NISTIR 4356

EXPERIMENTAL STUDY ON THE PERFORMANCE OF A COMBINATION APPLIANCE FOR DOMESTIC HOT WATER AND SPACE HEATING

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Charles P. Terlizzi

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ABSTRACT

A Type II combination appliance consisting of a 50-gallon gas-fired water heater and a fan-coil air handling unit was tested in the laboratory to evaluate different methods for the determination of the combined heating seasonal, non-heating seasonal efficiencies and combined annual efficiency. Laboratory tests were conducted in accordance with the ANSI/ASHRAE 103-1988 for boilers and the DOE 10 CFR Part 430 for domestic water heaters to obtain the steady state and heating seasonal efficiencies of the water heater functioning as a space heating boiler and the energy factor of the heater functioning as a domestic water heater. These efficiency values were used to compute the combined heating seasonal and non-heating seasonal efficiencies by two different calculation methods. A series of tests with part load space heating cycling combined with domestic hot water draws were also conducted to measure the combined efficiencies directly. Comparison of the measured heating seasonal efficiency with those obtained from the two proposed calculation methods showed very good agreement. Recommendation was made to adopt the NIST developed calculation method for the rating of the combination appliance.

Key words: ASHRAE SPC-124P, ANSI/ASHRAE 103-1988, boiler, combination appliance, DOE water heater test procedure, fan coil air handling unit, gas-fired heater, laboratory tests, methods of calculation, space heating, water heating

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1. INTRODUCTION

During the past several years, combination appliances which integrate the functions of domestic hot water heating and space heating/cooling into a single system have become increasingly common in the market place. Because these types of appliances have only recently entered into the residential market, test procedure and method for rating their performance do not yet exist. In response to this need, the ASHRAE SPC-124P committee has developed a draft standard [1] entitled "Method of Testing for Rating Combination Space Heating/Water Heating Appliances" and submitted it for public review.

In the proposed ASHRAE SPC-124P, combination appliances are classified into two types. Type I appliances are those whose primary function is space heating with domestic hot water heating as the secondary function. Type II appliances are the reverse of the Type I with domestic hot water heating as the primary function and space heating as the secondary function. In order to review and to validate the proposed ASHRAE standard, the National Institute of Standards and Technology (NIST) started a project, sponsored by the Department of Energy (DoE), to conduct experimental and computer simulation studies on the performance of the two types of combination appliances. In FY 1988-89, NIST developed a computer model and conducted laboratory tests on a clam-shell, wet-base, oil-fired, residential boiler with a tank-less domestic water heating coil [2]. Laboratory tests were used to verify the computer model of a boiler with tank-less coil as a Type I appliance. A series of computer simulations were run with the model and a test procedure was developed and proposed for ASHRAE Type I appliances.

In FY 1989, a commercially available Type II appliance was procured to evaluate the proposed ASHRAE 124P standard and develop new testing and rating procedures if required. The Type II appliance consisted of a conventional gas-fired, storage type domestic hot water heater with added piping arrangement for connecting it to a hydronic fan coil air handling unit. The appliance was set up in a controlled environment in the laboratory. Extensive instrumentation was installed on the test appliance in accordance with that required in ASHRAE 124P. Laboratory tests of the performance of the appliance as a boiler under steady-state, cool-down, and heat-up conditions were conducted in accordance with the ANSI/ASHRAE 103-1988 for central furnaces and boilers [3] to determine the steady-state efficiency and heating season efficiency of the appliance as a space heating equipment. Tests were also conducted for simulated domestic hot water draw in accordance with the uniform test method in Appendix E to Subpart B of DOE 10 CFR Part 430, "Energy, Conservation Standards for Water Heaters" [4], to determine the recovery efficiency and energy factor of the appliance as a domestic water heater. These efficiency values are required by the ASHRAE 124P proposed rating procedure for the computation of the combined appliance heating seasonal and non-heating seasonal efficiencies and the combined fuel utilization efficiency. Besides the above tests required by the ASHRAE 124P, a series of additional cyclic tests with the water heater running under space heating only condition and under a combined space heating and domestic water draw condition, both with various space heating part loads, were conducted to determine the actual combined heating seasonal efficiency. This report gives a description of the test set up, the instrumentation, and the results of the tests. Comparison with the results computed with the ASHRAE 124P method and with the method proposed in NISTIR 89-4104 [2] is discussed.

2. ASHRAE SPC-124P

The ASHRAE SPC-124P [2] proposed the method of testing for rating the Type I and II combination appliances on the basis of two test procedures. The space heating performance of the appliance is to be determined from tests in accordance with ANSI/ASHRAE 103-1988 [3], Methods of Testing for Annual Fuel Utilization Efficiency of Central Furnaces and Boilers. The domestic water heating performance is to be determined from tests similar to DOE 10 CFR Part 430, Subpart B, Appendix E [4], Test Method for Measuring the Energy Consumption of Water Heaters. The resulting steady-state efficiency and space heating seasonal efficiency from the space heating performance test and the recovery efficiency and energy factor from the water heating test are used to compute the combined annual efficiency (CAE) and the heating season and non-heating season efficiencies from the proposed formulas developed in ASHRAE 124P. These efficiencies and the CAE are used to rate the combined appliance. In essence, to rate the combined appliances, ASHRAE 124P requires individual performance testing of the appliance as a space heating equipment and as a water heating equipment, but not a combined space heating and water heating test.

The space heating test of ANSI/ASHRAE 103-1988 requires a minimum of 30 minutes duration steady-state test of the appliance followed by an approximately 50 minutes cool-down test and then followed by an approximately 6 minutes heat-up test. For gas heated appliances, the flue gas and the stack gas carbon dioxide (CO_2) values and the flue gas temperatures at specific times and locations as specified by the standard, are measured. A computerized calculation procedure based on the heat loss method is provided in the standard for the computation of the steady-state efficiency, the heating seasonal efficiency, and the annual fuel utilization efficiency (AFUE).

The domestic water heating test of DOE 10 CFR Part 430 requires a simulated daily total hot water draws of 243.4 liters (64.3 gallons) divided equally into six consecutive hourly draw of 40.6 liters (10.72 gallons). The draw begins at the start of each hour at a flow rate of 0.19 liter/s (3 gpm) until completion, followed by an 18-hour stand-by period. The mean tank water temperature which controls the gas burner cut-in and cut-out, the cold supply water temperature, and the room temperature are all specified by the DOE test procedure. The mean water temperature in the tank, the outlet water temperature and inlet water temperature during the draw, the tank skin temperature and room temperature, and the input energy to the gas burner and the pilot light are all measured at specified time intervals. The water heater recovery efficiency and the energy factor are computed from the measured data based on a detailed energy balance calculation procedure provided by DOE 10 CFR Part 430.

3. TEST SET-UP

The Type II combination appliance used for the validation test was a commercially available 50-gallon (nominal capacity) gas-fired hot water heater connected to a hydronic fan coil air handler unit. The water heater has a nameplate rated energy output of 15.4 kW (52500 Btu/h). However, subsequent tests showed an output capacity of about 13.9 kW (47500 Btu/h) at the nameplate specified manifold pressure and with the manufacturer's specified and supplied nozzle size. The water heater is similar to a conventional domestic gas-fired water heater except that two additional plumbing ports are provided for connecting the heater to the heating coil in the fan coil unit. Hot water from the heater is circulated through the heating coil by a 1/20 hp water pump when space heating is required. A 1/4 hp fan blows the return air across the coil to provide heated air to the space through the duct work connected to the plenum. There is no time delay between the on (and off) time of the pump and the fan. The circulation pump, fan, heating coil, filter, and return and supply air plenum comprise the air handling unit. A cooling coil was also included but not used. The water heater is equipped with a continuously burning pilot light. The on/off control of the main burner is by a thermostat located inside the lower quarter of the tank which mechanically closes the gas flow to the burner at an experimentally pre-selected cut-out temperature setting of 60 C (140 F) for the present set up. This controller cannot be by-passed electrically or electronically. The water circulating pump and the fan are turned on (and off) together by a room air temperature thermostat during normal mode of space heating operation. Figure 1 shows a schematic of the appliance. It is noted that unlike a central furnace or a conventional boiler used for space heating, the operations of the main burner and the circulation pump/fan are not linked in any pre-set way. The burner will not be on when the pump is on unless the burner cut-in temperature is reached.

For the tests conducted at NIST, the appliance was installed in a high-bay laboratory space with controlled space temperature (within 0.2 C tolerance). The water heater was installed with its integral draft hood in place. A five foot length of insulated stack was attached to the outlet of the draft hood collar as specified by the ASHRAE 124P. The stack was linked to a exhaust hood/vent pipe arrangement and exhausted to outside. The natural gas supply to the water heater was from the local gas utility company. To maintain a near constant supply water temperature to the tank during the hot water draw test, a 189-liter (50-gallon) preconditioning water tank was installed to supply 14 C (57.2 F) make-up water to the water heater. Laboratory chilled water was used to control the preconditioning tank at 14 C (57.2 F). A recirculating circuit ran the 14 C water continuously between the preconditioning tank and the make-up water inlet to the heater. For the fan coil air handling unit, a short length sheet metal duct was attached to the inlet to the unit to simulate the return duct. A longer length duct was also attached to the outlet plenum to simulate the supply duct. The heated air from the fan coil unit during the space heating tests was exhausted directly into the laboratory space. The capacity of air conditioning equipment for the laboratory space was large enough to keep the space temperature constant during the test. The physical distance between the water heater and the fan coil unit was less than 1 m (3 ft) and all the plumbing components were insulated to minimize the heat loss through the pipe.

