow-sensitive equipment such as a dishwasher, this flow rate limitation did not pose a problem. Figure ES-1 illustrates a typical load profile for an average hot-water-use day with the tank-type heater in operation. Figure ES-2 shows a plot of daily energy efficiency versus daily hot water use for the three water heaters.

[1] Gas Appliance Manufacturers Association (GAMA) Consumers' Directory of Certified Efficiency Ratings for Heating and Water Heating Equipment, August 1, 2007.

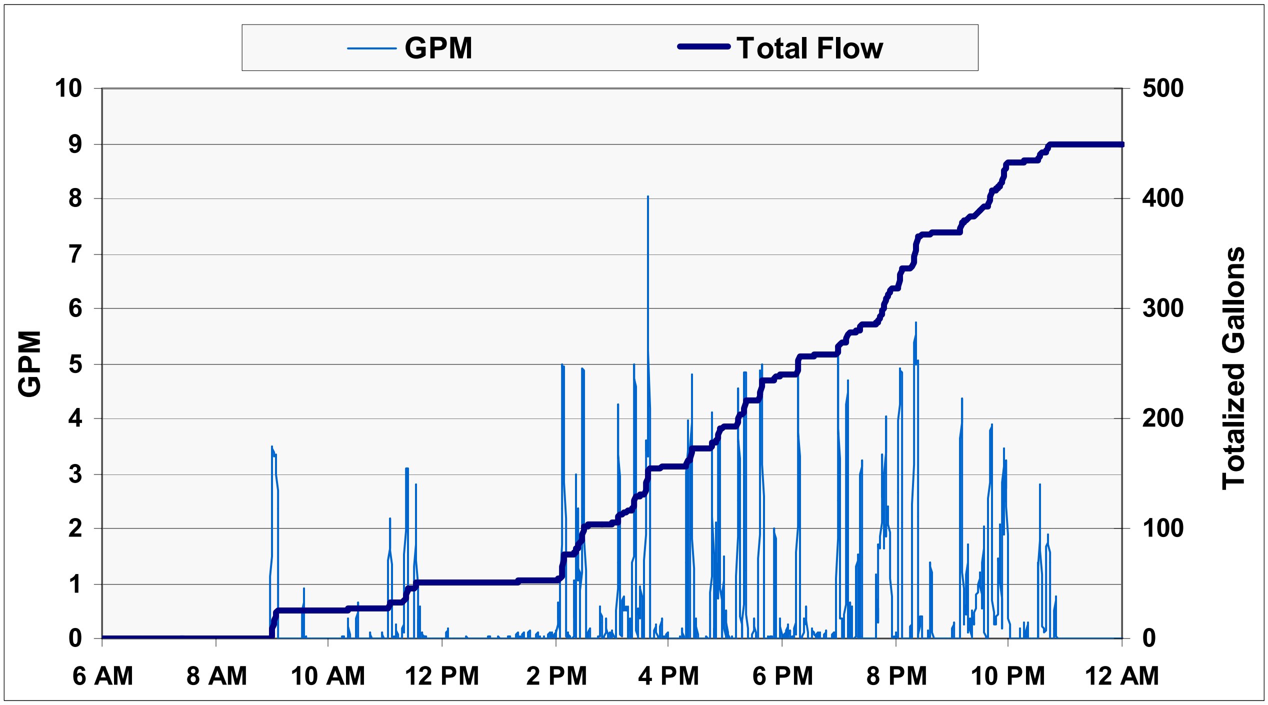

Figure ES-1. Typical Daily Hot Water Use Profile and Load

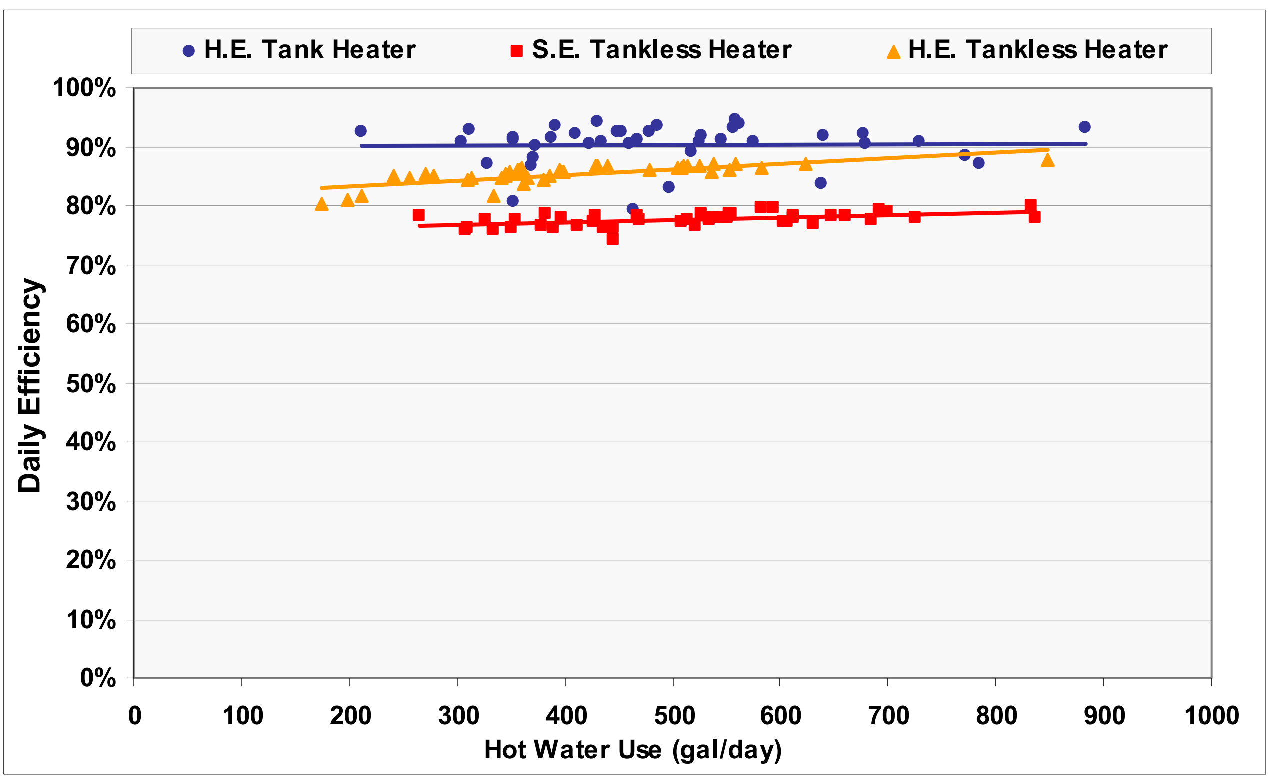

Figure ES-2. Daily Efficiency versus Hot Water Use

Calculated water heating energy efficiencies, projected annual gas consumption and operating costs for the three heaters are shown in Table ES-1. Results are normalized for a water consumption of 500 gal/day and a 70°F temperature rise. Daily system energy efficiencies averaged 90.3% for the high efficiency (H.E.) tank heater, 77.6%, for the standard efficiency (S.E.) tankless heater and 85.4% for the high efficiency (H.E.) tankless heater.

Table ES-1. Summary of Results and Energy Cost Projections.

	High Efficiency Tank Heater	Standard Efficiency Tankless Heater	High Efficiency Tankless Heater
Outlet Temperature Setpoint	135°F	140°F	140°F
Average Water Consumption (gal/day)	493	516	403
Average Gas Consumption (cu. ft./day)	312	419	231
Mass-Weighted Average Outlet Temperature	135.9°F	136.0°F	133.7°F
Mass-Weighted Average Inlet Temperature	65.5°F	61.5°F	74.3°F
Mass-Weighted Average Temperature Rise	70.4°F	74.5°F	59.4°F
Time-Averaged Outlet Flow Temperature	137.8°F	126.6°F	122.1°F
Average Daily Efficiency (%)	90.3 %	77.6 %	85.4 %
Projected Gas Consumption (therm/year)*	1178	1371	1246
Projected Annual Cost ($/year)**	$1,442	$1,663	$1,514

* Results normalized to 365 day/year operation, 500 gal/day hot water use and a 70°F temperature rise. Heating Value = 1020 Btu/ft^3
** Based on $1.20/therm. Includes electricity costs attributed to water heater blower motors, based on $0.15/kWh.

The annual energy cost of the high efficiency tank water heater was projected to be $1,442 while the annual energy cost for the standard efficiency and high efficiency tankless heater was projected to be $1,663 and $1,514 respectively (based on $1.20/therm). The high efficiency tank heater energy cost saving would be $221 per year over the standard efficiency tankless unit and a marginal $72 per year over the high efficiency tankless heater. Similarly, the high efficiency tankless unit would save $149 over its standard efficiency tankless counterpart.

