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ABSTRACT

A residential boiler for space heating and domestic hot water heating was studied by conducting laboratory tests and computer simulations. A clam-shell, wet-base, oil-fired, residential boiler with a tankless coil for heating domestic water was selected for this research project.

The purpose of this study was to develop a method for evaluating the performance of an integrated space and water heating appliance. Based upon laboratory tests, a computer model was developed and used with the HVACSIM$^+$ building system simulation program to simulate the operation of the integrated appliance.

The model was verified for heat-up, cool-down, cyclic, and standby modes of operation, along with various domestic hot water draw cycles. Using the verified model, computer simulations were carried out for both summer and winter operations of the appliance. As a result of these simulation studies, a simple method for determining the combined, seasonal efficiency of Type I appliance, whose primary design function is space heating and secondary function is domestic water heating, is presented.

ACKNOWLEDGMENTS

The authors are indebted to U.S. Department of Energy for funding this project and gratefully acknowledge Mr. Donald B. Ward and Mr. Charles P. Terlizzi for performing laboratory tests used in this report.

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NOMENCLATURE

A_{cf}	surface area where convective heat transfer takes place
A_{cross}	cross sectional area through which a fluid passes
A_j	boiler jacket surface area
A_{rc}	effective emissivity
A_{rf}	surface area where radiative heat transfer takes place
$C_{p,product}$	specific heat of combustion products
C_{pa}	specific heat of air
C_{pg}	specific heat of gas
C_{pw}	specific heat of boiler water
C_s	ratio of the boiler fire-box effective radiation heat transfer area to the total boiler fire-box area
d_c	domestic water heating coil diameter
d_h	hydraulic diameter
EF	energy factor
HHV	higher heating value of fuel
h_c	convective heat transfer coefficient
h_{cw}	convective heat transfer coefficient between the coil wall and the coil water
$I_{cfg,off}$	integration constant for gas during off-period
$I_{cfg,on}$	integration constant for gas during on-period
I_{cfw}	integration constant for boiler water
k	thermal conductivity
l_c	domestic water heating coil length
L_{gpf}	gas path length in the boiler fire-box
$\dot{m}_{cw}$	mass flow rate of coil water
$\dot{m}_{fuel}$	mass flow rate of fuel

$\dot{m}_{g,off}$	mass flow rate of the draft air during off-period
$\dot{m}_{g,on}$	mass flow rate of combustion products during on-period
M_w	mass of boiler water
$\dot{m}_w$	circulating water flow rate
NTU	number of heat transfer units
NTU,off	number of heat transfer units during off-period
NTU,on	number of heat transfer units during on-period
NTUf	number of heat transfer units between gas and boiler water at full load
Nu	Nusselt number
Pr	Prantl number
$\dot{Q}_{cw}$	heat flow rate from boiler water to coil water
$\dot{Q}_f$	heat flow rate from combustion gas/draft air to boiler water through the fire-box wall
$\dot{Q}_{f,off}$	radiative and convection heat transfer from combustion gas to sink surface during off-period
$\dot{Q}_{f,on}$	radiative and convection heat transfer from combustion gas to sink surface during on-period
$\dot{Q}_{hx}$	heat transfer rate between gas and boiler water through the heat-exchanger
$\dot{Q}_{hx,off}$	heat flow rate during off-period between combustion gas products and boiler water
$\dot{Q}_{hx,on}$	heat flow rate during on-period between combustion gas products and boiler water
Q_{input}	fuel input energy
$Q_{input,sb}$	fuel input energy during stand-by period
$\dot{Q}_{input}$	fuel input rate
$\dot{Q}_j$	jacket heat loss rate
$\dot{Q}_{lat}$	latent heat loss rate

$\dot{Q}_{s,out}$	average delivered heat flow rate to the space during a simulation period
$\dot{Q}_{ss}$	heat gain rate of boiler water
$\dot{Q}_{stk}$	heat loss rate through the stack
$\dot{Q}_{w,out}$	average heat flow rate for domestic water heating
Re	Reynolds number
R_{ptf}	ratio of the mass of combustion products to the mass of fuel
R_{wtf}	ratio of the mass of water in fuel to the mass of fuel
T_{af}	adiabatic flame temperature
T_{bw}	boiler water temperature
$T_{bw,ref}$	reference boiler water temperature at an equilibrium state
$T_{ex,g,f}$	exit gas temperature of the fire-box during on-period
$T_{g,ave}$	average of the fire-box exit gas temperature and adiabatic flame temperature
$T_{in,cw}$	inlet temperature of the domestic water heating coil
$T_{in,hx}$	gas temperature at the inlet of heat exchanger
T_{ks}	absolute temperature of the sink surface
$T_{out,cw}$	outlet temperature of coil water
T_{ra}	boiler room air temperature
T_{rw}	boiler return water temperature
$T_{stk,ss}$	stack gas temperature at steady state
$T_{surf,c}$	surface temperature of the coil wall
T_{sw}	boiler supply water temperature
U_j	overall heat transfer coefficient
V_{gf}	volume of gas in the fire-box
w	weighting factor
x_{space}	space load factor

x_{water}	water load factor
ΔT	temperature difference
ϵ_{gas}	gas emissivity
ϵ_{sink}	sink surface emissivity of the boiler fire-box
η_{225}	part-load efficiency at 22.5 % of design space heating load
η_c^*	efficiency at the load 0.225 + x_{water}
η_{ss}	steady-state efficiency
η_u	fuel utilization efficiency
μ	dynamic viscosity
σ	Stefan-Boltzmann constant
τ_g	nominal gas time constant
τ_w	nominal boiler water time constant

CONVERSION FACTORS FROM ENGLISH TO METRIC (SI) UNITS

Physical Characteristic	From	To	Multiply by
Length	ft	m	0.3048
	in	m	0.0254
Area	ft^2	m^2	0.0929
	in^2	m^2	6.4516 E-4
Volume	ft^3	m^3	2.8317 E-2
	gal	L	3.7854
Flow rate	gpm	m^3/s	6.30902 E-5
Mass	lb_m	kg	0.4536
Density	lb_m/ft^3	kg/m^3	1.60185
Pressure	in Hg	kPa	3.37685
	psi	kPa	6.89476
Temperature	^0F	^0C	$T_C=(T_F-32)/1.8$
Temperature Difference	^0F	^0C	0.55555
Power	Btu/h	W	0.29307
Energy	Btu	kJ	1.055056
U-value	$Btu/h\text{-}ft^2\text{-}F$	$W/m^2\text{-}K$	5.678264
Specific heat	$Btu/lb_m\text{-}F$	kJ/kg-K	4.1868

1. INTRODUCTION

Although boilers with tankless coils have been around for a long time, other types of residential integrated appliances designed for both space and domestic hot water heating have recently emerged in the market place. Because of the newness of these combined appliances, a new method for rating their performance has become necessary. Responding to this need, the ASHRAE SPC-124P committee has developed a draft standard [1] entitled "A Method of Testing for Rating Combination Space Heating/Water Heating Appliances" and submitted it for public review.

