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Predicting the Energy Performance Ratings of a Family of Type I Combination Appliances

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PREDICTING THE ENERGY PERFORMANCE RATINGS OF A FAMILY OF TYPE I COMBINATION APPLIANCES

ABSTRACT

ANSI/ASHRAE Standard 124-1991 specifies the laboratory tests and the calculation procedure for estimating seasonal and annual performance of combination appliances which are designed to provide both space heating and water heating. A boiler that includes a tankless coil for water heating is covered by those sections in ASHRAE Standard 124 that pertain to Type I combination appliances. In an effort to minimize the test burdens on manufacturers, a computer simulation study was conducted to determine if a subset of a family series of Type I combination appliances could be tested and used to predict the performance of the rest of the appliances in the family. Computer simulation was conducted on a family of five different size boilers with an identical tankless coil to calculate their Combined Annual Efficiency (CAE) as specified in ASHRAE Standard 124. To this end, the Energy Factor (EF) for water heating and the Annual Fuel Utilization Efficiency (AFUE) for space heating were calculated. For the water heating test that was simulated, daily hot water draw volumes of 243.4 liters (64.3 gal.) and 454.2 liters (120 gal.) were used. The results showed that for the five boilers, the AFUE for space heating differed by less than 1 percent. On the other hand, the EF for water heating depended strongly on the size of the boilers for the same daily hot water drawn and on the volume of daily water drawn for a given size boiler. However, for the same daily hot water draw volume, the EF was an approximate linear function of the boiler size. The results also showed that the CAE varied by slightly over 1 percentage point among the five boilers when the same daily water draw volume was used and by less than 0.8 percentage points for the same boiler when the two different hot water draw volume were used. Thus a single linear interpolation based on either water draw volume appears adequate for determining the Combined Annual Efficiency CAE.

Key words: Annual Fuel Utilization Efficiency, ANSI/ASHRAE Std.103, ASHRAE Std. 124-1991, boiler, building technology, combination appliance, combined annual efficiency, DOE water heater test procedure, energy factor, linear interpolation, rating, space heating, tankless coil, water heating

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1. INTRODUCTION

During the past several years, combination appliances that integrate the functions of space heating and domestic hot water heating into a single system have received renewed interest. A test method and calculation procedure for estimating and rating the seasonal and annual performance of such combination appliances, however, did not exist until 1991 when ASHRAE published ASHRAE Standard 124-1991, "Method of Testing for Rating Combination Space Heating/Water Heating Appliances" [1]. In this new standard (abbreviated in this report as ASHRAE Standard 124), combination appliances are classified into two types, Type I and Type II. Type I appliances are those whose primary function is space heating with domestic water heating as the secondary function. Type II appliances have domestic water heating as their primary function and space heating as their secondary function.

A boiler with a tankless coil, a Type I appliance, has been manufactured and sold for a long time. However, up until the publication of ASHRAE Standard 124, a boiler with a tankless coil was rated only as a space heating appliance without considering its domestic water heating function or the effect of domestic water heating on its annual performance. ASHRAE Standard 124 specifies that Type I appliances shall be tested as a boiler in accordance with the ANSI/ASHRAE Standard 103-1988 [2], as well as a water heater in accordance with a procedure similar to the DOE test procedure for water heaters [3]. ASHRAE Standard 124 does not, however, address the problem that different size boilers are usually combined with the same (and in some case, more than one size) tankless coil. If all combinations of boilers and coils had to be tested, a significant testing burden would be placed on boiler manufacturers. At the present time, most "family series (boilers with similar configuration in construction" of boilers incorporate only one or two different size tankless coils. If only two different size boilers in a family series with an identical tankless coil could be tested and the results used to predict the performance of other size boilers in the same family series by an interpolating scheme, a significant amount of testing could be avoided.

In 1988-1989, in order to evaluate the then proposed ASHRAE Standard 124P, the National Institute of Standards and Technology (NIST) carried out a project, sponsored by the Department of Energy (DOE), to conduct experimental and computer simulation studies on the performance of Type I combination appliance. NIST developed a computer model and conducted laboratory tests on a clam-shell, wet-base, oil-fired, residential boiler with a tankless domestic water heating coil [4]. The model was verified with laboratory test data for heat-up, cool-down, cyclic, and standby modes of operation along with domestic hot water draw cycles. A series of computer simulations were run with the model to predict the annual fuel utilization efficiency (AFUE, same as heating seasonal efficiency for oil-fired boilers) for space heating, the energy factor (EF) for water heating, and the combined annual efficiency (CAE) for combined space/water heating functions of the appliance and the results compared with the rating methodology in ASHRAE Standard 124. The study showed good agreement between the computer model simulation and the AFUE, EF and CAE determined from the ASHRAE Standard 124.

The present study described in this report used the above NIST developed computer model to simulate the laboratory tests specified in ASHRAE Standard 124 for a family series of five different size boilers with an identical tankless coil. For each set of simulations, the annual fuel utilization efficiency (AFUE), energy factor (EF) and the combined annual efficiency (CAE) were calculated on the basis of procedures in ASHRAE Standard 124. For each combination appliance, two different daily hot water draws of 243.4 liters (64.3 gal.) and 454.2 liters (120 gal.) were considered.

2. SIMULATION WITH HVACSIM$^+$

The NIST developed program HVACSIM$^+$, a modular variable time step energy and control analysis program, was used for the computer simulations of the boiler with a tankless coil and controls. The component models used with the HVACSIM$^+$ program consist of a hot water boiler, heating coil, and control algorithm for space heating and domestic water heating functions. A detailed description of the complete computer model is in Ref.4. The boiler component model considered the heat transfer processes at the gas-side, at the fire-box wall, at the heat exchanger/boiler water interface and between the boiler jacket and the ambient air in the calculation of the boiler water temperature and the flue gas temperature during the burner on-period and off-period. The computer model requires empirical integration multipliers that are applied to the calculated time constants of the boiler water and the stack gas during the burner on and off periods. These multipliers, which are specific to the particular boiler and which promote convergence during simulations, were determined from laboratory test results [4]. The tankless coil was modelled as flow through a pipe with constant surface temperature. The control algorithm for space heating emulated a manually controlled burner on and off periods that are used during the cool-down and heat-up phases of the test specified in ASHRAE Standard 103-1988. A temperature limit algorithm was used to emulate the on/off control of the burner when modelling the system during the hot water use test, referred to as the simulated use test, that is specified in ASHRAE Standard 124 [1]. The source code of the component models and the associated subroutines for physical property values and heat transfer coefficients, and the input and boundary data files are described in Ref.4.

3. ASHRAE STANDARD 124-1991

To rate a combination appliance, ASHRAE Standard 124 requires individual performance testing of the appliance as a space heating equipment and as a water heater. It does not require a combined space heating and water heating test. The space heating performance of the appliance is determined from tests in accordance with ANSI/ASHRAE 103-1988, Methods of Testing for Annual Fuel Utilization Efficiency of Central Furnaces and Boilers [2]. The domestic water heating performance is determined from tests in accordance with or similar to DOE 10 CFR Part 430, Subpart B, Appendix E, Test Method for Measuring the Energy Consumption of Water Heaters [3]. The steady-state efficiency Effy_{ss} and space heating seasonal efficiency Effy_{hs} (defined as the space heating part-load efficiency at 22.5% load, and equals to the Annual Fuel Utilization Efficiency, AFUE, for boiler without a continuous pilot) from the space heating performance test and the energy factor from the water heating test are used to calculate the combined annual efficiency (CAE) and the combined heating seasonal and non-heating seasonal efficiencies, as the rating descriptors, as specified in ASHRAE Standard 124.

The space heating test of ANSI/ASHRAE 103-1988 for hot water boilers requires a steady-state test lasting a minimum of 30 minutes, followed by a 45-minute cool-down test and a 9.68-minute heat-up test.

The domestic water heating test in DOE 10 CFR Part 430 requires that a total of 243.4 liters (64.3 gallons) of hot water shall be withdrawn by imposing six equal draws. These draws, which occur at a flow rate of 0.19 L/s (3 gpm) are imposed at the beginning of consecutive hours. The initiation of the first draw designated the beginning of the 24-hour (simulated use) test. Because the final draw is initiated at an elapsed time of 5 hours and the actual draw is completed within 4 minutes, the appliance operates in a standby mode for the more than 18 hours that remain before the test is terminated. During the test, the water temperature of the boiler controls the oil burner on/off status. The burner is set to be turned off when the boiler water reaches 87.8 °C (190 °F). The differential setting of the control is 5.6 °C (10 °F) as specified in ASHRAE Standard 124 (i.e., the burner is turned on when the boiler water decreases to 82.2 °C (180 °F)).

In ASHRAE Standard 124, by comparison, a total hot water draw of either 243.4 liters (64.3 gallons) or 454.2 liters (120 gallons) is used. The total volume used depends on the first hour draw capacity [3] of the boiler. The total draw is 243.4 liters (64.3 gallons) if the first hour draw capacity is less than 454.2 liters (120 gallons), and 454.2 liters (120 gallons) if the first hour draw capacity is greater than 454.2 liters. Both total hot water draw volumes were simulated in this study for each of the five boilers in order to determine the effect of the total water draw volume on the performance of the appliances.