Although not monitored within the scope of this project, it was calculated (assuming a daily water heating efficiency of 70%) that a standard efficiency tank-type water heater would have an annual energy cost of $1,830. Based on this assumption, there would be a $388 per year saving with the high efficiency tank heater, a $316 per year saving with the high efficiency tankless heater and a $167 per year saving with the standard efficiency tankless heater. It is important to recognize that this comparison is based on a realistic, but assumed, efficiency of 70% for the standard efficiency tank.

From an efficiency standpoint, and based on the results of this field testing, the FSTC recommends that the restaurant chain that participated in this study continue to specify high efficiency water heaters—either a tank-type heater or tankless unit. The increased Thermal Efficiency of the high efficiency tankless heater (i.e., 92%) has reduced its energy cost difference between the high efficiency tank heater (Thermal Efficiency of 95%) to the point where the selection of the heater type by the restaurant design team becomes a function of installation and maintenance cost experiences, along with any “foot print” reduction credit.

Within the scope of this field monitoring study, it was not possible to compare the purchase and/or installed cost for the three water heaters if they were independently installed in this restaurant. The high efficiency heater was pre-existing, while the tankless units were provided by the manufacturers at no charge. In addition, the installation was non-standard due to the instrumentation and piping of the testing configuration. Total installed cost comparisons can only be determined by the chain restaurant design team based on actual construction bids or invoices.

The PG&E Food Service Technology Center (FSTC) and Emerging Technology (ET) Program, in parallel with its California Energy Commission (CEC) Public Interest Energy Research (PIER) study on water heating efficiency potential, plans to develop design guidelines and energy cost modeling tools for water heating systems in commercial food service facilities.

