The Dependence of Water Heater Energy Factor on Deviations from Nominal Conditions

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ABSTRACT

An analytical study is carried out to assess the impact of corrections to nominal test conditions on the measured energy factor for residential water heaters. While test conditions are specified in the method of test, the difficulty in exactly achieiving these test conditions in the laboratory necessitates a computational approach to correct the results to nominal conditions. This paper examines the magnitude of those corrections for a range of water heaters of various fuel type, heating method, and size across a number of potential draw volumes during a 24 hour simulated use test. In making these corrections, a recovery efficiency and a standby heat loss coefficient are determined during the test; the effects of variations in those measured values on the resultant energy factor are discussed. Finally, the impact of tighter test tolerances on the variability of the energy factor is investigated to assist in evaluating the benefits of changing test conditions.

INTRODUCTION

When testing the energy performance of equipment to be used in buildings, an attempt is typically made to ensure that units are tested under the exact same conditions to ensure equitable comparisons between products. For example, the ambient temperature can alter the measured efficiency of some products, so a nominal temperature is prescribed with tolerances. Practically, however, it is very difficult to achieve this exact nominal temperature in a laboratory, so mathematical adjustments are often used to correct the measured efficiency to nominal conditions so that the performance of all equipment is reported at the same conditions.

This approach is taken in the efficiency test for residential water heaters. ASHRAE Standard 118.2 (ASHRAE 2006) provides a test method that is used to rate the energy efficiency of residential water heaters, and the Department of Energy (DOE) maintained a similar method that was used in the United States (United States Department of Energy 1998). This test method prescribes a 24 hour simulated use test during which 6 draws of hot water are taken from the water heater followed by a long standby period. The energy removed from the unit as hot water as well as the energy consumed by the water heater is measured. The efficiency metric is based on the ratio of the energy removed to the energy consumed, but this ratio is first adjusted to account for deviations from nominal conditions.

During the test as carried out in the United States in the year 2014, a number of conditions are required. The ambient temperature is to be maintained at 19.7 °C ± 1.4 °C (67.5 °F ± 2.5 °F), the temperature of water delivered to the water heater is to be 14.4 °C ± 1.1 °C (58 °F ± 2 °F), and the thermostat is to be set to store and deliver water at 57.2 °C ± 2.8 °C (135 °F ± 5 °F). Additionally, an underlying assumption of the test is that the thermal state of the water heater does not change from the beginning of the test to the end. Calculations are implemented to convert the ratio of the output energy to the input energy to the regulating metric, termed the energy factor (EF), by normalizing the energy consumption to the nominal conditions. While the test procedure for residential water heaters in the United States has changed based on a new rule published by the Department of Energy (United States Department of Energy 2014) , this study bases the analysis on the conditions in the test procedure in place between approximately 1991 and 2015. A similar approach to the one taken in this manuscript could be applied to determine the impacts of the changes incorporated in the new test procedure.

ASHRAE Standards Project Committee 118.2 is currently revising the standard, and questions have arisen regarding the need for such corrections and whether or not tolerances on prescribed conditions are sufficient to ensure consistent results. The purpose of this paper is to address the following questions: 1) What corrections have the most impact on the energy factor when test conditions deviate furthest from their nominal values? 2) How do errors in the key performance metrics of standby heat loss coefficient (UA) and recovery efficiency (η_r) affect the EF? 3) What effect would tighter tolerances on test conditions have on the accuracy of the EF metric?

OVERVIEW OF TEST METHOD AND CORRECTIONS

The current test method for rating the energy efficiency of residential water heaters as dictated by ASHRAE 118.2 (including parameters noted for the United States in Annex A) involves a 24 hour simulated use test. A water heater under test is plumbed according to a set piping arrangement considered as typical in a residence and is allowed to reach the prescribed operational temperature after being filled with water. During the 24 hour test, six draws of hot water that total 243 L (64.3 gallons) are taken from the water heater. These 6 equal-sized draws are taken at the start of the hour for the first 6 hours of the test, and the unit then sits in standby for the duration of the 24 hour period. During draws, inlet and outlet temperatures are measured to determine the amount of thermal energy delivered by the water heater. Energy input to the water heater (including electrical or fossil fuel) is measured for the entire 24 hour period. Additionally, a set of temperature sensors inserted in the tank measures the average temperature of the water inside the water heater, and a sensor located outside the tank provides a measure of the ambient temperature. The energy factor represents the ratio of the energy delivered in hot water at the nominal temperature rise from inlet to outlet to the energy input to the water heater adjusted to nominal conditions.

From the data collected during the test, two key performance metrics are determined that are used in adjusting the energy input. First, the recovery efficiency, η_r, is the ratio of the thermal energy added to the water for each unit of energy input to the unit. This metric captures, among other effects, the combustion efficiency, flue losses, standby loss during active heating, and leveraging of energy input by heat pump technology. The recovery efficiency is determined by dividing the thermal energy delivered as hot water in the first draw by the energy input required to bring the temperature of the stored water back to its level at the start of the test. If that recovery period extends beyond the first hour and into the time when subsequent draws occur, the thermal energy removed in those draws that occur prior to complete recovery are included in the numerator of the ratio. The second performance metric that is determined is the standby heat loss coefficient, UA. UA is determined during the long standby period at the end of the test. During this time, the average tank temperature, average ambient temperature, energy consumption, and elapsed time are recorded. UA is determined as:

$$\mathrm{UA} = \frac{Q_{\mathrm{consumed,stby}} - {}^{Q_{\mathrm{stored,stby}}}/_{\eta_r}}{t_{\mathrm{stby}}\left(T_{\mathrm{tank,stby}} - T_{\mathrm{amb,stby}}\right)} \tag{1}$$

where:

$Q_{\mathrm{consumed,stby}}$:	energy consumed during standby test period
$Q_{\mathrm{stored,\ stby}}$:	energy stored in hot water tank from start of standby test period to end
t_{stby}:	the duration of the standby test period

$T_{tank,stby}$: the average temperature of water in tank during standby test period

$T_{amb,stby}$: the average ambient temperature during standby test period

There are five primary adjustments that are made to normalize the energy input to the water heater.

Stored Energy from start of test to end: There is an inherent assumption in the test method that the resulting energy consumption represents steady operation over a cycle that repeats itself every day. If this ideal situation were achieved, the thermal energy stored within the tank at the start of the day would equal that at the end of the day, and the efficiency could truly be captured by dividing the energy output over the energy input. This ideal situation is difficult to achieve, however, so a correction is made to account for the fact that some of the input energy to the water heater may appear as stored energy instead of thermal output, thereby affecting the determination of the efficiency. This correction to the input energy is as shown in Equation 2:

$$Q_{adj,stored} = [m_{tank} * c_p * (T_{24} - T_0)] / \eta_r \tag{2}$$

where:

$Q_{adj,stored}$: energy input required to supply the amount of thermal energy stored in the water in the tank from the start of the test to the end

m_{tank}: mass of water inside storage tank

c_p: specific heat of water in storage tank evaluated at the average of T_{24} and T_0

T_{24}: average temperature of water in tank at end of 24 hour test period

T_0: average temperature of water in tank at start of 24 hour test period

$Q_{adj,stored}$ is subtracted from the measured energy consumption in determining the normalized energy input since that value represents input energy that does not show up as hot water delivered.

Ambient Temperature: The prescribed ambient temperature during the test is 19.7 °C (67.5 °F). If the actual ambient temperature is lower than this value, heat loss from the tank will be greater because of the greater temperature differential between the tank and the surrounding air. To normalize for this effect, the energy input is adjusted as:

$$Q_{adj,amb} = UA * t_s * (T_{amb,s} – T_{amb,n}) \tag{3}$$

where:

$Q_{adj,amb}$: difference in standby energy loss from the water heater between the measured ambient temperature and the nominal ambient temperature

t_s: period of 24 hour test during which water heater is in standby mode (defined as time when water is not being withdrawn from the unit)

$T_{amb,s}$: average ambient temperature during period of 24 hour test when water heater is in standby mode

$T_{amb,n}$: nominal ambient temperature

Note that in the current DOE test procedure, this adjustment refers to the energy input required to make up for this standby energy difference rather than to the thermal energy difference. To maintain consistency with that procedure, this manuscript uses the formulation noted. $Q_{adj,amb}$ is added to the measured energy consumption in determining the normalized energy input since a higher ambient temperature would underestimate standby losses.

Average stored water temperature: The current test method prescribes a setpoint temperature of 57.2 °C (135 °F) and adjusts the energy consumption should the average temperature of the water stored in the water heater deviate from this value. If the temperature drops below the nominal value, heat loss from the tank to the ambient will decrease. To adjust for this effect, the energy input is adjusted as:

$$Q_{adj,tank} = UA * t_s * (T_{tank,n} - T_{tank,s}) \tag{4}$$

where:

$Q_{adj,tank}$: difference in standby energy loss from the water heater between the measured stored water temperature and the nominal stored water temperature.

