WHAM: A Simplified Energy Consumption Equation for Water Heaters

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ABSTRACT

Energy analysts need a method to quickly and reliably estimate residential water heater energy consumption. The Water Heater Analysis Model (WHAM) is a simple energy equation that accounts for a variety of operating conditions and water heater characteristics when calculating energy consumption. The results of WHAM are compared to the results of detailed water heaters simulation programs and show a high level of accuracy in estimating energy consumption.

Introduction

Water heating comprises a significant portion of residential energy consumption — 17% in the U.S. according to the *Residential Energy Consumption Survey* (RECS). (EIA 1995) Energy analysts need a method to quickly and reliably assess current and future energy requirements for such a significant energy end use under a variety of conservation policies and programs.

Residential water heater energy consumption can be accurately estimated using a simplified energy equation. The Water Heater Analysis Model (WHAM) energy calculations are based on assumptions that account for a variety of field conditions and water heater types. By including seven parameters – recovery efficiency (RE), standby heat loss coefficient (UA), rated input power (Pon), average daily hot water draw volume, inlet water temperature, thermostat setting, and air temperature around the water heater – WHAM provides an accurate estimate of energy consumption in the majority of cases.

This paper begins by recounting the origins of the water heater test procedure that provide WHAM's foundation. In the next section, WHAM is described and the equation and its assumptions are given. The third section describes four other ways analysts have calculated water heater energy consumption and, in the fourth section, WHAM is compared to two simulation models.

Test Procedure Origins

The U.S. Department of Energy's (DOE) water heater test procedure provides the basis for the WHAM equation. The origins of DOE's water heater test procedure stem from the 1970s when fuel prices escalated rapidly. In 1975, the U.S. Congress determined the need for a program establishing energy conservation standards, labeling, and test procedures for certain major household appliances.

Energy Efficiency

The Energy Policy Conservation Act (EPCA) set voluntary labeling and efficiency guidelines for residential appliances and lighting products. Twelve years after Congress created EPCA, they amended it by setting the first national efficiency standards for appliances and established a schedule for regular updates. In 1987, the National Appliance Energy Conservation Act (NAECA) updated EPCA and charged DOE with the development of test procedures and standards for residential appliances. The purpose of the standards is to set a minimum energy efficiency that is technologically feasible and economically justified.

The initial water heater test procedures were issued September 27, 1977. Subsequent amendments have been made. DOE continues to maintain uniform testing procedures, periodically reassess the standards, and amend them as necessary. Energy labels are required on certain major appliances to allow purchasers to consider energy costs in making their purchase decisions. By law, all labeling and advertising claims made concerning the cost of operation, energy use, or efficiency of a product must be based on DOE test procedures. These test procedures are reviewed on a regular basis to determine if they need to be amended. (55 FR 42161)

The Energy Factor Calculation

DOE's water heater test procedure includes a method for calculating the Energy Factor (EF), a measure of efficiency. Manufacturers use EF to rate the energy efficiency of water heaters. During testing, a 24-hour trial is performed in which 6 equal draws are made for a total of 64.3 gallons. The energy consumption during the test is totaled and the mass of water drawn is summed over the six draws. The temperature of the water entering, leaving, and inside the water heater tank is recorded. The temperature of the air around the water heater is also noted. Additional equations appear in the test procedure to correct for any deviation from the standard testing specifications to guarantee uniformity in testing results in different laboratories. (CFR 1997) The equation's results are dependent on the following conditions:

daily draw volume = 64.3 gallons
tthermostat setpoint temperature = 135°F
inlet water temperature = 58°F
air temperature around the water heater = 67.5°F

Stated in general terms, EF is the ratio of the energy output to the energy input. More specifically, the equation computes EF as the added energy content of the water drawn from the water heater divided by the energy required to heat and maintain the water at the water heater's setpoint temperature:

$$E_f = \frac{M \cdot C_p \cdot (T_{tank} - T_{inlet})}{Q_{dm}}$$

where:

E_f = energy factor
M = mass of water drawn (lbs)
C_p = specific heat of water, (Btu / lb · °F)
T_{tank} = water heater thermostat setpoint temperature (°F)
T_{inlet} = the inlet water temperature (°F)
Q_{dm} = water heater's daily energy consumption (Btu)

This equation establishes the energy efficiency for water heaters, which forms the basis for certification testing and permits manufacturers to include the energy efficiency of their water heaters on labels and in advertising. The Gas Appliance Manufacturers Association (GAMA) consumer's directory states that residential gas, electric, and oil water heaters are tested in accordance with the DOE test procedures for water heaters to verify the energy factor. The directory confirms that "Federal law requires that manufacturers' efficiency claims be based on Department of Energy test procedures; the energy factor is the descriptor that is determined by those test procedures." (10CFR430, Subpart B) UA and RE are determined in the course of the test procedure. They are used in the equations to calculate EF.

