Variability in Energy Factor Test Results for Residential Electric Water Heaters

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Recent modifications to the minimum energy efficiency requirements for residential water heaters have spurred an investigation into the variability in testing high-efficiency electric water heaters. While initial interlaboratory comparisons showed excellent agreement between test results from different labs, subsequent interlaboratory comparisons show differences between measured energy factors of up to 0.040. To determine the source of these differences, analyses of various parts of the test procedure are performed. For one case studied, the uncertainty in test results can be as high as ±0.028 if instrument accuracies reach the minimum level allowed in the test procedure. Other areas of the test procedure where variability is introduced are the optional use of pre-draws, the location of the lower tank temperature-measuring device, the use of insulation on tank fittings, and the use of a warm-up period before the simulated-use test commences. The implications of these issues on test results are discussed.

INTRODUCTION

The latest revision to the efficiency standards for residential water heaters governed by the Department of Energy (U.S. DOE) in the United States began in 1997 (U.S. DOE 1997) and ended with regulatory review of the final rule in April of 2001 (U.S. DOE 2001). The goal of this process was to achieve the maximum efficiency that is technically feasible and economically justifiable. The efficiency descriptor that is used in describing water heaters for regulatory purposes is called the "energy factor" (EF). The energy factor is the energy delivered as hot water divided by the energy consumption of the tank under the conditions specified within the DOE simulated-use test. Details of this test will be discussed later. To estimate the energy factor of a residential water heater having various features, simulation models were used.

Hiller et al. (1994) describe the simulation model that was used to estimate the energy consumption of electric water heaters. This model allows the user to input the tank geometry, material properties, thermostat settings, energy input, and environmental conditions. The user can then apply any particular pattern of water draws to the water heater and monitor the energy consumption of the unit. The model splits the water heater into 24 equally spaced cylindrical zones in the tank and applies a finite-difference method to estimate energy transfer within the tank. This program was modified to simulate conditions present in the DOE simulated-use test in order to obtain an estimate of the energy factor. While preparations were made to use this model to predict the energy factor, tests were run on water heaters that incorporated insulations produced with various alternative blowing agents (Fanney et al. 2000). Results of these experiments matched well with simulation results, providing confidence in the use of the simulation model. Simulation modeling was then carried out on 190 L (50 gal) water heaters with 4.5 kW heating elements. This particular tank configuration was selected because it is the most common electric

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water heater sold in the U.S. A picture of one of the considered units is shown in Figure 1. A 90° pie-shaped piece was cut out of the side of the unit extending from top to bottom to show the interior components. This particular water heater has a jacket diameter of 0.61 m (24 in.), a tank diameter of 0.46 m (18 in.), and a height of 1.19 m (46 ¾ in.). The top and sides of the unit are insulated with 7.6 cm (3 in.) of a polyurethane insulation, and the bottom lies on a 2.5 cm (1 in.) fiberglass disk (not shown in the picture). The water heater has two heating elements rated at 4.5 kW each, positioned at 24 cm (9.5 in.) and 93 cm (36.5 in.) from the base. A separate thermostat controls each element.

A water heater modeled with 5.1 cm (2 in.) of insulation and heat traps yielded an EF of approximately 0.890. For comparison, the actual test results yielded an EF of 0.887. A simulation on a well-insulated tank with 7.6 cm (3 in.) of foam insulation, heat traps, insulation between the tank and the tank bottom, and a plastic tank yielded an EF of approximately 0.908.

These results raised a serious question as the rulemaking progressed: if the simulation model predicts that a very well insulated tank can only achieve an energy factor of 0.908, why are there so many models on the market with energy factor ratings above that value? The 1997 directory of ratings published by a trade association of residential water heater manufacturers shows ratings of electric water heaters up to a value of 0.95, with a significant number of tanks registering energy factors of 0.93 (GAMA 1997). A review of data from a certification testing laboratory used by the trade association showed that the measured energy factors for these water heaters were often well below the published rated energy factor.

The final rule raised the minimum efficiency standards for electric water heaters by a 0.04 energy factor. The new minimum efficiency for an electric water heater with a capacity of 190 L (50 gal) is 0.90. Considering that the maximum rated efficiency for any such water heater is currently 0.95 and the maximum theoretical energy factor is thought to be 0.98 because of losses in