$T_{tank,n}$: nominal stored water temperauture

$T_{tank,s}$: average stored water temperature during period of 24 hour test when water heater is in standby mode

As noted above, this adjustment refers to the standby energy input to the tank rather than the thermal energy loss. $Q_{adj,tank}$ is added to the measured energy consumption in determining the normalized energy input since a lower stored water temperature would underestimate standby losses.

Inlet Water Temperature: The existing test method specifies an inlet water temperature of 14.4 °C (58 °F). Should the inlet temperature be lower than this value, the water heater would require more energy to deliver the specified volume of water. The numerator of the energy factor calculation assumes that the volume removed during the test truly rises from an inlet temperature of 14.4 °C (58 °F) to 57.2 °C (135 °F); an adjustment is made in the energy consumed to correct for deviations from the inlet temperature:

$$Q_{adj,in} = [m_{del} * c_p * (T_{in} - T_{in,n})] / \eta_r \qquad (5)$$

where:

$Q_{adj,in}$: difference in input energy required to deliver water from an inlet temperature different from the nominal value.

m_{del}: the mass of water delivered by the water heater during draws

c_p: specific heat of water evaluated at the average of the inlet and outlet temperatures

T_{in}: the average temperature of the water going into the water heater during draws

$T_{in,n}$: nominal inlet temperature

$Q_{adj,in}$ is added to the measured energy consumption in determining the normalized energy input since a higher inlet water temperature would decrease the energy required by the water heater. Inlet water temperature also greatly impacts the recovery efficiency of heat pump water heaters, but that issue is not considered in this correction.

Outlet Water Temperature: The existing test method specifies an outlet water temperature of 57.2 °C (135 °F). Should the outlet temperature be lower than this value, the water heater would require less energy to deliver the specified amount of water. The numerator of the energy factor calculation assumes that the volume removed during the test truly rises from an inlet temperature of 14.4 °C (58 °F) to 57.2 °C

(135 °F); an adjustment is made in the energy consumed to correct for deviations from the outlet temperature:

$$Q_{adj,out} = [m_{del} * c_p * (T_{out,n} - T_{out})] / \eta_r \tag{6}$$

where:

$Q_{adj,out}$: difference in input energy required to deliver water at an outlet temperature different from the nominal value

$T_{out,n}$: nominal outlet temperature

T_{out}: the average temperature of the water delivered by the water heater during draws

$Q_{adj,out}$ is added to the measured energy consumption in determining the normalized energy input since a lower outlet water temperature would decrease the energy required by the water heater.

In summary, given a measured input energy Q during the 24 hour test, the energy factor is essentially computed as:

$$EF = m_{del} * c_p * (T_{out,n} - T_{in,n}) / (Q - Q_{adj,stored} + Q_{adj,amb} + Q_{adj,tank} + Q_{adj,in} + Q_{adj,out}) \tag{7}$$

ANALYSIS

Computational Approach

If, during the simulated use test, the water heater and environmental conditions are controlled so well that the conditions match the nominal conditions, no corrections are required and the energy factor simply equals the numerator noted in Eq. (7) divided by the energy consumed. In this case, η_r and UA are not used, so errors in those values have no impact on the computed EF. As the conditions deviate from the nominal conditions, however, those performance parameters are utilized and errors in them do manifest themselves in the EF. A spreadsheet program was developed to compute these effects.

The inputs to the program to describe the water heater are the storage tank volume (V), the UA value of the water heater, the recovery efficiency of the water heater, and the input power to the water heater. The storage volume is estimated as being 90 % of the rated volume for electric water heaters and 95 % of the rated volume for fossil fuel water heaters. These values are consistent with tolerances specified by the American National Standards Institute (ANSI 2009, UL 1989) for these types of water heaters and are typical of measured volumes. For a given water heater, its recovery efficiency can typically be obtained through a directory maintained by the Air-Conditioining, Heating, and Refrigeration Institute (AHRI 2013). This value, along with the published energy factor and input power, can be used to estimate the UA value as follows:

$$Q_{nom} = V_{nom} * \rho * c_p * (T_{out,n} - T_{in,n}) / EF$$

$$Q_{lost} = Q_{nom} * (1 - EF)$$

$$Q_{lost,te} = Q_{in,burn} - Q_{del} = [V_{nom} * \rho * c_p * (T_{out,n} - T_{in,n})] * (1/\eta_r - 1)$$

$$Q_{lost,stby} = Q_{lost} - Q_{lost,te}$$

$$t_{s2} = 24 - [V_{nom} * \rho * c_p * (T_{out,n} - T_{in,n})] / (P * \eta_r)$$

$$UA = (Q_{lost,stby} / t_{s2}) / (T_{tank,n} - T_{amb,n})$$

with V_{nom} being the nominal volume of water removed per day during the current test, which is 243 L (64.3 gallons), Q_{nom} being the energy input required during the test, Q_{lost} being the energy not used to deliver hot water, $Q_{lost,te}$ being the lost energy attributed to burner or heating element inefficiency during recovery periods, $Q_{in,burn}$ being the energy input during recovery periods, Q_{del} being the thermal energy delivered during the test, $Q_{lost,stby}$ being the estimated energy required to make up for heat transfer from stored water to the ambient, t_{s2} being the standby time during the 24 hour test when burners, heating elements, or heat pump systems are not active, and P being the power input to the water heater.

To describe the test conditions under an arbitrary simulated test, the user inputs the average ambient temperature, average tank temperature, average inlet and outlet temperatures during draws, and the average stored water temperatures at the beginning and the end of the test. Additionally, the user can alter the amount of water removed per day during the test. Since the ASHRAE 118.2 committee is considering changes in the volume removed from the tank per day, this feature allows the user to examine the effect of corrections for different draw patterns. To obtain an estimate of the energy that would be consumed in this simulated test, the UA value, recovery efficiency, the volume of water removed per day, and the simulated temperatures for the test can be used. This estimate is obtained as:

$$Q_{est} = [V_{del}*\rho_d*c_p*(T_{out} - T_{in}) + V_{st}*\rho_s*c_p*(T_{24} - T_0)]/\eta_r + UA*\{24\ h - [V_{del}*\rho_d*c_p*(T_{out} - T_{in})]/(P*\eta_r)\}*(T_{tank} - T_{amb}) \quad (8)$$

where:

V_{del} = volume of water delivered per day

ρ_d = density of water at delivered temperature

c_p = specific heat of water

V_{st} = storage volume of water heater

ρ_s = density of water at average storage temperature

P = power input to water heater

A slightly different approach is used to estimate the energy consumption of tankless (instantaneous) water heaters. For these units, it is assumed that the heat loss coefficient is zero, with any standby electricity consumption being ignored since it tends to be much lower in magnitude compared to the daily fossil fuel energy consumption. Since reported energy factors are typically approximately 0.02 below the reported recovery efficiencies, however, there are some heat losses. These heat losses can be attributed to heat loss from the unit to the environment after a draw has taken place. Therefore, the heat loss is related to the number of draws during the simulated use test.

To estimate the heat loss per draw, $Q_{lost,draw}$ is computed by dividing $Q_{lost,stby}$ by six (the number of draws in the DOE test). It is assumed that all heat is dissipated from the water heater to the ambient between draws of the test. For a new draw pattern, this heat loss per draw is multiplied by the number of draws in the new pattern from which heat is lost, N_{draws}. An adjustment is made to the total number of draws during the test, however, to account for the fact that newer draw patterns may consist of draws that are closely clustered together during which residual heat may be left in the heat exchanger prior to the next draw. To account for this variation in the amount of energy lost, any draw that begins less than 15 minutes after the end of the previous draw is considered to lose no energy to the environment and does not contribute to N_{draws}. Any draw occurring with between 15 minutes and 30 minutes of standby time following the prior draw is considered to lose 50 % of its energy; each of these draws is counted as 0.5 draws in the summation to yield N_{draws}. Draws occurring with greater than 30 minutes of standby time following the previous draw are assumed to lose all their energy to the environment; these draws count fully when computing N_{draws}. These selections are admittedly arbitrary but are sufficient to allow estimation of basic energy consumption during the simulated use test. For tankless, the estimated energy consumption during a simulated use test is then:

$$Q_{est} = [V_{del} * \rho_d * c_p * (T_{out} - T_{in})] / \eta_r + N_{draws} * Q_{lost,draw} \quad (9)$$

Experimental Plan

To determine the effect of these corrections, analyses were carried out given typical water heaters subject to the worst case scenario, that being when the conditions deviate most significantly from their nominal values. All values are chosen so that the conditions during the simulated test would result in the lowest energy consumption yet still fall within the tolerances specified in the test procedure. These values are provided in Table 1.

Table 1. Nominal Test Conditions and Simulated Extreme Conditions

Test Condition	**Nominal Value**	**Extreme Condition**
Average stored water temperature at beginning of test[1], T_0	57.2 °C (135 °F)	60 °C (140 °F)
Average stored water temperature at end of test[1], T_{24}	57.2 °C (135 °F)	54.4 °C (130 °F)
Ambient Temperature, T_{amb}	19.7 °C (67.5 °F)	21.1 °C (70 °F)
Average Stored Water Temperature during test[1], T_{tank}	57.2 °C (135 °F)	54.4 °C (130 °F)
Average Inlet Water Temperature during draws, T_{in}	14.4 °C (58 °F)	15.6 °C (60 °F)
Average Outlet Water Temperature During Draws, T_{out}	57.2 °C (135 °F)	54.4 °C (130 °F)

[1] Stored water values are not relevant to instantaneous water heaters.