Background

The hot water load represents a significant portion of the energy and water consumed in a commercial food service operation. A cursory estimate by the FSTC suggests that gas load associated with water heating in California commercial food service facilities could be as high as 400 million therms per year, closely matching the gas load associated with commercial cooking equipment. Both water heating and commercial cooking equipment are the target of a more in-depth study being conducted by the PG&E Food Service Technology Center (FSTC) within the scope of a California Energy Commission (CEC) Public Interest Energy Research (PIER) project. The goal is to quantify the gas saving potential in the commercial food service sector.

Objective and Scope

The objective of this field study was to characterize the hot water load and associated energy use of a high efficiency (condensing) gas-fired tank-type (storage) water heater, a standard-efficiency gas-fired tankless (i.e., instantaneous) water heater and a high efficiency gas-fired tankless gas water heater installed and monitored sequentially in a quick-service restaurant. All work was done under the auspices of the Pacific Gas and Electric (PG&E) Company within the scope of its Emerging Technologies (ET) Program. A previous ET field study compared a standard efficiency tank heater to a high efficiency tank heater in a full-service, casual dining restaurant with much higher water use [ref 1].

Water Heater Technologies

A high efficiency tank water heater differs from a standard efficiency unit in its ability to transfer energy from the combustion gases to the water. Generally, a high efficiency unit will utilize a multi-pass heat exchanger design as opposed to the single pass system of most standard efficiency units. The former allows substantially more heat to be extracted from the hot combustion gasses and transferred to the water. In this case, these gasses are cooled below the dew point temperature, causing water vapor in the combustion product to condense. High efficiency (condensing) water heaters exhibit thermal efficiencies around 95%, as opposed to 80% for standard efficiency, non-condensing units. A tank heater must be appropriately sized for input rate and tank volume to meet recovery capacity requirements.

An instantaneous or tankless water heater, as its name implies, has no hot water storage capacity (though it may be integrated with an external storage tank and temperature controlled recirculation pump). Without storage, this results in a water heating system that does not have the stand-by losses associated with tank style heaters. The nature of instantaneous water heaters, however, is that an individual unit will have a maximum water flow rate for a given temperature rise (e.g., 5 gpm at a 70°F rise) whereas a tank type heater can handle large transient loads because of its storage capacity. Depending on the particular application, this “flow limiting” characteristic may or may not be acceptable. In some instances, limiting hot water flow may interfere with the performance of other equipment, such as a warewashing machine. In other cases, it might only slow production a bit (e.g., time to fill a pot sink with hot water may increase). It is therefore important to determine the minimum acceptable peak flow rate for a given application. In the case of a full-service restaurant with high peak hot water demand, multiple tankless units would be needed to meet that demand. In restaurants without high hot water demand processes or equipment, such as quick service facilities without dishwashers, the restricted peak flow from one tankless heater may be adequate.

While the savings generated by the lack of stand-by losses may be substantial in low-water consuming applications (e.g., residential, office buildings, etc.), this is not the case for a restaurant application where the stand-by losses from the tank itself are a small fraction of the overall water-heating load. It is important to recognize the difference between Energy Factor and Thermal Efficiency reported in the GAMA directory [ref 2]. The Energy Factor rating is applicable only to residential water heaters while Thermal Efficiency is applied to commercial water heaters. The Energy Factor accounts for standby losses associated with a typical residential water-draw profile. For commercial tank-type water heaters the Standby Loss is reported as a separate parameter in the GAMA directory.

Venting requirements will affect the installed cost of water heaters. High efficiency, fully condensing water heaters generally use less expensive PVC venting that may offset the cost premium associated with this type of heater (compared to a standard efficiency tank heater). Instantaneous heaters require the use of stainless steel Category III venting. This additional cost can be reduced with strategic placement of the heater in order to minimize the required length of venting. Installation on an outside wall or roof, which reduces or eliminates the vent piping, may be an option (although this approach may be limited to more moderate climate zones).

Although both a standard efficiency and high-efficiency tankless heater were procured for this study, it should be noted that high efficiency tankless water heaters (e.g. with efficiencies greater than 90%) are not widely available in North America. (The high efficiency tankless unit tested in this study was the only high efficiency model identified in the U.S.) Although it has been anecdotally reported that high efficiency (condensing) tankless heaters are more common in the Japanese market, most of the models offered in the U.S. have reported thermal efficiencies in the low to mid 80% range [ref 2].

Site Description

The study was conducted at a multi-unit (chain) quick-service restaurant with a hamburger-theme menu located in Pleasant Hill, California. The water heating system was designed with a 60-gallon, 125,000 Btu/h high efficiency tank type water heater (GAMA reported [ref 2] Thermal Efficiency of 95% with Standby Loss of 560 Btu/h). The system handled all water-heating needs, which included hand sinks, a pre-rinse spray valve, general wash station and a mop sink. The heater was located adjacent to the kitchen (shown in Figure 1). The hot water system did not incorporate a circulation loop and pump. The FSTC contracted to have a 236,000 Btu/h (Thermal Efficiency of 82% calculated using manufacturer's input rate and capacity specifications) instantaneous water heater installed along side the existing heater. Subsequently, a high efficiency tankless heater with an input rate of 199,000 Btu/h (Thermal Efficiency of 91.7% from manufacturer's specification sheet) was installed in place of the standard efficiency tankless heater. The plumbing was arranged so that either the tank-type or tankless water heater could be "valved" in or out and operated independently (shown in Figure 2).