Extensive instrumentation was installed on the test appliance as required by the proposed ASHRAE 124P. Temperature sensors included type T, 24 gage premium grade thermocouple for the inlet and outlet water temperatures at the domestic water side and the space heating side, at six equally spaced locations inside the hot water tank, and for the air temperature after the supply air plenum in the fan coil unit. Type K, 24 gage thermocouple grid were installed for measuring the stack gas temperature 0.305 m (12 in.) above the draft hood, and Type K, 24 gage thermocouples were also installed for measuring the flue gas temperature inside the flue gas passage below the draft hood. Tank jacket surface temperature at four equally spaced locations around the tank and at four different heights, and air temperature near and at mid-height of the tank were also measured with Type T, 24 gage thermocouples. Water flow meters with electric pulse generator were installed at the return side of the space heating loop (after the coil) and after the domestic water outlet port. The amount of natural gas flow to the water heater was measured with a commercial laboratory grade gas meter. The higher heating value of the gas was measured continuously with a gas calorimeter. Gas temperature and pressures of the gas before the gas flow regulator and at the manifold were also monitored. The atmospheric pressure at the laboratory was monitored during the tests. In addition, samples of the flue gas and the stack gas (at the flue passage below the draft hood and inside the 5-foot stack, respectively) were run through a ice cooled condensing beaker and a small desiccant container and analyzed by an infrared gas analyzer for the carbon dioxide concentration.

All of the thermocouples were calibrated before installation and the closest matched pairs were installed at the tank inlet and outlet sides of the space heating loop and the domestic water supply and outlet ports where values of the temperature difference were needed in the energy balance calculation. In this way, an error of less than 0.2 C was obtained for the temperature difference measurement. The water flow meters were calibrated with the water near the test temperature by a weighing tank and scale set-up. The gas meter was calibrated by the Fluid Flow Group of the NIST Chemical Process Metrology Division and found to have a calibration constant (actual to indicated volume flow) of 0.995. The infrared gas (CO_2) analyzer was calibrated with reference gas with known CO_2 concentration of 2.992, 5.2, and 9.993 percent.

The sensors were connected to a data acquisition instrument and a micro-computer. The computer controlled the data scan rates, as well as the domestic water draw schedule and the space heating cycling rate, during part load test conditions by the use of off-the-shelf data acquisition and control application software. Due to the large amount of data collected, the data sampling rate varied from 15 seconds per scan during the hot water draw and longer (5 minutes to 15 minutes per scan) during standby period of the water draw test. For shorter test period the sampling rate was set at 15 seconds per scan. Data were stored on the computer's hard disk and analyzed with the help of a spreadsheet program.

The water flow rate for the hot water draw test was set at 0.19 liter/s (3 gpm) as specified by the ASHRAE 124P. The water flow rate through the space heating coil was set by the manufacturer at 0.23 liter/s (3.6 gpm). The micro-computer based data acquisition/control system controlled an in-line solenoid valve for the flow of the domestic hot water and the on/off cycling of the space heating water circulation pump and the fan.

4. TEST PROCEDURE

The following tests were conducted during the course of the study. These tests and the purpose for the tests are listed below:

4.1 Test 1 - Steady-state, cool-down, and heat-up test

This test follows the procedure specified by the ANSI/ASHRAE 103-1988 for the performance rating of residential boilers/central furnaces [3]. The appliance was operated with the burner and the water circulating pump and the fan turned on continuously until steady-state was established. This usually required a preconditioning period of between 10 to 15 minutes. Steady-state was established when the stack gas temperature did not vary by more than 1.7 C (3 F) over a 30 minutes period. The steady-state test was conducted under the following requirements for gas-fired boilers:

* Stack gas temperature should not vary by more than 1.7 C (3 F) over 30 minutes interval.

* Water heater inlet (return from coil) water temperature should be between 48.9 C - 51.1 C (120 F - 124 F)..

* Temperature difference across the heating coil should be between 10.6 C - 13.3 C (19 F - 24 F).

After the steady-state test period, the gas burner and the pump and fan were turned off, but the pilot light remained on for a 60-minute cool-down period. The burner and the pump and fan were then turned on for a 10- minute heat-up period to complete the test. During the whole test period, the flue and the stack gas temperatures and the flue and stack gas CO_2 concentrations were measured and recorded every 15 seconds. These data were used in the computerized heat loss method in the ANSI/ASHRAE 103-1988 to compute the steady-state efficiency, the heating seasonal efficiency and the annual fuel utilization efficiency (AFUE).

During the test period, the mean water temperature in the tank, the water temperature to and return from the heating coil, and the water flow rate were also recorded every 15 seconds. The total volume flow of the gas to the burner during the 30 minutes steady-state period was also recorded. These data were used to compute a steady-state efficiency of the water heater by a simple energy balance on the water side of the appliance (input/output method), and compared with the one obtained by the heat loss method.

It should be noted that initially during the steady-state test, difficulty was encountered in trying to keep the tank water temperature from increasing to a value that would turn the burner off before the required 30 minutes minimum run time was reached. The outlet water temperature to the heating coil reached near 69 C (156 F), the return water temperature reached 58 C (136.4 F), while the average tank water temperature reached 67.2 C (153 F). The tank water thermostat was set to its maximum possible position during the tests. Due to the mechanical way the thermostat turns off the gas control valve, the thermostat cannot be by-passed electrically or electronically as suggested in the ASHRAE 124P. To overcome this premature closing of the gas control valve which is caused by the over-sizing of the water heater with respect to the capacity of the air handling unit (most likely intentional to take care of the case of simultaneous water draw and space heating), an air blower was installed at the inlet to the air handling unit to increase the airflow and the air filter was taken out during the test. The room temperature was also lowered to the minimum required 18.3 C (65 F). The requirements in ASHRAE 124P for the water heater to be tested as a boiler stated in the previous paragraph were then satisfied and the steady-state test was conducted with the added blower in place. It should be noted that, when the water heater is tested as a boiler under ANSI/ASHRAE 103-1988, there should not be a problem. This is due to the fact that the test procedure requires a separated test set-up to keep the boiler return water temperature in the required 48.9 C - 51.1 C (120 F - 124 F) range and the fan-coil unit need not be connected. The fan-coil unit was used here in place of the special set-up for the boiler test.

4.2 Test 2 - Simulated hot water use test

The 24 hours simulated hot water use test for rating the appliance as a domestic water heater was carried out according to the detailed procedure specified in the DOE 10 CFR Part 430 [4]. The water heater was operated for a preconditioning period which consisted of three successive water draw of 37.8 liters (10 gallons) each and burner recovery cycles before the 24-hour test was started. The water flow rate during the draw was fixed at 11.36 liter/minute (3 gpm). After six hourly water draw of 40.6 liters (10.72 gallons) each for a total of 243.4 liters (64.3 gallons), with burner recovery following each draw, an 18-hour standby period was followed before stopping the test. The gas pilot light was on during the standby period. However, the heat loss was small enough for this test unit and the burner did not come on during the 18-hour stand-by. The gas use data, mean tank water temperature, water outlet and make-up water temperature, tank jacket skin and room temperature, pilot gas flow rate and water flow rate were recorded as specified by the DOE test procedure. The water heater recovery efficiency, standby heat loss coefficient and energy factor were calculated with these data according to the detailed calculating method given in the DOE procedure.

4.3 Test 3 - Space heating part load cycling test

The two tests stated above are required by the proposed ASHRAE 124P standard for the rating of the Type II combination appliance in terms of the combined annual efficiency and the heating seasonal and non-heating seasonal efficiencies. A series of part load tests were conducted to establish an efficiency versus space load factor curve. The heating seasonal efficiency was defined in ANSI/ASHRAE 103-1988 as the efficiency of the appliance at a space load factor of 0.225 [2]. The space load factor is given by:

$$X_{space} = Q_{s,out} / (Eff_{ss} * Q_{in}) \qquad (1)$$

where $Q_{s,out}$ = energy delivered to the space
Eff_{ss} = steady-state efficiency from Test 1 above
Q_{in} = gas energy input to the water heater

The space heating part load cycling tests were conducted by running the fan coil unit under cyclic conditions with various ratios of pump on time to complete cycle time, with the steady-state (100% on time) as the full load condition. Ratios of pump on time of 1/4, 1/2, and 3/4 were run, each for a period of four hours. A conditioning cycling of two hours preceded the four hours run where data were taken. The on-time and off-time of the pump/fan during the cycling tests are computed according to the equations from [5], and are listed below:

Table 1 Pump(and Fan) On Time and Off Time

Fractional Pump On Time	On Time (minutes)	Off Time (minutes)
1/13	3.25	36.75
1/7	3.50	20.50
1/4	4.00	12.00
1/2	6.00	6.00
3/4	12.00	4.00

Note that in the above table, the cases of fractional on time of 1/13 and 1/7 were not run during this series of tests. However, results for these part load conditions also can be computed from the tests conducted in Test 4 described later and discussed there.