The water heaters to be analyzed represent a cross-section of those that were available in 2014 or could conceivably be available on the market. Table 2 lists those water heaters with key performance characteristics. Some of the units are not currently covered by United States' requirements for reporting, so they do not currently have energy factor ratings. For these units, estimates for EF, η_r, and UA are made. Additionally, some of the units may have efficiencies below the minimum standards set by DOE that went into effect in 2015; those units are included in this analysis for illustrative purposes.

The ASHRAE 118.2 committee is considering changing the current test procedure, which applies the same amount of water drawn per day and number of draws regardless of delivery capacity, to one in which a water heater is subject to a varying demand based on its size or delivery capacity. For the sake of this study, four categories of water heaters are considered, and each category is subject to a different amount of water drawn per day and number of draws during the test. Those categories, along with the amount of water drawn per day during the simulated use test, are: Point of Use (57 L [15 gallons]), Low Use (151 L [40 gallons]), Medium Use (243 L [64.3 gallons]), and High Use (314 L [82.75 gallons]). For the Point of Use (POU) pattern, 9 draws are implemented per day, whereas the other three involve 12 draws per day. The particular number of draws does not affect the performance of storage water heaters in this analysis, but the spacing of the draws could have impact on the performance of tankless water heaters. Based on the criteria presented previously to determine the number of draws from a cold start for computing losses from tankless water heaters, N_{draws} for each pattern is 7.5. The water heaters listed in Table 2 are slotted into an expected sizing category; while the ASHRAE 118.2 committee is considering using the First Hour Rating or a calculation based on storage volume and input energy rate to put water heaters into different size categories, these bins were selected based on typical applications in which a particular volume of water heater would be selected.

Table 2. Water Heaters Investigated

Unit #	Unit Description	Rated Volume, L [gal]	Power, kW	EF	ηr	UA, W/K [Btu/(h*F)]	Size Category
1	Electric Resistance	23 [6]	1	0.94[1]	0.98	1.16 [2.21]	POU
2	Electric Resistance	114 [30]	4.5	0.95	0.98	0.48 [0.91]	Low
3	Electric Resistance	189 [50]	4.5	0.90	0.98	1.35 [2.56]	Medium
4	Electric Resistance	189 [50]	4.5	0.95	0.98	0.48 [0.91]	Medium
5	Electric Resistance	303 [80]	4.5	0.86	0.98	2.12 [4.02]	High
6	Electric Heat Pump	114 [30]	0.75	2.4	2.6	0.57 [1.08]	Low
7	Electric Heat Pump	189 [50]	0.75	2.4	2.7	0.81 [1.54]	Medium
8	Electric Heat Pump	303 [80]	0.75	2.4	2.8	1.03 [1.96]	High
9	Natural Gas	114 [30]	8.79	0.63	0.75	3.63 [6.89]	Low
10	Natural Gas	189 [50]	11.7	0.60	0.75	4.66 [8.86]	Medium
11	Natural Gas (Condensing)	189 [50]	11.7	0.75	0.90	3.08 [5.85]	Medium
12	Natural Gas	284 [75]	17.6	0.53	0.75	7.59 [14.4]	High
13	Natural Gas (Condensing)	284 [75]	17.6	0.75	0.90	3.03 [5.75]	High
14	Oil Storage	114 [30]	29.3	0.63	0.85	5.53 [10.5]	High
15	Electric Resistance Tankless	n/a	n/a	0.97[2]	0.99	n/a	Low
16	Natural Gas Tankless	n/a	n/a	0.82	0.84	n/a	Medium
17	Natural Gas Tankless (Condensing)	n/a	n/a	0.93	0.95	n/a	Medium

1 Storage Type Water Heaters < 76 L (20 gallons) are not currently covered by the test procedure. The EF for a 23 L (6 gallon) water heater for purposes of this analysis is taken as the minimum efficiency level for a 76 L (20 gallon) unit.

2 Electric Tankless water heaters are not currently covered by the test procedure. The values used here are estimated.

For each of the water heaters listed in Table 2, the computations described earlier to correct the daily energy consumption are carried out assuming the extreme test conditions for 3 different levels of water draw per day. For water heaters falling under the Point of Use or Low Use categories, calculations were conducted assuming the point of use, low, and medium draw patterns. For water heaters falling under the medium or high use categories, calculations were conducted under the low, medium, and high use draw patterns. This approach will help clarify how the corrections impact similar sized water heaters when subject to different draw volumes and will have the side benefit of estimating the change in efficiency with different draw volumes.

RESULTS

Effect and magnitude of corrections

In the first set of tests, it is assumed that the UA and η_r values are known, so these values are fixed throughout the runs. Table 3 lists the results for the three draw volumes applied to each water heater. These results present the computed energy factors in several different ways. The first column of data shows the value fully corrected to nominal conditions as shown in equation 7. The next five columns omit particular corrections, and the sixth column lists the value if no corrections are applied ($EF = m_{del} * c_p * (T_{out,n} - T_{in,n}) / Q_{est}$). Two other computations are provided. The seventh column provides the efficiency computed simply as the output of thermal energy divided by the energy input:

$$EF_{io} = m_{del} * c_p * (T_{out} - T_{in}) / Q_{est} \quad (10)$$

This metric differs from the one previously mentioned without corrections in that the actual inlet and outlet temperatures are used instead of the nominal values in determining the delivered energy. The last metric provided computes the energy factor by adjusting the measured delivered energy for the energy stored inside the water heater and dividing that quantity by the measured energy delivered:

$$EF_a = [m_{del} * c_p * (T_{out} - T_{in}) + m_{tank} * c_p * (T_{24} - T_0)] \ / Q_{est} \quad (11)$$

Table 4 summarizes the results by presenting the average difference between the EF computed without particular corrections and the fully corrected value across all tests; results are presented by key technology types.

Table 3. Computed Energy Factors Using Different Corrections and Different Approaches. The Draw Pattern in Bold Denotes the Typical Draw Pattern for Each Unit

Water Heater	**Test Pattern**	**Fully Corrected**	**w/o storage correction**	**w/o ambient correction**	**w/o stored water temperature correction**	**w/o inlet temperature correction**	**w/o outlet water temperature correction**	**No corrections**	**EF_{io}**	**EF_{a}**
1	**POU**	**0.711**	**0.745**	**0.718**	**0.726**	**0.729**	**0.758**	**0.848**	**0.772**	**0.731**
	Low	0.861	0.880	0.865	0.869	0.888	0.931	1.000	0.910	0.892
	Medium	0.905	0.917	0.907	0.910	0.934	0.982	1.042	0.949	0.937
2	POU	0.852	1.070	0.856	0.860	0.872	0.903	1.212	1.103	0.820
	Low	**0.929**	**1.013**	**0.931**	**0.933**	**0.952**	**0.990**	**1.127**	**1.025**	**0.926**
	Medium	0.948	1.001	0.950	0.951	0.973	1.012	1.109	1.009	0.949
3	Low	0.850	0.974	0.854	0.859	0.870	0.901	1.092	0.993	0.834
	Medium	**0.897**	**0.979**	**0.900**	**0.904**	**0.919**	**0.954**	**1.090**	**0.992**	**0.893**
	High	0.916	0.981	0.919	0.921	0.939	0.975	1.090	0.992	0.915
4	Low	0.929	1.078	0.931	0.933	0.952	0.990	1.208	1.099	0.923
	Medium	**0.948**	**1.040**	**0.950**	**0.951**	**0.973**	**1.012**	**1.156**	**1.052**	**0.947**
	High	0.956	1.026	0.957	0.958	0.981	1.020	1.139	1.036	0.956

5	Low	0.791	0.975	0.797	0.803	0.808	0.835	1.106	1.006	0.747
	Medium	0.857	0.982	0.861	0.866	0.877	0.908	1.101	1.002	0.842
	High	**0.884**	**0.984**	**0.887**	**0.891**	**0.905**	**0.939**	**1.100**	**1.001**	**0.876**
6	POU	1.784	2.126	1.806	1.829	1.817	1.868	2.410	2.193	1.629
	Low	**2.246**	**2.430**	**2.259**	**2.272**	**2.298**	**2.380**	**2.711**	**2.467**	**2.229**
	Medium	2.386	2.512	2.395	2.404	2.444	2.537	2.790	2.539	2.387
7	Low	2.188	2.482	2.205	2.223	2.235	2.309	2.790	2.540	2.131
	Medium	**2.382**	**2.590**	**2.395**	**2.408**	**2.438**	**2.527**	**2.893**	**2.632**	**2.369**
	High	2.462	2.632	2.473	2.483	2.522	2.617	2.932	2.668	2.461
8	Low	2.138	2.603	2.159	2.181	2.181	2.249	2.959	2.693	2.001
	Medium	2.378	2.714	2.395	2.411	2.432	2.517	3.054	2.780	2.335
	High	**2.481**	**2.757**	**2.495**	**2.508**	**2.539**	**2.633**	**3.091**	**2.813**	**2.463**
9	POU	0.401	0.462	0.408	0.415	0.406	0.415	0.523	0.476	0.346
	Low	**0.568**	**0.611**	**0.574**	**0.579**	**0.580**	**0.598**	**0.682**	**0.621**	**0.558**
	Medium	0.628	0.660	0.632	0.636	0.642	0.664	0.733	0.667	0.625
10	Low	0.530	0.595	0.536	0.542	0.540	0.556	0.668	0.608	0.505
	Medium	**0.598**	**0.648**	**0.603**	**0.608**	**0.611**	**0.631**	**0.723**	**0.658**	**0.588**
	High	0.628	0.670	0.632	0.636	0.642	0.664	0.745	0.678	0.623