WHAM Description

WHAM is an equation to estimate water heater energy consumption. WHAM permits the user to minimally describe both the operating conditions and the water heater. The operating conditions are characterized by four variables: daily draw volume, thermostat setpoint temperature, inlet water temperature, and ambient air temperature. The water heater operation and efficiency are described by Pon, UA, and RE.

Assumptions for WHAM

The equation is based on six assumptions that simplified the calculation:

- All the water in the tank is always at the thermostat setpoint
- All water and air temperatures are constant
- The density of water is constant
- The specific heat of water is constant
- Pon, RE, and UA are constant
- Pon, RE, and EF are equal to those determined by the EF test.

The WHAM Equation

WHAM is an equation in which the amount of energy used by the water heater is defined as the sum of the energy content of the hot water drawn from the heater plus the energy expended to recover from standby losses. The standby losses are calculated over a 24 hour period. To avoid double counting the standby loss amount, it is subtracted from the energy used while water is being drawn from the tank.

$$Q_{in} = \frac{vol \cdot den \cdot Cp \cdot (T_{tank} - T_{in})}{\eta_{re}} \cdot \left(1 - \frac{UA \cdot (T_{tank} - T_{amb})}{Pon} \right) + 24 \cdot UA \cdot (T_{tank} - T_{amb})$$

WHAM uses nine variables:

Q_{in} =	total water heater energy consumption (Btu/day)
η_{re} =	recovery efficiency
Pon =	rated input power (Btu/hr)
UA =	standby heat loss coefficient (Btu/hr · °F)
T_{tank} =	thermostat setpoint temperature (°F)
T_{in} =	inlet water temperature (°F)

T_{amb} = temperature of the air around the water heater (°F)
vol = volume of water drawn in 24 hours (gal/day)
den = density of water (lb/gal)
C_p = specific heat of water (Btu/lb · °F)

Alternate Ways to Calculate Energy Consumption

Four other methods of calculating energy consumption, all used by energy analysts, are described in this section. The first two methods described are water heater simulation models — TANK and WATSIM. The third method uses EF from the DOE test procedure as a constant efficiency, and the fourth is a simplified computer program.

TANK Simulation Model

TANK is a detailed computer simulation model written for the Gas Research Institute (GRI) that performs thermal analyses of gas-fired storage-type water heaters. (Paul *et al.* 1993) It was created specifically for use in reviewing proposed efficiency standards. The computer program numerically models a water heater undergoing the DOE test procedure.

The input file for the program includes a detailed description of the geometry and material properties of the water heater and its components. TANK gives the user some flexibility to adjust water and air temperatures.

The TANK model predicts water temperatures throughout the tank during the test. The program calculates the flame temperature and the convective and radiative heat transfer to the tank bottom and surrounding surfaces. Time-dependent heat losses are calculated based on the local water temperatures, the exposed area of the fitting, the conduction losses through the fitting wall and any insulation that might be present, and the natural convection losses to the local ambient room temperature.

At the end of the simulation, TANK calculates EF, RE, and UA using the procedures proscribed by the DOE test procedure. As output, TANK calculates five different energy flows throughout the water heater: Heat gained or lost by the water during the appliance cycle; Flue heat losses; Jacket heat losses; Fittings heat losses; and Combustion chamber heat losses.

WATSIM Simulation Model

WATSIM is a computer program written for the Electric Power Research Institute (EPRI) to simulate electric resistance water heating systems. WATSIM was created for tank and system design, equipment sizing, individual or broad-based electrical demand analyses, and energy consumption analysis. Draw patterns and temperatures can be specified by the user. The program requires detailed inputs on water heater specifications. (Hiller, Lowenstein & Merriam 1992)

It outputs information regarding: Heat losses; Energy consumption by each heat input; Efficiency and Coefficient Of Performance (COP); Electrical demand by time of day; Hot water availability and run-outs; Number of thermostat cycles; and Tank zone temperatures by time of day.

EF Used as a Constant Efficiency

EF has been used by energy analysts to estimate water heater energy input. By assuming the EF is a constant efficiency regardless of operating conditions, a value for energy use can be obtained.

WATSMPL

WATSMPL is a computer program written for EPRI in this case to evaluate the fundamental energy flows and energy costs for five different water heater system types: electric resistance, heat pump, natural gas, LP gas, and oil. WATSMPL was designed to calculate energy consumption under different operating conditions, but not to size systems (Wahler, Abrams & Shedd 1996).

Comparisons Between Models

Calculations based on EF are compared to the results of TANK and WATSIM simulations. These comparisons demonstrate the problems of calculating energy consumption from EF. Next WHAM and WATSMPL are compared. Finally WHAM is compared to TANK and WATSIM.