During the space heating test, the gas burner was controlled by the tank water thermostat and was independent of the room thermostat that controls the pump/fan operation. This is different from the typical mode of operation of a central furnace or a water boiler where the burner on/off time is, in general, coordinated with the blower or pump on/off time.

Data were collected every 15 seconds during the 4-hour test. Data collected included the water temperature to and from the heating coil; mean tank water temperature; tank jacket skin and room temperatures; gas temperature and pressure at the gas control valve; the barometric pressure; total burner on and off time; amount of gas used and the higher heating value of the gas; and the heating coil water flow rate. The data were input to a spreadsheet program and the rate of heat energy delivered to the coil at each time step were computed by the following equation:

$$Q_{coil} = (m_w)*(C_{p,water})*(T_{out} - T_{in}) \qquad (2)$$

where m_w = pump (coil) water mass flow rate
Q_{coil} = rate of energy delivered to the coil at time step
$C_{p,water}$ = specific heat at the average in and out water temperature
T_{out} = tank outlet water temperature (to the coil)
T_{in} = tank return water temperature (from the coil)

The trapezoidal rule was used to integrate the energy delivered to the coil during each pump on period. The energy to the coil during each pump on period was summed up over the whole test period as 'E_{coil}'. Because of the large capacity of the tank volume, the energy stored in the tank water over the test period was not negligible and was computed as,

$$E_{stored} = (M_{water})*(C_{p,water})*(T_{avg,2} - T_{avg,1}) \quad (3)$$

where E_{stored} = energy stored in the water tank over the test period
M_{water} = mass of water in the completely filled tank
$C_{p,water}$ = specific heat at the average tank water temperature
$T_{avg,2}$ = average tank water temperature at the end of test
$T_{avg,1}$ = average tank water temperature at the beginning of test

The total useful energy output of the appliance for the space heating test was the sum of the energy delivered to the coil and the stored energy in the tank water which could be delivered to the coil on demand. The part load space heating efficiency was therefore computed as

$$Eff_{s,part\_load} = (E_{coil} + E_{stored}) / Q_{in} \quad (4)$$

where E_{coil} = summation of energy to coil over the test period
Q_{in} = total fuel energy input to the water heater
= (volume of gas used corrected to standard condition)*(HHV)
and HHV = higher heating value of fuel

4.4 Test 4 - Combined hot water draw and space heating part load cycling test

The part load space heating cycling test above determines the space heating efficiency without the hot water draw function and is a check on the value of the heating seasonal efficiency obtained from the ANSI/ASHRAE 103-1988 standard. To compare with the values obtained from the proposed ASHRAE 124P method for the heating seasonal efficiency of the combination appliance, combined load tests were conducted. A series of space heating part load cycling tests similar to the ones described in Test 3 were combined with the 24-hour hot water simulated use test and run for a test period of 12 hours. During the test period, hot water was drawn for the first six hours the same way as in Test 2, while the part load space heating cycling was run as in Test 3, with the ratios of pump on time to cycle time of 1/13, 1/7, 1/4, 1/2, and 3/4 as listed in the table under Test 3. After the first six hours, the hot water draw part of the test was completed while the part load heating cycling continued to the end of the test period. To keep the output data file to a manageable size with data at every 15 seconds so that it could be loaded onto a spreadsheet program for calculation, the test periods were run for only 12 hours and not 24 hours. Since only space heating was run after the first six hours and the loads were cyclic in nature, data from the second six hours were used in place of the remaining 12 hours of cycling test. The computations for energy delivered to the heating coil and for the stored energy were the same as in Test 3 above. The energy delivered to the hot water draw during each of the six draw periods was computed the same way as for the space heating coil load. That is,

$$Q_{water} = (m_{hw})*(C_{p,water})*(T_{del} - T_{sup}) \quad (5)$$

where m_{hw} = hot water mass flow rate during water draw
Q_{water} = rate of energy to hot water draw at time step

$C_{p,water}$ = specific heat at the average hot water temperature
T_{del} = hot water delivery (outlet) temperature
T_{sup} = supply (make up) water temperature

The trapezoidal rule was used to integrate the total energy to the hot water draw during each draw period and the total hot water energy over the first six hours were summed up as 'Ehw'. The combined load efficiency were then calculated as,

$$Eff_{combined\_load} = (E_{coil} + E_{stored} + E_{hw}) / Q_{in} \tag{6}$$

where E_{coil} = total energy to coil over a 24-hour period
E_{stored} = energy stored in the tank water during a 24-hour period
E_{hw} = summation of total energy to the 6 hot water draws
Q_{in} = total energy to burner and pilot light over 24-hour period

Note that during these series of tests, the only load on the hot water heater after the first six hours of test was the space heating load. Since the space heating load was cyclic in nature, data from the last four hours of the 12 hours test can be used to compute the space heating efficiency the same way as in Test 3. In this way, the part load space heating efficiency ($Eff_{s,part\_load}$) for the fractional pump on time of 1/13, 1/7, 1/4, 1/2, and 3/4 can be computed as stated previously.

5. TEST RESULTS AND DISCUSSION

The results from the four sets of tests described above are given and discussed below:

5.1 Steady-state, cool-down and heat-up test

Figure 2 shows a plot of the temperature variations of the stack gas, flue gas, hot water to the heating coil, and hot water temperature returning from the coil during the 30 minutes steady-state test followed by 60 minutes cool-down and 15 minutes heat-up test period. It is seen that the stack gas and the flue gas temperature remained steady during the steady-state portion of the test. The tank return temperature was 50 C (122 F) and the temperature difference across the coil was 12 C (21.6 F). The values of all four temperatures agreed with the requirements stated in the test procedure.

The steady-state efficiency computed from the test data, treating the water heater as a boiler with indoor combustion air excluding infiltration loss, was 81.36% by the heat loss method, using the stack gas CO_2 and temperature in the computation. If the flue gas CO_2 and temperature were used in the heat loss method, the efficiency was 81.31%. An energy calculation on the output energy to the heating coil plus the energy stored in the water tank with respect to the gas energy input to the burner during the duration of the steady-state run gave a steady-state efficiency of 81.1%. This value agrees very well with the one from the heat loss method. The heating seasonal efficiency by the heat loss method was 76.0% excluding infiltration loss (72.1% including infiltration loss). The annual fuel utilization efficiency (AFUE) was 70.2%. If the system was assumed to be an isolated combustion system, the heating seasonal efficiency would be 70.5% and the AFUE would be 68.7%. It is seen that for this particular appliance, the heating seasonal efficiency was slightly lower for an isolated combustion system (70.5%) compared to an indoor air system (72.1%).

5.2 Simulated hot water use test

The result from the simulated hot water use test as calculated by the DOE procedure [4] gives a hot water heater recovery efficiency of 77.6%, an energy factor of 0.542, and a standby heat loss of 0.280 kW (956 Btu/h). The water heater was well insulated. The burner did not come on during the 18-hour standby period after the recovery following the 6th draw.

To investigate whether the draw schedule makes a difference in the value of the energy factor for this appliance, a test was run where the hot water draw was once every two hours instead of the once per hour, with a stand-by period of 13.7 hours following the last draw and burner recovery instead of the 18.7 hours as in the DOE procedure. Everything else remained the same as the DOE procedure. The energy factor for this particular test was 0.531, a difference of 1.1 percentage point from the 0.542 by the DOE procedure.

5.3 Space heating part load cycling test

Figure 3 shows a sample of the data collected during a 4-hour part load cycling test with the heating coil water circulation pump and fan on half the time during each cycle. Data shown were the flue and the stack gas temperatures, the burner on/off signal, and the pump/fan on/off signal. It is seen that the burner on time and the pump/fan on time were independent of one another except that the burner on time happened at fairly regular intervals and at a far lower frequency than the pump/fan cycling did.

Figure 4 shows the variation of the space heating efficiency under different ratios of the pump/fan on time to cycle time. It is seen that as the space load decreases, the efficiency decreases. The heating seasonal efficiency of the water heater (excluding infiltration loss) as computed from the steady-state, cool-down and heat up test based on the heat loss method of ANSI/ASHRAE 103-1988 (76.0% at a space load factor of 0.225)* was also plotted on the curve. It is seen that the agreement with the value derived from the energy balance method used in these tests is very good.

