Effect of Temperature Stratification Near Heating Elements on the Measured Energy Factors of Electric Water Heaters

William M. Healy, Ph.D.
National Institute of Standards and Technology
Building and Fire Research Laboratory
Building Environment Division
Gaithersburg, MD 20899-8632

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W.M. Healy

ABSTRACT

Two different models of 190 L (50 gallon) residential electric water heaters were tested to investigate problems that arise in determining their energy efficiencies due to the steep temperature gradient near the lower heating element. This gradient makes the determination of the average tank water temperature difficult because, in accordance with current test standards, temperature measurements are made at only six discrete locations within the water heater. Results show that errors in determining this average temperature can have significant effects on the Energy Factor by yielding inaccurate estimates of the stored energy within the tank. This estimate of the stored energy is part of the correction algorithm used to normalize the lab measured efficiency to the standard conditions that define the Energy Factor. The investigation's findings suggest that efforts should be made to ensure that conditions at the start of a test are similar to those at the end. For the two water heaters tested here, this scenario was best achieved by starting with a 24 hour idling period.

INTRODUCTION

The efficiency of residential electric water heaters can be estimated through tests prescribed by the United States Department of Energy (DOE 1998) and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE 2006). With water heating energy consumption amounting to 2.7×10^{18} J (2.53 quads) in the US and accounting for 15 % of residential energy consumption (United States Department of Energy 2000), accurate published data on the energy efficiency of water heaters is vital for evaluating and improving public energy policies and for allowing more informed purchasing decisions by consumers. In the United States, the primary mechanism for consumers to obtain this information is through the Energy Guide labels that are mandated by the Federal Trade Commission. The ratings on these labels are determined through testing in accordance with the DOE test procedure for residential water heaters.

In the U.S., the test procedure currently used to estimate annual energy consumption is a 24 hour simulated-use test. The efficiency of the water heater when tested and normalized to the conditions prescribed in the DOE test procedure is termed the Energy Factor (EF). In this test procedure, the water heater's thermostat(s) are adjusted to yield an average temperature in the water heater of 57.2 °C ± 2.8 °C (135 °F ± 5 °F). The ambient air temperature is maintained between 18.3 °C and 21.1 °C (65 °F and 70 °F); the inlet water is regulated to be 14.4 °C ± 1.1 °C (58 °F ± 2 °F). The consumption of water is simulated by drawing a total of 243 L ± 3.8 L (64.3 gal ± 1 gal) from the water heater via 6 equal draws, each at a flow rate of 11.4 L/min ± 0.95 L/min (3 gal/min ± 0.25 gal/min). These draws are initiated at the start of the first 6 hours of the test. No hot water draws are imposed during the remainder of the 24 hour test. Following the reheat cycle brought on by the sixth draw, the water heater may conduct additional heating cycles if the thermal losses to the ambient are sufficient to actuate the water heater's thermostat prior to hour 23 of the test. Afterwards, the energy consumed during the 24 hour test is normalized to account for differences between the conditions measured in the laboratory and the nominal test conditions. The Energy Factor is computed by dividing the amount of energy removed as hot water by the norrnalized energy consumption.

Energy Factors are typically reported to 2 decimal places, with each increase in Energy Factor of 0.01 amounting to an energy savings of 0.53 MJ/d (500 BTU/d). When multiplied by the millions of water heaters in operation, these potential energy savings place great importance on the ability to accurately determine the Energy Factor.

ISSUES INVOLVED WITH THE TEST PROCEDURE

The test procedure aims to provide an equitable method to compare water heaters under standard conditions. Several aspects of the procedure, however, allow flexibility that may either artificially inflate or deflate ratings. One test procedure issue that has been identified is the optional use of predraws. A predraw is carried out before the 24 hour test commences and involves the removal of water from the outlet until the thermostat turns the heating element on. The water heater is then allowed to recover, and the test is commenced after the tank recovers completely. The intended purpose of this process is to ensure that each water heater test starts in a consistent manner. Healy et al. (2003), however, found that this procedure may introduce errors in the calculation of the Energy Factor because of the large temperature gradient that is present around the lower heating element following a predraw. To further complicate matters, the current DOE test procedure allows the use of zero to three predraws. Considering the significant effect that predraws may have on results, this flexibility contributes to increased measurement uncertainty. The most recent ASHRAE test procedure removes this flexibility by mandating a single predraw, but questions still remain as to whether that step ensures an acceptably accurate measure of the Energy Factor.

Another area of vagueness in the current DOE test procedure is the method of starting the test when the water heater is first filled up with cold water. One option has been to heat the water in the tank and start the test immediately after that initial warmup period. Fanney et al. (2000) and Healy et. al (2003) report that such a method can lead to an inaccurately low EF since the initially cold solid material in the water heater removes heat from the water. The test procedure does not account for such heat storage. Since the test procedure aims to examine the operation of a water heater in a pseudo steady-state mode of operation, the question arises as to whether there are better ways to set up the water heater for such operation without placing an undue time burden on test facilities.

The above issues arose during the most recent revision process to the ASHRAE 118.2 test procedure. The committee concluded that insufficient data were available to justify any significant changes in the test procedure. Changes considered by the ASHRAE committee included using a different arrangement of in-tank temperature sensors to better capture the gradient at the bottom of the water heater and specifying alternative startup methods. The results reported here address these finer points and so should help identify improvements for future revisions to the residential water heater test procedures.

DESCRIPTION OF TESTS

To investigate the issues mentioned above, a series of simulated use tests were carried out on two dual-element electric water heaters purchased from retail outlets. Table 1 provides important parameters for each water heater. Each water heater was instrumented and plumbed according to the DOE test procedure except for the addition of extra thermocouples inside the tank. The DOE procedure calls for six temperature sensors to be placed in the water heater at the midpoint of equally partitioned, vertically stacked volumes. The average tank temperature is then estimated by averaging the measurements from these six sensors. To obtain better resolution of the temperature of the water inside the tank, an additional ten thermocouples were placed in the tank at the same radial and azimuthal position as the original six sensors to increase the measurement resolution of the temperature gradient at the bottom of the tank. Figure 1 shows the approximate locations of the thermocouples inside Tanks 1 & 2. Sensors at the bottom of the tanks were evenly spaced and were located to capture the temperature at points that vertically bracket the lower heating element. For Tank 1, two sets of 16 thermocouples were placed in the water heater, one each in the anode rod opening and the hot water outlet. The purpose of using two sets of thermocouples was to examine any differences that may arise from placing the thermocouples at different positions in the tank since the DOE procedure permits installing the thermocouples through any available water heater port (that does not contain a dip tube). For Tank 2, only one set of 16 thermocouples was placed in the water heater because the lack of an anode rod opening at the top of the tank resulted in only a single opening (the hot water outlet) for readily installing the thermocouples.