Operating Conditions

The energy consumption of a water heater under different operating conditions calculated using TANK and WATSIM were compared to the results of calculations based on EF. The four variables changed in this test were:

1. daily draw volume
2. water heater thermostat setpoint temperature
3. inlet water temperature
4. temperature of ambient air around the water heater

For each daily draw volume, 26 runs were made with different combinations of the three temperatures. Table 1 shows the different values for each variable. The water heater tank volume size, RE, and Pon remained constant for the each fuel type – 50 gallon tank (electric), 40 gallon tank (natural gas).

TABLE 1

Daily Draw Volume (gallon)	Thermostat Setpoint (°F)	Inlet Water (°F)	Ambient Air around tank (°F)
3	110	40	40
30	135	58	67.5
64.3	180	80	90
75			
150			

EF-Based Calculations Compared to TANK and WATSIM

Table 2 shows the ratio between the energy consumption using EF as a constant efficiency in relation to results of both TANK and WATSIM. At low water draws, the EF-based calculation significantly underestimates energy consumption compared to both simulation models. At low draws, standby losses become much more significant in TANK and WATSIM than they are in the EF-based calculation. As shown by Table 2 and Figures 1 and 2, the latter method gives poor approximations of water heater energy consumption amounts.

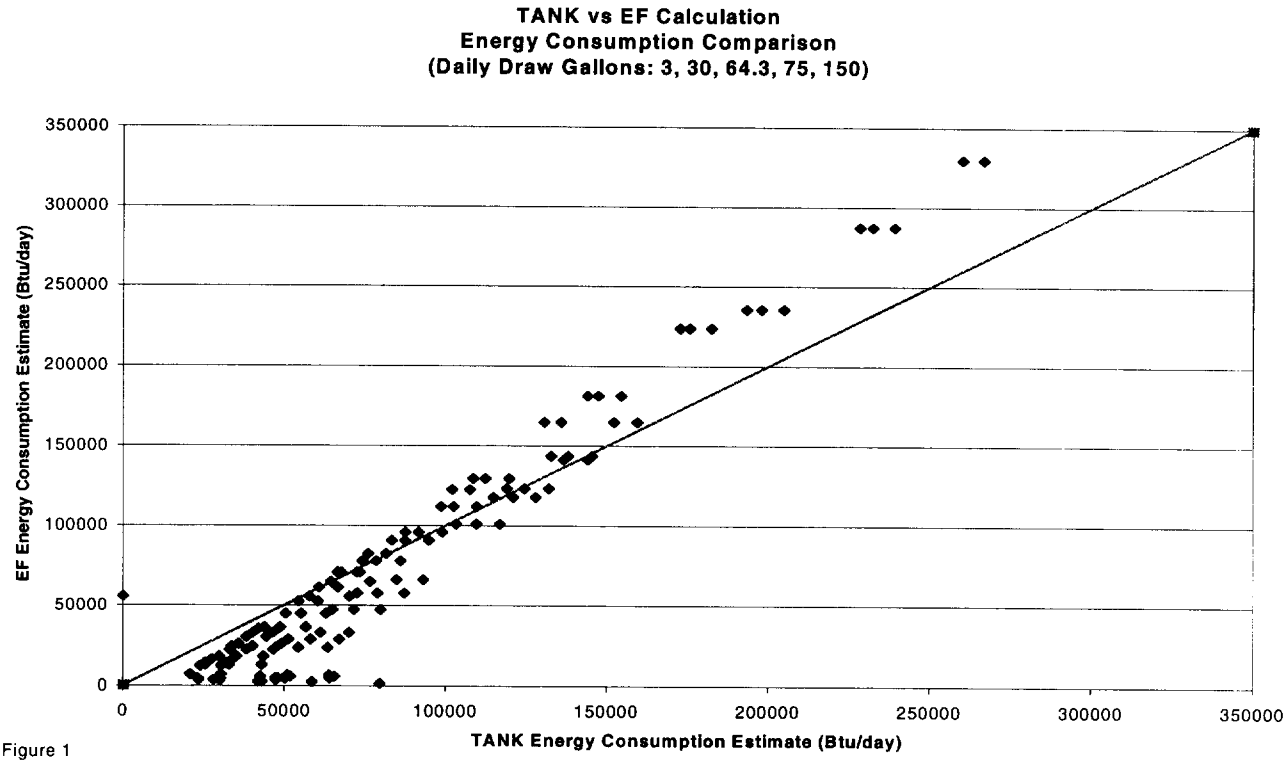

Figure 1

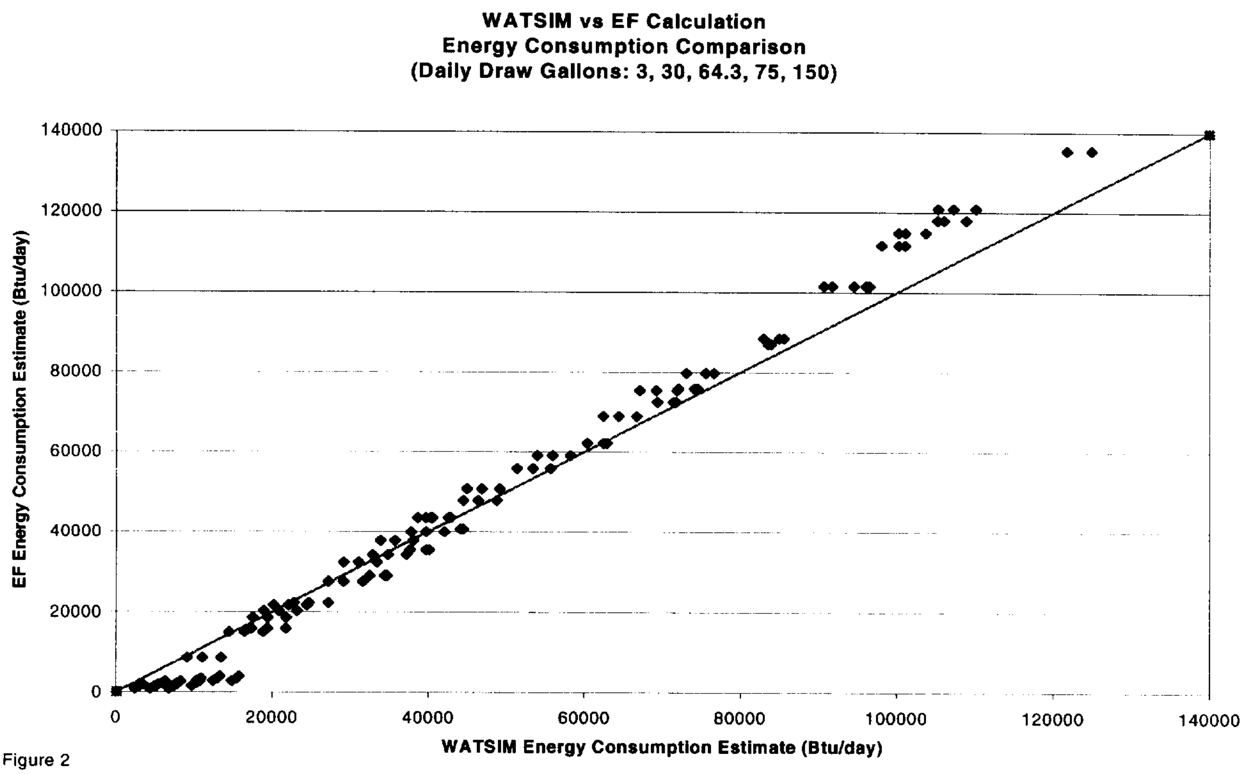

Figure 2

TABLE 2 - Ratio of EF-Based Calculation to Simulation Model Results

Daily Draw Volume	Average		Standard Deviation		Median	
	TANK	WATSIM	TANK	WATSIM	TANK	WATSIM
3	0.63	0.29	0.19	0.1	0.58	0.10
30	0.97	0.89	0.06	0.09	0.98	0.90
64.3	0.95	1.02	0.06	0.06	0.95	1.03
75	0.97	1.04	0.03	0.05	0.97	1.05
150	0.96	1.10	0.06	0.03	0.97	1.11

Comparing WHAM and WATSMPL

Under the same set of operating conditions as employed above, at hot water draws of at least 30 gallons, WHAM and WATSMPL are extremely close in their estimates of water heater energy consumption. Table 3 shows that the two calculation methods agree within 2% for the more common draw volumes. Figure 3 shows the same results graphically.