4. COMPUTER SIMULATION CONDITIONS

A family series of five commercially available oil-fired boilers with an identical tankless coil were chosen for this simulation study. This series of boilers were chosen because one of the boilers in the series was used for the testing and development of the computer model in Ref.4. That boiler was measured for its physical dimensions and configurations and tested to determine the various parameters required by the boiler model. Figure 1, which is taken from Ref.4, shows a cross-sectional view (composed of 5 sections) of that boiler. The other boilers in the series are composed of sections varying from 3 (including the section containing the tankless coil) to 7. The physically identical sections and the tankless coil section are connected together to form different size (capacity) boilers. The data for this family series of boilers were used in the computer simulation. The conditions for the simulation exercises are given below.

4.1 Space Heating - Steady-state and Cyclic Operation (Cool-down and Heat-up)

The spacing heating simulation follows the procedure specified by the ANSI/ASHRAE 103-1988 standard for the performance rating of residential boilers [2]. The appliance was assumed to be operated manually with the burner and the water circulating pump on until steady-state was established. Steady-state was established when the stack gas temperature did not vary by more than 1.7 °C (3 °F) over a 30-minute period. The space heating simulation was performed under the following conditions:

- * Boiler inlet (return from the load) water temperature at 48.9 °C (120 °F).
- * Boiler outlet (supply to the load) water temperature at 60 °C (140 °F).

After the steady-state period, the gas burner and the pump were turned off. The boiler was allowed to cool down for 33.26 minutes (This is the assumed boiler off-cycle time specified in ASHRAE Standard 103 for cyclic operation and is less than the 45 minutes cool-down test time described in section 3 of this report. However, the boiler temperature at the end of the 33.26 minutes decreases to almost the same value as after the 45-minute cool-down.) The burner and the pump were then turned on for a 9.68-minute heat-up period to complete a cool-down/heat-up cycle. This cycle was repeated several times before the simulation was stopped. During the whole test period, the energy consumption and energy transferred to the boiler water, the stack gas temperature and the boiler water temperature were recorded every five seconds in a data file. The data were used as inputs to a spreadsheet program to compute the part load space heating efficiency and the annual fuel utilization efficiency (AFUE) of the boiler when used solely for spacing heating. The spread sheet program summed up the energy transferred to the boiler water Q_{BLW} and the fuel energy input to the burner Q_{IN} (recorded every 5 seconds) during the first three cycles of the cyclic simulation. The part load space heating efficiency over the three cycles (42.94 minutes per cycle) is computed, using

$$Effy_{hs} = \sum_{n=0}^{1545} Q_{BLW} \Big/ \sum_{n=0}^{1545} Q_{IN}$$

where 1545 was the total number of the 5-second time intervals over the three cycles. For the boiler used in this simulation study, there is no continuous pilot and therefore, the annual fuel utilization efficiency AFUE is equal to $Effy_{hs}$.

4.2 Domestic Water Heating - Simulated Use Test

The computer simulation of the 24-hour simulated use test for rating a boiler as a domestic water heater was carried out according to the procedure specified in ASHRAE Standard 124 for Type I appliances with tankless coils. A slight departure from the ASHRAE Standard 124 procedure in this simulation was that the six hourly water draws were performed before the 18-hour standby test, instead of the other way around (that is, 18-hour standby followed by the 6 hour draws). This was done to simplify the boundary data file for the simulation program. This change should cause no significant changes in the results. The simulation boiler was operated for a conditioning period which consisted of running the boiler until a burner cut-in, recovery, and cut-out cycle were completed before the 24-hour test was started. The first of the six draws followed immediately after the burner cut-off. The water flow rate during the draw was fixed at 0.19 L/s (3 gpm). Two total water draw volumes, 243.4 liters (64.3 gallons) and 454.2 liters (120 gallons) were simulated. After the six hourly water draws and the burner recovery that follows the final draw were completed, the approximately 18-hour (the remaining time after the last hourly draw/recovery plus the 18 hour) standby period was simulated. During the simulated 24-hour test, the burner on/off operation was controlled at the boiler water temperature high/low limit setting of 87.8/82.2 °C (190/180 °F), corresponding to a 5.6 °C (10 °F) temperature differential as specified in ASHRAE Standard 124. The tankless coil inlet temperature was set at 14.4 °C (58 °F). The coil outlet temperature, boiler water temperature, stack gas temperature, and the energy consumption and energy transferred to the tankless coil from the boiler water were computed and output to a data file every 5 seconds. The energy factor was calculated from these data (as the ratio of the sum of the energy transferred to the water through the tankless coil during the 6 draws divided by the sum of the energy input to the burner in the 24 hour period) using a spreadsheet program and the equations specified in ASHRAE Standard 124.

5. SIMULATION RESULTS AND DISCUSSION

Five oil-fired boilers with the same size tankless coil and with output capacities of 26.08, 36.34, 46.89, 57.15, and 65.94 kW (89000, 124000, 160000, 195000, and 225000 Btu/h) respectively were simulated with the computer program. The results from the computer simulated tests described above are discussed below.

5.1 Steady-state and Cyclic (Cool-down and Heat-up) Tests

Figure 2 shows a plot of the stack gas and boiler outlet water temperatures during a 30-minute steady-state test followed by three 33.26-minute cool-down and 9.68-minute heat-up cycles. It can be seen that the stack gas temperature remained steady during the steady-state portion of the test and rose rapidly to the steady-state temperature during the heat-up portion of the cyclic test. The boiler outlet water temperature was held at 60 °C (140 °F).

The calculated rate of energy input to the burner and the rate of heat transfer to the boiler water over the three cycles during the cyclic tests were used to compute the part load space heating efficiency of each boiler. The calculated part load efficiency which represents the space heating seasonal efficiency (and the AFUE for the simulated boilers since there is no continuous pilot) varied from 80.47% to 81.44% for the five boilers that were simulated. Thus it is seen that the variations in the space heating seasonal efficiency among the five boilers was fairly small. This agrees well with the results published in Ref.5 for the AFUE values of a family series of boilers. This published data showed that the variation in AFUE within a family series of boilers were generally less than one percentage point. This small variation in the AFUE values showed that linear interpolation of both AFUE and space heating seasonal efficiency (which is closely related to AFUE and equal to AFUE for the present study) with respect to input capacity within a family series of boilers can be used to predict the AFUE values for other units in the family series.

5.2 Simulated Hot Water Use Test

Results from the simulated use test, as calculated by the computer model, are shown in Figures 3 to 10 for the boiler with an output capacity of 46.89 kW (160000 Btu/h). Figures 3 to 8 correspond to tests where the total hot water withdrawn is 243.4 liters (64.3 gallons). Figures 9 and 10 pertain to a simulation using a total volume of 454.2 liters (120 gallons).

Figure 3 shows the stack gas temperature during the first six hourly draws and a portion of the standby period following the last draw. During the six hourly draw periods, the burner was on during the actual hourly draw and also a shorter time during the standby period following each draw. This resulted from the 5.6 °C (10 °F) temperature differential setting of the boiler control. Whenever the boiler temperature dropped 5.6 °C below the high limit setting of 87.8 °C (190 °F), the burner came on to maintain the boiler temperature within the set range of 82.2 to 87.8 °C (180 to 190 °F). This temperature range assures that the hot water from the tankless coil is available at the set temperature of 60 °C (140 °F) when the draw started. Following the sixth draw and recovery, the boiler was operated in a standby mode until the elapsed time equalled 24 hours (from the beginning of the first draw). The burner cycled on for regular short intervals (as indicated by the last two stack gas temperature peaks in Figure 3) throughout the standby period.

Figure 4 shows the boiler water temperature during the first six hourly draws and for the initial part of the standby period. The boiler water temperature stayed within the 82.2 to 87.8 °C range (180 to 190 °F) as described in the previous paragraph and varied in a manner similar to the stack gas temperature. Figure 5 shows the tankless coil outlet water temperature during the same time period. The coil outlet temperature was in the 60 to 62 °C (140 to 144 °F) range during each of the short actual draw periods of 3.57 minutes (214 seconds). During other times the temperature was the same as the boiler water temperature in Figure 4.

Figure 6 shows the rate of heat flow to the boiler water during the six hourly draws and Figure 7 is an enlarged view during one hourly draw period. From Figure 7, it is seen that during the standby period following each draw when the burner was off, the heat flow to the water is a small negative value, indicating the loss of heat to the flue. During the short actual draw time interval, heat flowed from the boiler water to the coil water (large negative net flow values) until the burner came on. At this time, the net heat transfer (hot flue gas heat transfer to boiler water minus boiler water to coil water heat transfer) to the boiler water became positive. At the end of the draw the heat transfer to the water became very large until the burner was off. In between the actual hourly draws, the heat flow to the boiler shows another positive peak caused by boiler recovery.