11	Low	0.677	0.765	0.683	0.689	0.690	0.711	0.859	0.782	0.649
	Medium	**0.748**	**0.813**	**0.753**	**0.758**	**0.765**	**0.791**	**0.907**	**0.825**	**0.738**
	High	0.779	0.832	0.783	0.787	0.797	0.825	0.926	0.842	0.773
12	Low	0.446	0.518	0.453	0.460	0.453	0.464	0.585	0.533	0.397
	Medium	0.529	0.588	0.535	0.541	0.539	0.554	0.660	0.601	0.506
	High	**0.567**	**0.620**	**0.572**	**0.578**	**0.579**	**0.596**	**0.693**	**0.630**	**0.553**
13	Low	0.678	0.821	0.684	0.691	0.692	0.713	0.929	0.846	0.631
	Medium	0.749	0.851	0.753	0.758	0.765	0.792	0.953	0.867	0.730
	High	**0.779**	**0.862**	**0.783**	**0.787**	**0.796**	**0.825**	**0.962**	**0.876**	**0.768**
14	Low	0.542	0.576	0.550	0.557	0.551	0.566	0.644	0.586	0.526
	Medium	0.629	0.657	0.635	0.641	0.641	0.661	0.731	0.665	0.623
	High	**0.668**	**0.693**	**0.674**	**0.679**	**0.682**	**0.704**	**0.769**	**0.700**	**0.665**
15	POU	0.891	0.891	0.891	0.891	0.912	0.946	0.970	0.883	0.883
	Low	**0.949**	**0.949**	**0.949**	**0.949**	**0.973**	**1.012**	**1.040**	**0.946**	**0.946**
	Medium	0.964	0.964	0.964	0.964	0.989	1.029	1.057	0.962	0.962
16	Low	0.800	0.800	0.800	0.800	0.820	0.852	0.875	0.797	0.797
	Medium	**0.814**	**0.814**	**0.814**	**0.814**	**0.835**	**0.869**	**0.893**	**0.812**	**0.812**
	High	0.819	0.819	0.819	0.819	0.841	0.875	0.899	0.818	0.818

17	Low	0.909	0.909	0.909	0.909	0.933	0.970	0.996	0.906	0.906
	Medium	**0.924**	**0.924**	**0.924**	**0.924**	**0.948**	**0.986**	**1.013**	**0.922**	**0.922**
	High	0.929	0.929	0.929	0.929	0.953	0.992	1.020	0.928	0.928

Table 4. Average Difference between Energy Factor computed without a particular correction and the fully corrected value; by technology type.

Technology	**w/o storage correction**	**w/o ambient correction**	**w/o stored water temperature correction**	**w/o inlet water temperature correction**	**w/o outlet water temperature correction**	**No corrections**	**EF_{io}**	**EF_a**
Electric Resistance Storage	0.159	0.008	0.015	0.033	0.086	0.349	0.191	-0.020
Heat Pump Storage	0.267	0.015	0.030	0.051	0.132	0.576	0.320	-0.049
Gas/Oil Storage	0.061	0.005	0.011	0.013	0.033	0.141	0.073	-0.019
Tankless	n/a	n/a	n/a	0.023	0.059	0.086	-0.003	-0.003

A few sample charts from these data indicate major trends. Figure 1 shows the energy factors reported in Table 3 for Unit 3, a 189 L (50 gallon) electric resistance water heater having a rated energy factor of 0.90. For the computation with all corrections, it can be seen that the EF increases with higher draw volumes. This result is as expected, since higher draw volumes increase the amount of useful thermal energy removed from the tank while the standby loss remains essentially the same regardless of draw volume. This higher ratio of useful thermal energy to standby loss increases the EF when higher amounts of water are removed each day. The corrections for stored energy and outlet water temperature have the greatest effect on the results, while those for the ambient temperature and stored water temperature have the least effect.

The energy factor computed as EF_a compares favorably to that computed with all corrections. The EF computed simply as the output divided by the input suffers errors on account of neglecting stored energy changes.

Figure 2 shows the modified daily energy consumption and its components for Unit 3: the actual measured energy consumption and all corrections. It is valuable to consider these values to get a sense of when corrections are most necessary to obtain the correct energy factor. The contribution of the stored energy remains the same regardless of draw profile, but the outlet and inlet water temperature corrections depend upon the amount of water drawn from the water heater. As a fraction of the total modified daily energy consumption, the actual measured value ranges from 78 % at the low use case to 84 % at the high use case. At the low use case, the correction for stored energy amounts to 13 % of the total modified daily energy consumption, while it drops to 7 % for the high use case. The modification for outlet water temperature ranges between 5.6 % and 6.1 % for the three draw patterns.

Figure 3 shows results for Unit 17, a natural gas tankless water heater with a rated EF of 0.93. With no storage volume, there is no correction for stored energy. Likewise, there is assumed to be no standby heat loss from the unit to the ambient, so corrections for variations in the stored water temperature and the ambient temperature are not needed. For tankless water heaters, corrections are only made for the inlet and outlet water temperatures differing from their nominal values. Figure 4 provides the contributions to the modified daily energy consumption of the measured energy consumption and the corrections. The two corrections amount to 9 % of the total energy consumption across all draw patterns.

A final observation from the data in Table 3 relates to the performance of EF_a vis-à-vis the "true" EF, which is considered to be the one with all corrections. EF_a underpredicts for most tests despite the fact that the conditions imposed are considered to be most favorable to the water heater under test. That underprediction arises because of the smaller value in the numerator compared to the nominal value, but the discrepancy is rather small. The average discrepancy across different technology types ranged from approximately 0.003 (<0.5 % of nominal EF) for tankless units to 0.049 (approximately 2 % of nominal EF) for heat pump water heaters.

In examining all data from Table 3, a trend emerges that the corrections account for a larger portion of the modified daily energy consumption as the storage tank size gets larger and the draw volume per day gets smaller. Figure 5 shows this trend, with the percentage of the modified daily energy consumption attributed to corrections being plotted against the ratio of rated storage volume to volume of water drawn during the test. As the rated storage volume gets smaller, the effect of changes in stored energy from the start of the test to the end of the test become less important. As the amount of water drawn during the test increases, the energy delivered during the test increases, and the corrections to the modified daily energy consumption make up a smaller amount of that total. These two factors indicate that corrections play less of a role with smaller water heaters and during tests with larger draw volumes.

Effect of errors in UA and η_r

In making the corrections previously discussed, two key performance parameters are utilized. These are the standby heat loss coefficient, UA, and the recovery efficiency, η_r. UA provides a measure of the rate of energy input required to make up for the heat loss from the water stored in the water heater to the surroundings per unit temperature difference between the water and the ambient. η_r indicates the fraction of energy input to the water heater that goes towards increasing the temperature of the water within the tank during active heating. For each water heater tested, these values need to be determined, and they are currently determined during specific periods of the test as discussed previously. With any experimental measures, errors in the determinations are inevitable. With potential changes in the draw patterns and the approach to determine these quantities, the question arises regarding the effect of errors in these values on the resulting EF.

To address this question, a series of simulations were performed to determine the change. Once again, these results are computed at the extreme conditions shown in Table 1 to obtain the worst-case scenarios which would lead to an artificially high rating if corrections were not made. It should be stressed that errors in UA or η_r would result in no changes in EF if environmental conditions are at their nominal values and the temperature of the stored water does not change from the start of the test to the end.

The simplest water heaters to assess are electric resistance storage units and tankless units because these classes of water heaters only require one of the two performance measures to be determined during the test. Electric resistance water heaters are assigned a recovery efficiency of 0.98, leaving only UA to be determined during the test. Tankless water heaters are assumed to have no standby loss to ambient, so only η_r is determined during the test.

Figure 6 displays the variation in EF as a function of error in UA value for Unit 3, a 189 L (50 gallon) electric resistance water heater at three different draw levels. At the Medium Use level that might be expected of a water heater of this size, it can be seen that a large error in UA results in minimal change in EF. For each percent error in UA, EF changes by -9×10^{-5}. For reference, recent tests on a 189 L (50 gallon) electric resistance water heater using a range of simulated use profiles resulted in an average UA value of 3.0 W/K (5.6 Btu/(h*°F)) and a maximum deviation of 15 %. That 15 % level of error would result in only a 0.001 error in the EF value.