TABLE 1
Characteristics of tested water heaters

Characteristic	Tank 1	Tank2
Rated Volume	190 L (50 gal)	190 L (50 gal)
Rated EF	0.93	0.93
Height of outer case	1.17 m (46 in)	1.47 m (56 in)

Diameter of outer case	0.61 m (24 in)	0.56 m (22 in)
Jacket insulation thickness	7.6 cm (3 in)	5.1 cm (2 in)

A wide range of simulated-use tests was performed on these water heaters. Tests were performed on each tank with two different heating elements, one having a rated value of 4.5 kW and the other having a rated value of 3.5 kW. The two heating elements were used to explore any effect of heating rate on the gradients set up in the tank and on the resulting Energy Factors. Since the Energy Factor aims to estimate the amount of energy used while the water heater operates in a pseudo steady-state condition, such a condition is approximated by running the same cycle of draws over consecutive days. The end of one day's test is the start of the next day's test. Such a cyclical pattern leads to repeatability from one day's test to the next and avoids startup conditions that are not representative of operation after the water heater has been energized for some time. Several days of tests were run in such a fashion, and the estimate of the true Energy Factor is the average of those days in which a simulated-use test was commenced immediately at the end of a prior day's simulated-use test. As will be discussed, the Energy Factors for these tests are remarkably consistent. While running the actual test in such a manner would be desirable, such a method may not be practical given time constraints in the facilities of manufacturers and testing agencies.

For each configuration, the first set of tests examined the effect of predraws on the water heater performance. As the name suggests, a predraw is a procedure performed before the simulated-use test begins in which the outlet valve is opened and water is removed from the tank. Up to three predraws are allowed in the DOE test procedure and are carried out to pre-condition the tank before the simulated-use test commences. To implement a single predraw, the tank was fully heated and then allowed to remain in a standby mode for at least 24 hours. A draw was commenced (predraw) and terminated when the thermostat energized the lower heating element. The tank was then allowed to recover until the lower heating element was de-energized. (note: For this tank size, the draw size of 40.5 L [10.7 gallons] did not cause the upper heating element of the water heater to be energized during the test) The average tank temperature was monitored, and the simulated-use test was commenced within two min after the average temperature had reached its maximum. As an alternative, two additional predraws can be included in the pre-conditioning step, with each draw commencing after the tank has achieved a maximum temperature following the previous predraw. A third option for starting the test is without predraws. At the end of the 24 h idling period, the simulated use test was commenced without a pre-draw. The thermostat in the tanks did trigger recoveries during this idling period because of accumulated thermal losses to the environment, but it was ensured that no recovery had occurred in the hour before the test commenced. Tests were repeated for each of the three predraw conditions (0, 1, and 3 predraws) to provide an estimate of the repeatability of the results.

The second set of tests was performed to evaluate different options for test startup without a predraw. Three conditions were investigated. First, the tank was heated up from a cold start, and the simulated-use test was commenced immediately following that heating period. Second, the tank is heated up from a cold start, and the simulated use test is commenced following a 24 h wait period. The third startup attempted to condition the water heater as if a simulated test had occurred immediately before it. After the water heater was heated up from a cold start, a draw was taken having the same length as a draw in the simulated use test. This draw simulates the final/sixth draw of the current test. In the test procedure, an approximately 19 h standby period follows this final draw, so to simulate the start of a test following a previous day's simulated use test, the simulated use test was commenced 19 h after the initiation of the "simulated final draw".

In both sets of tests, various issues were investigated using the additional thermocouples. First, a better estimate of the average tank temperature was obtained with the additional thermocouples. This modified average tank temperature was used to compute a modified Energy Factor and was compared to the Energy Factor computed using the coarsely spaced thermocouples. Second, an estimate of the error introduced into the test results with a misplaced thermocouple could be made since more measurement locations were available.

Uncertainties in the determination of the EF during a single test can be estimated to be approximately ±0.012. Healy et. al further indicate that tolerances in the DOE test procedure could lead to uncertainties up to ±0.028 if instruments have uncertainty tolerances as allowed in the procedure. Instruments used in this study have tighter tolerances than those specified in the DOE test procedure, and, in averaging results from many tests, uncertainties in the averaged values are less than for a single test.

RESULTS

Temperature stratification

To demonstrate the stratification that occurs in an electric water heater, Figure 2 provides measured temperature distributions in Tank 1 at the beginning and end of two different tests. The first test used a single predraw before initiation of the simulated use test, while the second test started immediately after a previous day's simulated use test ended and, hence, did not have a predraw before the simulated use test began. Temperatures from all 16 measurement depths within the tank are included, with the large diamonds showing the location of the six sensors installed in accordance with the DOE procedure. Sensors were calibrated just before the test, and the uncertainty in temperature measurement of each sensor is estimated as ±0.1 °C (±0.2 °F) based on maximum deviation from the standard. As mentioned previously, one of the critical reasons for measuring the average temperature of water inside the water heater is to account for any change in stored energy from the beginning of the test to the end. Ideally, this value would be negligible so that all energy consumed by the water heater either results in heated water drawn from the outlet or waste heat given off to the environment. Since the average temperature within the tank is likely to change, the test procedure contains a correction to account for any change in stored energy. The difference between the average temperature at the beginning of the test and that at the end of the test is found and multiplied by the heat capacity of water in the tank. Thus, the determination of the average temperature of water in the tank is critical. It should also be noted that the average temperature of water in the tank is also used to adjust the energy consumption when the temperature difference between the water and the ambient is not the specified value of 19.7 °C (67.5 °F). Errors in temperature measurement inside the water heater will also affect this adjustment by modifying the computation of the heat loss factor and the average water temperature during the standby portion of the test. Examination of this effect, however, showed that errors in temperature measurement had a minimal effect on the resultant Energy Factor. Therefore, the effect of temperature measrurement errors on the adjustment of standby heat losses is not a significant source of error in the resultant Energy Factor and will not be discussed.

The DOE procedure calls for the water heater to be split into six equal volume zones with a sensor being positioned at the middle of each zone. Inherent in this specification is the assumption that the temperature within each zone is accurately represented by the temperature at the center of the zone. The dashed lines in Figure 2 show the boundaries between the lowest 3 zones. Figure 2 quantifies the large temperature gradient that exists near the lower heating element. Natural convection from the heating element creates a uniform temperature above that location, but conduction effects do not bring the water below the element to a uniform temperature in the time allotted. For this water heater during these tests, a gradient of up to 25 °C (45 °F) in a space of 14 cm (5.4 in.) was observed near the bottom of the tank. The most severe gradient is seen at the beginning of the test that began just after a recovery caused by a predraw (Test 1). For this test, the 14 °C (58 °F) make-up water was supplied to the bottom of the water heater during the predraw which ended approximately fifteen minutes before this measurement was taken; the heating element, in this case, had turned off within ten minutes prior to the start of the test (and the collection of the Figure 2 "start after predraw" data). The temperature distribution at this point can be well approximated as a step change. At the end of the test on the first day, the temperature gradient is less severe since the heating element had not been energized at least within the last hour of the test (as specified by the DOE test procedure). This time without heating has allowed heat to conduct from the hot water above the heating element to the colder water below the element (both through the water and through the adjacent metal tank). This heat conduction leads to a more gradual temperature gradient at the bottom of the tank.