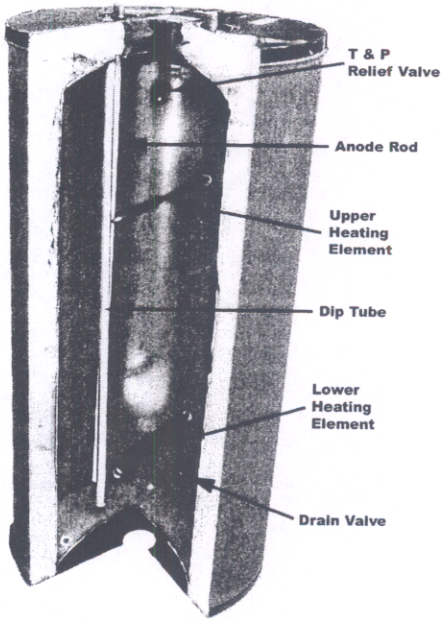


Figure 1. Photo of the Inside of a Typical Electric Water Heater

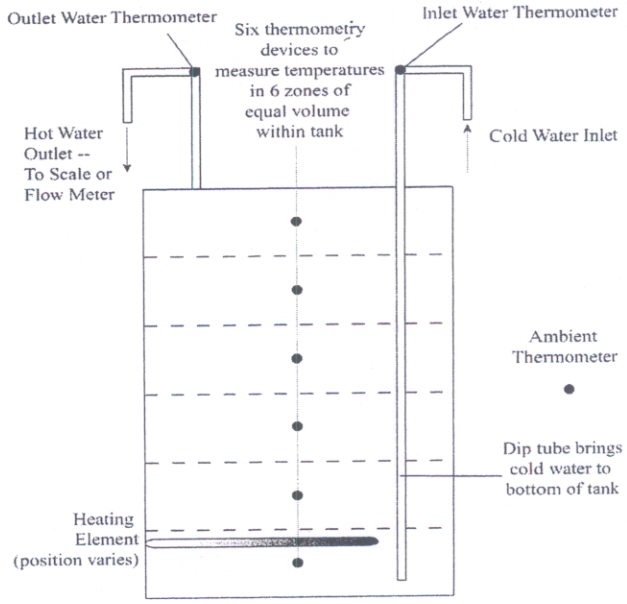


Figure 2. Instrumentation of Water Heater for Performing Simulated-Use Test

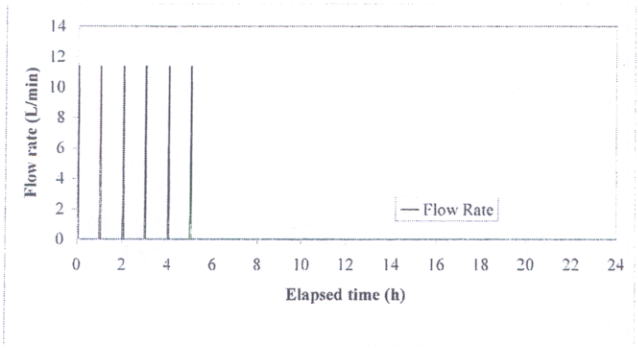
the electrical connections, the allowable range of energy factors is quite narrow. With this narrow range, it becomes critical that the test procedure accurately determine the energy factor to properly differentiate between tanks of varying efficiency.

This paper describes an evaluation of the test procedure for electric water heaters and indicates some deficiencies that could account for variability in the test procedure. Some suggestions for tightening up the test procedure are provided.

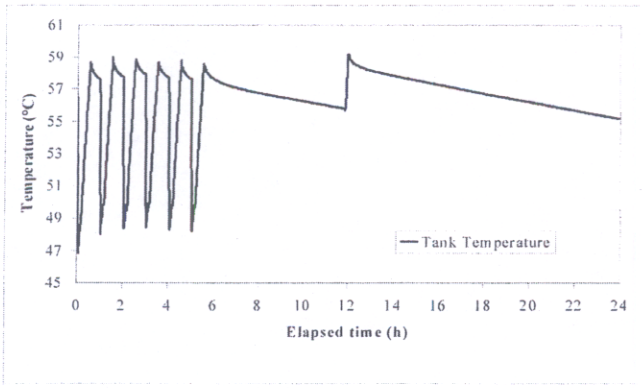
OVERVIEW OF TEST PROCEDURE

Ratings in the United States are obtained according to the DOE test procedure (U.S. DOE 1998). This document specifies a 24-hour simulated-use test that is performed to determine an efficiency under prescribed conditions. This efficiency, under the conditions stated in the test procedure, is termed an *energy factor* (EF). To start, a water heater is instrumented as shown in Figure 2. Thermometry devices measure the inlet water temperature, the outlet water temperature, the ambient temperature, and the average temperature of the water inside the tank. The average temperature inside the tank is determined by placing thermometry devices in the vertical center of six equally partitioned volumes. It is assumed that the temperature varies neither radially nor circumferentially in the tank and that the temperature at the vertical center of each volume approximates the average temperature in the volume. Cold water is delivered through the inlet port of the water heater to the bottom of the tank, and hot water is removed from the top of the tank. The amount removed is measured with either a flow meter or a scale. Heat input to the tank is provided by the heating element at the bottom of the tank. The location of this heating element may be either below or above the lowest thermometry device depending on the particular design of the water heater. The power input to this element is monitored to determine the energy consumption of the water heater.

The simulated-use test consists of six equal draws totaling 243 L (64.3 gal) of water. These draws are taken at a rate of 11.4 L/min (3 gal/min) once each hour for the first six hours of the



(a)



(b)

Figure 3. (a) Draw Pattern and (b) Typical Average Tank Temperature During Simulated-Use Test

test, as shown in Figure 3. Figure 3a shows the flow rate and Figure 3b shows the mean tank temperature. After the sixth draw, the tank sits in standby mode for approximately 18 hours to determine the heat loss coefficient. During this test, the energy removed in the hot water is divided by the energy consumed to determine the energy factor. The energy consumed is modified to account for deviations from the nominal conditions specified in the procedure. These corrections account for changes in stored energy in the water within the tank because of temperature changes from the beginning of the test to the end, deviations from the prescribed inlet and outlet temperatures, and variations in the prescribed water temperature within the tank and the prescribed ambient temperature. The nominal conditions are given in Table 1.