Previously, Subherwal [2], Pietsch [3], and Nordstrom and Fuller [4] discussed the performance rating of combination space heating/water heating appliances in several papers. In an effort to review the ASHRAE's proposed test method, laboratory tests and computer simulations were performed at the National Institute of Standards and Technology (formerly National Bureau of Standards) on a clam-shell, wet-base, oil-fired, residential boiler with a tankless domestic water heating coil. Based upon the commercial steam boiler model by Chi [5], a residential boiler computer model was developed and is discussed in this report. Some of the information from a commercial boiler model, which was developed by Chi, Chern, and Didion [6], was also incorporated in this boiler model.

The computer model was then used to simulate the operation of the selected appliance by incorporating it in the HVACSIM$^+$ program, which is a dynamic building system simulation program created at NIST [7,8]. The computer model was verified with laboratory test data for heat-up, cool-down, cyclic, and standby modes of operation, along with various domestic hot water draw cycles.

A series of computer simulations were performed for domestic water heating only (summer operation) and for combined space and domestic water heating (winter operation). A family of combined efficiency curves was obtained as a function of the space load factor for different domestic water loads. An analysis of the behavior of the selected boiler with a tankless coil leads to a new method for determining the combined, seasonal efficiency of appliances whose primary and secondary functions are space and domestic water heating, respectively.

2. LABORATORY TESTINGS

2.1. Test Setup

The integrated appliance under study was a residential wet-base hot water boiler with five sectional clam-shell, cast-iron heat exchangers. One of the heat exchanger sections contained a finned, copper coil for domestic hot water heating. The boiler's DOE rated heating capacity was 158 kBtu/h and the firing rate of the oil burner was 1.35 gal/h. The boiler used a No.2 fuel oil. The external view and the heat exchanger arrangement of the boiler are shown in Figures 1 and 2, respectively.

Figure 3 shows the overall sketch of test setup, excluding some of the data acquisition instruments. A six-inch diameter stack was directly connected to the boiler top, and an 1/125 HP circulating water pump for space heating