From the perspective of the restaurant design team, the goals of the study were to quantify the hot water usage and to determine if there would be an energy cost saving benefit to specifying an instantaneous water heater over their current high efficiency, tank-type heater specification.

Figure 1. Water Heater as Originally Installed

Figure 2. Water Heater Test Arrangement

Field Test Protocol

The instrumentation package included a gas meter with a 1 pulse per cu. ft. output, a water meter with a 20 pulse per gallon output installed on the cold water supply and temperature probes at the water inlet and outlet piping of each heater. A data acquisition system, operating with a 5-second scan interval and a 1-minute recording interval, logged the average inlet and outlet temperatures and cumulative water and gas consumption from the meter pulse outputs. System efficiency was calculated by dividing the "heat" energy transferred to the water by the "gas" energy consumed by the water heater.

Water heater daily efficiency was defined as the amount of energy required to heat the daily water volume (from the measured inlet temperature to the measured outlet temperature) divided by the daily gas consumption of the water heater. After collecting and analyzing the data, daily system operating efficiencies were calculated using the following formula:

Eff = Energy into Water / Energy Consumed by Heater

$$Eff = (100 * \text{mass flow}_{water}\,[lb/day] * \Delta T_{water}\,[°F] * C_{water}\,[Btu/lb*°F]) / (\text{flow}_{gas}\,[ft^3/day] * HHV_{gas}\,[Btu/ft^3])$$

In calculating these daily efficiencies, $\textit{mass flow}_{water} * \Delta T_{water}$ was computed for each one-minute test interval, summed over the day and then divided by gas energy. This technique eliminated the inclusion of any no-flow periods when the measured temperature in the outlet pipe would drop below the tank temperature or when the instantaneous heater was off. If this data were included in the average ΔT_{water} calculation, the efficiency would be incorrectly calculated. Reported average mass-weighted inlet and outlet temperatures were calculated by dividing the daily summed one-minute interval $\textit{mass flow}_{water} * T_{water}$ values by the daily $\textit{mass flow}_{water}$ total. A higher heating value (HHV) of 1020 Btu/ft^3, representative of gas supply in the area, was used in all efficiency calculations.

Results and Discussion

Hot Water Load. The restaurant's average daily hot water consumption was 475 gal/day and ranged between 175 and 883 gal/day over the 173-day monitoring period. A typical hot water flow profile, measured with the tank heater in operation, is shown in Figure 3. With the high efficiency tank heater, the peak demand, based on the average over a 1-minute period, was as high as 10 gpm. Note: flow rates based on 1-minute averages may not represent the peak instantaneous hot water demand, as the actual peak based on short-draw events may be somewhat higher. Peak flow with either of the tankless heaters in operation was limited to about 5 gpm as it was dependent on the given temperature rise. As reflected in Figure 3, most upper-range flow events were below 5 gpm, and since the restaurant did not have any flow-sensitive equipment such as a dishwasher, the peak flow rate for the tankless heater was considered adequate. Figure 4 shows a histogram of daily hot water use throughout the monitoring period, represented in 20-gal/day intervals.