TEST RESULTS

The initial response to questions raised in the rulemaking concerning the overrating of high-efficiency water heaters involved testing several of these units. Five 190 L (50 gal) units from five different manufacturers having rated energy factors from 0.92 to 0.94 were tested at Lab 1. Test results on all tanks yielded energy factors below the rated values, as shown in Table 2; uncertainties on the values presented in Table 2 are ±0.012, as will be discussed later. The overratings ranged from 0.012 EF up to 0.052 EF, with an average of 0.038. To check these

Table 1. Nominal Conditions and Allowable Tolerances for 24-Hour Simulated-Use Test

Test Parameter	Value
Average Tank Temperature	57.2°C±2.8°C (135°F±5°F)
Ambient Air Temperature	19.7°C±1.4°C (67.5°F±2.5°F)
Inlet Water Temperature	14.4°C±1.1°C (58°F±2°F)
Volume Flow Rate	(11.4±0.95) L/min ([3.0±0.25] gal/min)
Water removed	(243±3.8) L ([64.3±1.0] gal)

Table 2. Energy Factor Results of Initial Tests

Tank	Rated EF	Lab 1 Result	Lab 2 Result
1	0.93	0.896	--
2	0.92	0.908	--
3	0.93	0.884	0.876
4	0.94	0.888	0.881
5	0.94	0.894	--

Table 3. Energy Factor Results During Second Round of Testing

Tank	Rated EF	Lab 1 Result	Lab 2 Result
6	0.93	0.918	0.949
7a	0.93	0.909	0.936
7b	0.93	0.904	--
8a	0.93	0.896	0.881
8b	0.93	0.895	--

results, the two tanks with the lowest energy factor were shipped to a second testing lab (Lab 2); results from tests at this lab closely matched those at the first facility.

After discussions with manufacturers, several models were re-rated based on available data. After these ratings, some tanks were still being rated with energy factors upward of 0.93 despite the doubt cast by the simulation models. To examine these tanks, two units of each of three models were bought from a retailer and tested at Lab 1. One tank was damaged during testing, so results are not reported. Once again, the energy factors determined at the test laboratory were below the rated values. One tank of each model was then shipped to the same independent test laboratory at which the first set of tanks was tested (Lab 2). In this case, however, discrepancies between the results of the two labs were seen. For two of the tanks, test results from Lab 2 were significantly higher than those measured at Lab 1. In the third case, the energy factor determined by Lab 2 was lower than that measured at Lab 1. Table 3 shows results of these tests; the uncertainty for the results from Lab 1 is ±0.012, while Lab 2 has not specified their uncertainty in measurements.

In addition to these tests, a second government lab (Lab 3) tested two tanks and then sent those same tanks to a different independent laboratory (Lab 4). Once again, significant variability was seen in the results of tests performed on the same identical tank. On this tank rated at 0.93, results varied, as shown in Table 4. The key point in this table is that the variability in test results is significant even on the same exact tank.

Following this rash of puzzling results, the authors set out to determine areas in which variability is introduced into the test procedure. Tanks were retested under varying conditions, analyses of the test procedure were made, and additional measurements were taken. The following

Table 4. Energy Factor Results During Third Round of Testing

Tank	Rated EF	Lab 3 Result	Lab 4 Result
9a	0.93	0.909	0.890
9b	0.93	0.900	0.940

discussion describes some areas where variability is introduced into the test procedure and indicates potential magnitudes of these variations.

POTENTIAL CAUSES OF VARIATION

Uncertainty Analysis of Test Procedure

As a first step in analyzing the test procedure, it is valuable to estimate the uncertainty in any one particular measurement based on instrument tolerances and historical analysis of test variability. To do so, the technique described by Taylor and Kuyatt (1994) is used as a guide for determining the uncertainty in the determined energy factor. This discussion will focus on the uncertainty involved in one particular test. Discussion of the uncertainty in the rating of an entire population of water heaters is not included here, though a key ingredient to such an analysis is the uncertainty in one particular test. Currently, DOE requires the EF to be reported to two decimal places. Typical reports often quote three decimal places. The logical question arises, however, as to how precisely the energy factor can be measured. While the energy factor test may often be reported with a single number, any measurement actually yields a probable range of values for the measured quantity. Such a range is typically given as an uncertainty bound. An attempt is made here to give that range for a typical water heater test.

Uncertainty in any test can be considered to be of two types—Type A uncertainty and Type B uncertainty. Type A uncertainty is "a component of uncertainty arising from a random effect," whereas Type B uncertainty is a "component of uncertainty arising from a systematic effect." Type A effects are not known a priori but appear in the statistics when running several tests on one particular unit. Type B effects, on the other hand, can be limited beforehand. Typical sources of Type B effects are the uncertainties in the individual measurements that comprise a test. In other words, Type A uncertainty is the variation in several tests on one unit with the same measurement equipment, and Type B uncertainty is the variation in several tests on one unit with different measurement equipment validated at the same accuracy.