Figure 7 displays the change in EF as η_r changes for Unit 16, a natural gas tankless water heater with a "true" $\eta_r = 0.84$ under the Medium Use draw profile, which would likely represent the typical pattern for this unit. The lowest value for η_r shown (0.71) is 15 % lower than the true value while the largest value (1) is 19 % larger than that value. Depending upon the computed η_r, the resulting EF could range from 0.80 to 0.83. For reference, laboratory tests on a gas tankless water heater using a range of different simulated use patterns resulted in a range of η_r from 0.76 to 0.83, with an average value of 0.788. Taking the average value as the true value, the largest error in a single test is 5 %. For Unit 16, all of these recovery efficiencies would yield an EF = 0.81.

Fossil fuel fired storage water heaters and heat pump water heaters require both UA and η_r to be determined during the test. Figure 8 shows how the computed energy factor changes with errors in both UA and η_r for a 189 L (50 gallon) gas water heater (Unit 10) subjected to the Medium Use profile. As the error in UA changes from -50 % to +50%, the variation in EF amounts to approximately 0.01. A variation in η_r from -30% to +33% (which corresponds to $\eta_r = 1$) yields an average change in EF of 0.06. Test data on a 151 L (40 gallon) gas water heater, however, suggest that UA and η_r vary much less than these extremes. Under a range of different simulated use patterns, computed recovery efficiency varied from 0.69 to 0.75, with an average value of 0.723. UA varied from 5.83 W/K (11.06 Btu/(h*F)) to 6.58 W/K (12.37 Btu/(h*F)), with an average of 6.23 W/K (11.81 Btu/(h*F)). The UA deviated from the average value a maximum of 6 % and η_r varied by -5 %. The error in UA would cause no change in computed EF whereas the span of computed recovery efficiency would change the EF from 0.60 to 0.59.

Figure 9 shows the variation in computed EF with variations in UA and η_r when conditions are furthest from their nominal values for a 189 L (50 gallon) heat pump water heater (Unit 7) under the Medium Use profile. Heat pump water heaters present a unique challenge in that the recovery efficiency will be dramatically different if backup resistance elements energize during the test period. In that case, the recovery efficiency could drop to the value used for electric resistance water heaters, 0.98. This effect is demonstrated in the figure, with energy factors dropping from approximately 2.4 to 1.9 when the lower recovery efficiency is used compared to the true value under heat pump only operation. Additionally, the recovery efficiency of heat pump water heaters is typically a function of the temperature of the water in the tank because of changes in the heat transfer from the condenser coil (Sparn et al. 2011), so some variation could be expected even if the measurements were perfect. Data from actual tests on a 189 L (50 gallon) heat pump water heater, shown in Table 5, provide information on variability expected in η_r and UA for a heat pump water heater. For multiple tests using the same draw volume per day, η_r and UA are consistent except for the high use case. During the third test of the high use case, the resistance elements were energized during the recovery period, leading to a low value of the recovery efficiency. It should be noted that this draw pattern is higher than the typical delivery capacity of the water heater, so the use of the resistance elements is not unexpected. For the daily draw pattern appropriate for the delivery capacity of the water heater (medium), the values are consistent. Recovery efficiency, η_r, under heat pump only mode operation increases with higher volume draw patterns because the average water temperature during recovery is colder when more water is removed from the tank, leading to a higher heat pump coefficient of performance. UA values are also consistent within a size category, but the values for the high use case are lower on average than those for the other two by approximately 9 %. These variations are accounted for by the change in η_r, since η_r is used in the computation of UA to determine the amount of thermal energy inserted into the tank based on electricity readings. The large value for UA determined during the third test of the high use pattern resulted from the decreased recovery efficiency.

Table 5. Measured values for η_r and UA for a 189 L (50 gallon) heat pump water heater under different simulated use draw patterns

Draw Pattern Size Category	**Test**	**η_r**	**UA, W/K [Btu/(h*°F)]**
Low	1	2.58	0.939 [1.78]
	2	2.60	0.918 [1.74]
	3	2.60	0.918 [1.74]
Medium	1	2.62	0.913 [1.73]
	2	2.64	0.923 [1.75]
High	1	2.87	0.849 [1.61]
	2	2.84	0.849 [1.61]
	3	1.26	0.950 [1.8]

These findings raise interesting questions regarding the appropriate correction factors to use for heat pump water heaters. At what temperature should the recovery efficiency be determined to make these corrections? For corrections to account for changes in stored water temperature from the start of the test to the end, deviations of the stored water temperature from the nominal value, and delivered water temperature, it makes sense to consider the recovery efficiency at the nominal delivery or stored water temperature. The argument could also be made to use this η_r to correct for changes in ambient temperature during standby, since adjustments to the computed heat input would be done with the water heater at the nominal stored temperature. Deviations in the inlet water temperature, however, may require a recovery efficiency at a lower temperature, since one is trying to estimate changes in heat input when the water is around 14.4 °C (58 °F). Considering that this cold water gets mixed with other water in the tank and that the condenser will be exposed to a water temperature above this value further complicates the issue. However, one must keep in mind the relatively low impact of the inlet water temperature correction as described earlier in determining the level to which an accurate value of recovery efficiency outweighs the extra burden of the calculation.

Effect of tightening test tolerances

One way to avoid any potential errors introduced in the EF through improper adjustment to nominal conditions is to tighten the tolerances of various quantities to minimize the need for corrections. This analysis will not consider the feasibility of those tolerances in a particular lab, but it will try to assess the effect of those new tolerances. It is acknowledged that controlling quantities such as inlet water temperature and ambient temperature to the tolerances discussed here may not be possible in some laboratories, but the results are presented to help assess whether any such changes would assist in making consistent ratings.

In examining the five conditions necessitating corrections (stored energy from start to end, ambient temperature, stored water temperature, inlet water temperature, and outlet water temperature), one sees that it is feasible to tighten tolerances on some but others are out of the control of the test laboratory. For example, changes in stored energy from the start of the test to the end of the test are a function of thermostat deadbands and water heater control schemes and cannot easily be affected in the laboratory. Crafting a test method, however, that minimizes those corrections is feasible, but no particular setting during the test would minimize the need for this correction. For this analysis, it will be assumed that the initial tank temperature matches the final tank temperature, so no energy is stored. The other four corrections are under the control of the test laboratory to some extent (deadbands still would have some effect on stored water temperature and delivered water temperature), so those four corrections will be examined in detail.

The same simulations discussed in the "Effect and magnitude of corrections" section are carried out with tolerances that are 50 % tighter than present in the current test procedure. Table 6 in comparison with Table 1 shows how the extreme conditions are closer to the nominal values with tighter prescribed tolerances on these quantities. For these tests, the stored water temperature at the start of the test and the end of the test match with a value of 57.2 °C (135 °F). Figure 10 shows the deviations from the fully normalized energy factor for a 189 L (50 gallon) gas storage water heater (Unit 10) subject to the Medium Use profile with conditions at their extremes when particular corrections are omitted and when alternative methods of computing EF are implemented. Results are shown when the test conditions are at their extremes based on the tight tolerances shown in Table 6 as well as the normal tolerances provided in Table 1. While there are some non-linearities in the corrections, the data show that the tighter tolerances decrease the deviations associated with each correction by half. This finding is consistent across all 17 water heater types examined; data presented in Table 3 can therefore be used to estimate what the deviations would be if 50 % tighter tolerances were implemented by halving the difference between each value of EF and the fully normalized value. The small deviation in the alternative measures (Output/Input and EF_a) should be noted; those values are slightly below the fully normalized result owing to the fact that the numerator is computed based on the actual delivered temperature as opposed to the nominal value as is done in all of the other calculations. While the denominator (heat input) also drops, the net result of the two is a very slight decrease below the fully normalized value.

Table 6. Nominal test conditions and simulated extreme conditions with tight tolerances

Test Condition	Nominal Value	Extreme Condition
Ambient Temperature, T_{amb}	19.7 °C (67.5 °F)	20.4 °C (68.75 °F)
Average Stored Water Temperature during test, T_{tank}	57.2 °C (135 °F)	55.8 °C (132.5 °F)
Average Inlet Water Temperature during draws, T_{in}	14.4 °C (58 °F)	15 °C (59 °F)
Average Outlet Water Temperature During Draws, T_{out}	57.2 °C (135 °F)	55.8 °C (132.5 °F)

DISCUSSION

The results herein are presented to help developers of test methods evaluate the tradeoffs between accuracy and ease of testing residential water heaters. While all stakeholders strive for the most accurate method of test, everyone involved must accept the fact that any experimental measurement will involve some degree of uncertainty. Those factors that are under control of the test laboratory should be made as inconsequential as possible, but the challenge in doing so may involve costs that may not be justified by the benefits. These data will hopefully aid devlopers of the test method in understanding the benefits and drawbacks of ways to implement a water heater test method. The issue of costs and practicality in tightening tolerances or implementing alternative means to normalize ratings is left to other studies.