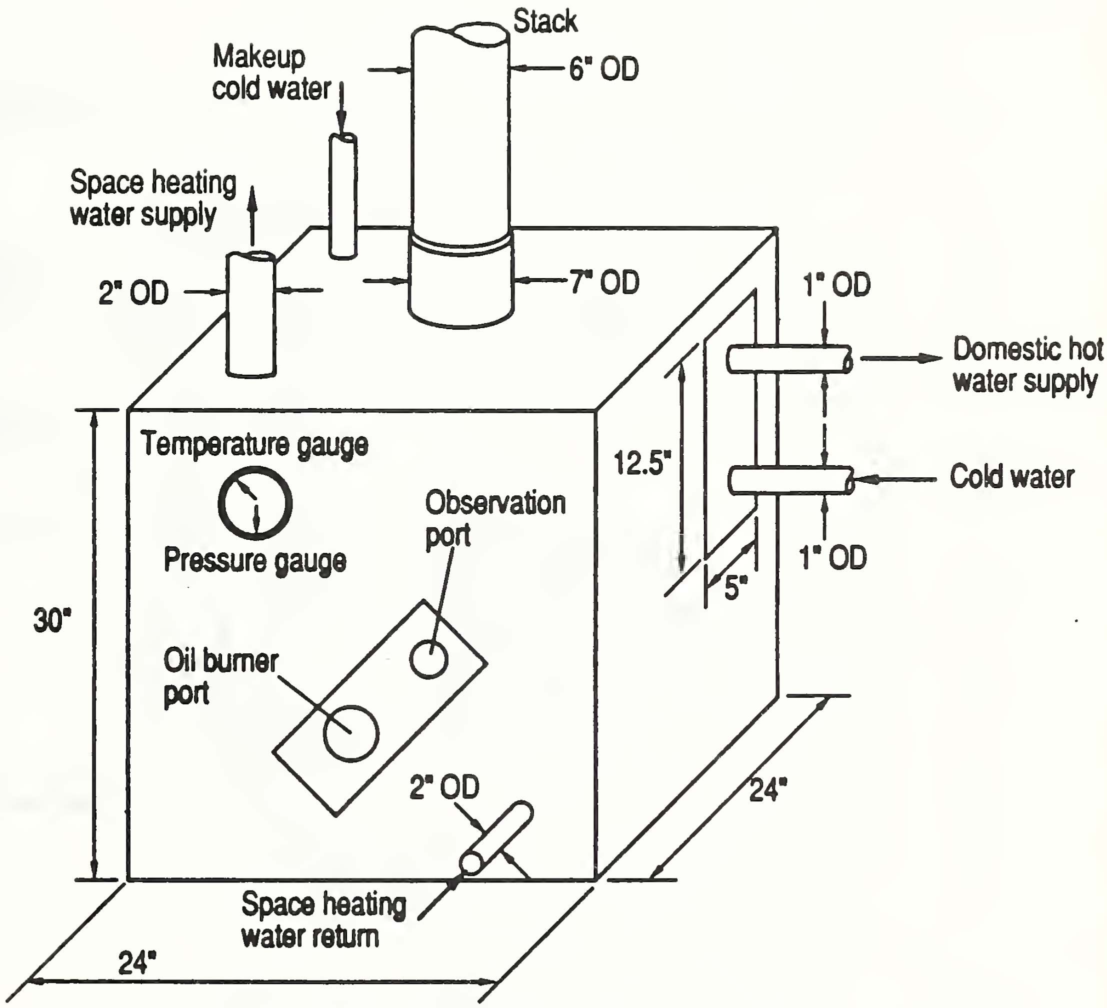

Figure 1 External view of the wet-base hot water oil-fired boiler

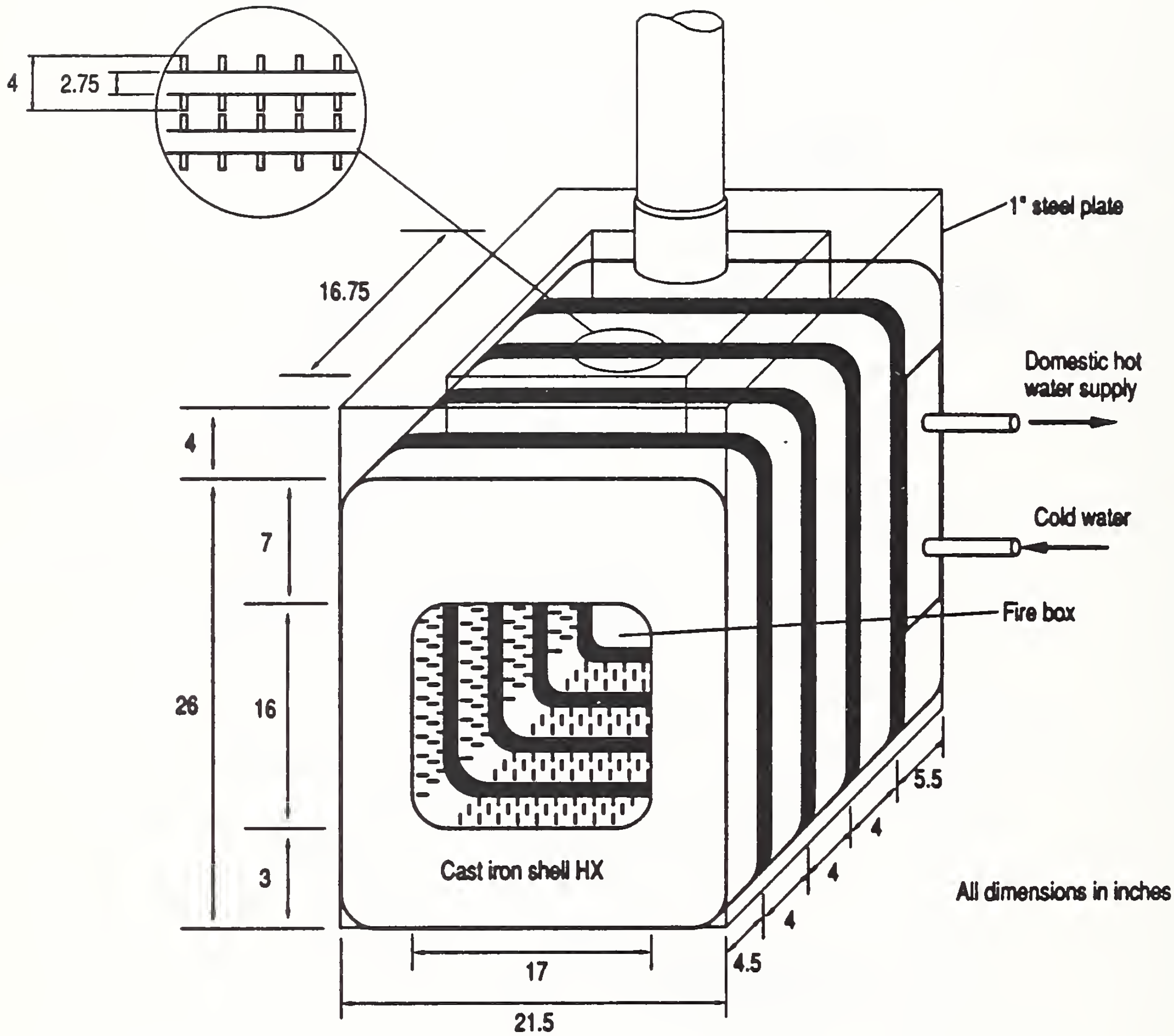

Figure 2 Heat-exchange arrangement of the boiler

Test Set-up of a Boiler with a Tankless Coil

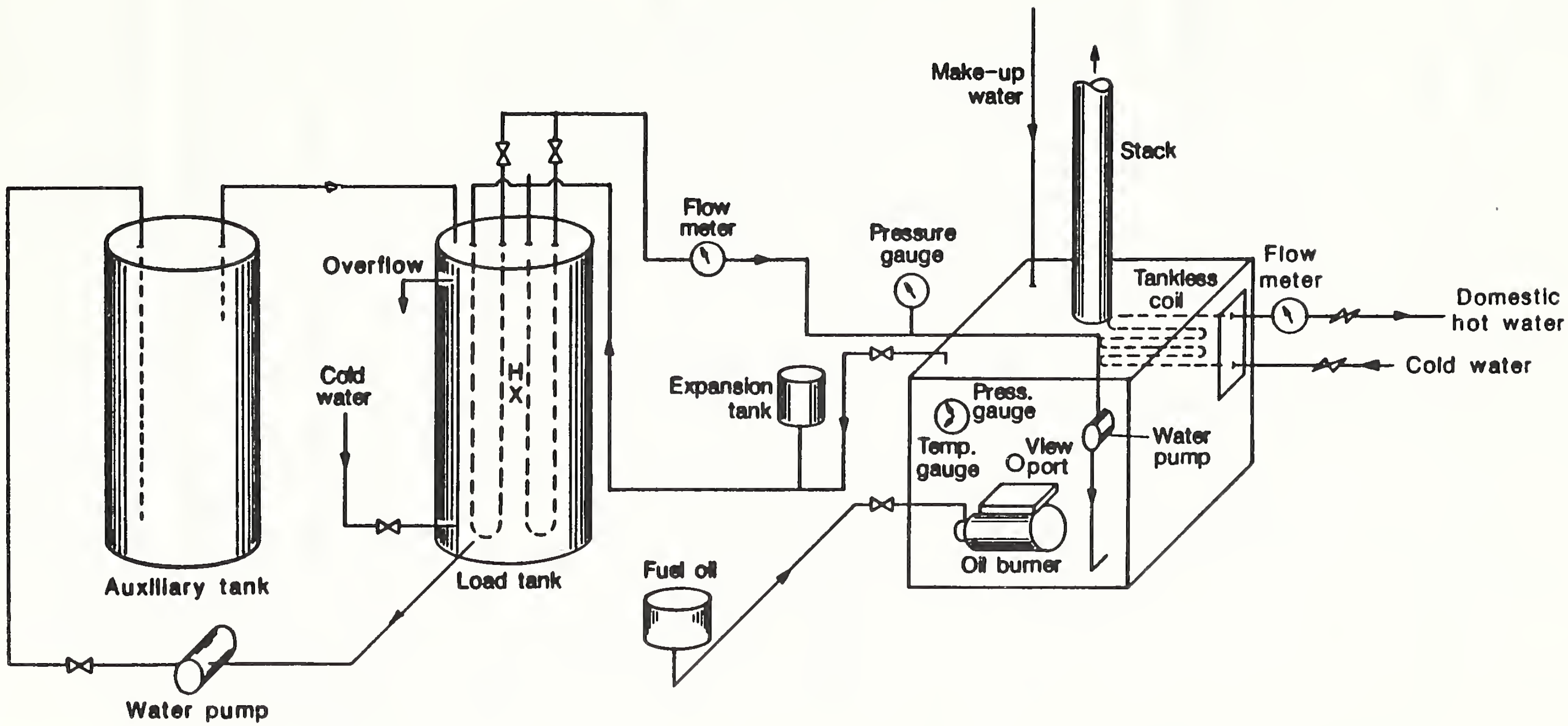

Figure 3 Test set-up of the boiler with a tankless coil

loop was located near the return port to the boiler. Two one-inch pipes were also connected to the inlet and the outlet ports of the domestic water heating coil. The majority of water piping was insulated with 1/2-inch insulation. A barometric damper for draft control was located in the stack.