Uncertainties in individual measured quantities can be translated into an uncertainty in EF by using the functional relationship between EF and all of the measured quantities. Equations 1 through 5 provide this relationship, assuming that all draws are of equal quantity.

$$\mathrm{EF} = \frac{Q_{load}}{Q - Q_{stored} - Q_{loss,adj} + Q_{load,adj}} \tag{1}$$

$$Q_{load} = MC_p \cdot \Delta T_{nom} \tag{2}$$

$$Q_{stored} = \frac{V_{st}\rho C_p(\bar{T}_{24} - \bar{T}_0)}{\eta_r} \tag{3}$$

$$Q_{loss,adj} = \left[\frac{Q_{stby} - \dfrac{V_{st}\rho C_p(\bar{T}_{24} - \bar{T}_{su})}{\eta_r}}{\tau_{stby1}(\bar{T}_{t\_stby1} - \bar{T}_{a\_stby1})}\right][(\bar{T}_{stby2} - \bar{T}_{a,stby2}) - \Delta T_{nom}]\tau_{stby2} \tag{4}$$

$$Q_{load,adj} = \frac{MC_p[\Delta\overline{T}_{nom} - (\overline{T}_{del} - \overline{T}_{in})]}{\eta_r} \tag{5}$$

where

Q_{load} = nominal hot water load
Q_{stored} = energy stored in hot water during simulated use test
$Q_{loss,adj}$ = adjustment to heat loss from tank when water or ambient temperatures differ from nominal conditions
$Q_{load,adj}$ = adjustment to hot water load when inlet or outlet temperatures differ from nominal conditions
M = mass of water removed
C_p = specific heat of water
ΔT_{nom} = nominal temperature difference between outlet and inlet water
Q = energy consumed during 24-hour test
V = tank volume
ρ = water density
$\overline{T}_{24}$ = average tank temperature at end of 24-hour test
$\overline{T}_o$ = average tank temperature at start of 24-hour test
$\overline{T}_{stby,2}$ = average tank temperature during standby portion at end of test
$\overline{T}_{a,stby,2}$ = average ambient temperature during standby portion at end of test
$\Delta T_{a,nom}$ = nominal temperature difference between tank and ambient
Q_{stby} = energy consumed during standby portion of test
$\overline{T}_{su}$ = average tank temperature at beginning of standby portion
η_r = recovery efficiency
$\tau_{s,1}$ = time tank is in standby mode at end of test
$\tau_{stby,2}$ = time throughout 24-hour test when tank element is not energized
$\overline{T}_{t,s,1}$ = average tank temperature during 24-hour test when tank element is not energized
$\overline{T}_{a,s,1}$ = average ambient temperature during 24-hour test when tank element is not energized
$\overline{T}_{out}$ = average outlet temperature during draws
$\overline{T}_{in}$ = average inlet temperature during draws

The Type B uncertainty in EF, $u_{EF,B}$, can be calculated from the individual uncertainties through the use of the partial derivatives of the functional relationship:

$$u_{EF,B} = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial(EF)}{\partial x_i}\right)^2 (u_i)^2}\,, \tag{6}$$

where

x_i = parameters of the functional relationship
u_i = measurement uncertainty in the ith parameter
n = number of parameters in the functional relationship

The uncertainty obtained in Equation (6) yields an approximate standard deviation on the result based upon the known factors. To obtain an overall uncertainty, u_{EF}, the Type A uncertainty, $u_{EF,A}$, and the Type B uncertainty are added in quadrature to obtain

$$u_{EF} = \sqrt{(u_{EF,A})^2 + (u_{EF,B})^2}\,. \tag{7}$$

Table 5. Uncertainties in Measured Quantities

Quantity	Lab 1	Test Procedure Tolerances
Mass of Water Removed	±0.25%	±1%
Electrical Energy Consumption	±0.5%	±1%
Tank Volume	±0.25%	±2%
Average Tank Temperature	±0.006°C (±0.01°F)	±0.11°C (±0.20°F)
Inlet Water Temperature	±0.12°C (±0.22°F)	±0.11°C (±0.20°F)
Outlet Water Temperature	±0.11°C (±0.20°F)	±0.11°C (±0.20°F)
Ambient Temperature	±0.08°C (±0.15°F)	±0.11°C (±0.20°F)
Timing	±0.5 s/h	±0.5 s/h

This number is typically multiplied by a coverage factor, k, to create a number similar to a confidence interval. A value of $k = 2$ yields an approximate confidence interval of 95%. The expanded uncertainty, $U_{EF} = k \cdot u_{EF}$, then provides the bounds for a confidence interval surrounding the measured value of EF.