These temperature gradients have significant implications on the measurement of the average water temperature within the tank. In the top four zones of the water heater, the temperature approximation of the zone is not sensitive to the location of the sensor because the temperature is uniform in those zones. The situation is different, however, for the lower two zones. Temperatures at the beginning of the test following the predraw will first be examined. For the fifth zone from the top, the temperature measured using the sensor positioned in accordance with the DOE test procedure (i.e., the large diamond in zone 5 of Figure 2) does not capture the temperature dip that occurs at the lower end of the zone. Therefore, the measured temperature for this zone will be slightly above the true average temperature in that zone. For the lowest zone, the temperature sensor specified in the DOE test lies in a region that appears to have achieved a uniformly low temperature. This sensor greatly underestimates the average temperature in the lowest

zone since the warmer water near the heating element is not represented by the temperature measurement at the center of the zone. For this case, an estimate of the average tank temperature was made using numerical integration of all available data and with the assumption that the temperature below the lowest sensor is uniform at the temperature of the lowest sensor. This estimated average temperature was 55.1 °C (131.2 °F) compared to a value of 54.6 °C (130.3 °F) when the average is computed from the six thermocouples specified in the DOE test procedure.

For the other test conditions at which Figure 2 shows temperature distributions, errors in estimating the zone temperatures may still be present but are not as dramatic as at the start after a predraw. A nearly linear temperature profile is shown in both lowest zones, so a temperature measurement at the center of each zone approximates the average temperature throughout the zone. Comparison of average temperature calculations at the end of test 1 show that the value computed using all 16 thermocouples matched that computed using six thermocouples within 0.1 °C (0.2 °F). For day 2, the average temperature computed using six thermocouples exceeded that computed using 16 thermocouples by 0.17 °C (0.31 °F) and 0.13 °C (0.23 °F) at the start and end of the test, respectively.

Overall, the steep temperature gradient near the lower heating element presents great challenges in obtaining an accurate measurement of the average temperature of the water inside the electric water heater.

Effect of thermocouple tree location

While testing Tank 1, two sets of 16 thermocouples were placed inside the water heater. One set was placed through the anode rod opening at the top of the tank while the other was placed through the hot water outlet. Both locations are permitted in the DOE test procedure, so this part of the study aimed to determine any temperature differences seen between the two locations.

Data at the start and end of tests were examined at 13 times during testing. It was found that the difference in average tank temperature measured using each set of 16 thermocouples was 0.2 °C (0.4 °F) or less. The difference in the average tank temperatures measured at the six locations specified by the DOE test procedure was 0.16 °C (0.29 °F) or less. No consistent bias was shown in the results, so it is not felt that significant differences in the Energy Factors would result from placing the sensors in different positions. It should be noted that each set was positioned at approximately the same radial distance from the center of the tank, so no conclusions can be drawn regarding radial temperature variations.

Effect of predraws

Figures 3 and 4 display the average Energy Factors determined from testing using four tank configurations; error bars indicate the standard deviation in the results for each test condition. On each plot, an estimate of the true EF is displayed. This estimate was obtained by averaging all tests that were carried out on back-to-back days. Standard deviations of this estimate of the true EF were 0.002 for each heating element of Tank 1, 0.007 for Tank 2 with the 3.5 kW heating element, and 0.004 for Tank 2 with the 4.5 kW heating element. For both tanks, no statistically significant difference was observed in the EF between the two heating elements. Tests performed without a predraw yielded the closest estimates to the true Energy Factor, and the effect of the predraw was markedly different for each tank.

For Tank 1, the use of a predraw tended to raise the measured EF above the “true” value. With Energy Factors typically reported to two decimal places, the estimate of the true EF is 0.92 for both heating element sizes. For the 3.5 kW heating element, a single predraw raised the Energy Factor to a value of 0.924, and the test run with 3 predraws raised the Energy Factor to 0.928. The use of three predraws would therefore raise the reported Energy Factor by 0.01. For the tank with the 4.5 kW heating element, the test run with one predraw would still be reported as 0.92, but the test run with three predraws would be reported as a 0.93. Considering the efforts expended to achieve a 0.01 increase in EF, this difference is significant to the industry and the public.

For Tank 2, the predraws act to decrease the measured Energy Factor compared to the estimate of the true Energy Factor. With the 4.5 kW heating element in place, the tests with 3 predraws yielded an Energy Factor of 0.88 compared to the estimate of the true EF of 0.90. Tests with a single predraw yielded the true EF, but the large standard deviations indicate the variability in the test results. For the tank with a 3.5 kW heating element installed, tests with a single predraw yielded an Energy Factor of 0.88 while tests with 3 predraws yielded an EF of 0.89.

The reason that predraws affect the value of the Energy Factor is that a predraw and the subsequent heating of the water creates a peak temperature gradient in the bottom of the water heater that makes

accurate measurement of the average water temperature very difficult. The average tank temperature at the beginning and end of the test are used to adjust for any stored energy in the water heater, so errors in estimating the average tank temperature lead to errors in the resulting Energy Factor. As shown in Figure 1 and discussed in the previous section, the measured average tank temperature of Tank 1 at the beginning of a "start after predraw" test underestimates the true average tank temperature. If the true tank temperature did not change from the beginning of the test to the end, no energy storage would have occurred. However, the measured temperatures in this situation suggest that the tank temperature actually increases since the temperature at the beginning of the test is erroneously measured to be less than the true temperature. This error leads to the conclusion that the water heater consumed energy that went towards increasing the stored energy within the water heater, and this energy would then be credited towards the water heater by subtracting it from the total energy consumed over the course of the simulated use test. The Energy Factor would therefore be higher because it would appear that the water heater had used less energy to achieve the hot water output specified in the test procedure.

For Tank 2, the position of the heating element in the tank lies just above the lowest thermocouple (as positioned according to the DOE test procedure). This positioning causes the measured tank temperature to be higher right after a predraw than the true tank temperature since water in the lowest zone is colder beneath the thermocouple. This error in temperature measurement makes it appear that the water heater has lost more stored energy than it truly has, and the resulting correction then penalizes the water heater by adding that amount of energy to its overall energy consumption. The resulting EF is therefore lower than the true EF.

For these two water heaters in the configurations provided, the use of no predraw has provided the best estimate of the true Energy Factor, while the use of one or three predraws has introduced errors into the results.

Effect of startup methods

While the optional use of predraws just before a simulated use test commences adds some variability into the DOE test procedure, another area of ambiguity arises regarding the method of heating up the water heater from a cold start in anticipation of the simulated-use test. The test is not intended to estimate the energy consumption of a water heater from a cold condition but, rather, is meant to estimate that consumption once the water heater reaches operational temperature. Even without the use of a predraw before the test, the method of startup may have an effect on the measured Energy Factor. When a water heater is to be tested, it is first filled up with water and then allowed to heat up. The thermostat setting is evaluated by calculating the average tank temperature at the end of the initial heating period and seeing if it falls within the temperature range specified in the test procedure. If outside the range, the thermostats are adjusted accordingly, a large draw is imposed, and the evaluation process is repeated.