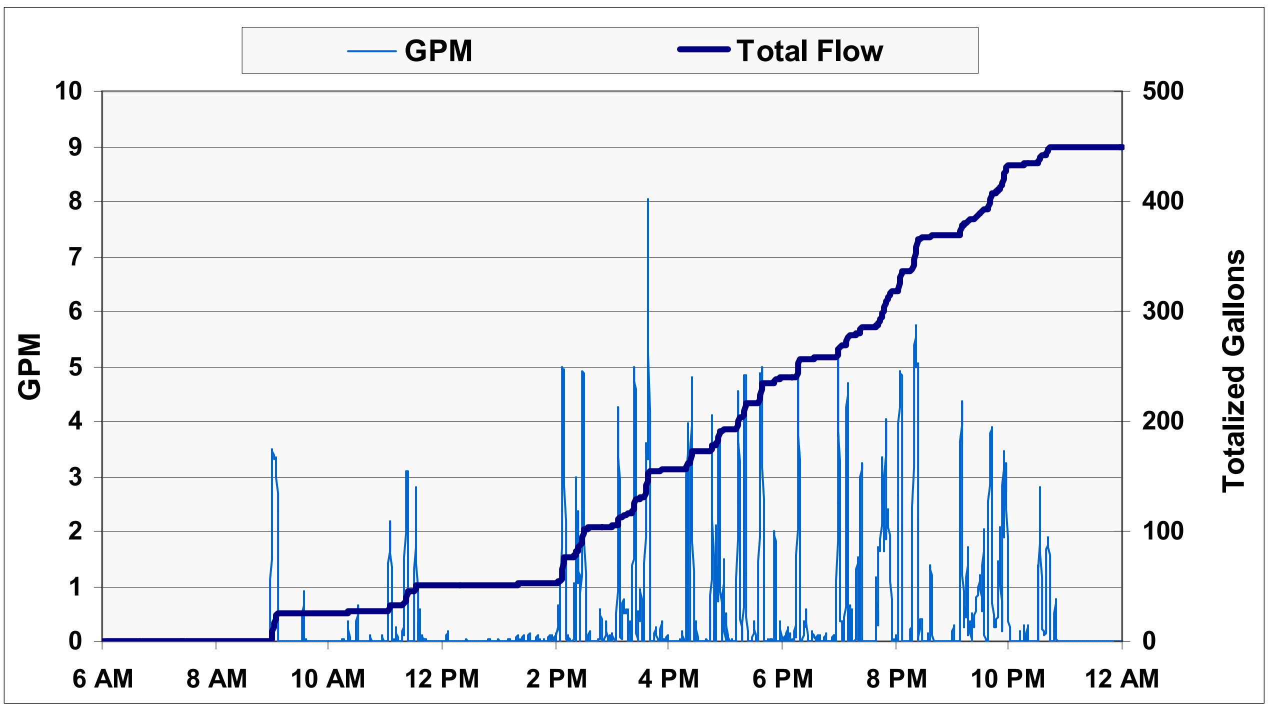

Figure 3. Typical Daily Hot Water Use Profile and Load

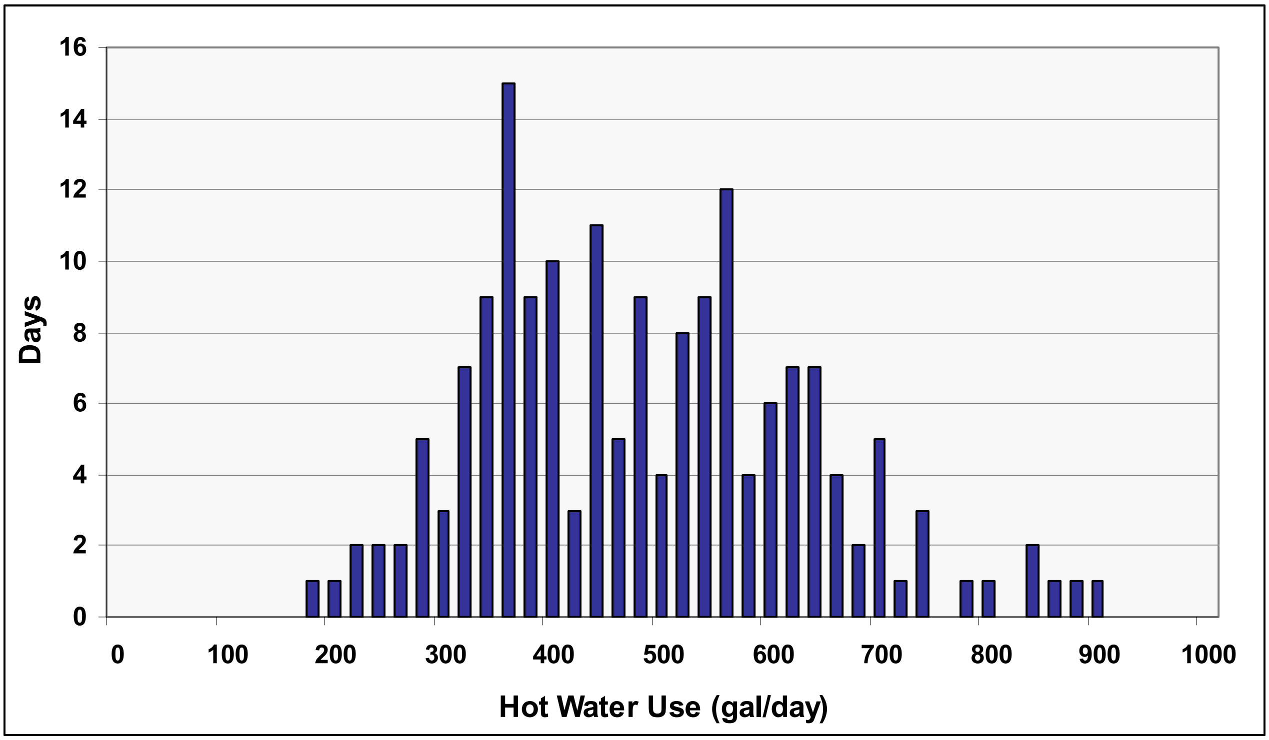

Figure 4. Daily Hot Water Use Frequency Distribution

Water Heater Characteristics and Performance. Performance differences between the two water heating technologies were observed with respect to the delivered outlet temperature. Intrinsic to its design, the tank-type heater cycles to maintain the average tank temperature at or above the thermostat setpoint; it typically delivers hot water with a mass weighted outlet temperature above its setpoint during short-draw, low-flow intervals and below this setpoint under heavy draw intervals. On the other hand, the instantaneous heater requires that initial water flow be established for a finite amount of time before the burner sequence initiates and then slightly more time before the delivered water reaches setpoint temperature. It therefore delivers water below its setpoint under short-draw, low-flow intervals but can supply continuous hot water at its setpoint temperature within its flow capability for a given temperature rise.

The high efficiency tank heater, when first monitored, was operating with a temperature setpoint adjusted to 140°F. A mass-weighted average delivered outlet temperature of 140.3°F was measured. The standard efficiency tankless heater was also set to a temperature setting of 140°F. However, the calculated mass-weighted outlet temperature was only 136.0°F. Figure 5 shows superimposed typical-day recorded outlet temperature profiles with the high efficiency tank heater and standard efficiency tankless heater both set to 140°F. The differences in heater performance and associated outlet temperatures are apparent.