Two load tanks were used to simulate the building load. Cold water from the tap cooled down the circulating boiler water in the main load tank. An auxiliary load tank served to increase the heat removal capacity of the cooling water. A pump circulated the cooling water through both load tanks. Only the main load tank contained a heat exchanger for cooling the circulating boiler water.

A controller, supplied by the manufacturer, controlled the operation of the oil burner. The input signal to the controller was provided by the thermocouple located in the clam-shell section of the heat exchanger which contained the tankless coil. The controller also controlled the water circulating pump depending upon the on/off condition of a thermostat that, in this case, sensed the load tank water temperature. An override switch was installed to bypass this thermostat and permit manual control of the pump.

A number of thermocouples were installed at various locations in the test apparatus. These thermocouples were connected to a data acquisition/control instrument that was connected to a personal computer. The test was automated using off-the-shelf data acquisition and control application software. A gas analyzer was used to measure the CO_2 concentration in the flue gas of the boiler.

The water flow rate for the space heating function was set by a manually operated valve, while the flow rate for domestic hot water remained constant during all water draws. Two water flow meters with electric pulse generators were used for measuring the amount of water flow through the boiler and the tankless coil. An in-line solenoid valve, controlled by the computer based data acquisition/control system, controlled the flow of domestic hot water.

2.2. Test Procedures

Laboratory testings were performed to provide input data for the computer model and to verify the model. Experimental work involved heat-up and cool-down tests, a steady-state test, and tests to determine the effects on efficiency of various space loads, water loads, and combined space and domestic water loads.

Prior to a test, the data acquisition sequence and control sequence were programmed into the computer. Measured data was automatically stored on the hard disk in the personal computer. Measurements of oil consumption and electric energy use were, however, performed manually. Oil consumption was determined by recording the weight of the oil container before, during, and after a test. Electric energy consumption was measured manually reading a watt-hour meter.

The data sampling period was limited by the size of data file that could be stored on the hard disk. In order to keep the data file manageable, two periods were used. A small sampling period was used for fast changing situations, while a large one was used for slow changes.

During a test, a color monitor displayed plots of selected variables with respect to time. The displayed plots revealed very valuable information on the status of the test. Figure 4 is a sample screen dump to a printer. The numeric value appearing inside a rectangular box is the totalized value of water flow in gallons for this particular test.

Heat-up and cool-down tests were made without any external water flow, i.e. no space heating load or domestic hot water load was imposed. The oil burner of the boiler stayed on until the boiler water temperature reached its cutoff point. Since no external water flow was allowed, the boiler water cooled down very slowly.

During steady-state tests, the space heating water circulated continuously through the boiler and the heat exchanger of the main load tank. The water flow rate was adjusted to make the burner run continuously without causing significant variation of the boiler water temperature. It was found, however, that it was very difficult to make such an adjustment due to variations in boiler and load tank temperatures. Because of this, steady-state experiments usually lasted less than 30 minutes. No domestic hot water was drawn during these tests.

The performance rating test was carried out following the test procedure given by the ASHRAE/ANSI Standard for rating the performance of residential boilers/furnaces [9]. The quantities required by the Standard were measured and then used to calculate the boiler seasonal fuel utilization efficiency and steady-state efficiency.

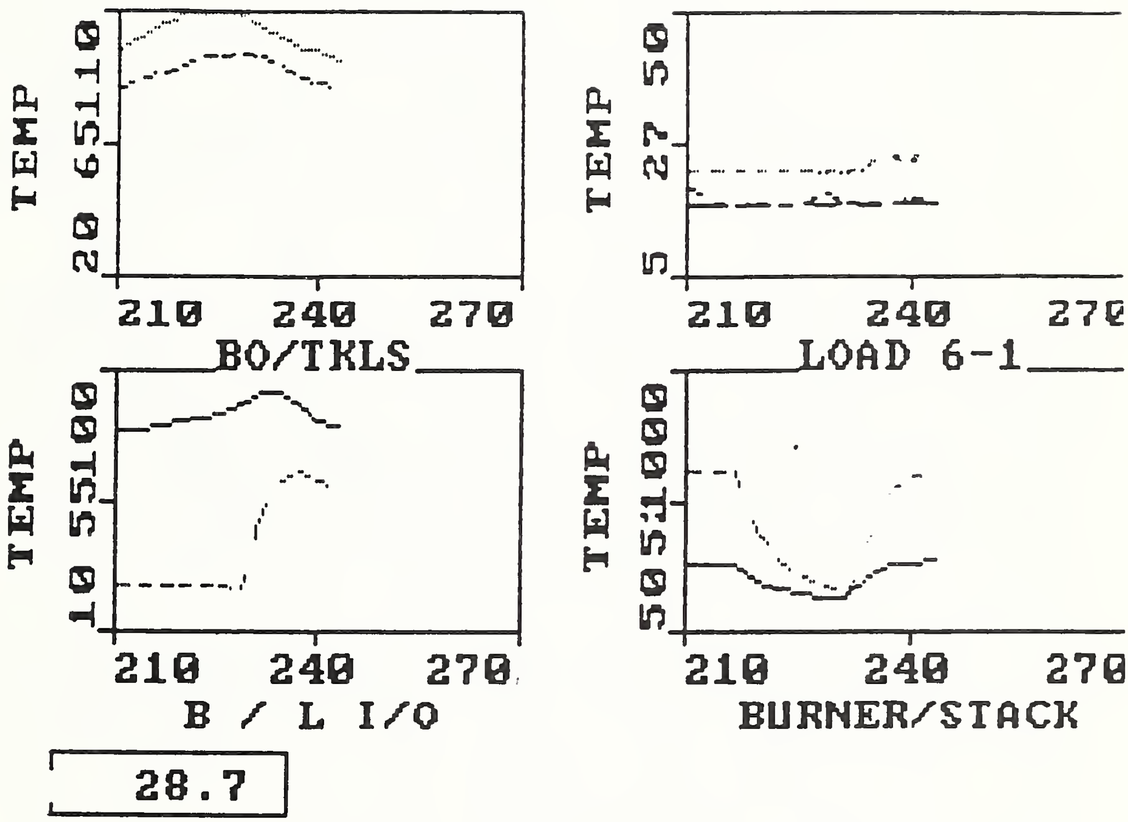

Figure 4 Sample screen dump of the displayed plots on a monitor

Space heating loads were simulated through the use of a load tank previously described. The water temperature within the load tank was controlled by means of the thermostatically controlled water pump. The thermostat's upper and lower limits were set before each test. No domestic water was drawn during a space load test and the controller supplied with the boiler controlled the burner operation. Using the water flow rate and the temperature difference between the boiler's supply and the return water, the amount of energy delivered to the load tank was computed. The effect of the water pump cycling rate on the boiler's energy consumption was also investigated.