No specification is currently given in the DOE test procedure as to when a test should start following this startup period, though the most recent version of the ASHRAE test procedure specifies a 24 hour wait period following initial heat up. The reason for this waiting period is to allow the tank jacket and insulation to reach a temperature that is seen in operation. Without this waiting period, heat is removed from the water inside the tank to heat the surrounding pressure vessel, penetrations, and insulation. Since there are no provisions in the test procedure to account for the stored energy inside the water heater's solid materials, the water heater is then penalized. Healy et al. (2003) report that this effect can account for a 0.01 decrease in Energy Factor from the actual value.

Tests were carried out to investigate this issue in further detail and to examine potential startup methods. As with the predraw investigation, the best-case scenario would be one in which the state of the tank at the beginning of the test is exactly the same as that at the end of the test. In this situation, no corrections would be needed to account for any change in stored energy, and the uncertainty in determining the value would be eliminated.

Three startup methods were examined. To simulate the placement of a water heater in a test facility, the tank was completely drained, refilled with cold water, and allowed to sit at least 24 h with power shut off to the water heater. The first startup method involved allowing the water heater to operate until both thermostats are satisfied, and then immediately starting a simulated-use test. The second method specified that the water heater sit idly for 24 h after completing the intial heating process before starting the simulated use test. The third method explored the possibility of mimicking the beginning of a test immediately following a simulated use test. After the initial heat up, a simulated sixth draw is imposed on the water heater and a normal recovery is allowed. The tank then sits idly for 19 h (relative to the initiation

of this sixth draw) as it would during a simulated use test. The actual simulated use test is then started. It was hoped that such a procedure would result in a tank state at the beginning of the test that is very similar to that at the end of the test.

Interesting results were found from the tests. For Tank 1, Figure 5 shows the opposite trend than what was expected based on the assumption of heat storage by the water heater's solid materials. In this case, the initial heating period sets up a steep gradient at the bottom of the tank that erroneously leads to a higher EF as discussed in the previous section. Tests done with a 24 h wait and a mock sixth draw resulted in EF's that are very close to the "true" value. For Tank 2, Figure 6 once again shows that the 24 hour wait period and the mock sixth draw startup methods resulted in Energy Factors very close to the estimated true value. For this tank, the EF falls below the true value as expected based on the fact that heat is stored in the tank materials that is not accounted for in the test procedure. This drop, however, may also be attributed to the large gradient present in the bottom of the tank immediately after the initial heat up of the tank. The previous section indicated that the gradient following a predraw led to a decrease in the Energy Factor from the true value of about 0.01. Figure 6 shows that the Energy Factor lagged below the true value by approximately 0.02. It can reasonably be concluded that the drop in EF found when the test was started immediately after initial heat up can be attributed to both the gradient present at the bottom of the tank and the fact that the cold tank materials absorb some heat from the water.

For these tanks under the conditions tested, the startup method in which a 24 h waiting period follows the initial heat up provided the best combination of accuracy and simplicity.

Sensitivity of results to errors in thermocouple placement

When sensors are placed inside the water heater, there is some uncertainty regarding their actual position despite the best efforts of the person installing the sensors. Using the data available, we investigated the sensitivity of the test procedure to errors in thermocouple placement. As seen by the thermoclines in Figure 2, the positions of the four highest thermocouples have little effect on results for these tanks since the temperature throughout the zones are essentially uniform. The positions of the lowest two thermocouples, however, could have a significant effect on the results. This part of the study aims to examine that effect.

EF's were computed for both Tank 1 and Tank 2 with the lowest two sensors in three different positions. In Tank 1, each sensor in the bottom two zones could be at the point specified in the DOE test or 2.7 cm above or below that position. In Tank 2, each sensor in the bottom two zones could be at the point specified in the DOE test or 3.3 cm above or below that position. Since each of the lower two thermocouples then had three possible positions, EF's were computed using average tank temperatures computed from all nine combinations of thermocouple positions.

Interesting trends emerged that supported previous findings regarding the trouble caused by sharp temperature gradients at the bottom of the water heater. Tests carried out to determine the "true" EF in which the first draw commenced at the end of a previous day's test showed little variation when different sensors were used to compute the EF. For Tank 1 with 4.5 kW heating element, EF's computed with seven of the nine thermocouple positions were 0.919 while the other two were 0.918. Other tests used to examine the performance of tanks under zero predraw startup methods showed similarly low variation among the results. Table 2 shows the ranges of EF's for a variety of conditions for both Tank 1 and Tank 2. Overall, tests with predraws and those starting immediately after heating lead to the largest variations between the computed EF's. The variations for these flawed approaches ranged from a best case of 0.011 (Tank 1, one or three predraws) to a worst case of 0.042 (Tank 2, one or three predraws). As noted previously, the temperature gradient is significant in the lowest two zones of the water heater for these predraw and immediate start approaches.

Table 2
Range of Energy Factors computed using 9 different combinations of the positions of the lowest two tank thermocouples

Test	Tank 1	Tank 2
"True" EF Tests	0.918 – 0.919	0.892 – 0.899
Tests with 1 or 3 predraws	0.921 – 0.932	0.878 – 0.920
Tests with 0 predraws	0.919 – 0.920	0.892 – 0.899

Tests begun immediately after initial heating	0.916 – 0.939	0.883 – 0.901
Tests begun 24 hrs after initial heating	0.916 – 0.922	0.893 – 0.901
Tests begun 19 hrs after a simulated 6th draw	0.917 – 0.922	0.902 – 0.910

As one example of the effect of sensor placement on the Energy Factor calculation, Figures 7 and 8 show the average Energy Factors computed for Tank 1 and 2, respectively, when the position of the lower two sensors is changed. On these plots, results are shown for cases where a predraw was used and also for tests that examined a test start with no predraw, both including an idling period after the initial cold-start recovery. The three bars for each TC position indicate that the sensor is either at the prescribed DOE position ("0"), above the DOE position by the amount specified in the previous paragraph ("+"), or below the DOE position by the amount specified in the previous paragraph ("-"). TC 6 refers to the thermocouple that measures the temperature of the bottom zone in the tank (Zone 6) while TC 5 refers to the thermocouple that measures the temperature in the 2nd zone from the bottom of the tank (Zone 5). Each value was computed by averaging EF's obtained in all tests for a particular condition (e.g., a predraw test) and for a particular thermocouple setting. For example, the value for TC5 at position "+" was obtained by averaging the three values for each test in which thermocouple 5 was taken as one position above the DOE value. Those three values include the three possible positions of thermocouple 6.

Both figures show that tests with predraws are more susceptible to measurement error should a thermocouple be placed in an incorrect position than tests with no predraws. For Tank 1, the EF is sensitive to positions of temperature measurements in both zones, though the lowest zone shows more change in EF from the highest position to the lowest position. For Tank 2 (Figure 8), the position of the lowest thermocouple has a significant effect on EF's obtained when predraws are present, but the position of the sensor in the second zone from the bottom is not as significant. It is interesting to note that the trend in EF with lowest sensor position is opposite for Tank 1 and Tank 2, with the average EF falling when the position is lowered for Tank 1 and the average EF rising when the position is lowered for Tank 2. Since it was hypothesized that the change in computation of stored energy in the tank led to the differences in EF, the differences in average tank temperature measured at the beginning and end of the tests were examined.