As an example of this type of analysis, a typical test on a 190 L (50 gal) tank will be considered. The data presented are from a simulated DOE test on a high-efficiency tank. The measured tank volume in this instance is 173 L (45.8 gal), and the energy factor in this test is 0.920. Partial derivatives as specified in Equation (6) are calculated, and the uncertainties in individual components are then determined. Table 5 shows the uncertainties in each of the measurements that were determined either from instrument manufacturers' literature or calibration data. All instruments were calibrated against standards traceable to national standards. To estimate the Type A uncertainty, historical data from the test lab (Fanney et al. 2000) indicate that a standard deviation of 0.0023 is seen on tests of the same tank in that laboratory. That value was used as $u_{EF,A}$. In this example, the Type B uncertainty is 0.0053, and the resulting expanded uncertainty using $k = 2$ is ±0.012. This result indicates that there is nearly 95% confidence that the energy factor of the tank that was measured is between (0.920 – 0.012 =) 0.908 and (0.920 + 0.012 =) 0.932. This range of 0.024 is significant when one considers that energy factors are reported to two decimal places and that the entire range of known energy factors after the new regulations will be from 0.90 to 0.95.

While this result may seem disheartening, results are even more alarming when one considers the tolerances allowed in the test procedure. The third column in Table 5 shows the tolerances allowed for each of the measurements in the test procedure. If these numbers are used as the uncertainties in the evaluation of the Type B uncertainty, the resulting Type B uncertainty is 0.014, the Type A uncertainty remains at 0.0023, and the expanded uncertainty increases to ±0.028. In this case, the confidence interval on the result stretches from 0.892 to 0.948. This range spans nearly the entire range of possible energy factors!

It is insightful to examine the key contributors to the uncertainty. While the uncertainty may be high for a particular instrument, some of those measurements have a small effect on the energy factor, as determined by the partial derivatives in Equation (6). Figure 4 shows the partial derivatives multiplied by the individual uncertainty for each of the measurements for both of the cases considered. This chart indicates the contributions to the overall uncertainty from each of the measurements. The largest contributors are uncertainties in the measurement of the mass withdrawn and the electrical energy consumption. Since the energy factor is essentially a measure of the amount of hot water removed divided by the energy consumed, it stands to reason that these factors would have the greatest effect. For example, the 1% uncertainty in the electri-

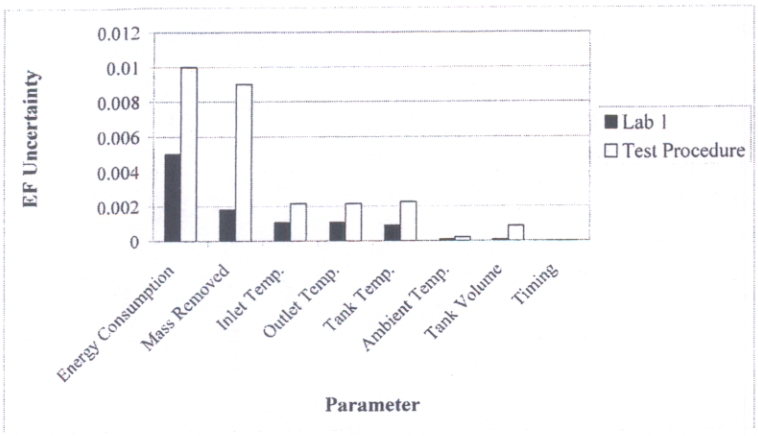


Figure 4. Contributions to Overall Uncertainty from Each Measured Parameter Based on Uncertainties at Both Lab 1 and Those Allowed in Test Procedure

cal energy measurement contributes a nearly 1% uncertainty to the final energy factor in the worst-case scenario where the tolerances of the instruments are at the level specified in the test procedure. The various temperature measurements have less of an effect on the overall uncertainty but still contribute to the final number.

These results indicate that variations in energy factors are expected even when all procedures are followed properly. Differences of at least 0.01 are certainly to be expected given the uncertainty in results. To help decrease the uncertainty of these results, an evaluation of the allowed tolerances in the test procedure should be undertaken. While tolerances on temperature-measuring devices are tight, it should be determined whether the tolerances on the measurement of the amount of water removed and the electrical energy consumed can be tightened considering technology that is currently available to make those measurements.

In addition to tolerances in the measurements during a test, the test procedure itself also contains several ambiguities that may lead to significant variations in determined EF. These include the optional use of pre-draws, the lack of clarity on how to locate temperature-measuring devices within the tank, the lack of a standard method of reaching steady-state operating conditions before a test begins, and vague specifications about use of insulation. All of these are discussed in detail below.

Pre-Draws

A pre-draw in which a small amount of water is removed from the tank before the 24-hour test commences is permitted in the test procedure: "After the cut-out occurs, the water heater may be operated for up to three cycles of drawing until cut-in, and then operating until cut-out, prior to the start of the test" (U.S. DOE 1998). This specification in the test procedure gives test labs the option of using this technique to precondition the tank, thereby adding some flexibility to the test procedure. The simulation models address the pre-draw issue indirectly by utilizing empirically derived expressions for mixing between cold water and warmer water (already in the tank) during the periods of water draws or reheats. The mixing relationships were developed as a function of water flow rate, temperature differences, and diffuser geometry and were validated through extensive testing.

At the time the test procedure was written, it was thought that this aspect of the procedure had no effect on results. Questions were raised, however, as to whether this procedure affected the results when it was observed that Lab 2 used one pre-draw before tests, while Lab 1 did not apply a pre-draw before commencing the test.