Figure 5 illustrates how the burner and pump on/off status and the stack gas temperature changes with respect to time for a typical space load simulation test. Due to the limitation of the load tank cooling capacity, the cycle rate could not be increased over a certain limit. The duration of a typical test with repeatable cycles was usually between 2 and 3 hours.

Domestic hot water load simulation tests were carried out according to the ASHRAE 124P proposed Standard [1]. Even though the measured first hour rating was 138 gal, the maximum allowable total daily draw of 120 gal specified in the proposed Standard was used in all draw tests. After the 18-hour standby period, six equal draws of domestic hot water were imposed at the beginning of each hour. The sampling rate of data collection was one scan per 15 seconds.

During the water load simulation tests, no space load was applied. The lower and upper setpoints of the boiler controller were set to 190^0F (87.78^0C) and

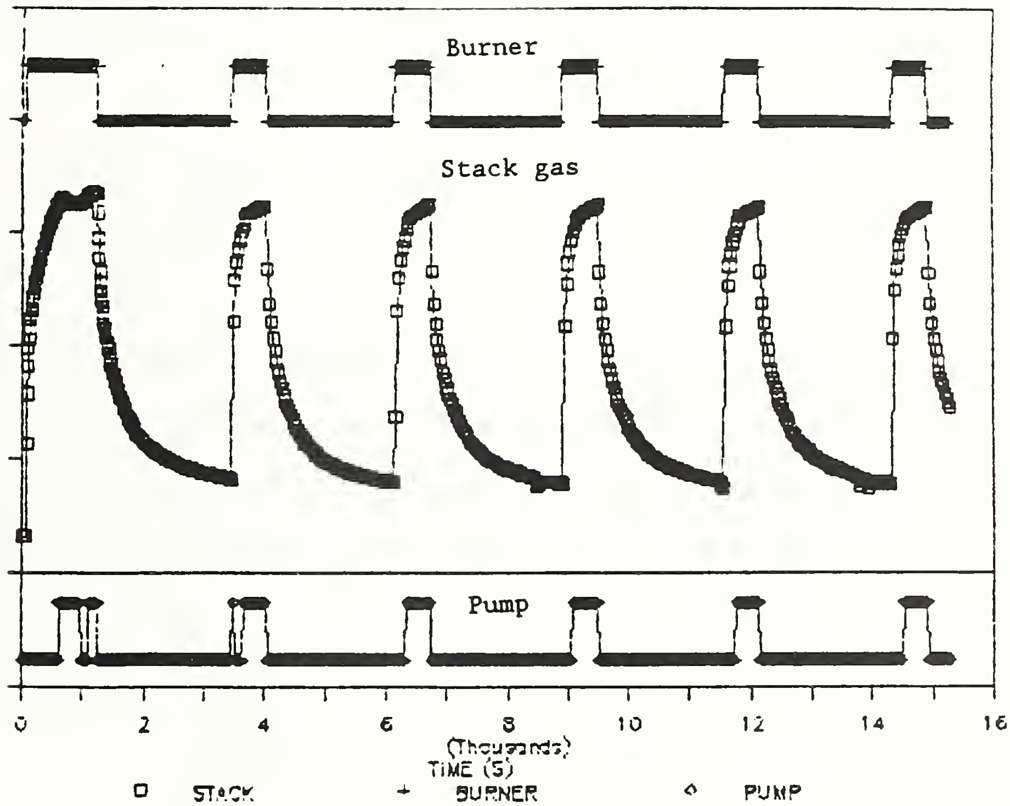

Figure 5 The burner and pump on/off status and the stack gas temperature of a typical space load simulation test

210^0F (98.89^0C), respectively. The flow rate of domestic hot water was fixed as assigned by the Standard at 3.0 gal/min.

In the 18-hour standby period, the boiler water temperature was maintained between these setpoints by operating the burner to compensate the heat losses due to the stack gas flow, heat flow through the boiler jacket, and heat conduction to pipes.

By combining space load and domestic water load, combined load tests were performed. The simulation tests were, however, restricted to low space loads, due to the limited cooling capacity of the load tanks. The water pump circulated the space heating water with a constant flow rate, when space heating was demanded. To simulate the domestic water load simulation tests, one-sixth of the daily usage of hot water was drawn at a fixed rate at the beginning of each hour of the six-hour draw period. The combination of two space heating and domestic water heating loads resulted in complex cycles as, for example, shown in Figure 6. The status of the burner and circulating pump and the stack gas temperature are shown in this figure.

3. COMPUTER SIMULATIONS

The $HVACSIM^+$ program was used for computer simulations of the boiler with a tankless coil. Component models consisting of a water boiler model, a simple heating coil model, and an algorithm for boiler control, were developed to be compatible with the $HVACSIM^+$ program. These component models were connected to each other to form a model of the boiler with a tankless coil.