Figure 8 shows the heat flow rate to the tankless coil during the six draw periods. Figures 9 and 10 show the same heat flow rates as Figures 6 and 8 except that the total daily draw volume was 452.2 liters (120 gallons), almost double the amount in Figures 6 and 8. It can be seen that with the longer hourly draw interval (twice the draw time at the same flow rate), the heat flow to the boiler water was first negative due to the transferring of heat from boiler water to the tankless coil water, then positive when the burner came on, then negative when the burner was off (after it reached the high temperature limit) and the draw still underway, and finally positive when the burner again was on for boiler recovery.

The computer simulated results for the other four boilers during the hot water simulated use test were similar to those shown in Figures 3 to 10 and are not presented.

5.3 Energy Factor

Figure 11 shows a plot of the energy factors calculated from the computer simulation of the five boilers for two total hot water draws of 243.4 liters (64.3 gallons) and 454.2 liters (120 gallons). The energy factor was calculated as the ratio of the net energy delivered to the tankless coil over the six hourly draws to the total energy input to the burner over the 24-hour simulated use test period (six hourly draws with the short standby periods following each hourly draw and recovery plus the final 18-hour standby). It can be seen that the energy factor decreased with increases burner input capacity. However, the rate of decrease is nearly linear (especially for the higher total draw volume. Thus, conducting the tests to determine the energy factor of two combination appliances within a family series that use the identical tankless coil and then using linear interpolation to determine the energy factors for other boilers within the family series appears reasonable. The small concave (upward) nature of the plot will make the predicted energy factor slightly larger than it should be if the smallest and the largest units in the family series are used for the interpolation. This over-estimation may be eliminated if two intermediate size units in a family series are tested and an interpolation/extrapolation is used. Figure 11 also shows that the difference in the energy factor for the two different daily draws is large. Therefore, interpolation between units with different daily draws is not possible. Since in a family series of boilers the boiler input capacity can vary from small to large by a factor of three, the smaller ones likely will be tested at the lower daily draw and the larger ones at the higher daily draw if the two values of daily water draws as specified in ASHRAE Standard 124 are used. However, if only one value of the daily water draw is required for rating purposes as is the case when rating conventional waters (see DOE 10 CFR 430, Appendix E to Subpart B [3]), interpolation of the energy factors as described in the preceding paragraph would be possible for all size boilers in a family series.

5.4 Combined Annual Efficiency

Figure 12 is a plot of the combined annual efficiency (CAE) defined in ASHRAE Standard 124 as the rating descriptor for combination appliances. The CAE was calculated from the steady-state efficiency and space heating seasonal efficiency $Effy_{hs}$ (from the space heating simulation) and the energy factor EF (from the 24-hour simulated use test) using the procedure specified in ASHRAE Standard 124. The procedure is included in the appendix of this report for reference. It can be seen from Figure 12 that the CAE varies nearly linearly with boiler capacity, indicating that linear interpolation is applicable. Furthermore, the graph shows that CAE depends only weakly on the total daily draw volume, indicating that the space heating function predominates the overall performance of the combination appliance. Thus linear interpolation of CAE based on test results from two selected units at either of the two total daily hot water draw volumes appears possible.

The values of the space heating seasonal efficiency $Effy_{hs}$, the energy factor EF, and the combined annual efficiency CAE are tabulated in the following table for the five boilers that were simulated.

				Total Daily Hot Water Drawn			
				243.4 Liters		454.2 Liters	
Boiler No.	Input (kW)	Effy_{ss} (%)	Effy_{hs}(or AFUE) (%)	EF	CAE (%)	EF	CAE (%)
1	31.9	84.7	80.47	0.370	76.12	0.495	76.76
2	44.6	84.9	80.94	0.310	76.43	0.451	77.23
3	57.4	85.0	81.13	0.279	76.85	0.410	77.37
4	70.1	85.2	81.45	0.248	77.15	0.365	77.42
5	80.8	85.2	81.45	0.226	77.15	0.347	77.42

6. CONCLUSIONS

Computer simulations of the performance of a family series of Type I combination appliances, consisting of five sizes of oil-fired boilers with identical tankless coils, were conducted to evaluate an interpolating scheme for predicting the Energy Factor and the Combined Annual Efficiency of a family series of the appliances from test results on two units of different capacities within the series. The conditions for the simulation of space heating and domestic water heating were specified in accordance with ASHRAE Standard 124-1991. The energy factors (EF) for domestic water heating and the combined annual efficiencies (CAE) computed on the basis of procedures in ASHRAE Standard 124 for two different daily hot water draws of 243.4 liters (64.3 gal.) and 454.2 liters (120 gal.) were determined. The results showed that the annual fuel utilization efficiency (AFUE) for space heating for the five boilers differed by less than 1 percent. The energy factor (EF) depended strongly on the size of the boilers for the same daily water draw and on the volumes of daily water draw for any given boiler. However, for the same hot water draw, the EF was an approximate linear function of the boiler nominal input capacity. Therefore, linear interpolation of the EF as a function of boiler size can be used for a constant value of daily hot water draw. For a conservative estimate of the EF it is recommended that two boilers which are not the smallest and largest in a family series be used in the interpolation/extrapolation process. The results also showed that the combined annual efficiency (CAE) varied by slightly over 1 percentage point for the five boilers using the same daily water draw and by less than 0.8 percentage points for the same boiler with two different hot water draws. Thus, a single linear interpolation based on either water draw appears adequate for determining the combined annual efficiency, CAE.

7. REFERENCES

1. ASHRAE Standard 124-1991, "Method of Testing for Rating Combination Space Heating/Water Heating Appliances", ASHRAE, 1991

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APPENDIX

Calculation of Combined Heating Seasonal Efficiency and Combined Annual Efficiency (CAE) by the ASHRAE Standard 124-1991 Method

The following computation of the Combined Heating Seasonal Efficiency and the Combined Annual Efficiency is from Section 11 of ASHRAE Standard 124. The following definitions and equations were used in a spreadsheet program:

$Effy_{ss}$ = Steady-state space heating efficiency from ASHRAE Standard 103-1988
$Effy_{hs}$ = Space heating seasonal efficiency from ASHRAE Standard 103-1988
EF = Energy factor from DOE 10 CFR Part 430 procedure
Q_{in} = Boiler nameplate rated energy input rate
T_{dd} = 18.3 °C (65 °F) = temperature base for degree days
T_{avg} = 5.6 °C (42 °F) = average outdoor temperature during the heating season
T_{des} = -15 °C (5 °F) = outdoor heating design temperature
T_t = 57.22 °C (135 °F) = nominal tank temperature
T_c = 14.4 °C (58 °F) = nominal cold water supply temperature
d = density of water at measured tank outlet temperature
U = daily domestic hot water consumption
a = 0.7 = oversize factor
R = (8760 - 4160) / 4160 = 1.106 = ratio non-heating season hours to heating season hours, national average

1. Heating Season Space Heating Factor (SHF):
   $SHF = (Effy_{ss}/Effy_{hs})*[(T_{dd} - T_{avg}) / (T_{dd} - T_{des})]*[1/(1 + a)]$

2. Heating Season Water Heating Factor (WHF):
   $WHF = U * (T_t - T_c) * d / (Q_{in} * Effy_{ss} * 24)$

3. Non-heating Season Factor (NHF):
   $NHF = U * (T_t - T_c) * d / (Q_{in} * EF * 24)$

4. Combined Annual Efficiency (CAE):
   $CAE = (SHF * Effy_{hs} + WHF * Effy_{ss} + R * NHF * EF) / (SHF + WHF + R * NHF)$