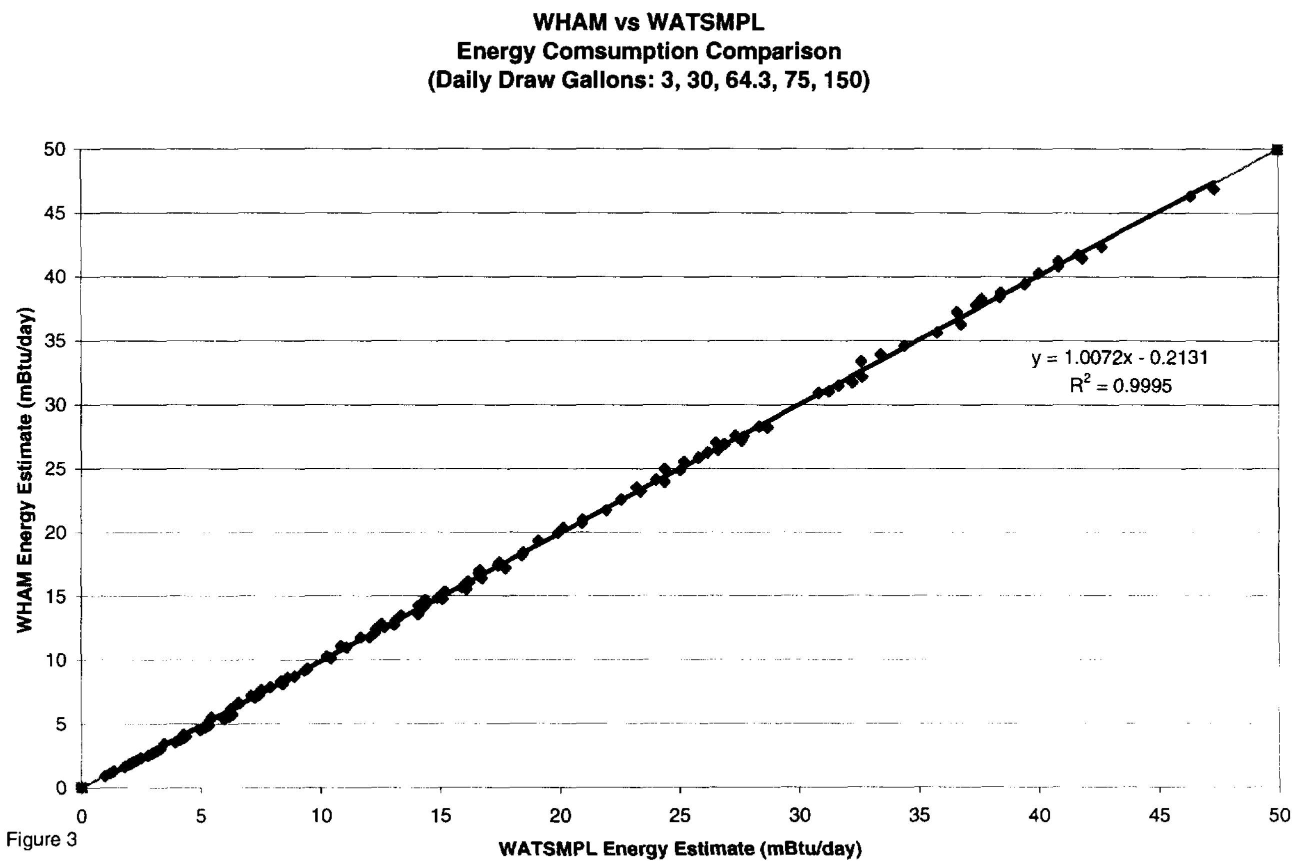

Figure 3

TABLE 3 - Ratio of Energy Consumption from WHAM and WATSMPL at Various Operating Conditions

Daily Draw Volume	Average	Standard Deviation	Median Value
3	0.91	0.01	0.91
30	0.98	0.01	0.98
64.3	1.00	0.01	0.99
75	1.00	0.01	1.00
150	1.01	0.01	1.01

Comparing WHAM to TANK and WATSIM

WHAM's accuracy was compared to the detailed simulation models described above by testing WHAM against each model in three ways:

1. by varying the operating conditions while holding the water heater parameters constant;
2. by varying the water heater size while keeping the operating conditions constant; and
3. by varying design options to improve efficiency while keeping the operating conditions constant.

Each set of variations was considered separately to better compare WHAM to the different methods of calculating water heater energy consumption.

For the purpose of comparison with WHAM, TANK's energy estimates were balanced so that the ending water temperature in the tank would be equal to the starting temperature. Since the TANK simulation runs specified different conditions for the water at the beginning as compared to the end of the test period, a small energy compensation was added to balance the tank conditions. The energy compensation was calculated by taking the imbalance in energy and dividing it by the recovery efficiency to get an estimate of how much energy the water heater would have to use to get back to the state it was in at the beginning of the simulation run. The total energy consumption for the water heater becomes the value reported by TANK plus the estimated energy consumption value needed to get back in "balance." When modeling small hot water draws that do not cause the burner to fire, the RE values given by TANK are not precise, and so it is not possible to determine the necessary amount of compensation.

When DOE test procedure conditions are used with WATSIM, EF, RE and UA can be calculated from the outputs, using the procedures specified in the test procedure. Calculations to "balance" the water heater, similar to those performed on the TANK results, were also done for these simulation runs. The effect is not as significant because the RE of electric water heaters is close to 1.