This examination raised some interesting findings. It was initially expected that the large gradient present after a predraw would lead to large differences in average tank temperature at the start of the test should the sensors measuring the temperature of the bottom two zones be misplaced. This expectation was not always met. For example, with Tank 1, tests with predraws showed a difference in average tank temperature of only 0.1 °C (0.2 °F) when the lowest sensor was modified from its highest position to its lowest, while tests without predraws showed a temperature difference of 0.7 °C (1.2 °F). In examining the temperature profiles, it was found that the steep temperature gradient in the water heater lies just outside of the locations of the sensors used in this investigation. Away from this steep gradient, the temperature is relatively uniform immediately after a predraw, so modification of the sensor position did not significantly change the measured water temperature. When no predraw occurs, a gradual thermocline is set up and any adjustment of sensor location will result in a change in measured temperature. For Tank 2, adjustments in sensor position resulted in greater changes in the measured average tank temperature since the lowest sensor is very close to the heating element, the cause of the steep temperature gradient. After a predraw, the average tank temperature at the start of the test varied 4.2 °C (7.6 °F). With no predraw, the average tank temperature at the start varied only 0.7 °C (1.5 °F).

Measured average tank temperature at the end of the test showed variation with sensor position for all situations. Since a gradual temperature gradient is set up in both tanks and in all situations, adjustment of the location of the temperature sensors at the bottom of the water heater resulted in changes in the measured tank temperature. The interesting aspect of this finding, however, is that the change in the measured average tank temperature is very similar to changes seen at the start of tests when no predraw is present. This observation suggests that the errors in measuring the average tank temperature are less important when no predraws have occurred since the key factor is the difference in tank temperature from the start of the test to the end. Since the conditions in the tank are similar at the start and end when no predraw is used to start a test, errors in sensor positioning lead to similarly biased errors in the average tank temperature at the beginning and end of the test. Therefore, the error in the temperature difference from start to end is minimal. This situation is not the case, however, when predraws are used to start the test. Since the error in average tank temperature is different at the start and end of the test, the difference in the average tank temperature is in error.

To check whether the differences in average tank temperatures at the start and the end of the test truly caused the changes in the Energy Factor as opposed to some other issue, an analysis was carried out to determine the impact of changes in these temperatures on the resulting Energy Factor. The changes in temperatures due to the adjustment of sensor positions were converted to corrections in energy by multiplying by the volume of water in the tank, the density of the water at 57 °C (135 °F), and the specific heat at 57 °C (135 °F). The energy delivered was determined by multiplying the nominal mass of water removed from the tank by the specific heat and nominal temperature rise from inlet to outlet, 43 °C (77 °F). For each water heater, the baseline energy consumption was determined by dividing the delivered energy by the measured "True" Energy Factor. This energy consumption was modified by the changes in stored energy arising from the differences in measured average tank temperatures.

For Tank 1, the prediction of changes in the EF during tests with predraws from adjustment of the lowest temperature sensor position was 0.008. This value is precisely the difference shown between the average EF when TC6 is at its highest position and when TC6 is at its lowest position in Figure 7 (Tank 1). For Tank 2, the predicted change arising from the change in TC6's position was 0.045, while Figure 8 shows a change in EF from TC6 position + to position – of 0.034. While other factors may certainly play a role in the computation of the EF, it appears that the change in the computation of stored energy when sensors are in different positions plays a significant role in affecting the resulting EF.

These results show that the Energy Factor calculation is much more sensitive to sensor position when tank conditions at the beginning of the test are markedly different from those at the end of the test. Such a situation is present when a predraw is used before commencement of a test or when a test is started immediately after the initial heat up.

CONCLUSIONS

This study has examined a number of issues that affect the rated energy consumption obtained from the simulated-use test for electric water heaters. The test allows for optional predraws to occur before commencement of the test, but these predraws have been shown to introduce errors in the results for the two 50 gallon electric water heaters tested in this study. Additionally, the use of predraws makes the proper placement of temperature sensors within the tank more critical, as it was shown that Energy Factors are affected more by misplacement of sensors after a predraw than when no predraw is used.

Alternative methods of starting the tests from a cold start were also investigated. It was found that starting a test immediately after the initial heat up led to variability in the results because of the large temperature gradient present in the bottom of the tank and because the water heater's solid materials are absorbing heat that is not accounted for in the test procedure. Tests run with a simulated sixth draw 19 hours before the actual start of the simulated use test aimed to put the water heater in a pseudo steady state condition, but it was shown that simply waiting 24 hours after initial heat up provided consistent results that were close to the estimated true Energy Factor.

Overall, this study showed the pitfalls that can occur in measuring the energy efficiency of equipment when accurate temperature measurements are needed. In this case, the measurement of the average temperature inside the water heater using 6 discrete temperature sensors encountered problems because of the steep temperature gradient present inside the water heater. Such factors should be considered when drafting test procedures. In this situation, a viable technique for dealing with potential errors in temperature measurement was to remove the importance of these measurements. With regards to water heaters, the measurement of tank temperature takes on less importance when the condition of the water heater at the beginning of the test most closely matches the condition at the end of the test. For the two water heaters tested in this study, it is concluded that the use of optional predraws creates a condition at the beginning of the test that is far different from that at the end, and it would be recommended that a predraw not be taken to ensure the most accurate results. While the evidence is strong that predraws introduce potential errors, studies should be taken on a wider range of water heaters to confirm these findings. Other parameters that could be investigated include the effects of tank volume, tank shape, and tank manufacturer on the results. One potential approach for doing such a study is to use a computational model of water heaters (e.g., Hiller et al, 1994) or a computational fluid dynamics code, with the data from the present study being used to help verify the performance of the model. Additionally, to ensure an equitable test procedure for a wide range of fuels, test should be performed on fossil-fuel powered and heat pump water heaters to ensure that Energy Factor results are not adversely affected by modifications aimed at making tests on electric water heaters more accurate.

REFERENCES

ASHRAE Standard 118.2: Method of Testing for Rating Residential Water Heaters. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. Atlanta, GA. 2006.