Tests were performed at Lab 1 to investigate this question. The same tanks that had been tested at the certification lab were tested with zero, one, or three pre-draws. Results shown in Table 6 indicate that pre-draws have a significant effect on the results. For the first two tanks, the application of a pre-draw increases the measured energy factor. For the third tank, the application of a pre-draw decreases the energy factor. Little difference is seen between one and three pre-draws for Tank 6, but a sizeable change is seen for Tank 8a.

A pre-draw has such a profound effect on the computed energy factor because it affects the measurement of the initial tank temperature. This effect then modifies the correction for stored energy within the tank from the beginning of the test until the end of the test. If the true initial tank temperature could be determined, pre-draws would have no effect. In the test procedure, however, six thermocouples are placed at discrete locations in the tank to estimate the overall average tank temperature. Temperature measurement is complicated by a very nonuniform temperature profile in the tank. Two aspects of the water heater can lead to very steep, nearly step-like, gradients in the temperature. First, a draw of water brings cold water into the bottom of the tank. If the design of the tank minimizes mixing at the bottom of the tank, this cold water will form a slug below the existing hot water in the tank, and a steep temperature gradient exists at this level. The heating element also creates a significant temperature gradient in the water. Water below the heating element remains relatively cold because heat from the element is convected to the top of the tank. Therefore, a steep gradient in temperature exists at the height of the heating element. Depending upon the locations of the lower thermocouple, the heating element, and the lower thermostat, the slug of water brought in during the pre-draw could either artificially increase or decrease the measurement of the initial tank temperature.

These two features of the temperature profile could account for the variations caused by pre-draws. To determine the average tank temperature, six thermocouples are placed in the tank at the vertical midpoint of layers of equal volume. This discretization of the temperature measurement creates errors in the determination of the average tank temperature, especially if a nearly step-like gradient exists in the temperature profile. For example, if the cold slug of water barely reaches the lower thermocouple, the measured average tank temperature would be lower than the true average tank temperature. As the heat conducts throughout the tank, steep gradients are smoothed out, and the measured tank temperature more closely approximates the true tank temperature; this situation exists at the end of the test where no draws have taken place for nearly 18 hours and the elements have not been energized for at least one hour. Since the measured initial tank temperature is lower than the true initial tank temperature, it appears that the tank has stored more energy than it actually has. This amount of energy is credited to the water heater, and it therefore appears that the tank has used less energy to heat water than it truly has. This modification to the energy factor would cause the determined energy factor to be greater than the true energy factor. The situation described here is likely the cause of the increase in

Table 6. Effect of Pre-Draws on Measured Energy Factor

Tank	No Pre-Draw	1 Pre-Draw	3 Pre-Draws
6	0.918	0.927	0.927
7a	0.905	0.925	--
8a	0.887	0.870	0.859

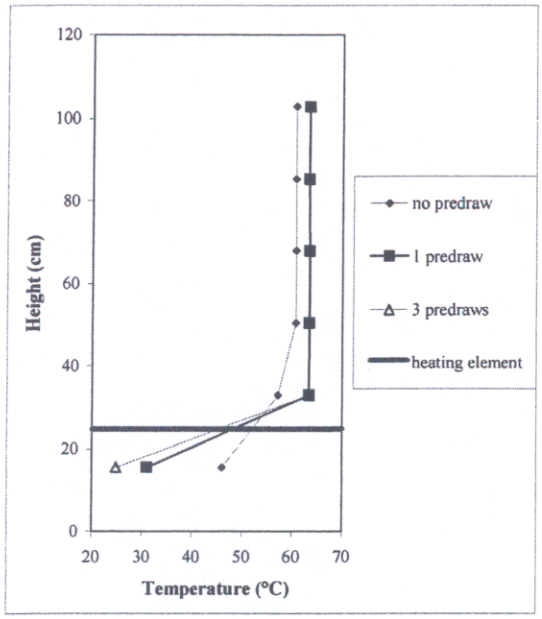


Figure 5. Initial Temperature Distribution in Tank 6 with Varying Number of Pre-Draws

energy factors seen for Tanks 6 and 7a when pre-draws are applied. The initial measured temperatures are plotted along with the location of the heating element in Figure 5 to show the difference between the profile when pre-draws occurred compared to the case where the tank had been idling before the simulated-use test. Note that the heating element lies above the lowest thermocouple, causing a steep temperature gradient between the lowest two thermocouples. This gradient is accentuated after pre-draws occur because insufficient time has passed to allow for conduction of heat into the cold slug of fluid below the heating element, and the eddies set up by natural convection do not reach down to the lowest thermocouple. Little difference is seen here between the temperature profile observed after one pre-draw compared with that seen after three pre-draws.

A different scenario is present if the water slug taken in during the pre-draw does not reach the lower thermocouple or if the thermocouple lies above the lower heating element. In such a situation, the measured initial tank temperature is greater than the true temperature. Because the measured initial tank temperature is too high, it appears that the tank has either (1) not stored significant energy or (2) lost energy from the start of the test to the end. This tank may then be penalized for this loss of energy. This scenario is likely the case for the results shown for Tank 8a.