5.4 Combined hot water draw and space heating part load cycling test

Figure 5 shows the result of the efficiency calculation from the combined hot water draw and part load space heating test. The space heating loads were varied during this series of tests by changing the ratio of the pump on time to total cycle time while the amount of the hot water draw was kept the same. The efficiency curve obtained from the previous test (figure 4) was superimposed on the plot also. The efficiency values are also tabulated in the table below together with those for the space heating only condition.

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* The ANSI/ASHRAE 103-1988 standard actually calculates the furnace/boiler's cyclic efficiency at an on-period to off-period ratio of 0.225 and assumes this is the furnace/boiler efficiency at a space load factor of 0.225.

Table 2 Efficiency vs Space Load Factor

	Space heating only		Combined water draw/space heating	
Fractional pump on time	Space-load factor	Efficiency	Space-load factor	Efficiency
1/13	0.046	0.602	0.047	0.679
1/7	0.051	0.617	0.072	0.706
1/4	0.158	0.738		
1/4	0.162	0.733	0.153	0.745
1/2	0.273	0.773		
1/2	0.290	0.777	0.286	0.780
3/4	0.416	0.775		
3/4	0.419	0.783	0.419	0.785

It is seen in fig.5 that at a space load factor of 0.225, a combined heating seasonal efficiency of approximately 0.765 to 0.770 was obtained. Also, as the space heating load decreases, the combined efficiency again decreases but at a slower rate. When the space heating load is zero, the efficiency becomes the energy factor (EF=0.542) of the water heater obtained from Test 2 above. When the space heating load was high, the two curves tended to merge into one because the magnitude of the heating load over-shadowed the hot water load. This can be seen from the table below where the daily hot water load and the daily space heating load are shown for various space heating part load.

Table 3 Daily Hot Water Loads and Space Heating Loads

Fractional pump on time	Hot water (Btu/day)	space heating (Btu/day)	Ratio of space heating to hot water
1/13	41270	46840	1.1
1/7	39200	69980	1.8
1/4	36730	146380	4.0
1/2	32990	266620	8.1
3/4	32300	389800	12.1

It is noted in the above table that the values of the hot water load were not the same even though the amount of hot water drawn were the same for all five tests. This is because the tank water temperature was lower during the hot water draw for the higher space load. Since the tank had to supply energy to cycles of space heating load after a hot water draw/burner recovery during the time period between water draw, the tank water temperature would decrease to below the normal hot water draw temperature of near 58 C (136.4 F) but not below the burner cut in temperature of 45.7 C (114.3 F). Also, when both water draw and space heating are on at the same time before the burner cut-in temperature was reached, the water temperature decreased farther as a result. The more frequent the pump/fan were on (higher space load), the lower the initial hot water temperature would be at the beginning of a draw. This results in a lower net hot water load for the same volume of water drawn.

6. ESTIMATION OF SEASONAL PERFORMANCE

In the proposed ASHRAE 124P, formulas were proposed to estimate the heating seasonal efficiency and combined annual efficiency for the combination appliance based on test results from the ANSI/ASHRAE 103-1988 test and the DOE 10 Part CFR 430 test. In Reference 2, a NIST developed simple method for determining the combined seasonal efficiency of Type I appliances was presented on the basis of test results from the ANSI/ASHRAE 103-1988 test. Both methods were used here to estimate the seasonal efficiency of the appliance tested in this report. The results of the computation are presented and discussed below.

6.1 NIST method

(1). Compute the combined space heating/hot water efficiency ($Eff_{combined}$) at space load factor = 0.225 following steps described on page 43 of Ref. 2:

$$Eff_{combined} = a\ x\ /\ (x + b) \tag{7}$$

where
$a = Eff_{ss}\ (1 + b)$
$b = -0.225*(Eff_{ss} - Eff_{225})\ /\ (0.225*Eff_{ss} - Eff_{225})$
$x = 0.225 + x_{water}$
Eff_{ss} = steady-state efficiency from ANSI/ASHRAE 103-1988
Eff_{225} = heating seasonal efficiency from ANSI/ASHRAE 103-1988

$$x_{water} = U * (T_t - T_c) * Rho\ /\ (Q_{in} * Eff_{ss} * 24) \tag{8}$$

and
U = nominal daily hot water consumption (=64.3 gallons)
T_t = nominal tank water temperature (=135 F)
T_c = nominal cold water supply temperature (=58 F)
Rho = density of water at temperature of metered water (=8.25 lb/gal)
Q_{in} = nameplate rated energy input rate (hourly) to the water heater

The values in the parenthesis for the above variables were the values given in ASHRAE 124P as nominal values. For the appliance under test, Q_{in} = 52500 Btu/h which gives $x_{water} = 0.040$.

The values of a and b for the steady-state efficiency of 0.814 and heating seasonal efficiency of 0.76 are shown in Table 4 below under the columns 'CURVE FIT'. At a load factor of $x = 0.225 + x_{water} = 0.265$, a combined heating seasonal efficiency of 0.770 was obtained from Equation 7. This value agrees very well with the value of approximately 0.765 to 0.770 from the combined load test efficiency curve shown on fig. 5.

(2). Calculate a combined space heating/hot water efficiency versus space load factor curve using the equation

$$Eff = (a\ x\ /(x + b)) + c \tag{9}$$

where
x = space load factor
$a = (Eff_{ss} - c) * (1 + b)$
$b = -0.225\ (Eff_{ss} - Eff_{225})\ /\ (0.225*Eff_{ss} - Eff_{225} + 0.775*Eff_0)$
$c = Eff_0$

Eff_0 = EF = energy factor from DOE 10 CFR Part 430 test
Eff_{225} = $Eff_{combined}$ as computed in step (1) above at $x = .225 + x_{water}$
Eff_{ss} = steady-state efficiency from ANSI/ASHRAE 103-1988 test

Table 4 below shows the values of the constants a, b, c used in equation 9 under the columns 'PREDICTED'. The values of the efficiencies at various space load factors are also shown on table 4. The columns labeled 'MEASURED' are the efficiency values listed previously in table 2 under the 'Space heating only' columns. The columns labeled 'CURVE FIT' were from equation 7 and the columns labeled 'PREDICTED' were from equation 9. It is seen that the measured values and the curve fit values of the efficiency are very close to each other. The data were also plotted and shown in figure 6. It is seen that as the space load factor becomes larger, the predicted values which represent the combined space heating/hot water efficiency and the curve fit values which represent the efficiency for space heating only tend to merge into one curve. The values of the combined load efficiency calculated from equation 9 were compared with the combined test data and the agreement was very good as shown in figure 7.

Table 4 Measured, Curve Fit, and Predicted Efficiency Values

CURVE FIT		PREDICTED	
Eff_0	0	Eff_0	0.542
Eff_{225}	0.760	Eff_{225}	0.770
Eff_{ss}	0.814	Eff_{ss}	0.814
c	0	c	0.542
b	0.0210	b	0.0594
a	0.8307	a	0.2877

MEASURED (Space heating only)		CURVE FIT (Space heating only)		PREDICTED (Combined space and hot water heating)	
x_{space}	Eff	x_{space}	Eff	x_{space}	Eff
0	0	0	0	0	0.542
0.046	0.602	0.046	0.570	0.046	0.668
0.051	0.617	0.051	0.588	0.051	0.675
0.158	0.738	0.158	0.733	0.158	0.751
0.162	0.733	0.162	0.735	0.162	0.753
0.273	0.773	0.273	0.771	0.273	0.778
0.290	0.777	0.290	0.775	0.290	0.781
0.416	0.775	0.416	0.791	0.416	0.794
0.419	0.783	0.419	0.791	0.419	0.794
1	0.814	1	0.814	1	0.814

Using the hourly bin data given in the report by Parken, Kelly, and Didion [6], and applying the bin method on the curve represented by equation 9, a combined heating seasonal efficiency of 0.771 was computed. Table 5 shows the output of a spreadsheet program for the bin data analysis.