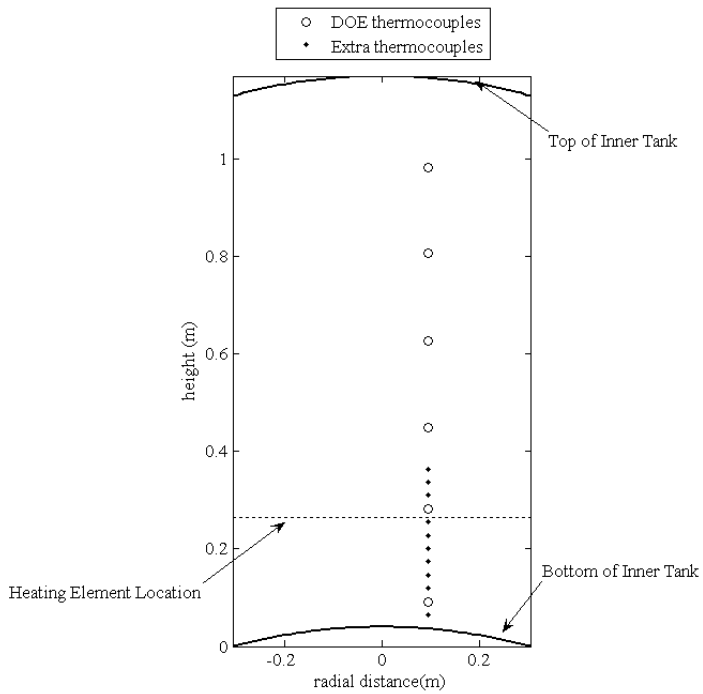
Fanney, A.H., Zarr, R.R., and Ketay-Paprocki, J.D. 2000."Thermal Performance of Residential Electric Water Heaters Using Alternative Blowing Agents" *ASHRAE Transactions* 2000, Vol. 106, No. 2, 1-13.

W.M. Healy, J.D. Lutz, and A.B. Lekov, "Variability in Energy Factor Test Results for Residential Electric Water Heaters," *HVAC&R Research Journal* 9:4, pp. 435-449, October 2003.

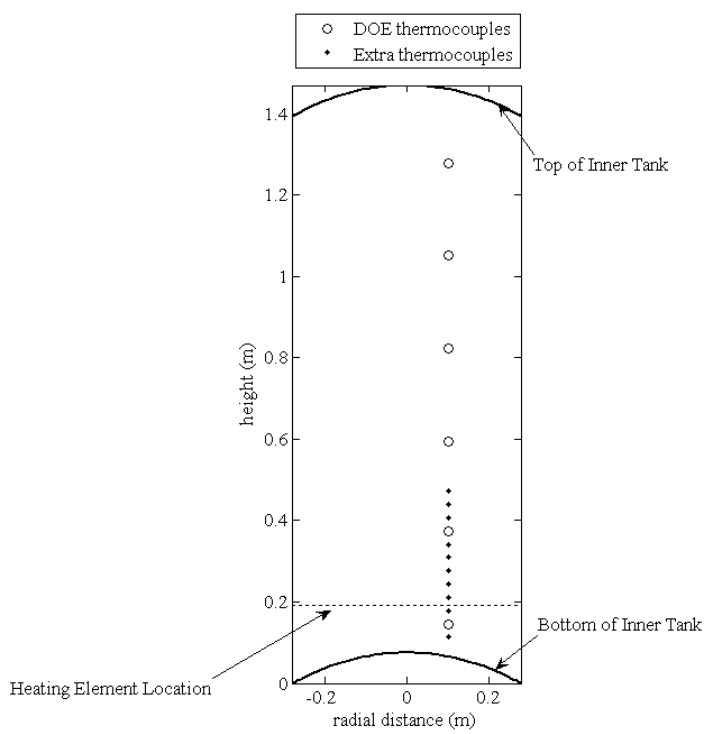
C.C. Hiller, A.I. Lowenstein, and R.L. Merriam 1994. "Detailed water heating simulation model" *ASHRAE Transactions* 1994, Vol. 100, No. 1, 948-955.

U.S. Department of Energy. Technical Support Document: Energy Efficiency Standards for Consumer Products: Residential Water Heaters. http://www.eere.energy.gov/buildings/appliance_standards/residential/waterheat_0300_r.html. December 2000.

U.S. Department of Energy-Office of Energy Efficiency and Renewable Energy, "Energy Conservation Program for Consumer Products:Uniform Test Method for Measuring the Energy Consumption of Water Heaters" 10 CFR Part 430. Appendix E to Subpart B of Part 430, 1998.



(a) Tank 1



(b) Tank 2

Figure 1. Thermocouple placement inside (a) Tank 1 and (b) Tank 2

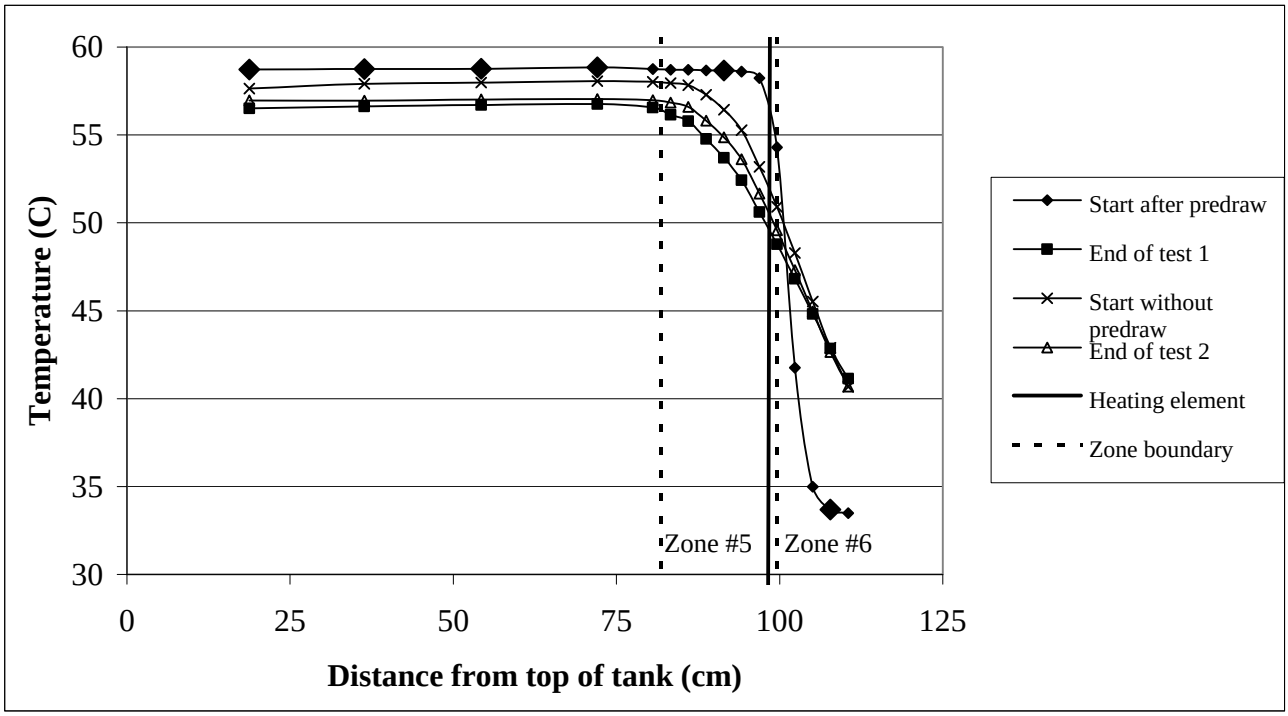


Figure 2. Temperature profile of water inside water heater.