Figure 6 displays the initial temperature profile in Tank 8a for tests involving three different numbers of pre-draws. Since the lowest thermocouple is at the same level as the heating element, the cold water below the heating element contributes little to the temperature measurement, and the initial tank temperature is in error. This effect is magnified after a pre-draw because a steeper temperature gradient occurs immediately after the heating element is energized. When no pre-draw occurs, the temperature gradient is lessened by heat conduction to the slug of water at the bottom of the tank during the long idle time experienced by the water heater. This time allows for a more accurate temperature measurement of the lowest one-sixth of the

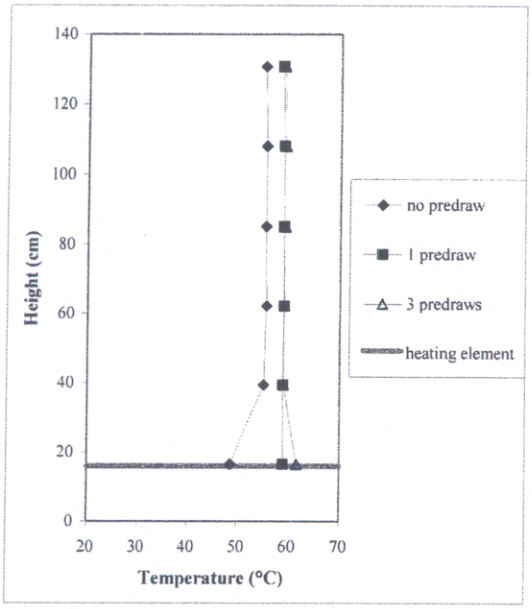


Figure 6. Initial Temperature Distribution in Tank 8a with Varying Number of Pre-Draws

tank and of the entire initial tank temperature. Figure 6 also displays a difference in the initial tank temperature during the test where one pre-draw was applied compared to the case where three pre-draws were applied. The lowest thermocouple measures a higher temperature after three pre-draws than it does after only one pre-draw. Investigation of other data, however, shows that this trend is not a consistent one. Because the lowest thermocouple is so close to the heating element, any residual heat from the heating element affects the temperature measurement. In these tests, the heating element was monitored once per minute, and the simulated-use test was commenced when the minutely reading indicated that the heating element was not energized. This approach means that the heating element could have been off anywhere from 1 s to 59 s before the start of the test. With the lowest thermocouple being so close to the heating element, that variability in time lag between cut-out of the heating element and the recording of the initial tank temperature could alter the initial temperature measurement. Obviously, when a thermocouple is so close to the heating element, average temperature measurements of the water in the tank could be in serious error. It is suggested, therefore, that a lag time of several minutes be inserted after cut-out and before commencement of the simulated-use test to allow heat to dissipate away from heating elements in case any temperature-measuring devices are close to the heating elements.

It is suggested that the flexibility of an optional pre-draw in the test procedure be eliminated to remove a degree of variability in the results. Either no pre-draws should be allowed or a specific number of pre-draws should be mandated in the procedure.

Thermocouple Location

Related to the issue of pre-draws is thermocouple location. The test procedure specifies that six thermocouples should be placed inside the tank to estimate the average tank temperature. These six thermocouples are placed at the vertical midpoint of six equal volumes. The exact

technique to determine this location, however, is not specified. One method of determining the lowest thermocouple location is to fill the tank up with one-twelfth of the overall volume and locate the surface of the water. This position will be the midpoint of the lowest one-sixth volume. The positions of the other thermocouples can subsequently be determined by adding one-sixth of the total volume to the tank and monitoring the location of the water surface. An alternative procedure is to measure the distance between the bottom and the top of the tank and calculate the position of the thermocouples by equally dividing these dimensions. This technique, however, will lead to errors in thermocouple location if any curvature exists in the top or bottom of the tank. A hybrid method whereby the position of the lowest thermocouple is obtained by filling the tank with water and the location of the remaining thermocouples are determined geometrically based on the tank dimensions yields slightly better approximations of the thermocouple positions than a method based solely on tank geometry.

In electric water heaters, the location of the lower thermocouple has a dramatic effect on the results of the test because the lower thermocouple typically lies in a region of severe thermocline within the tank, as mentioned previously. The locations of the other five thermocouples are not as critical because tank temperature is relatively uniform in the upper portion of the tank. Incorrect placement of the lower thermocouple, however, could add significant error to the calculation of the average tank temperature.

To investigate this effect, additional thermocouples were located in the lower portion of the water heater for some of the tests. Figure 7 shows the measured average tank temperature obtained with the bottom thermocouple located 63 mm (2.5 in.) higher than the standard location and the measured average tank temperature obtained with the bottom thermocouple in the standard location. Both temperatures were obtained during the same test on one water heater. By raising the position of the lowest thermocouple, the average tank temperature rises because of the severe temperature gradient in that region of the tank. The spikes in the trace occur immediately after the heating element is energized because of the steep thermal gradient that is created in those instances. In this test, the disparity in the average tank temperature leads to a difference in the reported EF of 0.044. The location of the bottom thermocouple in the tank during the test should be reviewed and specified more accurately.