Table 5 Bin Data Analysis

Region IV
Design outdoor temperature = 5 F
Oversize factor = 0.7
Daily domestic hot water use = 64.3 gallons
Tj = Bin temperature
Xspace = Space heating load factor
Xwater = Domestic water heating load factor
Xload = Combined load factor = (Xspace + Xwater)
Eff = Part-load efficiency

Bin#	Tj (F)	Nj	Xspace	Xwater	Xload	Eff	Nj*Xload	Nj*Xload/Eff
1	62	0.132	0.029	0.040	0.069	0.637	0.009	0.014
2	57	0.111	0.078	0.040	0.118	0.706	0.013	0.019
3	52	0.103	0.128	0.040	0.168	0.738	0.017	0.023
4	47	0.093	0.177	0.040	0.217	0.757	0.020	0.027
5	42	0.100	0.226	0.040	0.266	0.770	0.027	0.035
6	37	0.109	0.275	0.040	0.315	0.779	0.034	0.044
7	32	0.126	0.324	0.040	0.364	0.785	0.046	0.058
8	27	0.087	0.373	0.040	0.413	0.790	0.036	0.045
9	22	0.055	0.422	0.040	0.462	0.794	0.025	0.032
10	17	0.036	0.471	0.040	0.511	0.798	0.018	0.023
11	12	0.026	0.520	0.040	0.560	0.800	0.015	0.018
12	7	0.013	0.569	0.040	0.609	0.803	0.008	0.010
13	2	0.006	0.618	0.040	0.658	0.805	0.004	0.005
14	-3	0.002	0.667	0.040	0.707	0.806	0.001	0.002
15	-8	0.001	0.716	0.040	0.756	0.808	0.001	0.001
						Sum =	0.275	0.356

Heating Seasonal Eff (excluding infiltration loss) = 0.771

6.2 ASHRAE SPC-124P method

The value of the heating seasonal efficiency for the combination appliance as computed from the formulas [2] in the proposed standard 124P was equal to 0.7674. The value was also plotted on figure 5. Detailed calculation steps using the proposed method [2] are given in the Appendix A. It is seen that the agreement with the result of the combined test is good. However, as mentioned previously, the burner on time (recovery) after each hot water draw of 40.5 liters (10.7 gallons) was approximately 13.5 minutes. Therefore the burner was off for approximately 46.5 minutes between draws. Thus it is unlikely that the assumption used in the proposed ASHRAE 124P standard that hot water heating is at the steady-state efficiency is strictly valid. Never-the-less, as just mentioned, the proposed formulas in the ASHRAE 124P gave a combined heating seasonal efficiency of 0.767. This was only 0.4 percentage point below the value of 0.771 obtained using the bin calculation in table 5, and 0.3 percentage point below the combined space and water heating efficiency found in Section 6.1-(1) above (the NIST 'curve-fit' method without the bin calculation).

7. CONCLUSIONS

Four different sets of tests were conducted on a gas-fired Type II combination appliance to evaluate the rating methodology for determining the heating seasonal efficiency, non-heating seasonal efficiency, and combined annual efficiency as proposed in the ASHRAE 124P, and to evaluate an alternate NIST developed rating method. Both the ASHRAE proposed method and the NIST developed method require the water heater to be tested as a space heating boiler according to the ANSI/ASHRAE 103-1988 to obtain the steady-state and heating seasonal efficiency values, and also tested as a domestic hot water heater according to the procedure in the DOE 10 CFR Part 430 to obtain the energy factor value. No combined space heating and hot water draw test is required in either method. Results from a series of combined hot water draw and part load space heating tests showed that the ASHRAE 124P proposed method and the NIST developed method gave results that agreed well with those from the more time consuming combined loads test for the Type II combination appliance described in this report. However, the proposed ASHRAE 124P method arbitrarily assumed that the water heating during the heating season is always done with an efficiency equal to the steady-state efficiency. Test data during the cool-down and heat-up portion of the ANSI/ASHRAE 103-1988 test showed that this was not the case. Therefore, even though both methods gave good results for this particular type of combination appliance under test, it is recommended that the alternate NIST developed method which requires a simple curve fitting, described in Sec. 6.1-(1) of this report, be considered as the rating procedure for the Type II combination appliances covered by ASHRAE 124P.

Because of the intentional oversizing of the water heater with respect to the space heating coil capacity, difficulty was encountered in trying to maintain the water temperature in the storage tank to a constant value during the steady-state test according to ANSI/ASHRAE 103-1988. The rising water temperature would trigger the tank thermostat to turn the burner off before the required time interval for the steady-state run was completed. The design of the burner gas control for the appliance under test was mechanical in nature and the control could not be by-passed electrically. An additional blower placed in front of the fan coil unit of the appliance had to be used to increase the air flow across the heating coil and hence its capacity. The premature turning off of the burner before steady-state test is completed could happen to other unit on the market if oversizing of the water heater is intentionally designed into the combination appliance. However, if the special test set-up for boilers tested under the ANSI/ASHRAE 103-1988 is available such that the boiler return temperature can be regulated within the specified range, oversizing of the burner would not be a problem.

8. REFERENCES

1. ASHRAE SPC-124P, "Method of Testing for Rating Combination Space Heating/Water Heating Appliances", Working Draft, ASHRAE, June 15, 1989

2. Park,C; Kelly, G.E., "A Study on the Performance of Residential Boilers for Space and Domestic Hot Water Heating", NISTIR 89-4104, June, 1989

3. ANSI/ASHRAE 103-1988, "Methods of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers", ASHRAE, 1988

4. Federal Register, DOE 10 CFR Part 430, "Energy, Conservation Standards for water Heaters", Amendment to Appendix E to Subpart B, January 17, 1989

5. Kelly, G.E., Chi, J., Kuklewicz, M.E., "Recommended Testing and Calculation Procedures for Determining the Seasonal Performance of Residential Central Furnaces and Boilers", NBSIR 78-1543, October, 1978

6. Parken, W.H., Kelly, G.E., and Didion, D.A., "Method of Testing Rating and Estimating the Heating Seasonal Performance of Heat Pumps", NBSIR 80-2002, April, 1980