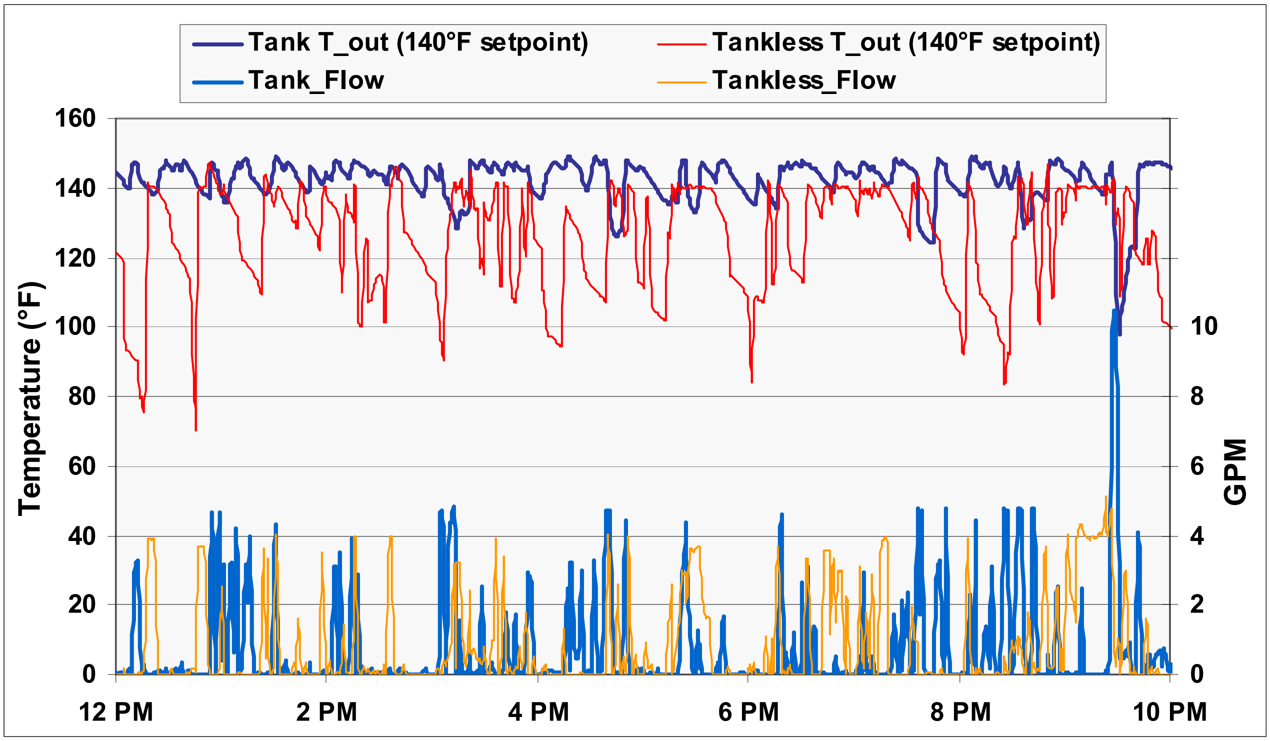

Figure 5. Recorded Outlet Temperatures with 140°F Setpoints

Because of the discrepancy in output temperature (and associated difference in water heating energy), the high efficiency tank heater temperature setpoint was lowered to 135°F to attain a closer match in the mass-weighted temperature. Figure 6 shows the temperature profile comparison with the tank heater set to 135°F and the tankless set at 140°F. With the new setpoint of 135°F for the tank heater, the average mass-weighted outlet temperature was reduced to 135.9°F—virtually the same as that the 136.0°F mass-weighted outlet temperature of the tankless heater. All subsequent testing and all the efficiency and energy consumption comparisons were performed with these temperature setpoints. When the high efficiency tankless heater was installed and operated at the 140°F setpoint, its recorded mass-weighted outlet temperature was slightly lower at 133.7°F. In this case, however, the 140°F setpoint was not adjusted upwards. The difference in water heating load due to its lower mass-weighted temperature was compensated for in the analysis by normalizing gas consumption to a nominal 70°F temperature rise.