5. Heating Seasonal Efficiency:
   $Effy_{hs,combined} = (SHF * Effy_{hs} + WHF * Effy_{ss}) / (SHF + WHF)$

6. Non-heating Seasonal Efficiency:
   $Effy_{nhs,combined} = EF$

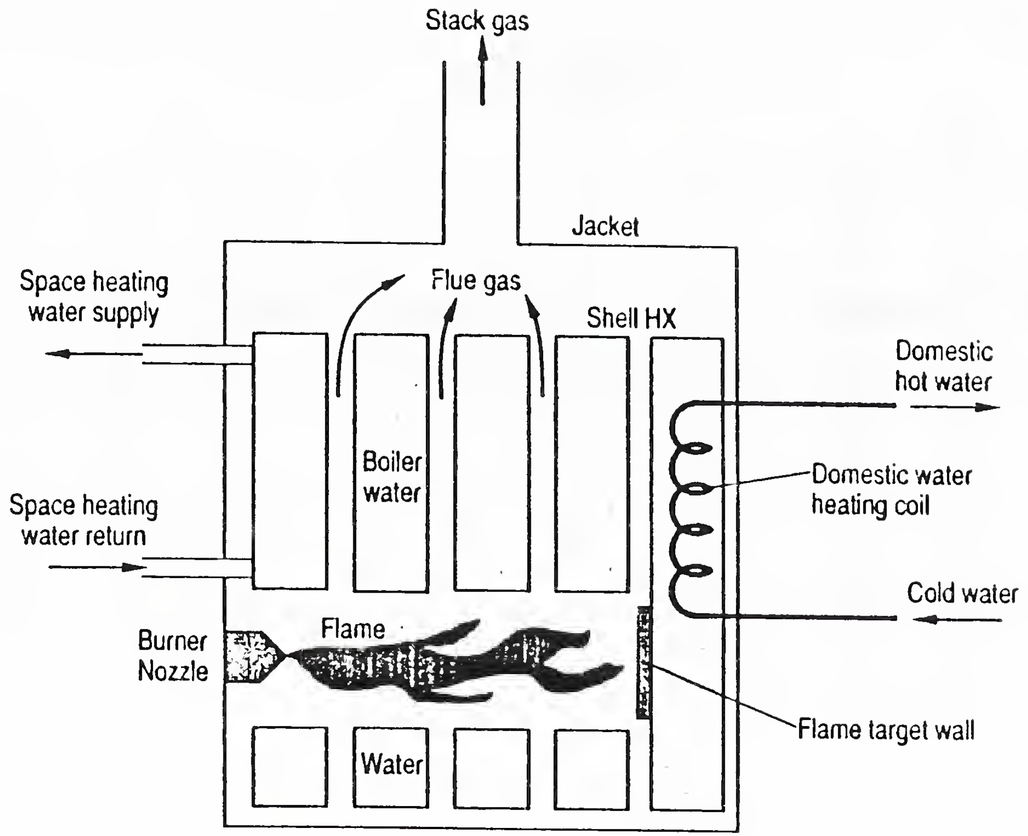

Fig. 1 Schematic of a boiler with tankless coil

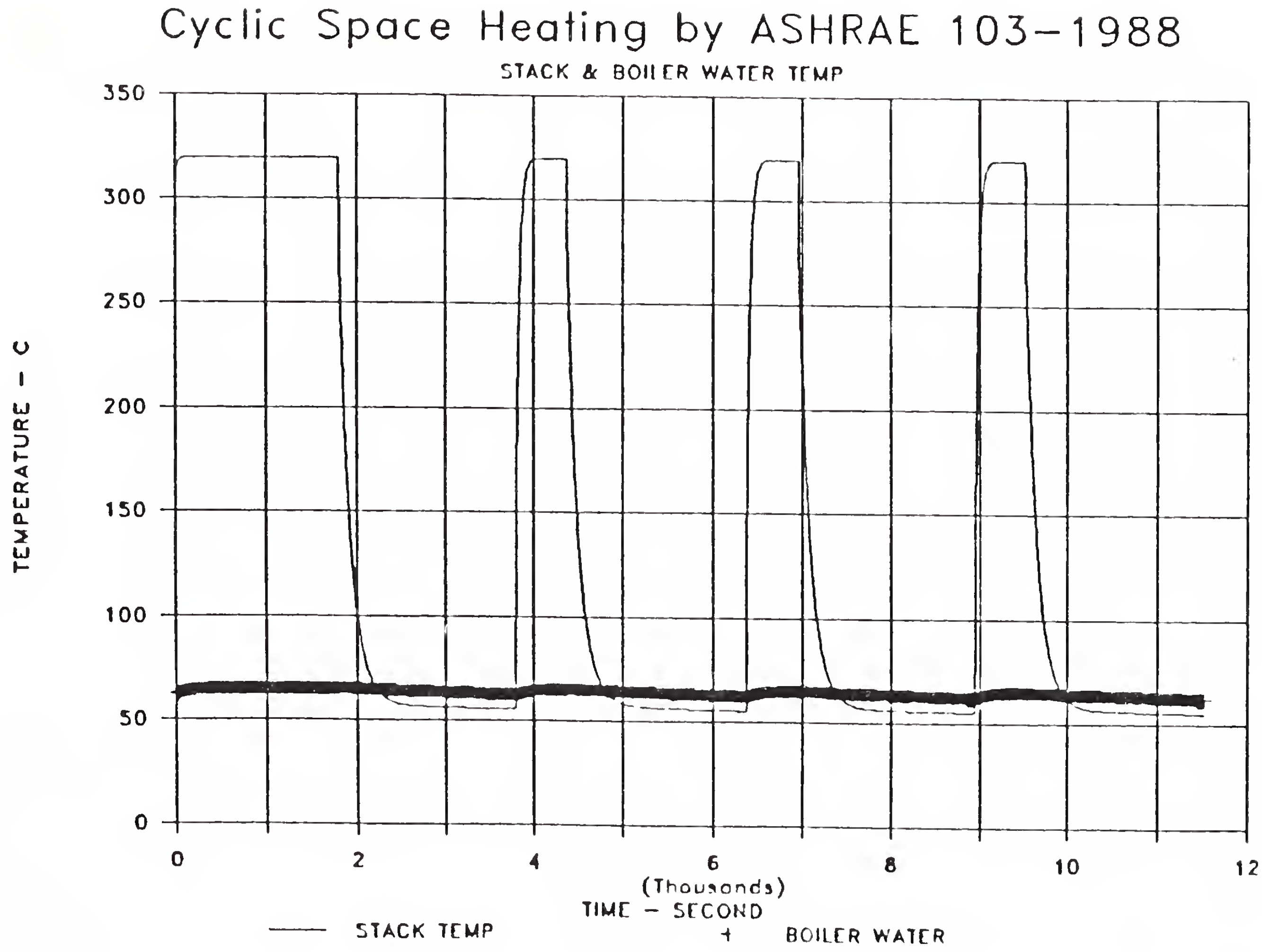

Fig. 2 Stack and boiler water temperatures under cyclic space heating

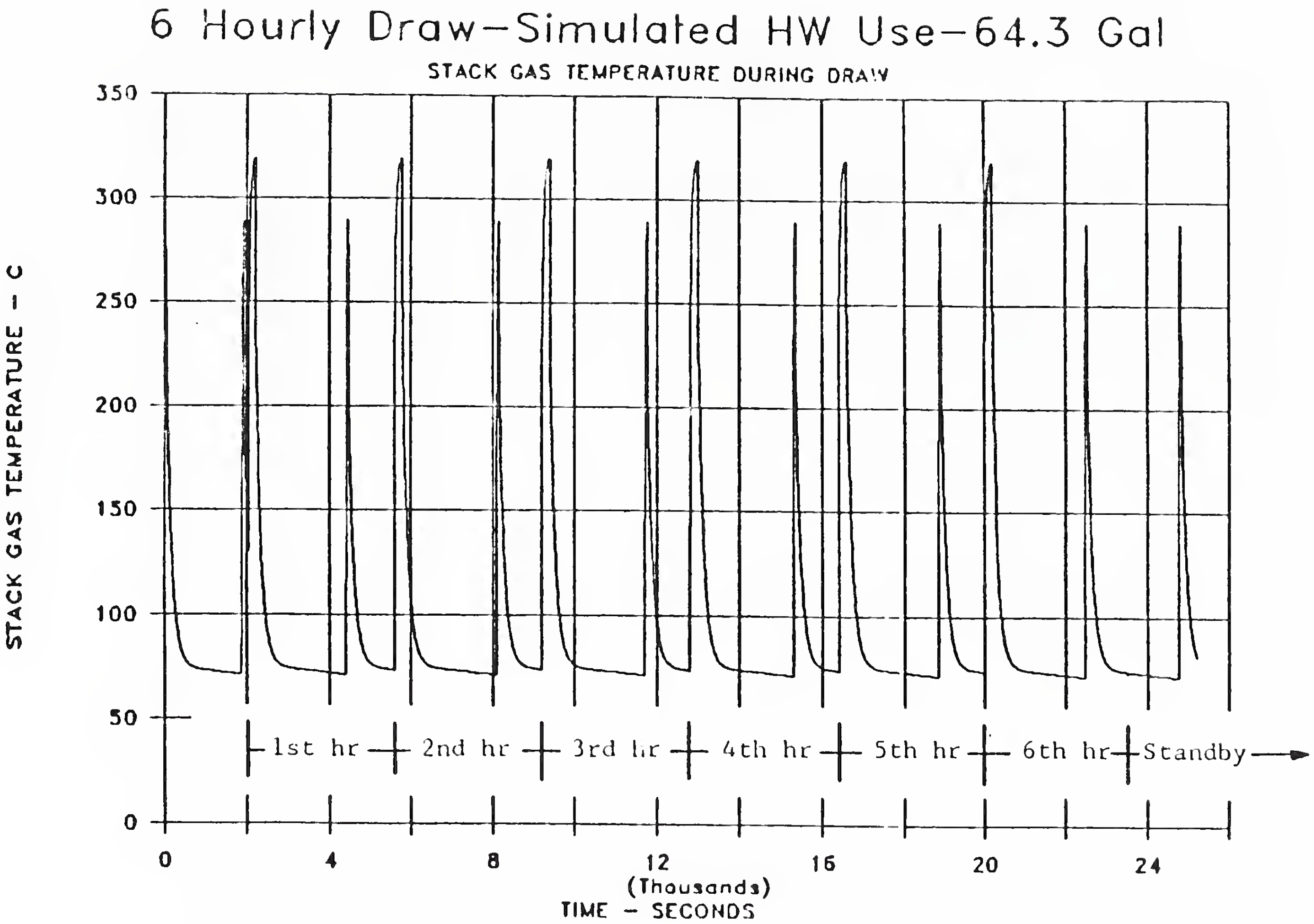

Fig. 3 Stack gas temperature under simulated use test condition - 243 L daily draw volume