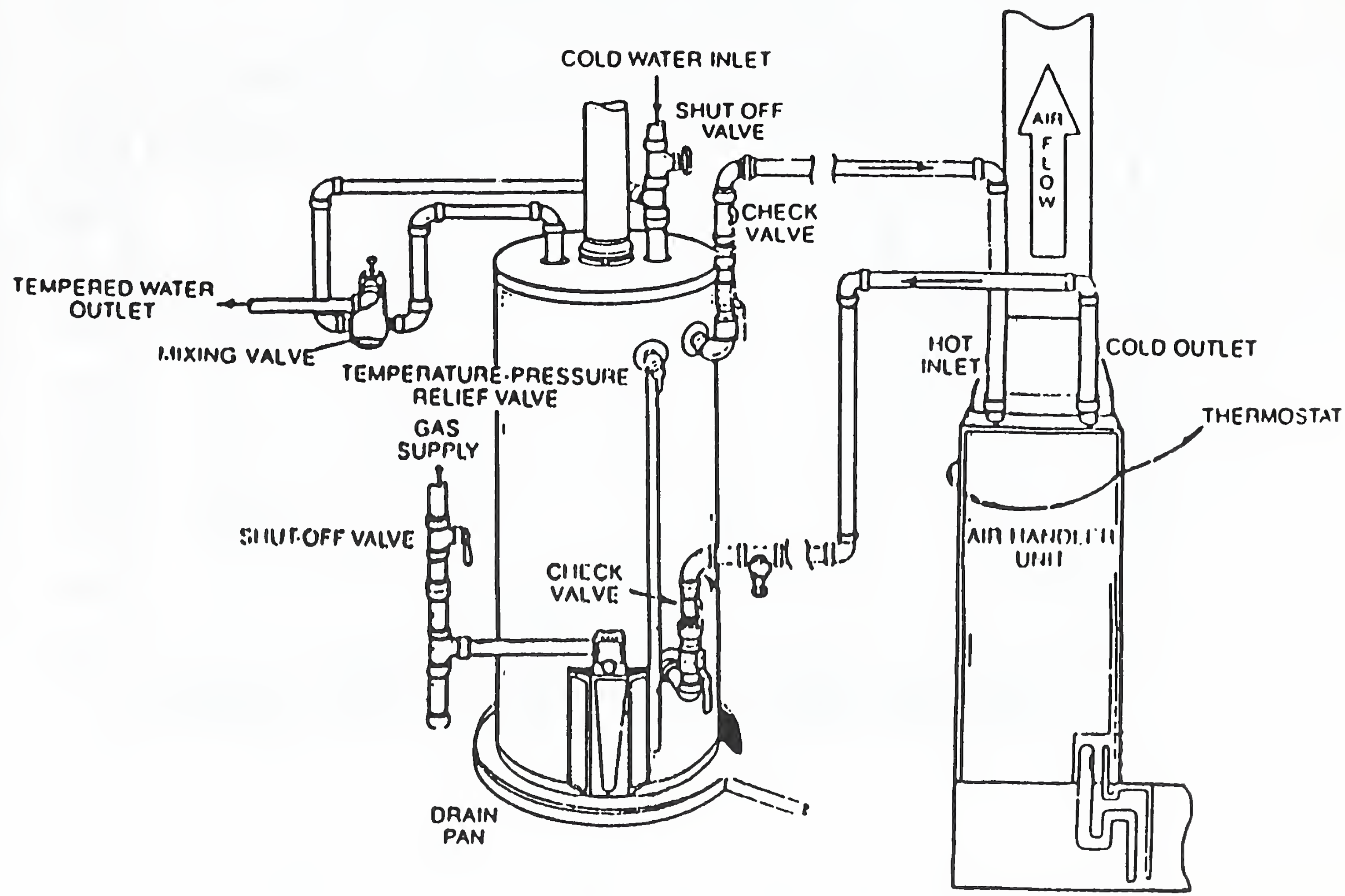

Fig. 1 Schematic of the Type II combination appliance

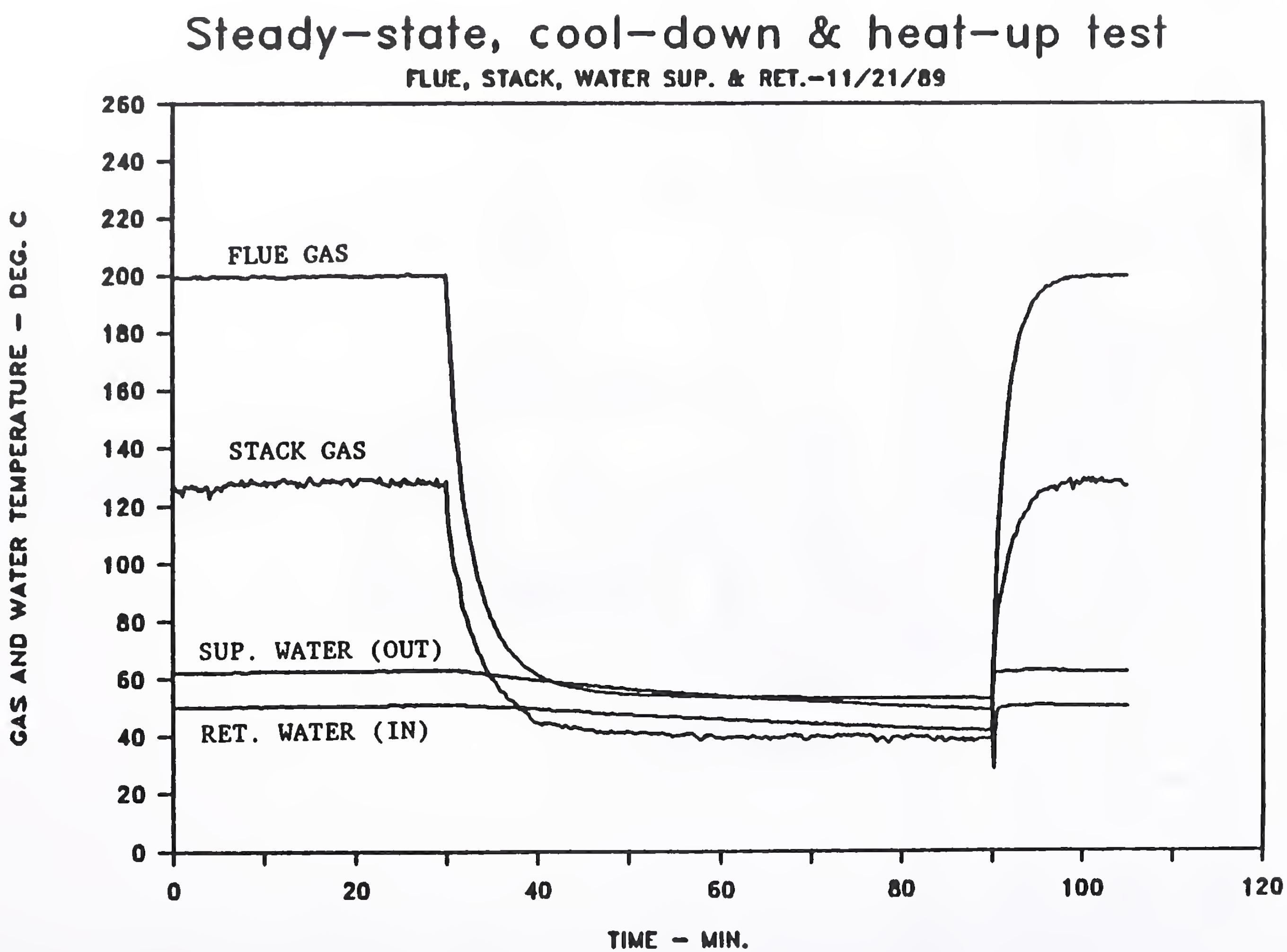

Fig. 2 Flue gas, stack gas and water temperature variations during the steady-state, cool-down and heat-up test