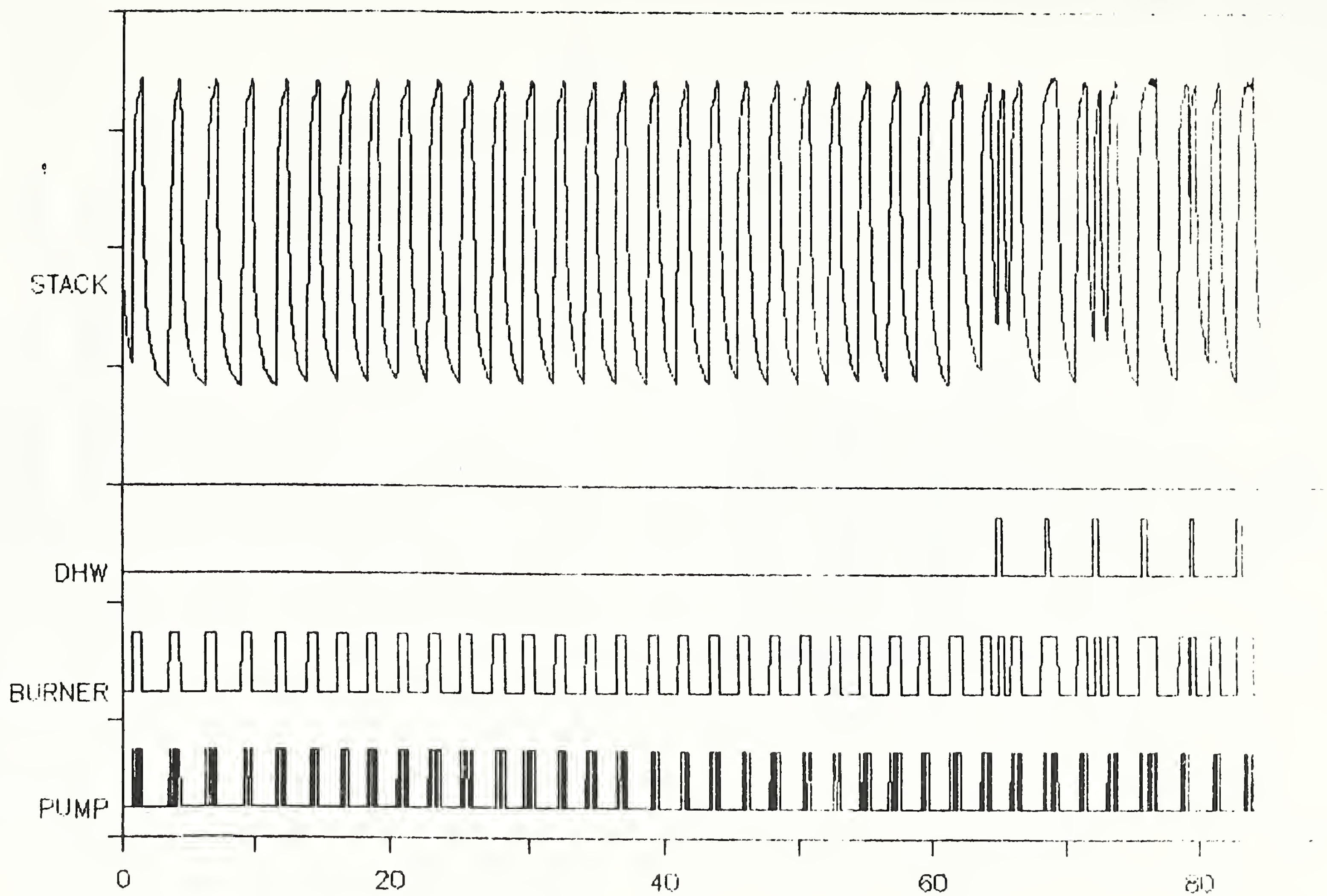

Figure 6 The status of the burner and circulating pump and the stack gas temperature of a combined load test

The boiler model was an empirical model that required reasonably good initial input data based on the actual data. The input data were prepared from laboratory tests and the boiler configuration. As will be discussed later in this report, a number of simplifying assumptions were made in modelling the boiler/tankless coil system.

3.1 Computer Model

3.1.1. Water Boiler Component Model

Figure 7 shows a cross-sectional view of the boiler that was modelled. As seen in the figure, a domestic water heating coil is located in the right-hand side of the heat exchanger. For modelling purpose, the boiler and the coil were considered as separate component models.

The empirical, residential, fossil fuel-fired, water boiler model was based on the simplified commercial boiler model by Chi [5]. The schematic diagram of the boiler model is depicted in Figure 8. The supply water temperature to the load was assumed to be the same as the boiler water temperature. The boiler water temperature, in turn, was assumed to be uniform inside the boiler. These assumptions were made to simplify the modelling task.

As shown in Figure 8, the boiler can be divided into the following five sections: combustion gas product, fire-box wall, heat exchanger wall, boiler water, and boiler jacket. The heat transfer phenomena within the boiler are different during the on and off periods of the burner.

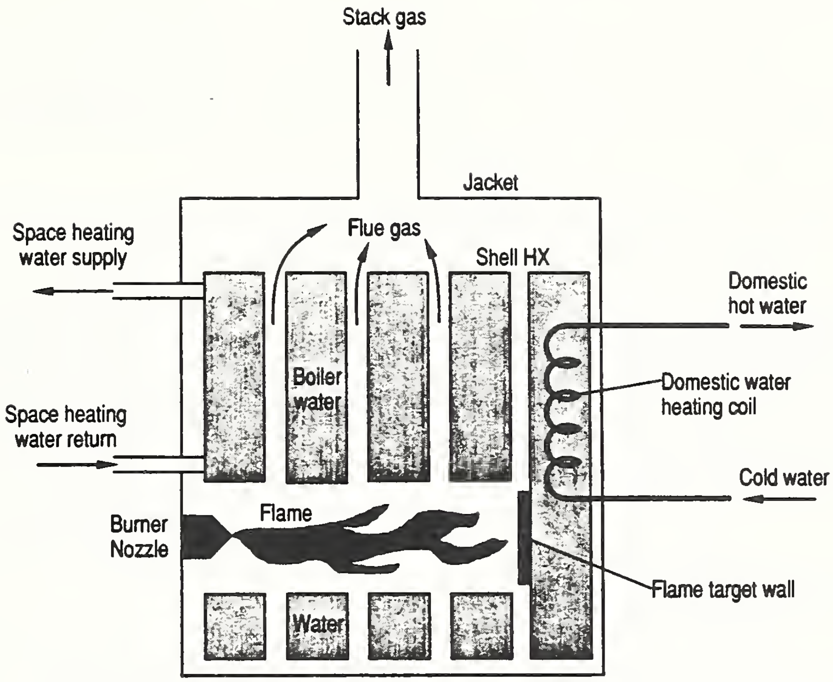

Figure 7 The cross-sectional view of the boiler

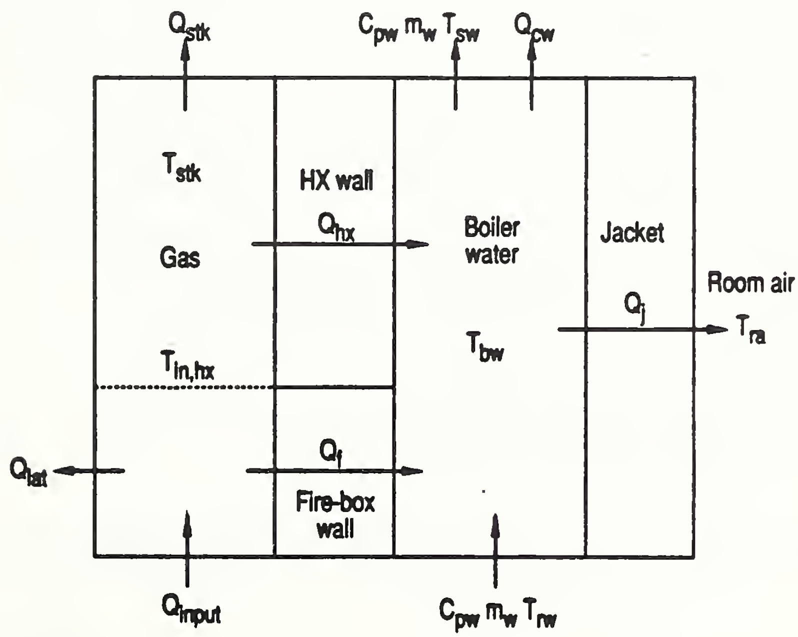

Figure 8 A schematic diagram of the modelled boiler sections

3.1.1.1 Gas-side Heat Transfer

Referring to Figure 8, a heat balance on the gas-side can be represented by:

$$\dot{Q}_{input} - \dot{Q}_{lat} - \dot{Q}_{f} - \dot{Q}_{hx} - \dot{Q}_{stk} = 0. \tag{1}$$