Another key point to raise is the fact that intermediate values such as UA and η_r have use to those who simulate water heater performance in addition to being used as part of the rating methodology. The benefits and drawbacks discussed in this work are focused on those that apply to a rating of water heater energy efficiency. Should a test method strive to also provide accurate data for modelers, considerations on the benefits of such steps in a test procedure would need to be examined separately.

CONCLUSION

Results of a computational analysis are presented to indicate changes in the energy factor of a broad range of residential water heaters with changes in test conditions and with variations in the measured standby heat loss coefficient and recovery efficiency. It is shown that corrections for stored energy can have the most impact, especially with larger water heaters. Corrections for deviations from the nominal outlet water temperature can have a marked effect, particularly for large draw volumes per day. A simplified calculation that only considers changes in stored energy is shown to closely match the fully corrected value. Variation in the determination of the UA and η_r values during the test lead to some variation in the resulting energy factor, but test data suggest that typical measurement variations lead to small changes in the EF for most water heaters. Special challenges with heat pump water heaters were found if resistance elements energize during the calculation of the η_r, thereby significantly decreasing the measured value and modifying the EF. A tightening of tolerances on the ambient temperature, inlet water temperature, and delivered water temperature show a nearly linear decrease in variation of EF with a tightening of tolerances. It should be stressed that these results apply to worst-case scenarios in the test when conditions are furthest from their nominal values. The results presented here are to be considered along with practical concerns of conducting a test to determine the proper course of action in crafting a test procedure that is accurate yet achievable.

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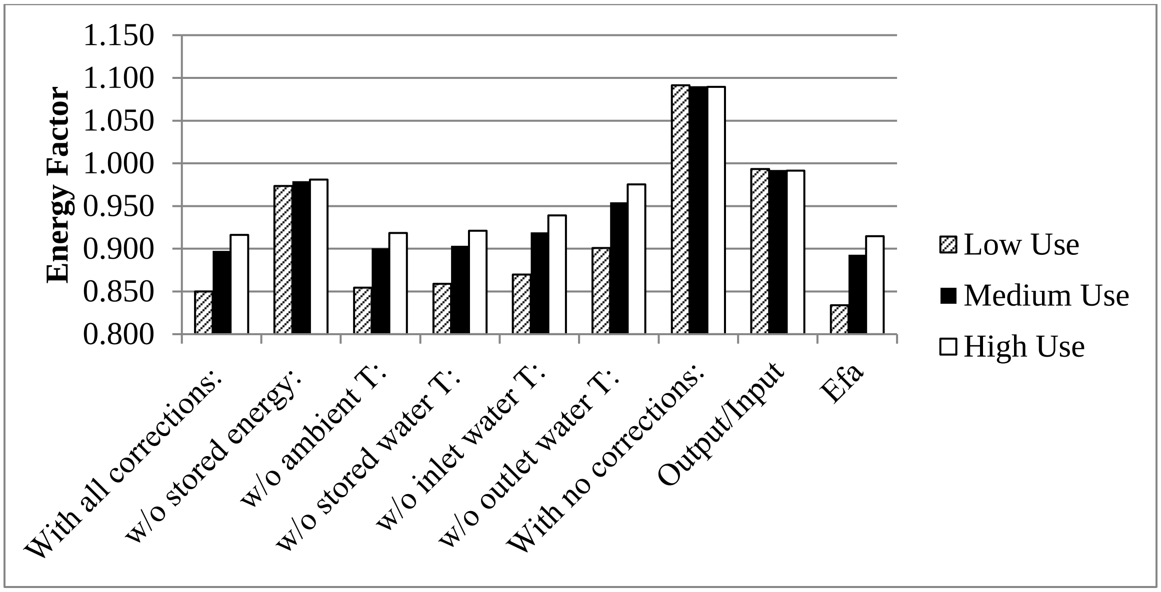

Figure 1. Energy factors computed in a variety of manners for Unit 3, 189 L (50 gallon) electric resistance water heater with a rated EF of 0.90

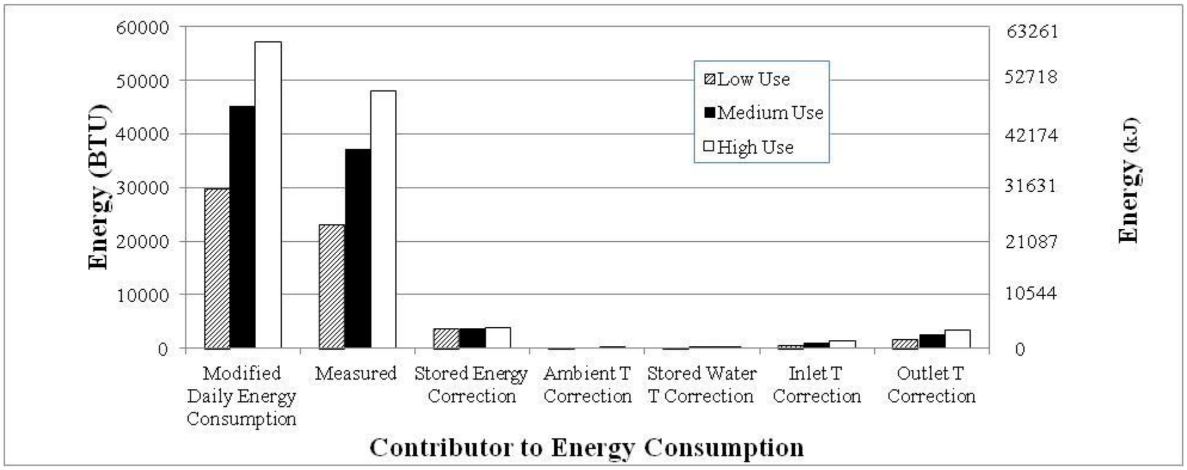

Figure 2. Energy contributions of measured energy and corrections to modified daily energy consumption for Unit 3, 189 L (50 gallon) electric water heater

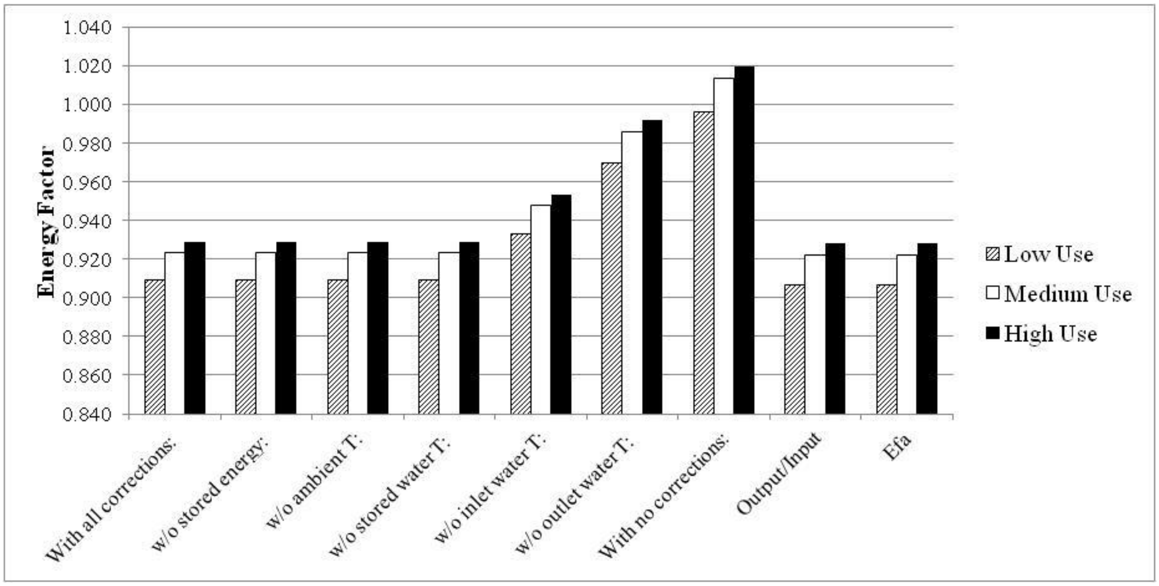

Figure 3. Energy factors computed in a variety of manners for Unit 17, natural gas tankless water heater with a rated EF of 0.93