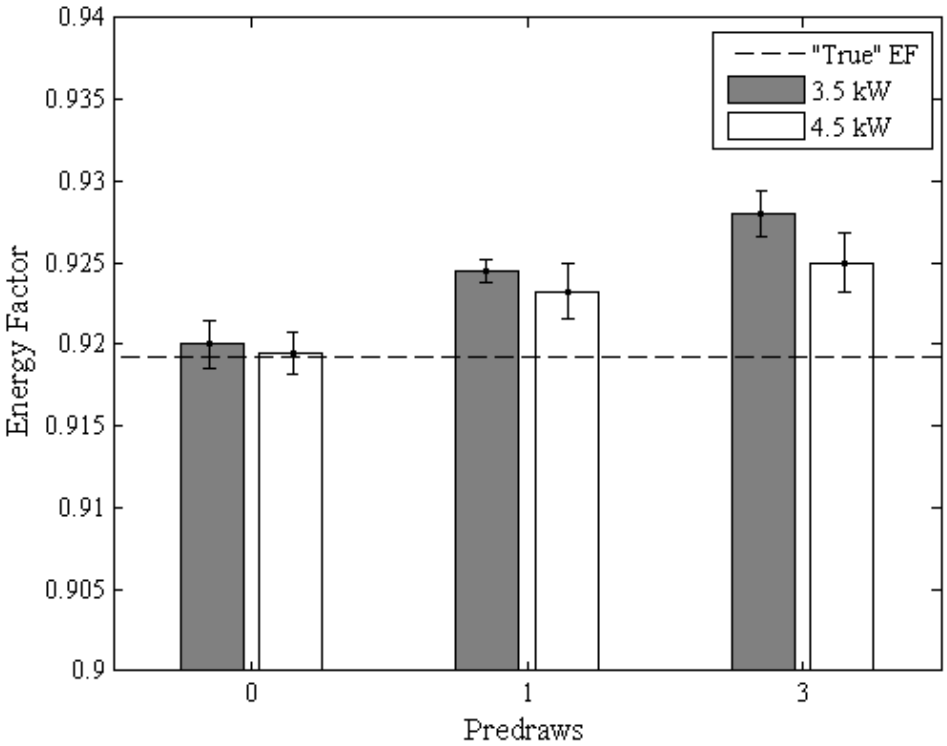


Figure 3. Effect of predraws on Energy Factor of Tank 1 with each heating element.

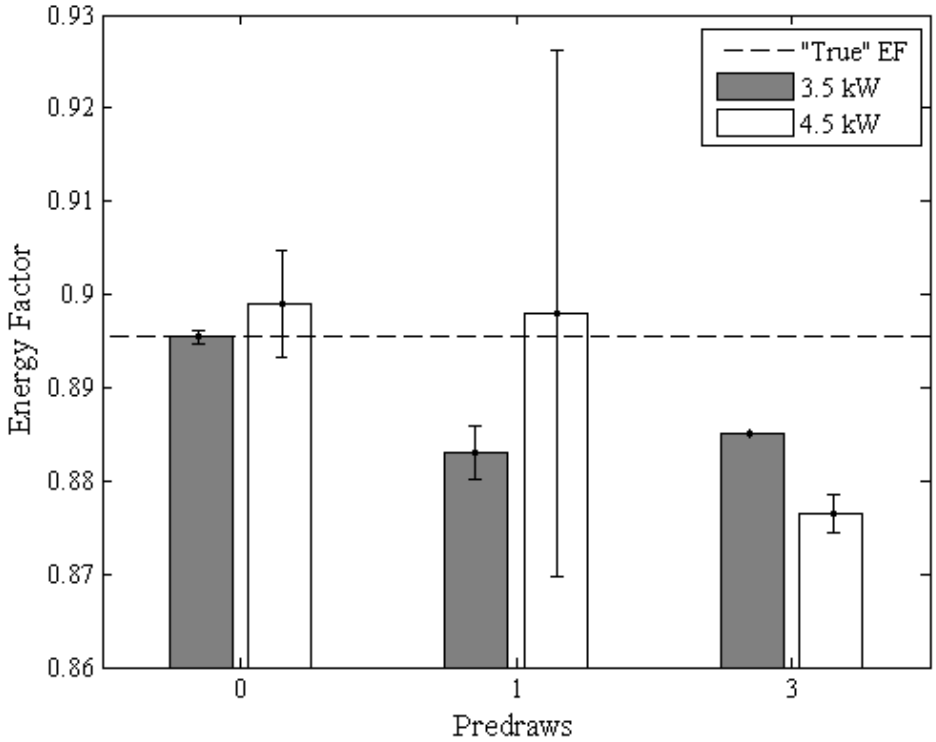


Figure 4. Effect of predraws on Energy Factor of Tank 2 with each heating element.

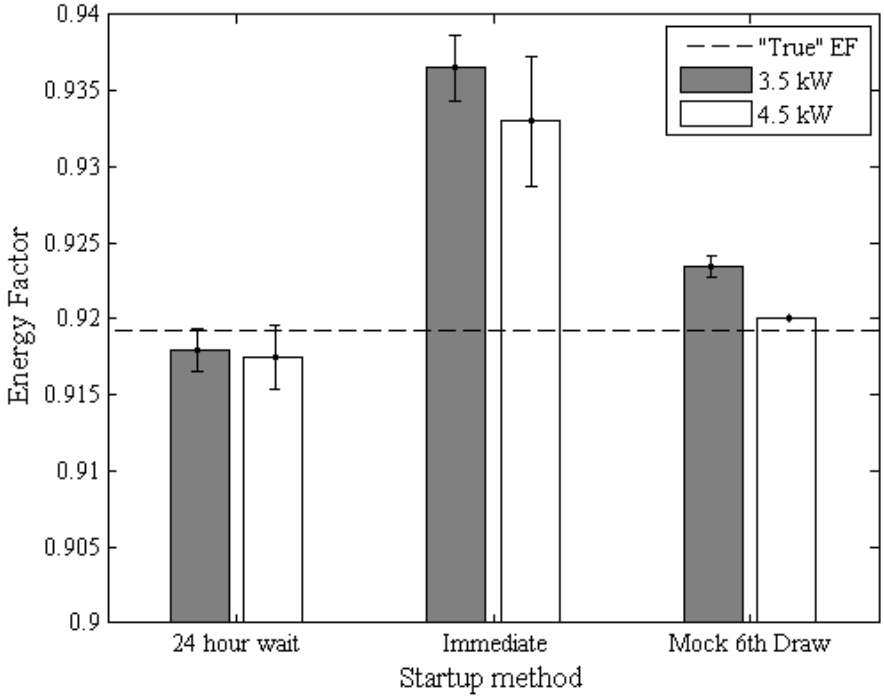


Figure 5. Effect of startup method on EF of Tank 1 with each heating element.