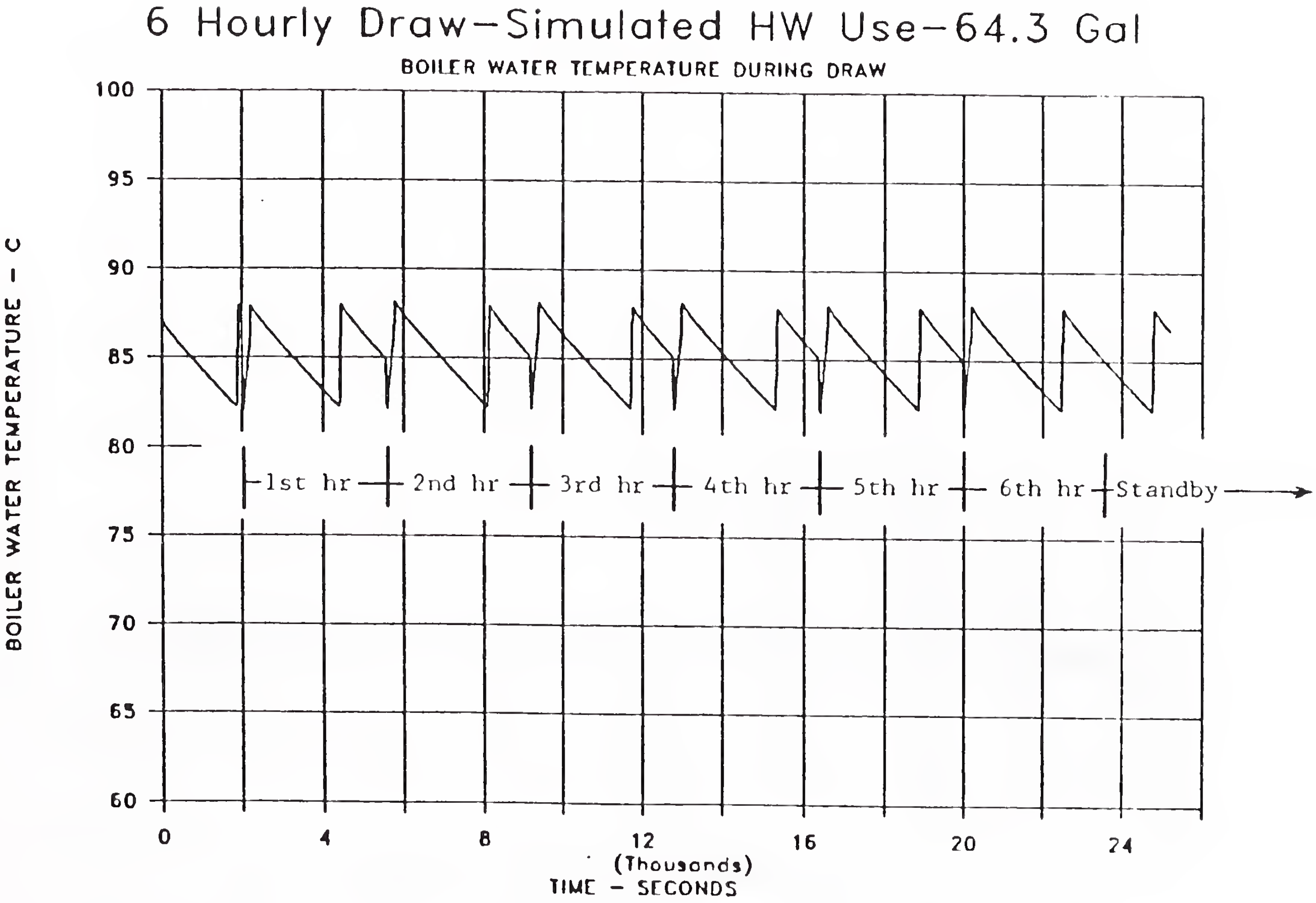

Fig. 4 Boiler water temperature under simulated use test condition - 243 L daily draw volume

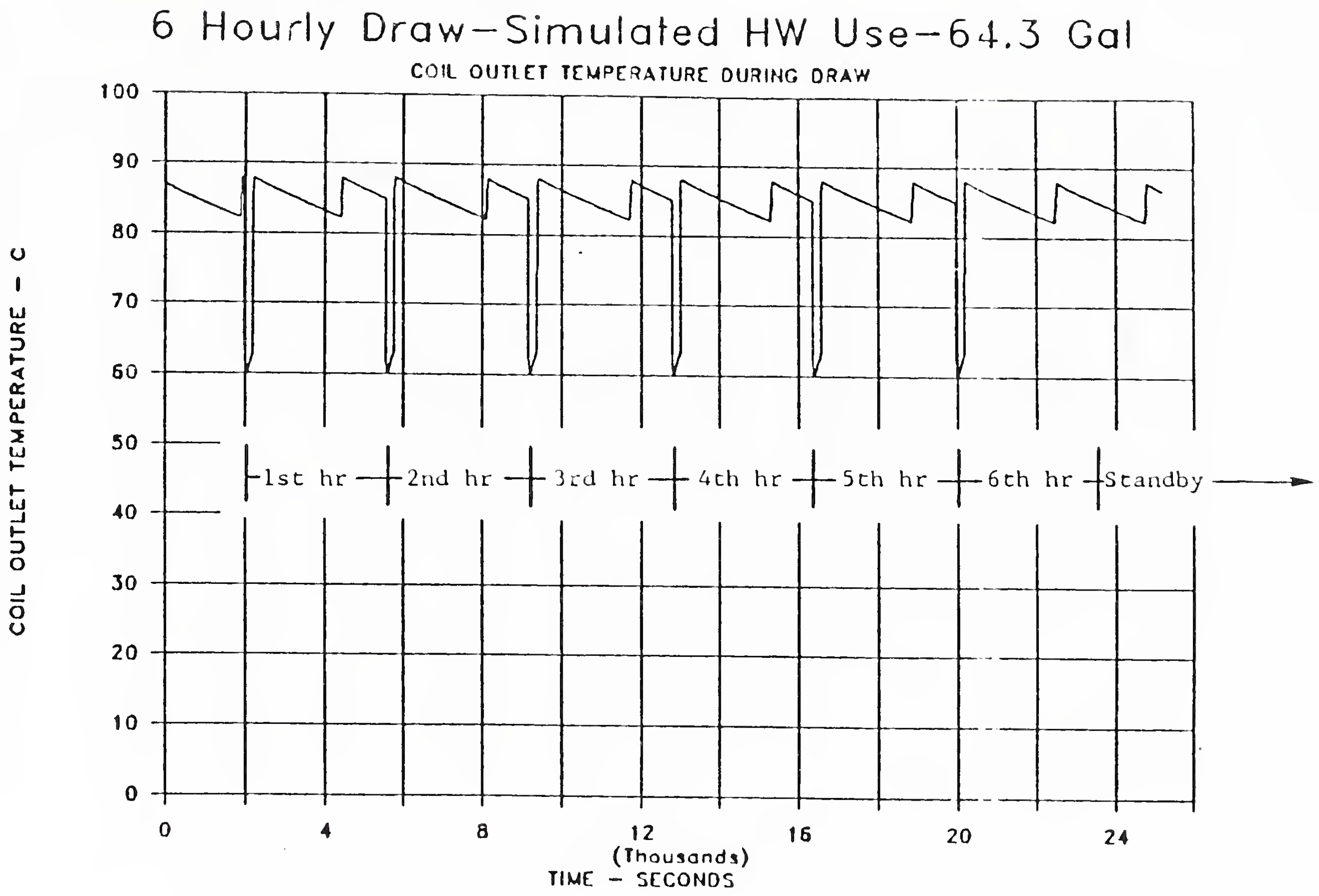

Fig. 5 Tankless coil temperature under simulated use test condition - 243 L daily draw volume