In this equation, $\dot{Q}_{input}$ is the fuel input rate which is computed from the mass flow rate of fuel, $\dot{m}_{fuel}$, and its higher heating value of fuel, HHV, using

$$\dot{Q}_{input} = \dot{m}_{fuel}\ HHV. \tag{2}$$

The quantity $\dot{Q}_{lat}$ is the latent heat loss calculated using:

$$\dot{Q}_{lat} = 2442.0\ \dot{m}_{fuel}\ R_{wtf}, \tag{3}$$

where R_{wtf} is the ratio of mass of water in the fuel to the total mass of the fuel and the constant 2442.0 (kJ/kg) is latent heat for evaporation of water. The term $\dot{Q}_{f}$ is the heat flow rate from the combustion gas/draft air to the boiler water through the wall of the fire-box. The term $\dot{Q}_{hx}$ denotes the heat transfer rate between the gas and the boiler water through the heat-exchanger. Once these four heat flow rates are determined, the heat loss through the stack is $\dot{Q}_{stk}$ and is obtained using equation (1).

3.1.1.2 Fire-box Wall Heat Transfer

Heat transfer through the fire-box wall during the burner on-period was calculated using the well-stirred combustion chamber theory [10]. The radiative and convection heat transfer from combustion gas to a sink surface is given by:

$$\dot{Q}_{f,on} = A_{rc}\ \sigma\ (T_{g,ave}{}^4 - T_{ks}{}^4), \tag{4}$$

where σ is the Stefan-Boltzmann constant ($5.67*10^{-11}$). The absolute temperature $T_{g,ave}$ is the average gas absolute temperature of the fire-box exit gas temperature and the absolute adiabatic flame temperature, T_{af}. The absolute adiabatic flame temperature is given by:

$$T_{af} = T_{ra} + (HHV - 2442\ R_{wtf})/(C_{p,product}\ R_{ptf}) + 273.15, \tag{5}$$

where T_{ra}, $C_{p,product}$ and R_{ptf} are the boiler room air temperature, the specific heat of the combustion products and the mass ratio of combustion products to fuel, respectively. The absolute temperature of the sink surface, T_{ks}, is assumed to be the same as the absolute boiler water temperature. The quantity A_{rc} is an effective emissivity, the sum of radiative and convective heat transfer parts and given by:

$$A_{rc} = G_s\ (1 - K^3)/(1 - K^4) + 2\ A_{cf}\ h_c/[\sigma\ (T_{g,ave} + T_{ks})^3], \tag{6}$$

where

$$G_s = (A_{rf} + A_{cf})/[1 / \epsilon_{gas} + 1 / (C_s\ \epsilon_{sink}) - 1], \text{ and} \tag{7}$$

$$K = T_{ks} / T_{g,ave}.$$

In the above equation, A_{cf} and A_{rf} are the surface areas of convective heat transfer and radiative heat transfer, respectively; h_c is the convective heat transfer coefficient; ϵ_{gas} and ϵ_{sink} are the gas emissivity and the sink surface emissivity of the boiler fire-box; and C_s is the area ratio of boiler fire-box effective radiation heat transfer area to the total boiler fire-box area.

Using the Nusselt number, Nu, expressed in terms of Reynolds number, Re, and Prantl number, Pr, the convective heat transfer coefficient, h_c can be evaluated.

$$Nu = 0.023\ Re^{0.8}\ Pr^{0.4} \qquad \text{for } Re \geq 2000, \tag{8}$$

$$Nu = 3.66 \qquad \text{for } Re < 2000, \tag{9}$$

and $$h_c = Nu\ k\ /\ d_h, \tag{10}$$

where k is the thermal conductivity, and the hydraulic diameter, d_h, can be represented in terms of the volume of fire-box gas, V_{gf} and the gas path length, L_{gpf}, using:

$$d_h = [\ 4\ V_{gf}\ /\ (\pi\ L_{gpf})\ ]^{1/2}. \tag{11}$$

During the on-period of the boiler burner, the mass flow rate of combustion product, $\dot{m}_{g,on}$, is given by:

$$\dot{m}_{g,on} = \dot{m}_{fuel}\ R_{ptf}. \tag{12}$$

The Reynolds number and Prantl number used in equation (8) are given by

$$Re = \dot{m}_{g,on}\ d_h\ /\ (\ \mu\ A_{cross}\ ),\ \text{and} \tag{13}$$

$$Pr = \mu\ C_p\ /\ k, \tag{14}$$

where μ is the dynamic viscosity, C_p is the specific heat, and A_{cross} is the cross sectional area through which a fluid passes.

During the off-period of the burner, the mass flow rate of the draft air, $\dot{m}_{g,off}$, can be obtained using an equation similar to the one used in ASHRAE/ANSI Standards [9], or in the report by Kelly, Chi, and Kuklewicz [11]:

$$\begin{aligned}\dot{m}_{g,off} &= \dot{m}_{g,on}\ [(T_{stk} - T_{ra})/(T_{stk,ss} - T_{ra})]^{0.56} \\ &\quad * \ [(T_{stk,ss} + 273.15)/(T_{stk} + 273.15)]^{1.19},\end{aligned} \tag{15}$$

where $T_{stk,ss}$ is the stack gas temperature at steady state.

The effectiveness method for a compact heat exchanger [12,13] is applied to calculate the off-period convective heat transfer, $\dot{Q}_{f,off}$.

$$\dot{Q}_{f,off} = C_{pa}\ \dot{m}_{g,off}\ (T_{ra} - T_{bw})\ (1 - e^{-NTU}), \tag{16}$$

where $\quad NTU = A_{sf}\ h_c\ /\ (C_{pa}\ \dot{m}_{g,off}). \tag{17}$

NTU is the number of heat transfer units, C_{pa} is the specific heat of air, and T_{bw} is the boiler water temperature. The exit gas temperature of the fire-box during the off-period, $T_{ex,g,f,}$ is obtained using equation (16):

$$T_{ex,g,f} = T_{ra} - \dot{Q}_{f,off} / (C_{pa}\ \dot{m}_{g,off}). \tag{18}$$

During the on-period, the exit gas temperature is estimated iteratively using Newton's method.