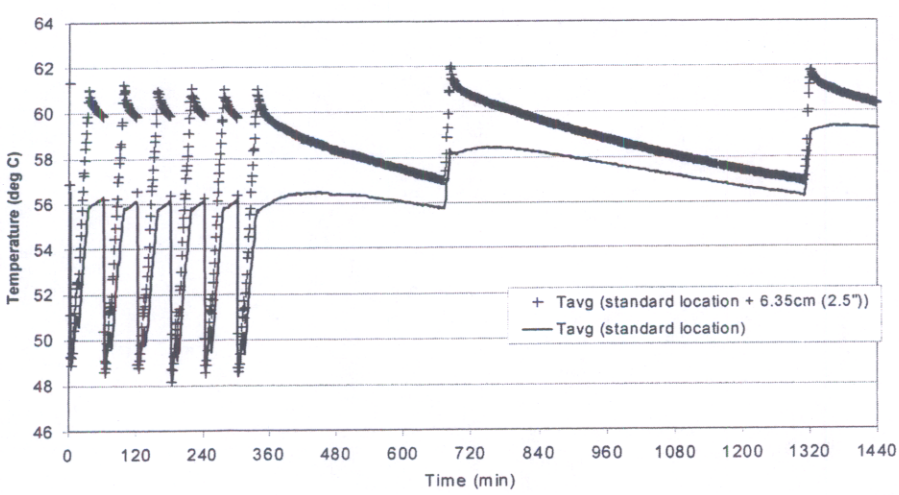


Figure 7. Average Calculated Tank Temperature During One Test Using Different Locations for the Bottom Thermocouple—The Standard Location Specified in the Test Procedure and a Location 6.35 cm Above the Standard Position

Tank Insulation

The test procedure specifies a particular piping configuration for the tests. If the tank comes with pipe insulation included in the box, that insulation is to be installed on the inlet and outlet pipes. Otherwise, the pipes are left exposed to the elements. Other features of the tank, such as the temperature and pressure relief valve and the drain valve, are not to be insulated during the test unless the manufacturer provides such insulation. (*Note*: ANSI/ASHRAE Standard 118.2-1993 [ASHRAE 1993] specifies that the relief valve be insulated, but the DOE test procedure does not allow for insulation beyond that which is provided by the manufacturer) It is thought that some test laboratories have included insulation on these tank parts to reduce heat loss through these significant thermal leaks. This practice unjustly raises the determined energy factor.

One area where insulation is needed is on any temperature-measuring devices used for the test. Test labs should ensure that these devices are insulated according to the requirements of the test procedure to prevent any unwanted heat losses that would decrease the energy factor. No other insulation is allowed to prevent extraneous heat losses during the test. Clarification of insulation requirements may be needed in subsequent modifications of the test procedure.

Warm-Up Period

The test procedure is meant to evaluate the water heater under steady-state operating conditions. No mention is made, however, of ensuring that a tank has reached steady-state conditions. To reach steady state, the tank insulation and jacket must warm up so that these components do not absorb heat during the test. The procedure does not account for this heat, so it appears that the tank has consumed more energy than it would during steady-state operation because the heat that goes toward warming up the insulation and tank jacket as opposed to heating water is not credited to the unit. Tests have shown that energy factors are higher by approximately 0.01 when a 24-hour warm-up period is applied before tests, as opposed to the situation where the test is begun immediately after initially heating it up. Longer warm-up periods show no effect on the energy factor compared to the case where a 24-hour soak-in period is used. To remove ambiguity in the test procedure, it is suggested that a 24-hour soak-in period be applied before the commencement of the simulated-use test.

CONCLUSIONS

Any scheme used to determine the efficiency of an appliance or HVAC equipment is subject to uncertainty because of the instruments used to measure various quantities, flexibility in procedures, and details that are omitted from the scheme but that play a vital role. These issues have been demonstrated in this study in which tests on high-efficiency electric water heaters have indicated several sources of variability in the current test procedure in the United States. Results from different labs on the same tanks varied dramatically, and the significance of this variability is demonstrated when one examines the tolerances required by regulations. For example, new regulations for water heaters are due to take effect in 2004 that will require a 190 L (50 gal) water heater to have a rated efficiency of 0.90. With the range of possible energy factors reduced by these regulations, greater precision is needed in tests to differentiate between models. Based on instrument tolerances currently allowed in the test procedure, uncertainties up to ±0.02 can be seen in the results from an energy factor test. Tightening tolerances on power meters and flow-measuring devices may be needed to decrease the measurement uncertainty to an acceptable level, as these instruments account for the greatest uncertainty among all of the instruments used in the test.

This work has also demonstrated how details that are overlooked in a test procedure can lead to excessive variability in results. Sources of ambiguity in the water heater test procedure may lead to significant variations in the determined energy factor. A number of aspects of the test procedure, including the use of optional pre-draws, the technique of locating temperature-measuring devices within the tank, the lack of a standard method of reaching steady-state operation of the tank, and the vagueness of insulation specifications, all lead to areas of variation in test results. A critical finding has been that knowledge of temperature gradients in equipment should be used in prescribing spatial measurements so that sufficient sampling occurs in regions of high gradients. In this work, it was found that spacing between thermocouples used to measure average tank temperature was inadequate to resolve the steep temperature gradient in one area of the tank while several thermocouples were devoted to regions of nearly uniform temperature. By examining the physics behind the operation of the water heater, improved spacing of thermometry devices will make better use of these devices and will provide a more accurate estimation of the average tank temperature.

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