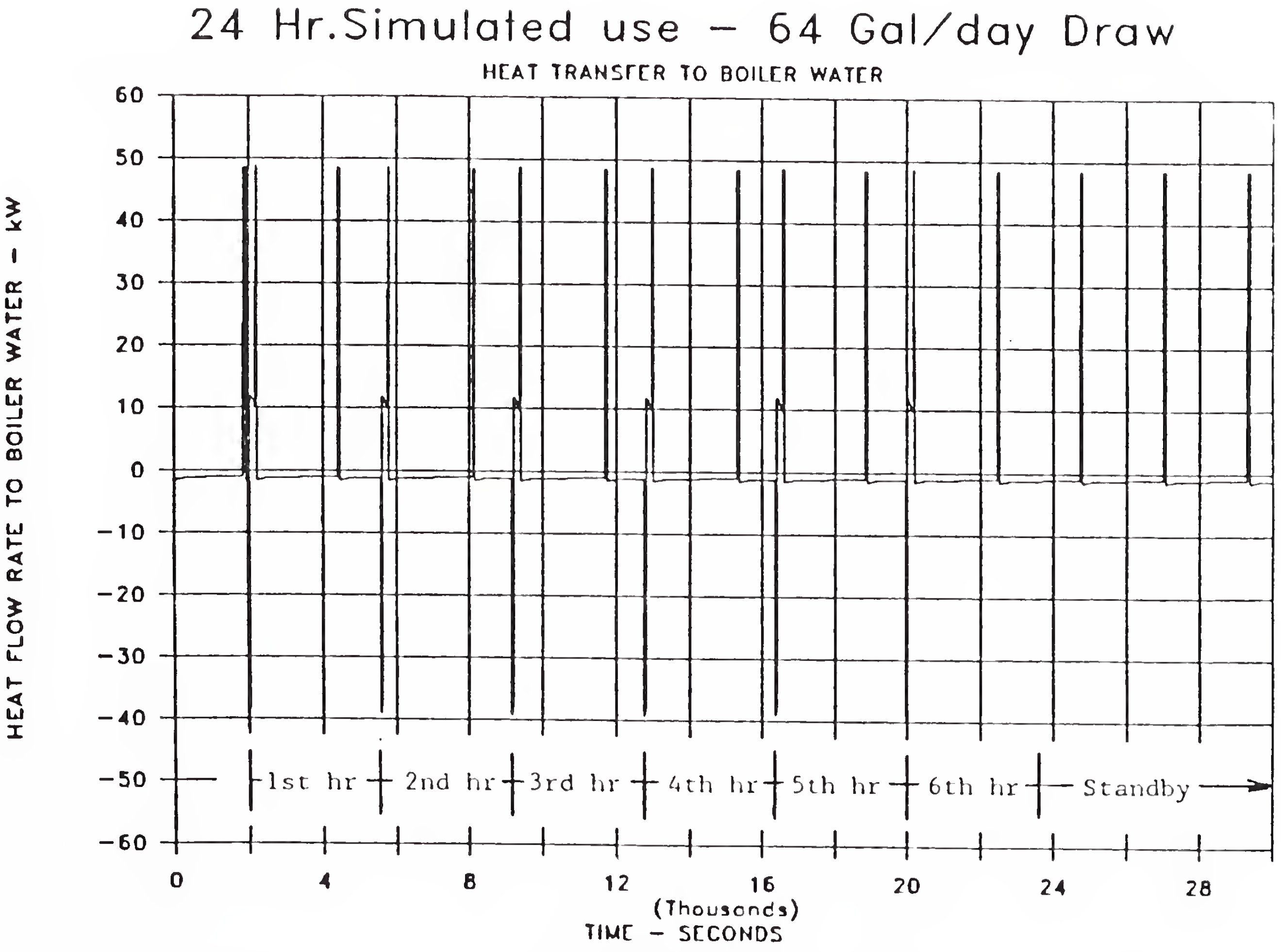

Fig. 6 Heat transfer to boiler water under simulated use test condition - 243 L daily draw volume

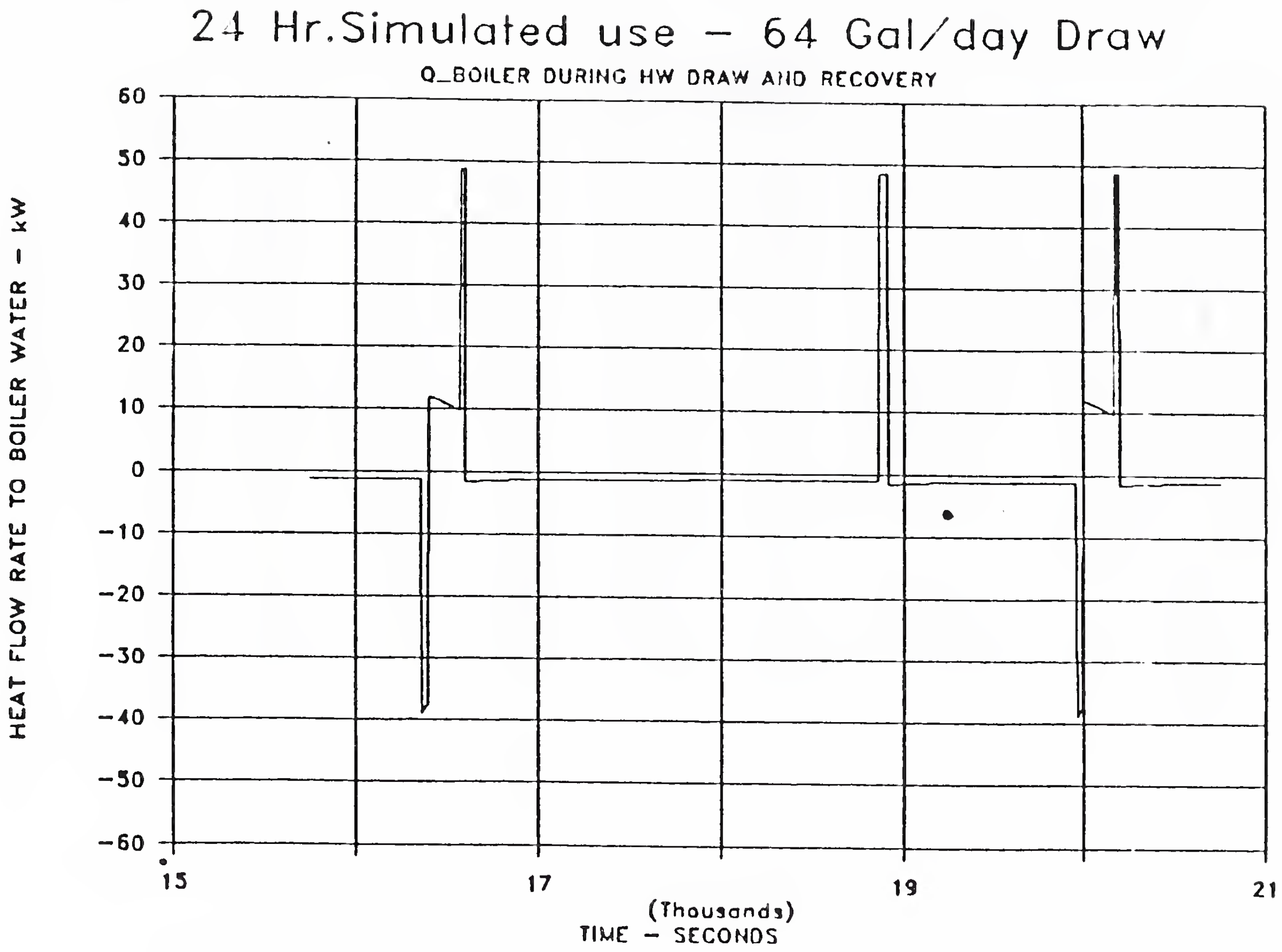

Fig. 7 Heat transfer to boiler water during one hourly draw/recovery/standby period - 243 L daily draw volume