The next section describes each of the three tests and reports the results.

Operating Conditions

Energy consumption estimates from WHAM were compared to the results of TANK and WATSIM for a variety of operating conditions. The conditions are the same as listed above.

TANK

While WHAM slightly underestimates energy consumption *vis-á-vis* TANK, WHAM's estimates are near those of TANK at daily draws of 30 gallons or more. Figure 4 shows close agreement in the mid-range draw volumes with wider variation at the lowest draws. Table 4 lists the results of the test for all

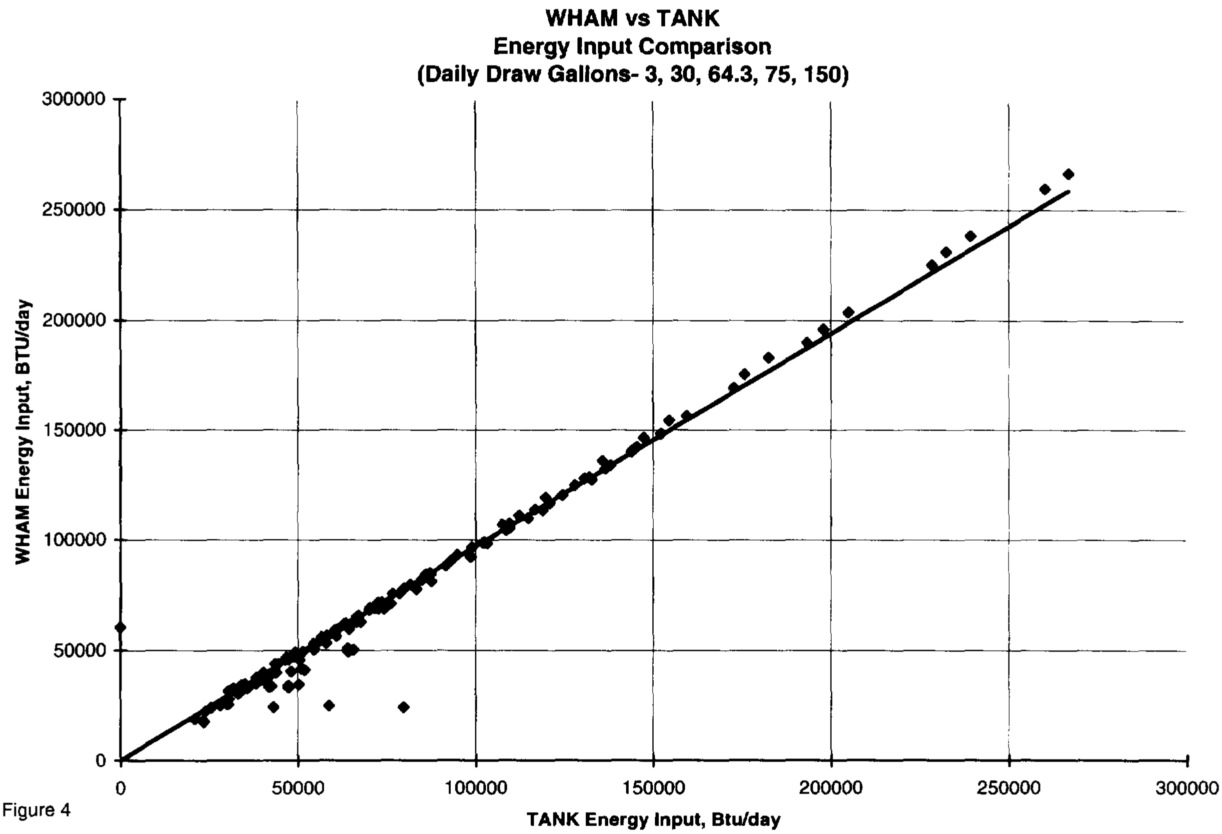

Figure 4

volumes. The 3-gallon draw volume has a significantly lower average percentage agreement when compared to the other draw volumes. Agreement between the two methods increases as the draw volume rises. Without the 3-gallon draw volume, the methods agree within 5% ± 3%. WHAM and TANK estimates do not coincide as much at uncommon temperature conditions when the inlet water temperature and the air temperature surrounding the water heater are within 30°F.

TABLE 4 - Ratio of Energy Consumption: WHAM and TANK at Various Operating Conditions

Daily Draw Volume	Average Ratio	Standard Deviation	Median Value
3	0.73	.15	0.78
30	0.96	.03	0.96
64.3	0.95	.03	0.96
75	0.96	.02	0.97
150	0.99	.01	0.99

WATSIM

Agreement between energy consumption estimates of WATSIM and WHAM over five different daily draw volumes is quite close. Figure 5 shows almost compete agreement at all draws. Table 5 shows the agreement at each draw volume. The methods agree within 3% ± 2%.