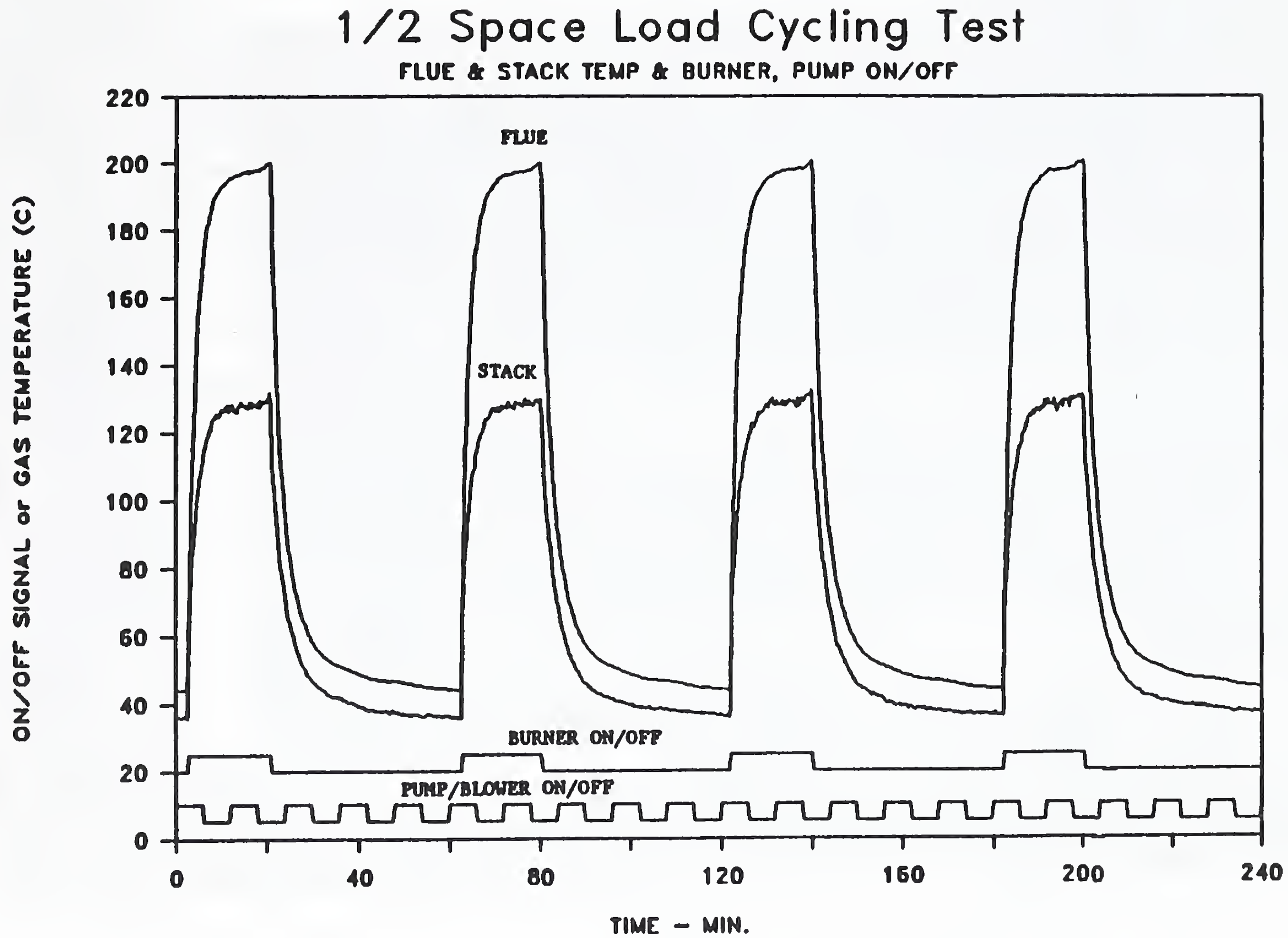

Fig. 3 Temperature and control history during part load cyclic operation

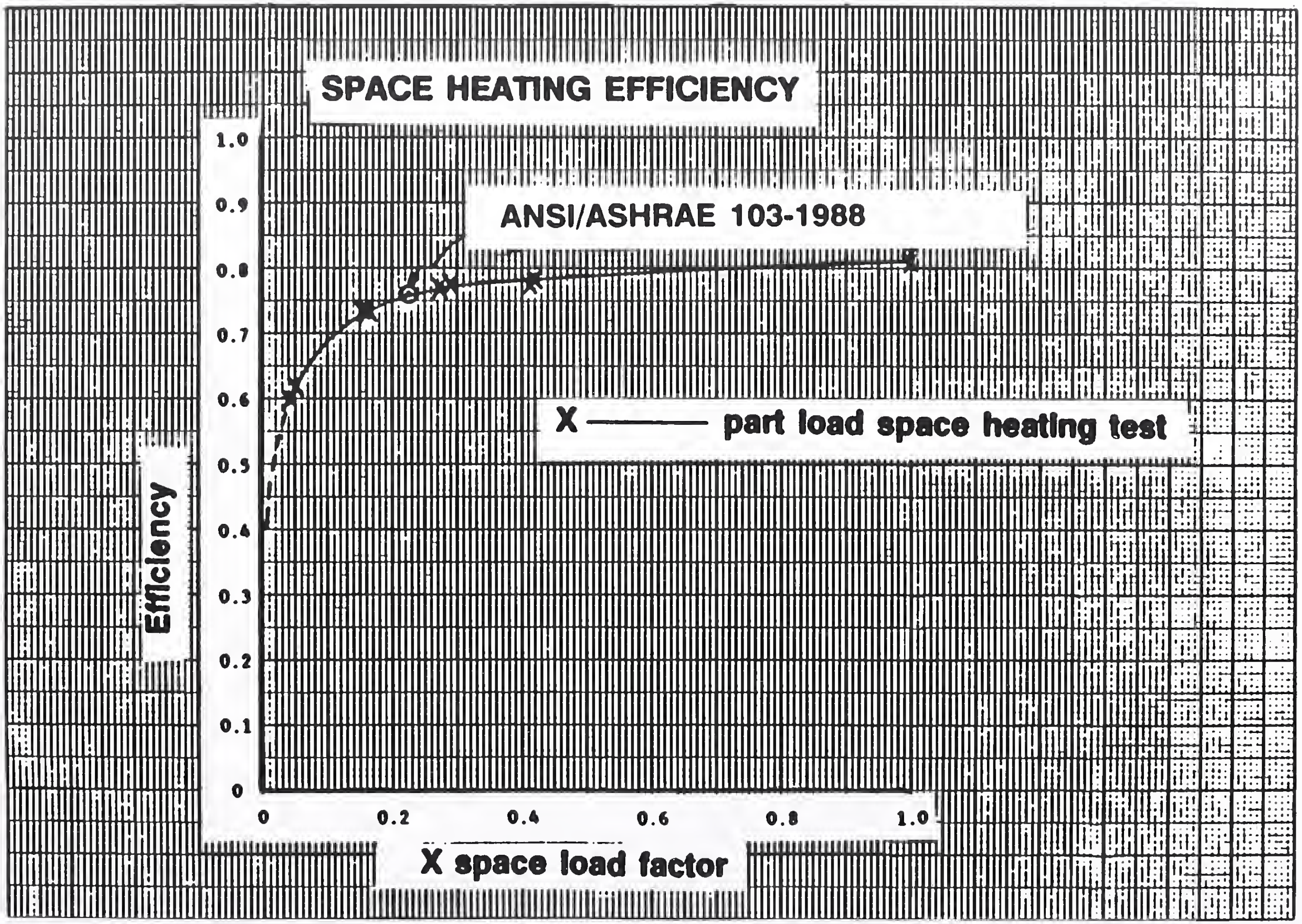

Fig. 4 Part load space heating efficiency

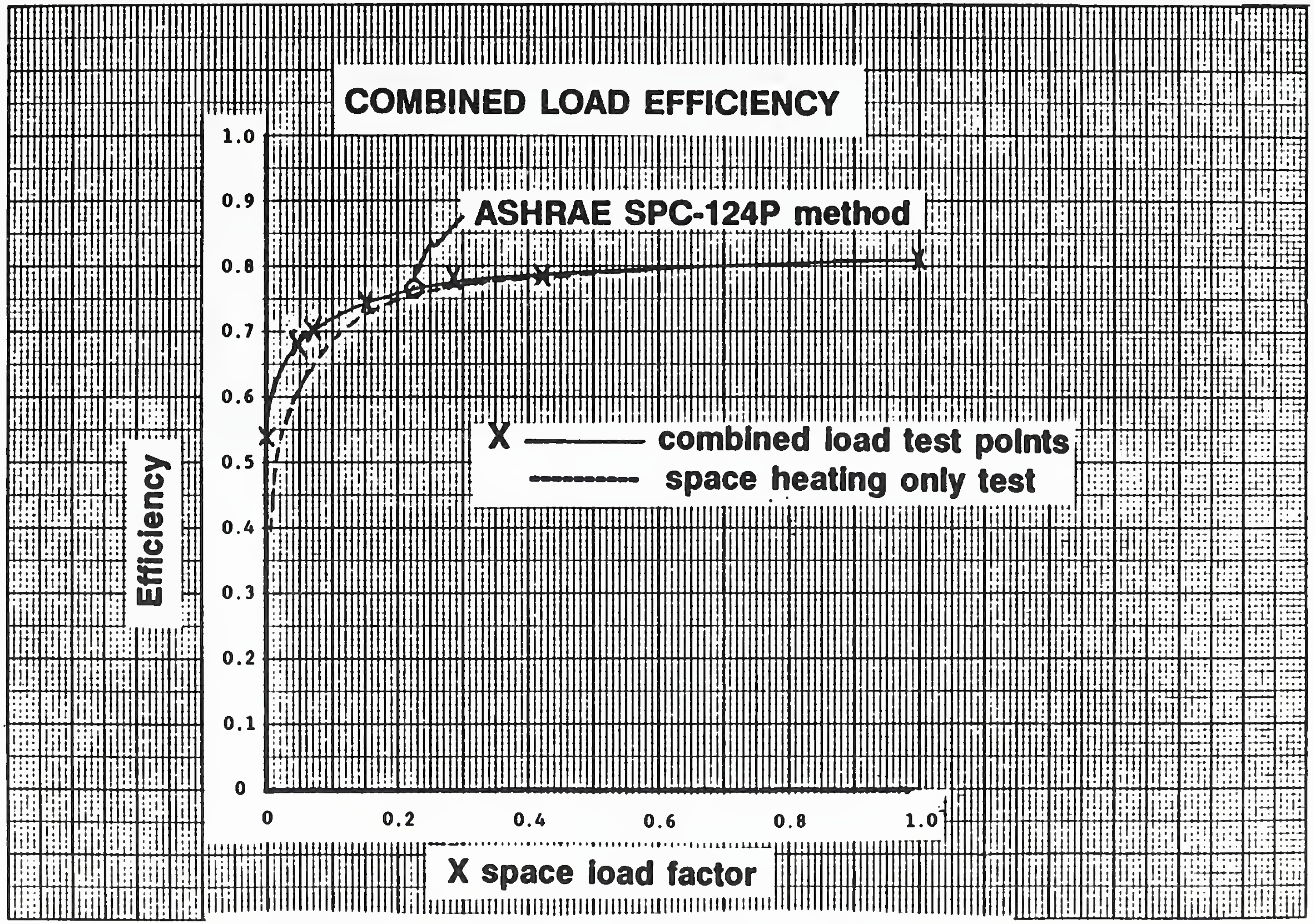

Fig. 5 Combined water heating and part loads space heating efficiency

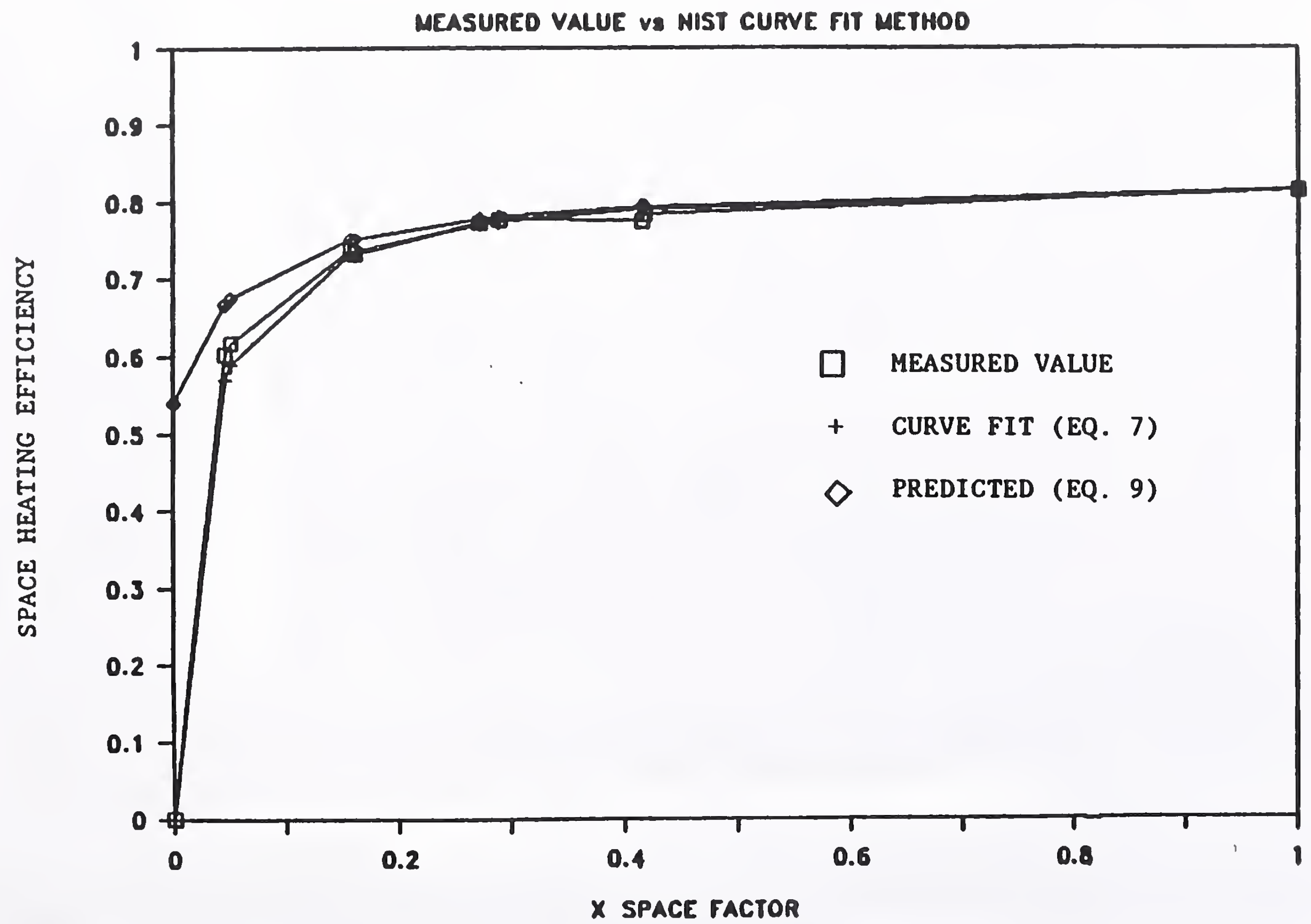

Fig. 6 Comparison of space heating efficiency, measured values vs NIST curve fit method

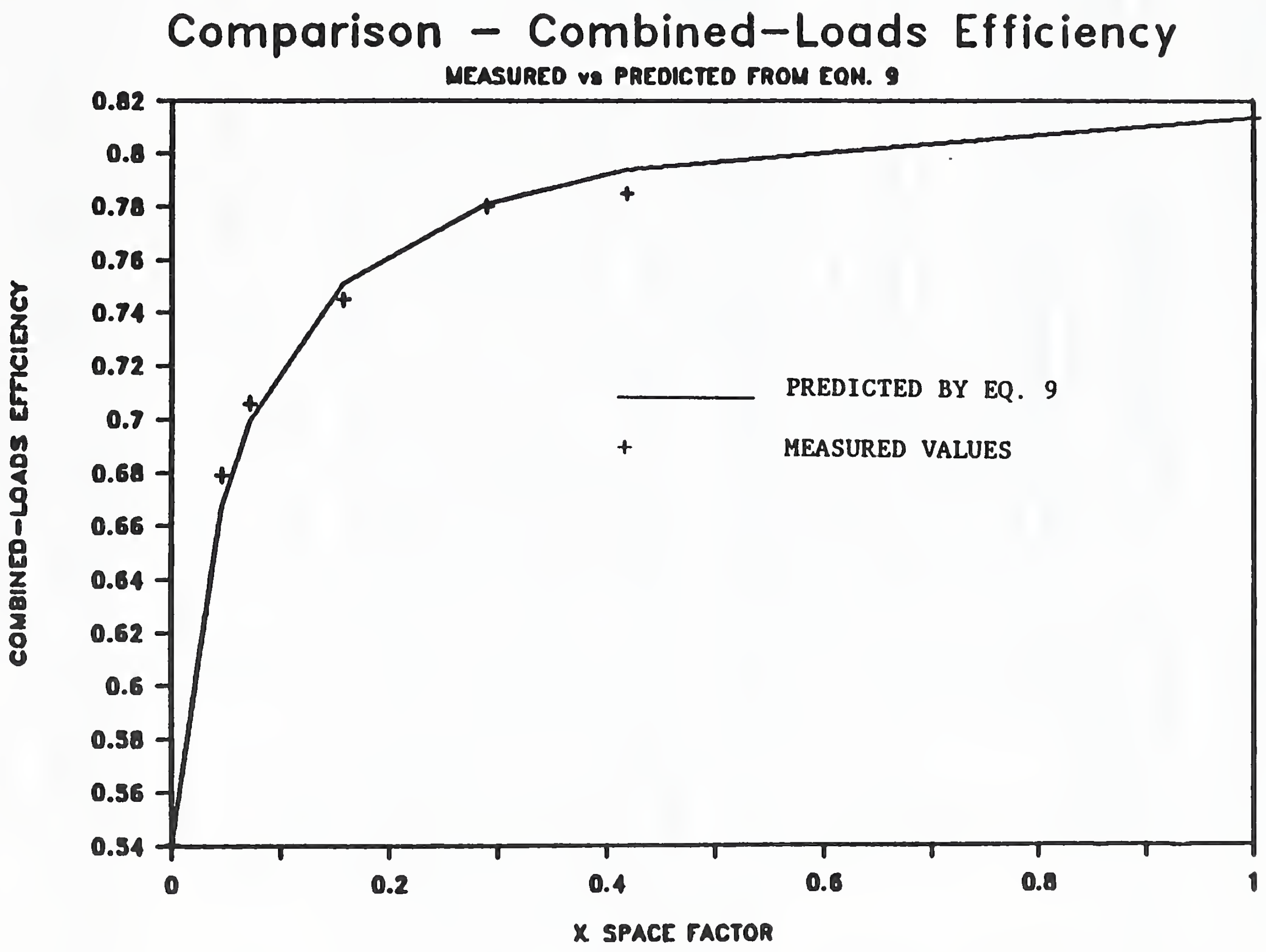

Fig. 7 Comparison of combination efficiency, measured values vs predicted values by NIST method

APPENDIX A

Calculation of Combined Heating Seasonal Efficiency and Combined Annual Fuel Utilization Efficiency (CAE) by the Proposed ASHRAE 124P Method

The computation of the combined heating seasonal efficiency and the combined annual fuel utilization efficiency follows Section 11.3 of ASHRAE 124P. The section numbers follow those used in 124P. The following numerical values were used in the calculation:

Eff_{ss} = 0.814 (test result of ANSI/ASHRAE 103-1988)
Eff_{hs} = 0.760 (test result of ANSI/ASHRAE 103-1988)
EF = 0.542 (test result of DOE 10 CFR Part 430 test procedure)
Q_{in} = 52500 Btu/h = test appliance nameplate rated energy input rate
T_{dd} = 65 F = temperature base for degree days
T_{avg} = 42 F = average outdoor temperature during the heating season
T_{des} = 5 F = outdoor heating design temperature
T_t = 135 F = nominal tank temperature
T_c = 58 F = nominal cold water supply temperature
d = 8.25 Lb /gal = density of water at measured tank outlet temperature
DD = 5200 h = number of heating degree days
DDA = 5200 h = national average heating degree days
U = 64.3 gallons = 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

11.3.1 - Heating Season Space Heating Factor (SHF):

$$SHF = (Eff_{ss}/Eff_{hs})*[(T_{dd} - T_{avg}) / (T_{dd} - T_{des})]*(DD/DDA)*[1/(1 + a)] = \underline{0.242}$$

11.3.2 - Heating Season Water Heating Factor (WHF):

$$WHF = U * (T_t - T_c) * d / (Q_{in} * Eff_{ss} * 24) = \underline{0.04}$$

11.3.3 - Non-heating Season Factor (NHF):