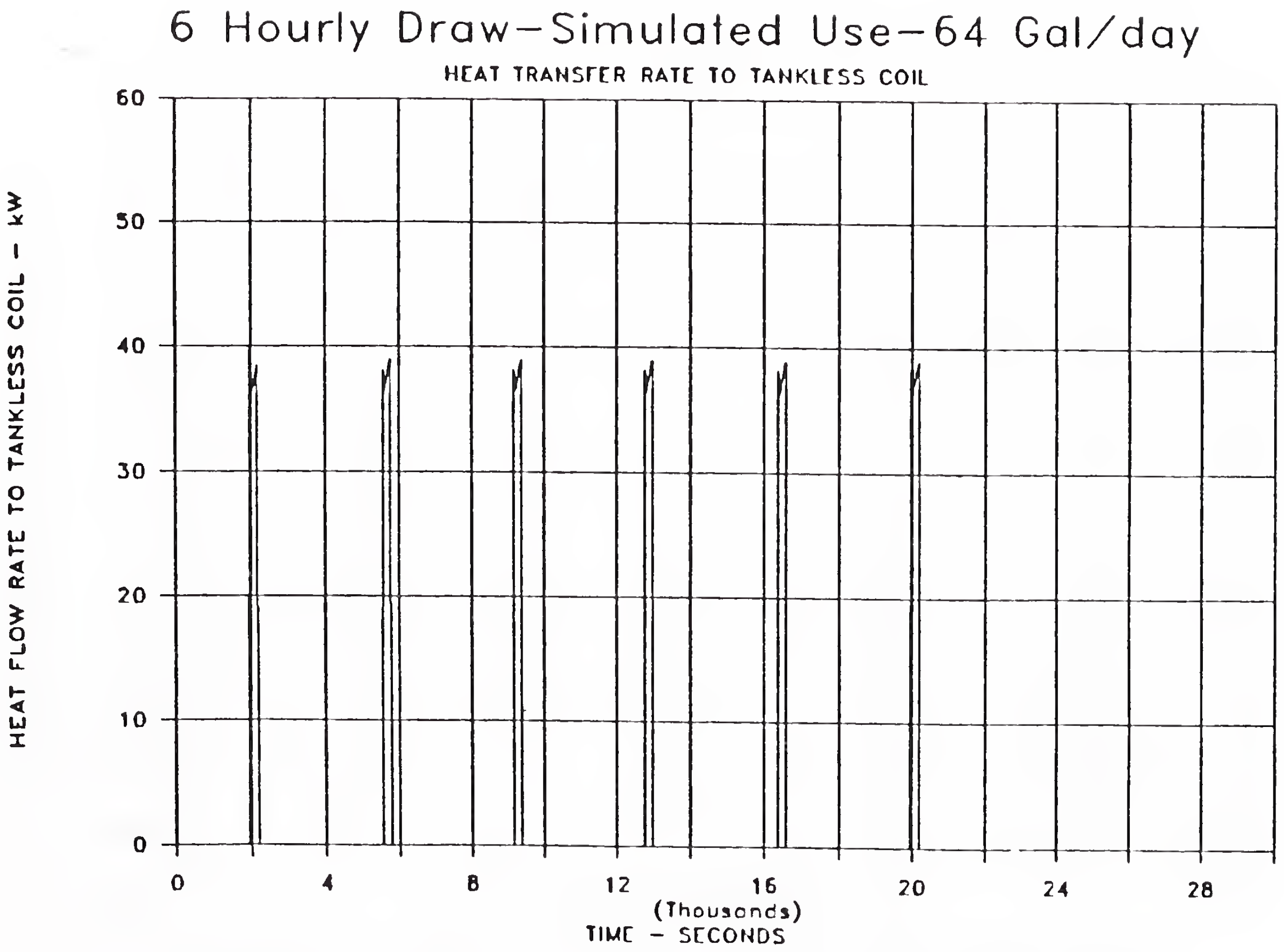

Fig. 8 Heat transfer to tankless coil under simulated use test condition - 243 L daily draw volume

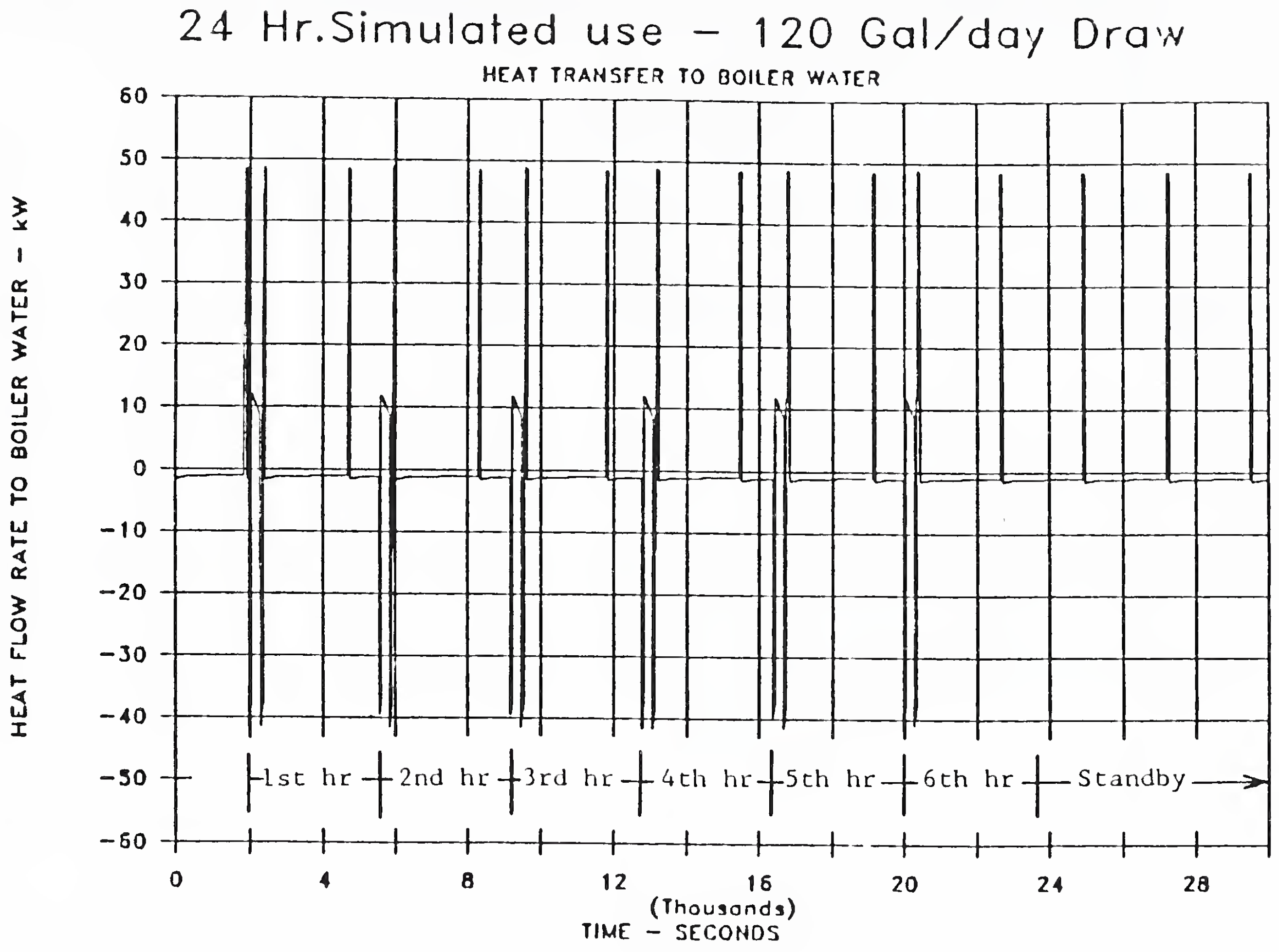

Fig. 9 Heat transfer to boiler water under simulated use test condition - 454 L daily draw volume

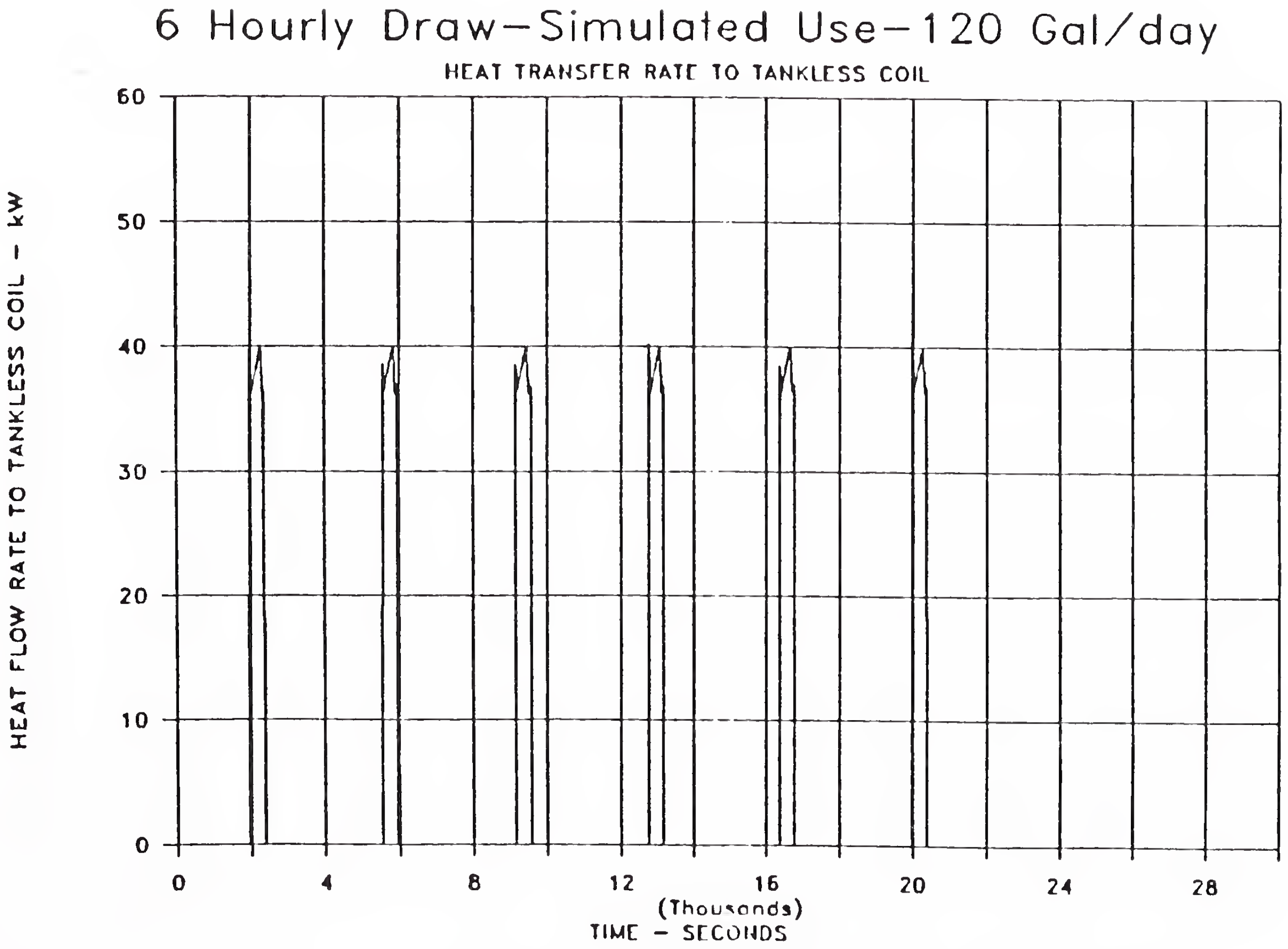

Fig. 10 Heat transfer to tankless coil under simulated use test condition - 454 L daily draw volume