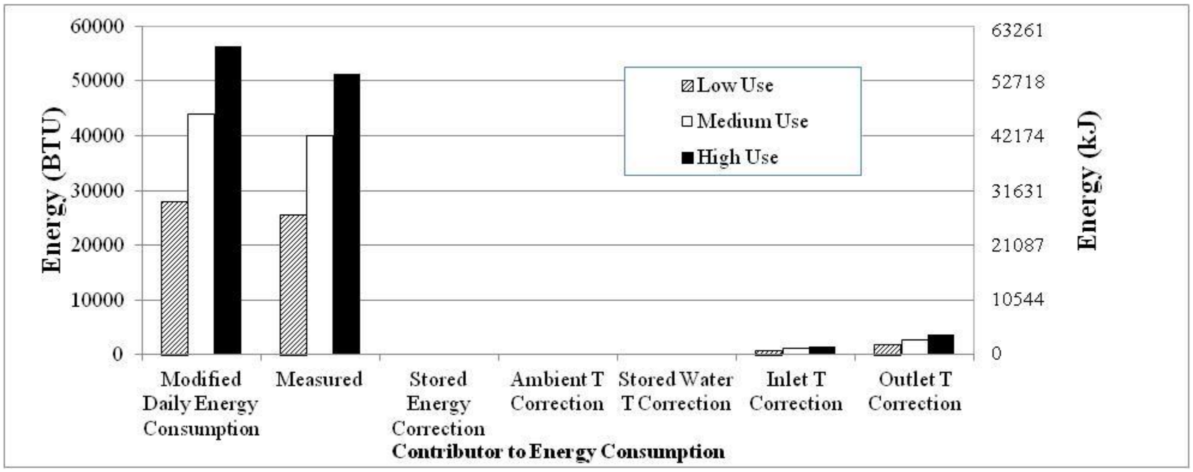

Figure 4. Contribution of measured energy and corrections to modified daily energy consumption for unit 17, natural gas tankless water heater

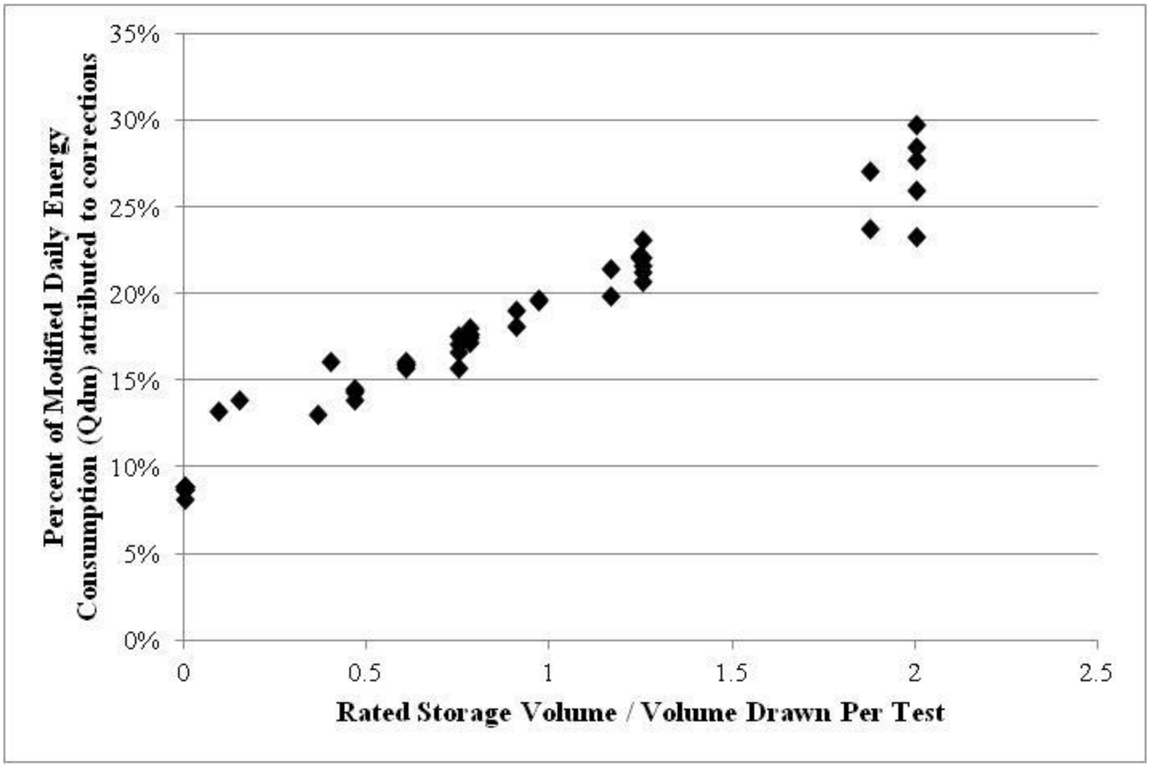

Figure 5. Percent of modified daily energy consumption made up of calculated corrections for nominal conditions as a function of the ratio of rated storage volume to the total volume of water drawn during the test

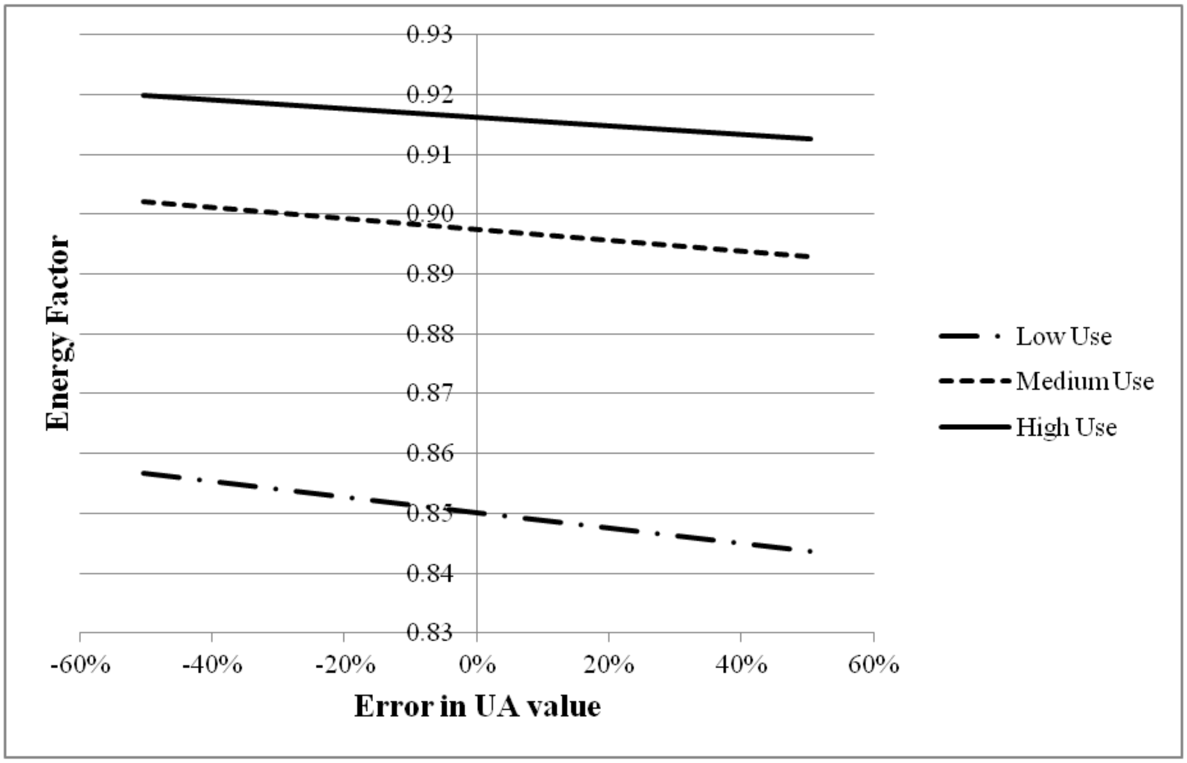

Figure 6. Change in Energy Factor due to correction of test conditions to nominal values for a 189 L (50 gallon) electric water heater with errors in the computed UA value; test conditions furthest from their nominal values

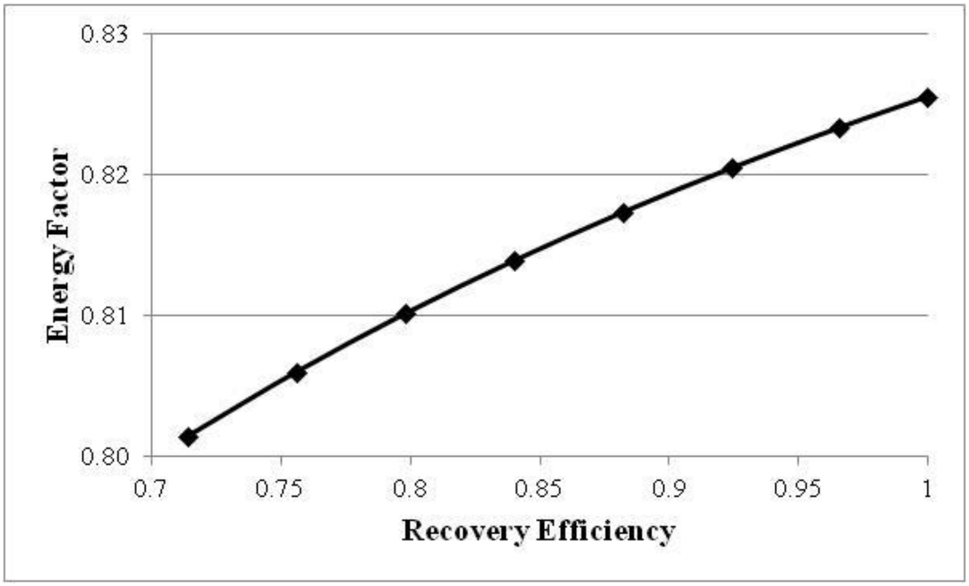

Figure 7. Change in energy factor due to correction of test conditions to nominal values for a gas tankless water heater (Unit 16) with recovery efficiency; medium use profile and test conditions furthest from their nominal values