$$NHF = U * (T_t - T_c) * d / (Q_{in} * EF * 24) = \underline{0.06}$$

11.3.4 - Combined Annual Efficiency (CAE):

$$CAE = (SHF * Eff_{hs} + WHF * Eff_{ss} + R * NHF * EF) / (SHF + WHF + R * NHF) = \underline{0.724}$$

11.3.5 - Season Efficiencies:

11.3.5.1 - Heating Seasonal Efficiency:

$$Eff_{hs,combined} = (SHF * Eff_{hs} + WHF * Eff_{ss}) / (SHF + WHF) = \underline{0.767}$$

11.3.5.2 - Non-heating Seasonal Efficiency:

$$Eff_{nhs,combined} = EF = \underline{0.542}$$

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

A Type II combination appliance consisted of a 50-gallon gas-fired water heater and a fan-coil air handling unit was tested in the laboratory to evaluate different methods for the determination of the combined heating seasonal, non-heating seasonal efficiencies and combined annual efficiency. Laboratory tests were conducted in accordance with the ASHRAE/ANSI Standard 103-1988R for boilers and the DOE 10 CFR 430 for domestic water heaters to obtain the steady state and heating seasonal efficiencies of the water heater functioning as a space heating boiler and the energy factor of the heater functioning as a domestic water heater. These efficiency values were used to compute the combined heating seasonal and non-heating seasonal efficiencies by two different calculation methods. A series of tests with part load space heating cycling combined with domestic hot water draws were also conducted to measure the combined efficiencies directly. Comparison of the measured heating seasonal efficiency with those obtained from the two proposed calculation methods showed very good agreement. Recommendation was made to adopt the NIST developed calculation method for the rating of the combination appliance.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)
ASHRAE 124P standard, ASHRAE/ANSI Standard 103, boiler, DOE water heater test procedure, combination appliance, fan coil air handling unit, gas-fired heater, laboratory tests, methods of calculation, space heating, water heating

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