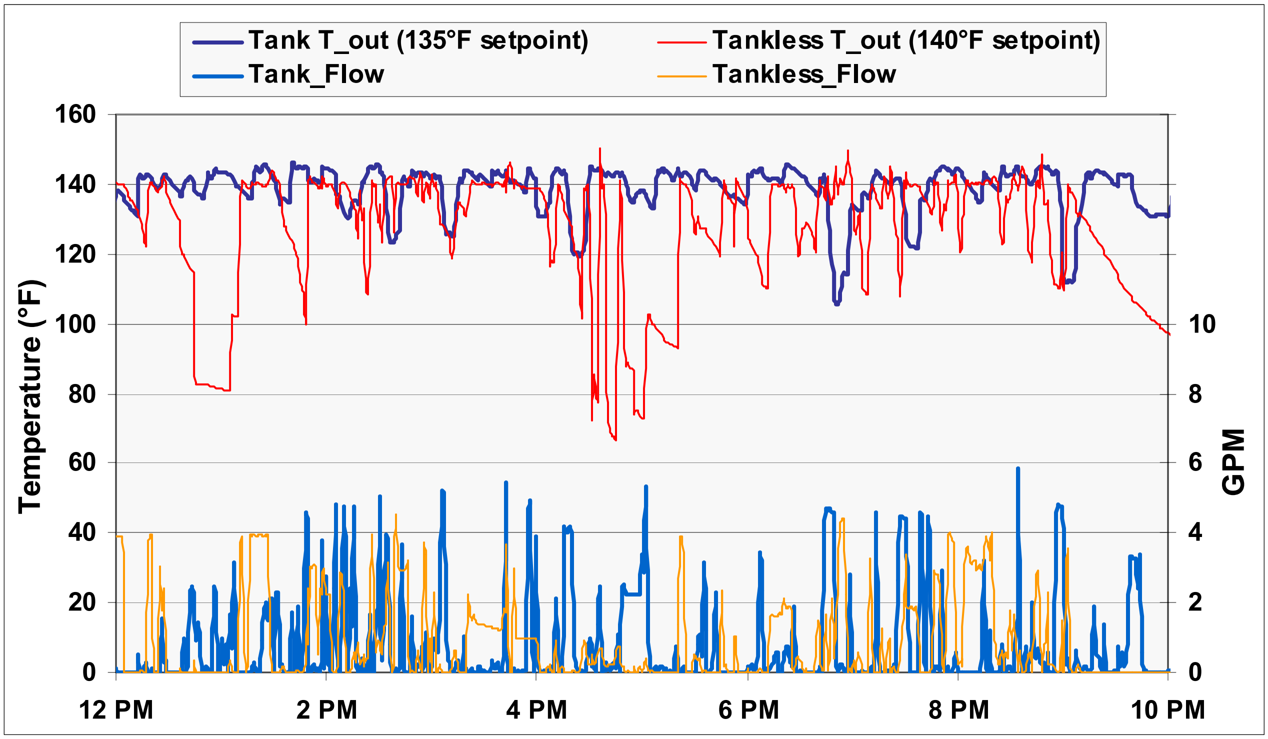

Figure 6. Recorded Outlet Temperatures with Equivalent Setpoints

Other performance differences can be observed from the profiles. The recorded outlet temperature of the tank heater would cycle between 130°F and 140°F during normal operation and would at times drop lower during high flow periods. The instantaneous heater would generally reach and maintain its 140°F setpoint during steady draws and at times would have brief peak temperatures of approximately 150°F. The sharp drops in the tankless heater profile indicate periods of no or little flow, whereas the large sags in the tank heater profile indicate heavy draws that would push recovery capacity of the heater to its limit.

Water Heater Efficiency and Energy Use. Figure 7 shows a plot of daily energy efficiency versus daily hot water use for the three water heaters. Daily system energy efficiencies averaged 90.3% for the high efficiency (H.E.) tank heater, 77.6%, for the standard efficiency (S.E.) tankless heater and 85.4% for the high efficiency (H.E.) tankless heater. Using the average daily system efficiency determined for each particular heater, normalized annual gas consumption was calculated assuming a standard temperature rise of 70°F (based on an average inlet water temperature of 65°F and outlet water temperature of 135°F) and a higher heating value of 1020 Btu/ft^3. This normalization is extremely important in field testing, as the inlet water temperature can vary significantly over the course of a multi-month test. During this study, recorded inlet water temperatures ranged from 48°F in the winter to 74°F in the summer—having a direct impact on measured gas consumption (independent of water heater efficiency). Table 1 presents a summary of the test data and energy cost projections for this quick service restaurant application.