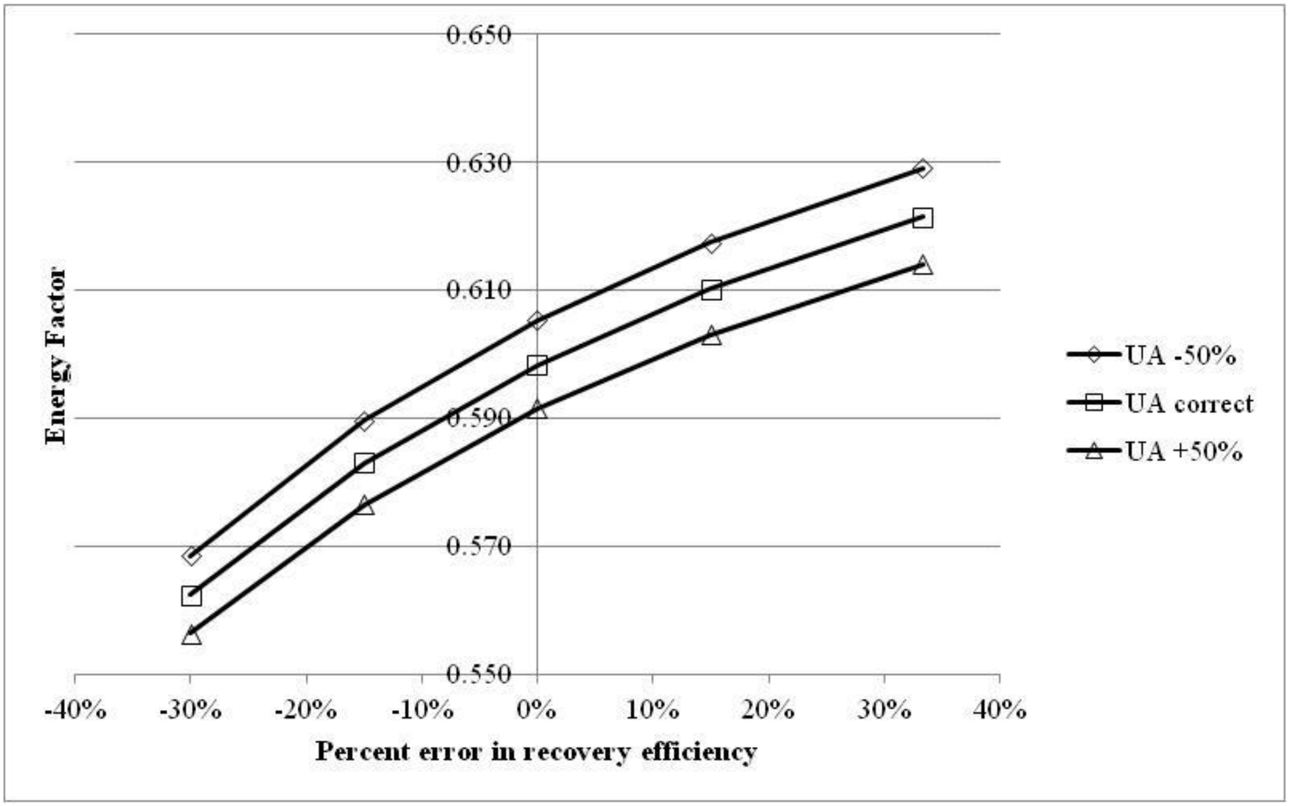

Figure 8. Changes in energy factor for a simulated 189 L (50 gallon) gas water heater (Unit 10) under the Medium Use profile with errors in UA and η_r when those values are used to normalize extreme test conditions to nominal conditions

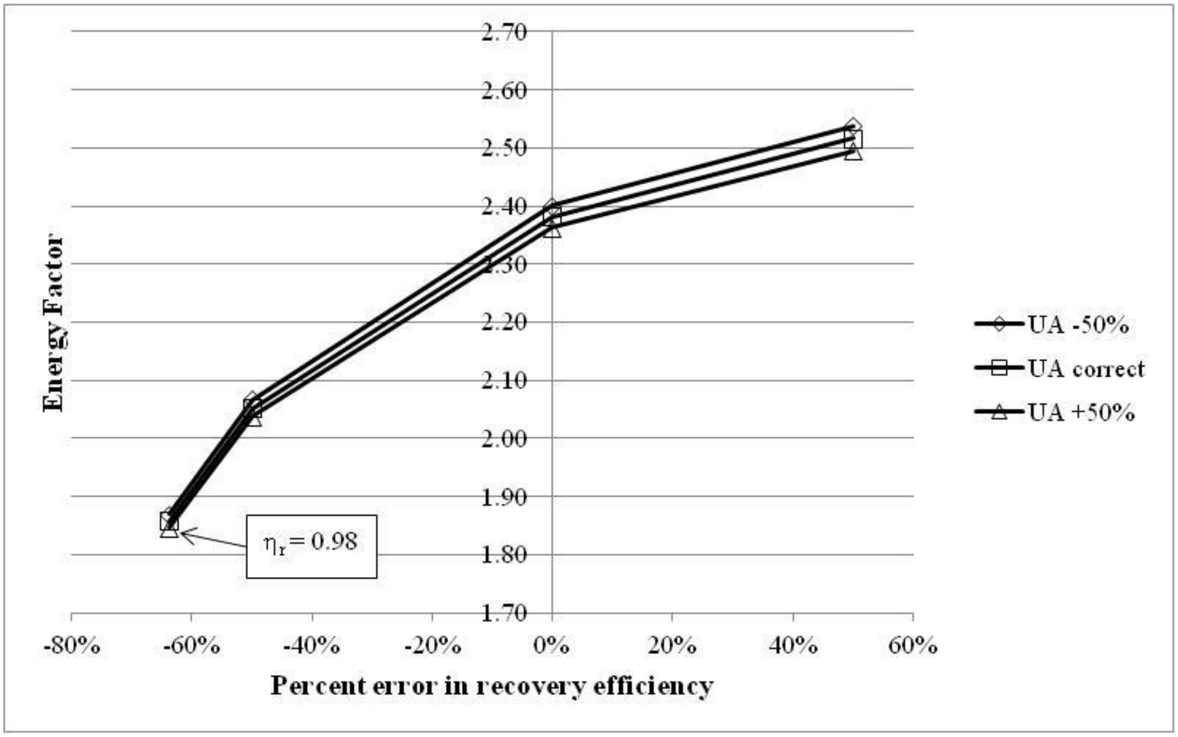

Figure 9. Changes in energy factor for a simulated 189 L (50 gallon) heat pump water heater (Unit 7) under the Medium Use profile with errors in UA and η_r when those values are used to normalize extreme test conditions to nominal conditions

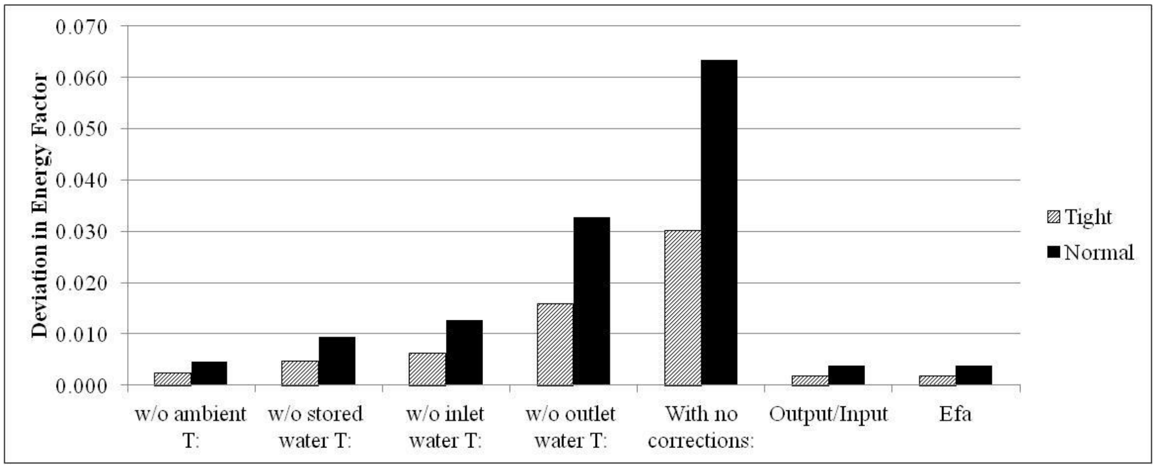

Figure 10. Deviations in energy factor from the fully corrected value for a 189 L (50 gallon) natural gas water heater (Unit 10) subject to the Medium Use profile for calculations using a variety of correction methods when test conditions are at the extremes defined by the normal tolerances and tighter tolerances that are 50 % more stringent than normal