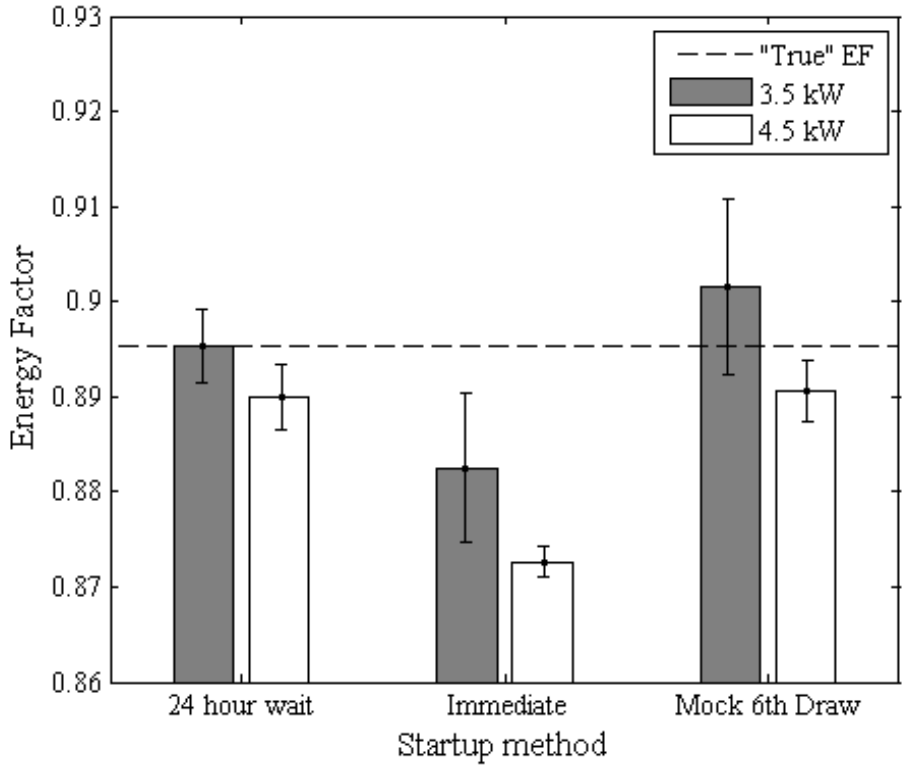


Figure 6. Effect of startup method on EF of Tank 2 with each heating element.

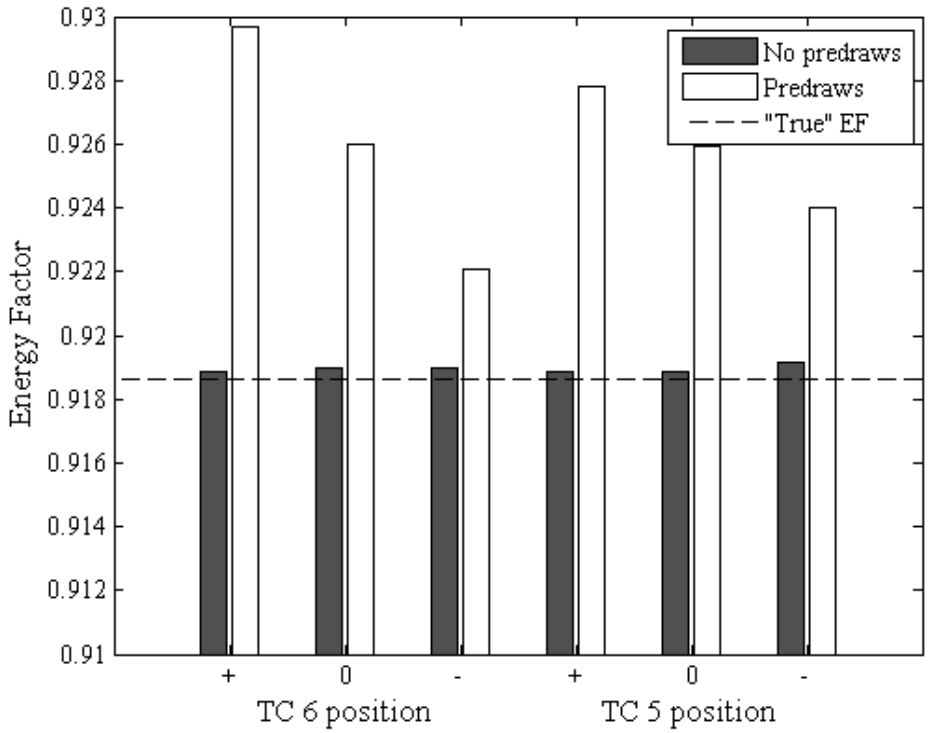


Figure 7. Effect of temperature sensor position on EF during tests with predraws and with a zero predraw start condition. Tank 1 with 4.5 kW heating element.

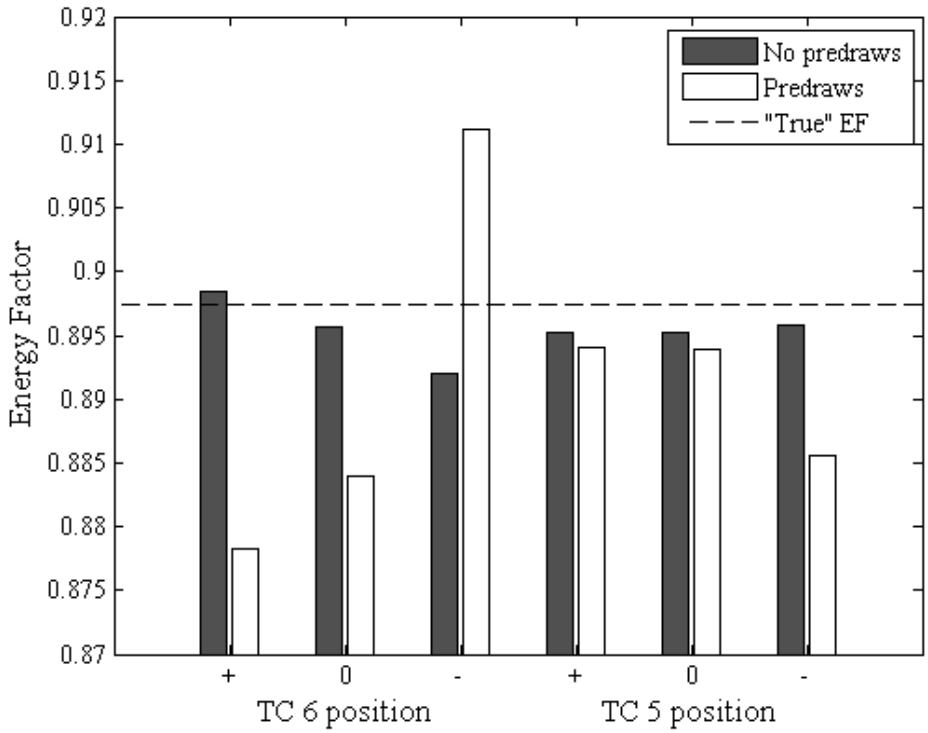


Figure 8. Effect of temperature sensor position on EF for tests with predraws. Tank 2 with 3.5 kW heating element.