However, some deviation from complete agreement does occur at the highest draw of 150 gallons where run-out is an issue. Run-out occurs when the water heater has exhausted its supply of hot water and the elements are energized while the water heater delivers cold water. Standby losses are not as great, given that the temperature difference between the tank and surrounding air is not as high as when the tank is filled with hot water. With WHAM, no run-outs can occur since it assumes the water is always delivered at the thermostat setpoint; therefore, it will over-predict energy input during run-out situations.

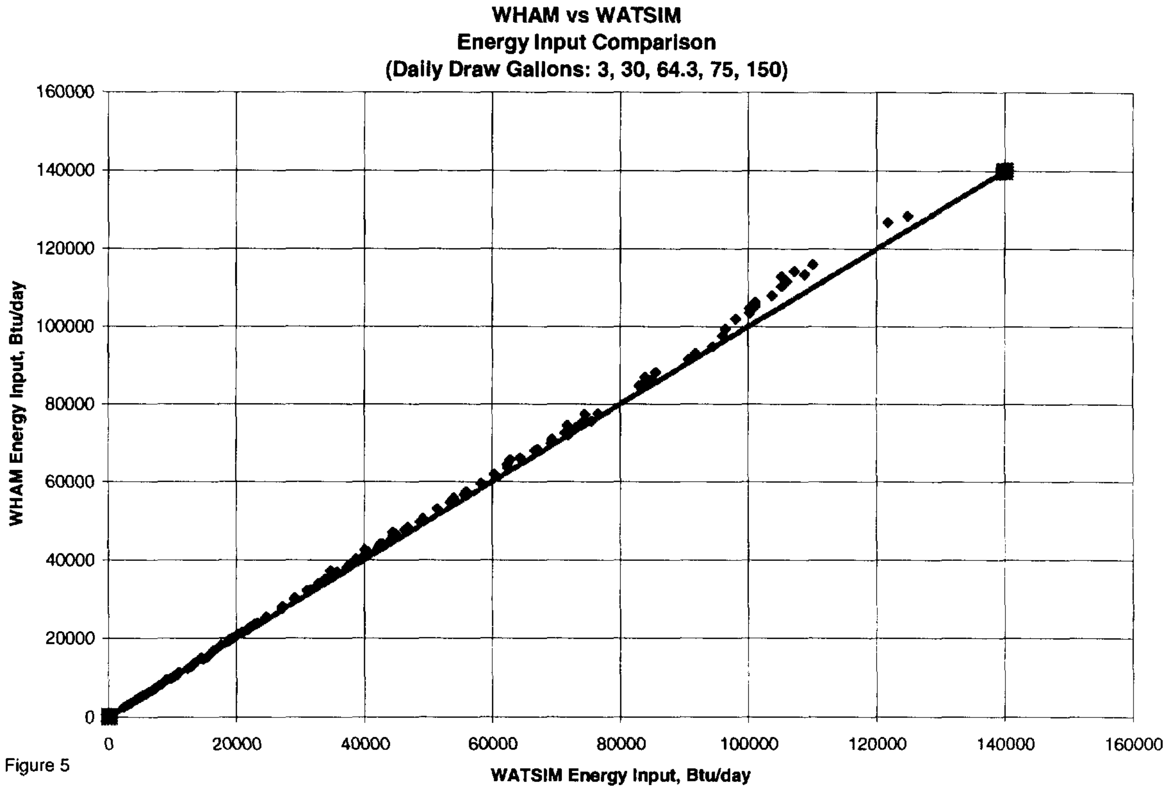

Figure 5

TABLE 5 - Ratio of Energy Consumption: WHAM and WATSIM at Various Operating Conditions

Daily Draw Volume	Average Ratio	Standard Deviation	Median Value
3	1.01	0.02	1.01
30	1.03	0.01	1.03
64.3	1.03	0.01	1.03
75	1.03	0.01	1.03
150	1.03	0.02	1.04

Water Heater Tank Volumes

Varying the water heater tank volumes while keeping the operating conditions constant demonstrates WHAM's ability to estimate energy consumption for different baseline water heaters. WHAM was compared to the two simulation models, TANK and WATSIM. Three different tank volumes were used for gas-fired and electric resistance water heaters. Each tank volume was used with the typical rated inputs. Table 6 shows the values for the baseline condition.

TABLE 6

Daily Draw (gal)	Thermostat Setpoint Temperature (°F)	Inlet Water Temperature (°F)	Ambient Air Temperature (°F)	Insulation Thickness (inch)	Heat Trap
64.3	135	58	67.5	1	NO

TANK

The results of the TANK/WHAM comparison are shown in Table 7. The energy input values of TANK and WHAM agree within 4%. The closest agreement occurs at the 30- and 100-gallon tank sizes where the amount of rated input power per tank volume is lowest. This computer model displays the values it used to calculate energy used to heat the water. Among the reported values are UA and RE. The TANK reported UA and RE values were used in WHAM while making this comparison.