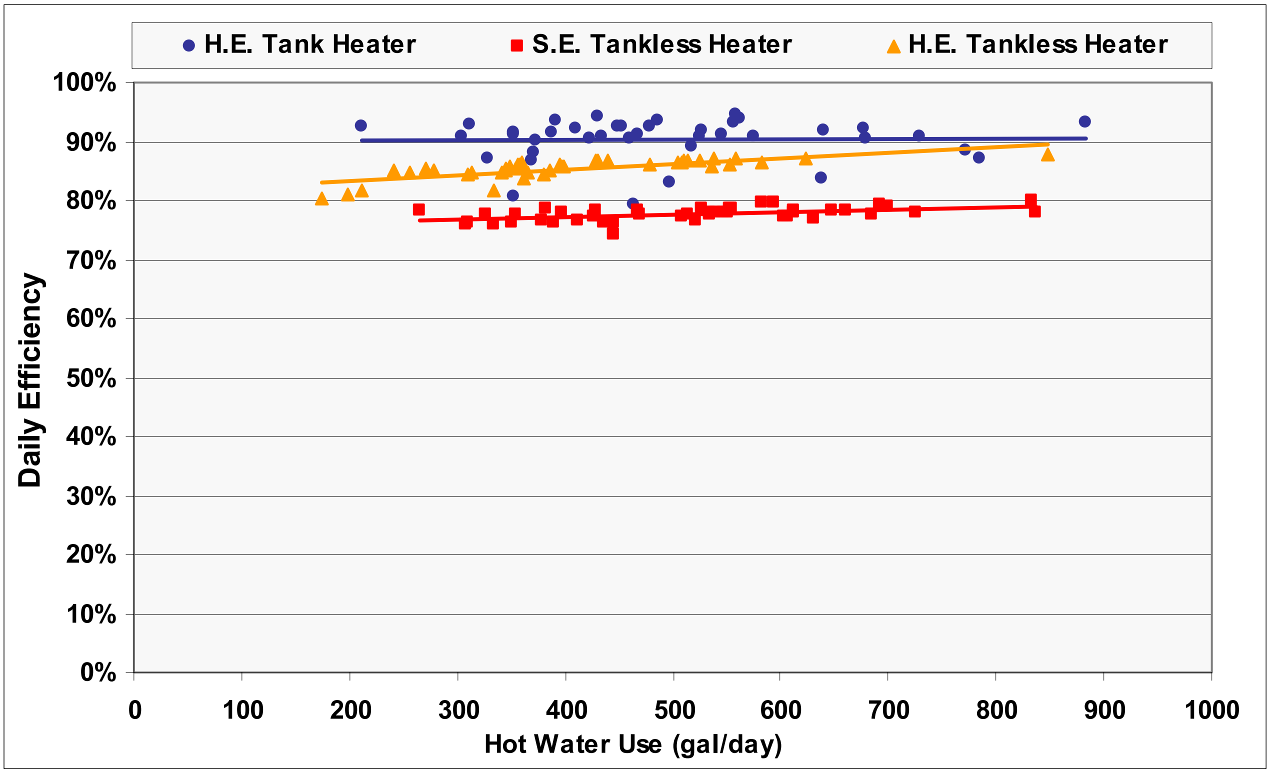

Figure 7. Daily Efficiency versus Hot Water Use

Table 1. Summary of Results and Energy Cost Projections.

	High Efficiency Tank Heater	Standard Efficiency Tankless Heater	High Efficiency Tankless Heater
Outlet Temperature Setpoint	135°F	140°F	140°F
Average Water Consumption (gal/day)	493	516	403
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* Results normalized to 365 day/year operation, 500 gal/day hot water use and a 70°F temperature rise. Heating Value = 1020 Btu/ft^3
** Based on $1.20/therm. Includes electricity costs attributed to water heater blower motors, based on $0.15/kWh.

Conclusions and Recommendations

The annual energy cost of the high efficiency tank water heater was projected to be $1,442 while the annual energy cost for the standard efficiency and high efficiency tankless heater was projected to be $1,663 and $1,514 respectively (based on $1.20/therm). The high efficiency tank heater energy cost saving would be $221 per year over the standard efficiency tankless unit and a marginal $72 per year over the high efficiency tankless heater. Similarly, the high efficiency tankless unit would save $149 over its standard efficiency tankless counterpart.

Although not monitored within the scope of this project, it was calculated (assuming a daily water heating efficiency of 70%) that a standard efficiency tank-type water heater would have an annual energy cost of $1,830. Based on this assumption, there would be a $388 per year saving with the high efficiency tank heater, a $316 per year saving with the high efficiency tankless heater and a $167 per year saving with the standard efficiency tankless heater. It is important to recognize that this comparison is based on a realistic, but assumed, efficiency of 70% for the standard efficiency tank.

From an efficiency standpoint, and based on the results of this field testing, the FSTC recommends that the restaurant chain that participated in this study continue to specify high efficiency water heaters—either a tank-type heater or tankless unit. The increased efficiency of the high efficiency tankless heater (Thermal Efficiency of 92%) has reduced its energy cost difference between the high efficiency tank heater (Thermal Efficiency of 95%) to the point where the selection of the heater type by the restaurant design team becomes a function of their installation and maintenance cost experiences, along with any “foot print” reduction credit. Specification of a tankless water heater with a GAMA rated Thermal Efficiency greater than 90% may stimulate other manufacturers to introduce higher efficiency tankless models to the U.S. market.

Within the scope of this field monitoring study, it was not possible to compare the purchase and/or installed cost for the three water heaters if they were independently installed in this restaurant, much less any maintenance cost differences. The high efficiency heater was pre-existing, while the tankless units were provided by the manufacturers at no charge. In addition, the installation was non-standard due to the instrumentation and piping of the testing configuration. Total installed cost comparisons can only be determined by the chain restaurant design team based on actual construction bids or invoices.

PG&E Focus. In general, hot water load characterization in commercial food service facilities should be expanded and water heater testing should continue both in field and laboratory environments. As more field studies are completed, the industry will have a better understanding of hot water use profiles for various types of commercial food service facilities. These load profiles can be replicated in the laboratory, where, with more sophisticated data acquisition equipment than that used in the field, PG&E will gain a better understanding of the driving parameters for overall system efficiency. The PG&E Food Service Technology Center (FSTC) and Emerging Technology (ET) Program, in parallel with its California Energy Commission (CEC) Public Interest Energy Research (PIER) study on water heating efficiency potential, plans to develop design guidelines and energy cost modeling tools for water heating systems in commercial food service facilities.

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1. PG&E Food Service Technology Center. 2007. Energy Efficiency Potential of Gas-Fired Commercial Hot Water Heating Systems in Restaurants: An Emerging Technology Field Monitoring Study. FSTC Report 5011.07.04
2. GAMA Product Directories: http://www.gamanet.org. Gas Appliance Manufacturers Association (GAMA) Consumers' Directory of Certified Efficiency Ratings for Heating and Water Heating Equipment, August 1, 2007.