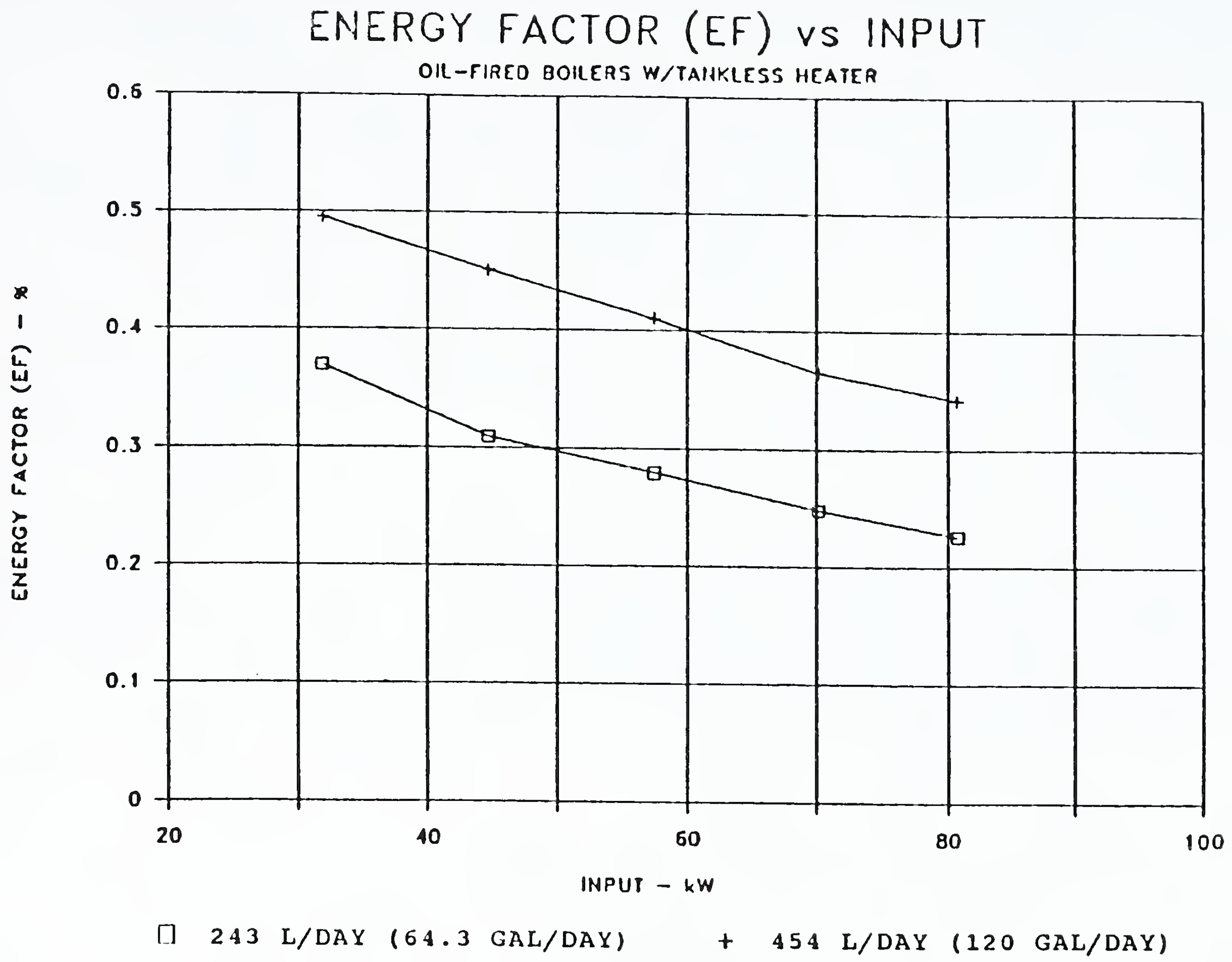

Fig. 11 Energy factor as a function of rated input of a family series of boilers with identical tankless coil

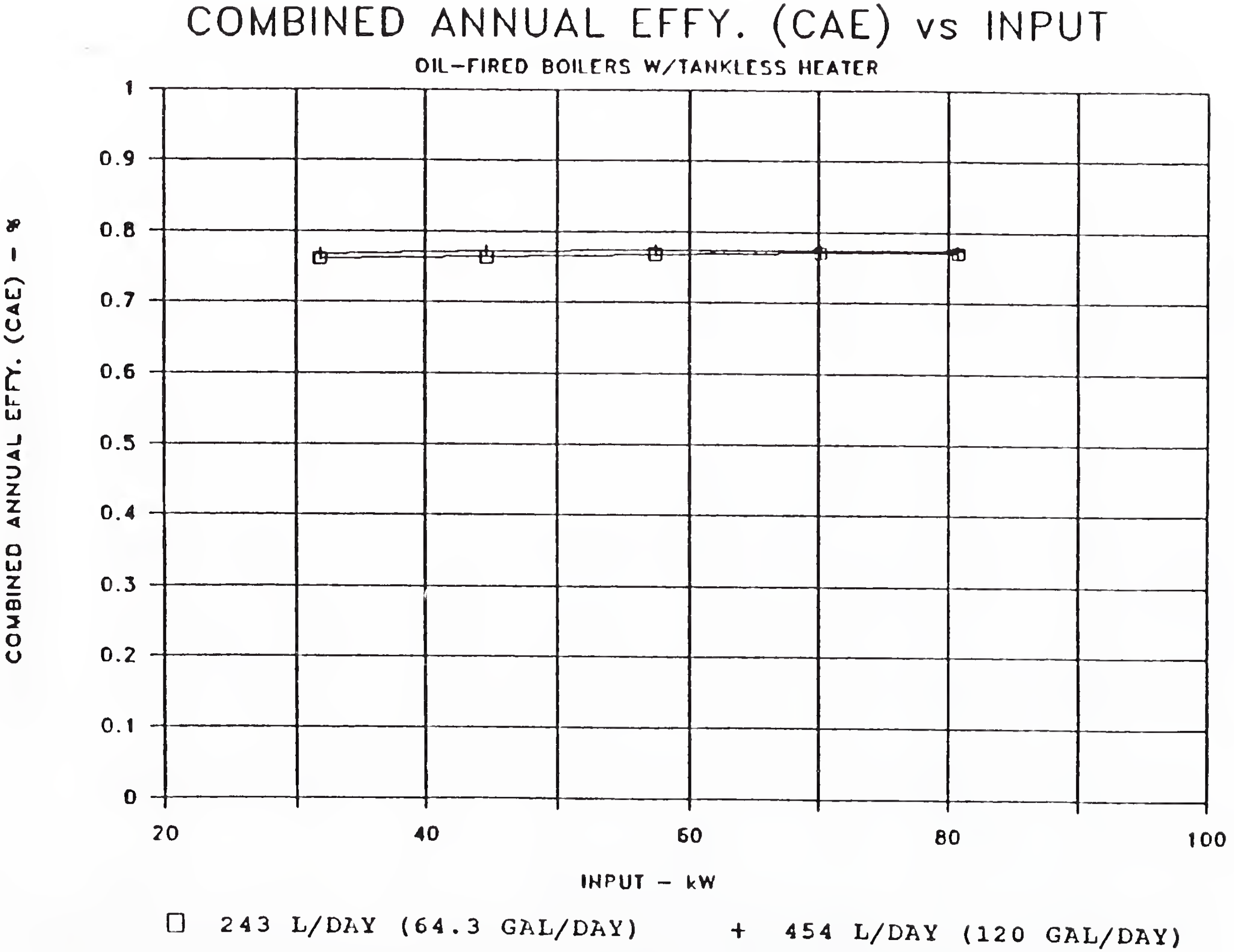

Fig. 12 Combined annual efficiency as a function of rated input of a family series of boilers with identical tankless coil