TABLE 7 - Ratio of Energy Consumption from WHAM vs TANK for Various Tank Volumes

Tank Volume	Rated Input	Ratio	TANK Reported UA	TANK Reported RE
30	25000	0.98	10.5	0.78
40	40000	0.96	13.8	0.76
100	75000	0.98	23.0	0.70

WATSIM

This computer model displays the values it used to calculate energy used to heat the water. Among the reported values are UA and RE. The WATSIM reported UA and RE values were used in WHAM while making this comparison. Overall agreement between the two methods is close — within 4%. Agreement improves as the tank size volume increases.

TABLE 8 - Ratio of Energy Consumption: WHAM and WATSIM at Various Tank Volumes

Tank Volume	Rated Input	Ratio	WATSIM Reported UA	WATSIM Reported RE
30	3000	1.03	2.90	0.97
50	4500	1.03	4.40	0.96
80	5500	1.03	4.40	0.96

Design Option Variations

Each change in water heater design affects the UA and RE. This test evaluates WHAM's ability to estimate energy consumption for water heaters with design options intended to improve the water heater's efficiency. In this test, WHAM was compared to TANK and WATSIM. The operating conditions were kept constant at:

daily draw volume = 64.3 gallons
tank setpoint temperature = 135°F
inlet water temperature = 58°F
air temperature around the tank = 67.5°F

TANK

The results of WHAM and TANK agree to within 5%. Agreement is better for lower efficiency models. Table 9 shows a list of ten different design options and the TANK reported value for UA and RE. WHAM used the baseline UA and RE values for this comparison.

TABLE 9 - Ratio of Energy Consumption: WHAM and TANK at Various Design Options

Design Option	Ratio	Reported UA	Reported RE
Baseline	0.97	13.86	0.756
Heat Traps (plastic)	0.96	12.96	0.756
Increased Insulation (2" — R16 Foam)	0.96	11.92	0.762
Increased Insulation (2.5" — R20 Foam)	0.96	11.51	0.764
78% RE (Improved Flue Baffle)	0.97	13.21	0.780
78% RE (Improved Flue Baffle) + Increased Insulation (2")	0.96	11.55	0.780
78% RE (Improved Flue Baffle) + Increased Insulation (2.5")	0.95	11.23	0.780
Electronic Ignition & Electromechanical Flue Damper	0.95	12.38	0.755
Electronic Ignition & Electromechanical Flue Damper + Increased Insulation (2")	0.95	10.45	0.763
Electronic Ignition & Electromechanical Flue Damper + Increased Insulation (2.5")	0.95	10.03	0.764

WATSIM

Agreement between WHAM and WATSIM in the design option test is 3% as seen in Table 10. For the design options with the lowest standby loss, the disagreement decreases to 2%.

TABLE 10 - Ratio of Energy Consumption: WHAM and WATSIM at Various Design Options

Design Option	Percentage Ratio	Reported UA	Reported RE
Baseline	1.03	3.64	0.967
Heat Traps	1.03	3.39	0.968
Increased Insulation (2" — R16 Foam)	1.03	3.15	0.969
Increased Insulation (2.5" — R20 Foam)	1.03	2.87	0.970
Insulated Tank Bottom (Polyurethane Foam Support Ring)	1.03	3.49	0.967
Insulated Bottom (Polyurethane Foam Support Ring) + Heat Traps + Increased Insulation (2" Foam)	1.02	2.46	0.972
Insulated Bottom (Polyurethane Foam Support Ring) + Heat Traps + Increased Insulation (2.5" Foam)	1.02	2.13	0.973
Plastic Tank	1.03	3.48	0.964

Conclusion

For energy consumption estimates of residential water heaters, WHAM is an accurate tool. WHAM can account for different operating conditions such as average daily draw and water and air temperatures. The results for most cases compare very favorably with the results of detailed simulation programs such as TANK and WATSIM. WHAM has the advantage over the simulation models in two regards: no detailed engineering information about the water heater is necessary for estimations and WHAM is easily inserted into spreadsheets resulting in faster calculations.

Because WHAM can account for different operating conditions, it estimates energy consumption more accurately than calculations using EF as a constant efficiency. The results of WHAM are nearly identical to the results of WATSMPL. Because WHAM is a simple equation, it can easily be incorporated into other computer programs or spreadsheets used by analysts concerned with water heater energy consumption.

For many purposes, WHAM is the best method to estimate energy consumption by residential water heaters.

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