3.1.1.3 <u>Heat Exchanger Heat Transfer</u>

The number of heat transfer units between the gas and the boiler water at the full load condition, NTU_f, can be determined from the boiler test data using a semi-empirical equation [14]:

$$NTU_f = \ln\{1 - (\eta_{ss}\ \dot{Q}_{input} - \dot{Q}_f - \dot{Q}_j)/[C_{pg}\ \dot{m}_{g,on}(T_{in,hx} - T_{sw})]\}^{-1} \tag{19}$$

where η_{ss}, $\dot{Q}_j$, C_{pg}, $T_{in,hx}$, and T_{sw} are the steady-state efficiency, the jacket heat loss rate, the specific heat of gas, the gas temperature at the inlet of the heat exchanger, and the supply water temperature, respectively. With the boiler heat exchanger heat transfer number at full load given by equation (19), the number of heat transfer units at part load, NTU,on, can be evaluated by scaling as follows:

$$NTU,on = NTU_f\ (\dot{m}_{g,on,f}/\dot{m}_{g,on,p})^{0.2}\ (\mu_{g,on,f}/\mu_{g,on,p})^{0.4}$$
$$*(C_{p,on,f}/C_{p,on,p})^{0.6}\ (k_{on,p}/k_{on,f})^{0.6}, \tag{20}$$

where the subscript p indicates part-load condition and f indicates full load.

The heat flow rate during the on-period between the combustion gas products and the boiler water, $\dot{Q}_{hx,on}$, is obtained using equation (20),

$$\dot{Q}_{hx,on} = C_{pg,on}\ \dot{m}_{g,on}\ (T_{in,hx} - T_{sw})\ (1 - e^{-NTU,on}). \tag{21}$$

Similarly, the heat flow rate during the off-period is

$$\dot{Q}_{hx,off} = C_{pg,off}\ \dot{m}_{g,off}\ (T_{in,hx} - T_{sw})\ (1 - e^{-NTU,off}). \tag{22}$$

The off-period number of heat transfer units, NTU,off, is determined based on gas properties during the off-period. When the gas flow rate is very small, equation (20) becomes infinite, and the following expression is instead used:

$$\dot{Q}_{hx,off} = C_{pg,off}\ \dot{m}_{g,off}\ (T_{in,hx} - T_{sw}). \tag{23}$$

3.1.1.4 <u>Boiler Water Heat Transfer</u>

Dynamic changes in the boiler water temperature, the most important quantity in the boiler model, are considered using an ordinary differential equation as follows:

$$C_{pw}\ M_w\ (dT_{bw}/dt) = C_{pw}\ \dot{m}_w\ (T_{rw} - T_{bw}) + \dot{Q}_{ss}, \tag{24}$$

For this relation, the boiler water temperature is assumed to be the same as the supply water temperature to the space load. C_{pw} is the specific heat of the boiler water, M_w is the mass of boiler water, $\dot{m}_w$ is the circulating water flow rate, T_{rw} is the return water temperature, and $\dot{Q}_{ss}$ is the heat gain rate of the boiler water given by

$$\dot{Q}_{ss} = \dot{Q}_f + \dot{Q}_{hx} - \dot{Q}_j - \dot{Q}_{cw}, \tag{25}$$

where $\dot{Q}_{cw}$ is the heat flow rate from the boiler water to the tankless coil water.

Considering the temperature lag due to the thermal mass of the heat exchanger and boiler water, the heat gain at the current time can be replaced by the heat gain at the previous time step. In addition, the capacitance of the boiler water, C_{pw} M_w, can be given as the nominal time constant times a constant, I_{cfw}, that is determined empirically. Equation (24) can thus be written as

$$I_{cfw}\ \tau_w\ (dT_{bw}/dt) = C_{pw}\ \dot{m}_w\ (T_{rw} - T_{bw}) + \dot{Q}_{ss,-1}, \tag{26}$$

where

$$\dot{Q}_{ss,-1}(t) = \dot{Q}_{ss}(t - \Delta t), \tag{27}$$

I_{cfw} is an empirically determined integration constant, and

τ_w is the nominal boiler water time constant.

3.1.1.5 Boiler Jacket Heat Transfer

Heat transfer through the boiler jacket from the boiler water to the ambient air is calculated from the overall heat transfer coefficient, U_j, the jacket area, A_j, and the temperature difference across the jacket, ΔT.

$$\dot{Q}_j = A_j\ U_j\ \Delta T = A_j\ U_j\ (T_{bw} - T_{ra}) \tag{28}$$

Since the mass of the jacket is much lower than the mass of the boiler water or that of the heat exchanger , instantaneous thermal response is assumed in the equation above.

3.1.1.6 Stack Gas Temperature

Thermal properties of the gas in the heat exchanger such as μ, C_p, and k, are determined using the average temperature of the inlet and outlet gas temperature of the heat exchanger. The inlet gas temperature is the exit gas temperature of the fire-box, but the outlet gas temperature is the stack gas temperature as shown in Figure 8. Moreover, the off-period mass flow rate of the gas depends upon the stack gas temperature (see equation 15).

Separate differential equations for the stack gas temperature are considered for the on-period and the off-period, since the patterns of rising and decay of the stack gas temperature are usually different in each case.
During the on-period,

$$I_{cfg,on}\ \tau_g\ (dT_{stk}/dt) + T_{stk} = T_{stk,ss} \tag{29}$$

and during the off-period,

$$I_{cfg,off}\ \tau_g\ (T_{stk}/dt) + T_{stk} = w\ T_{bw,ref} + (1 - w)\ T_{ra}, \tag{30}$$

where τ_g is a nominal gas time constant and $I_{cfg,on}$ and $I_{cfg,off}$ are integration constants. Appropriate integration constants and the real time constants, τ_g for the on-period and τ_g for the off-period, can be determined based on laboratory test results. The quantity $T_{stk,ss}$ is the steady-state stack gas temperature, $T_{bw,ref}$ is a reference boiler water temperature corresponding to the stack gas temperature at an equilibrium state, and w is a weighting factor that is used to obtain a good fit to the measured stack gas temperature decay curve. The values of $T_{bw,ref}$ and w used in most of computer simulations were 97.5^{0}C and 0.8 respectively. These assigned values can be changed depending upon the characteristics of a boiler of interest.

It should be noted that the stack gas temperature specified by equations (29) and (30) bound the heat transfer rates of the heat exchanger during the on- and off-periods.

3.1.2. Domestic Water Heating Coil Model

The coil model for domestic water heating was developed. This model was an extension of a simplified approach for calculating the heat transfer resulting from flow through a pipe with a constant surface temperature, $T_{surf,c}$ [14]. For the model, the boiler water temperature is assumed to be uniform everywhere inside the boiler, and the capacitance of the coil wall is neglected. Properties of the water in the coil are evaluated at the average temperature of the coil inlet and outlet temperatures.

The convective heat transfer coefficient between the coil wall and the coil water, h_{cw}, is calculated in a similar manner as given by equation (10). The value of h_c is obtained for given values of the pipe diameter, d_c, the pipe length, l_c, the inlet temperature, $T_{in,cw}$, and the mass flow rate of coil water, $\dot{m}_{cw}$. The outlet temperature of the coil water, $T_{out,cw}$, and the heat transfer rate, $\dot{Q}_{cw}$, can be computed from:

$$T_{out,cw} = T_{surf,c} - (T_{surf,c} - T_{in,cw}) \, e^{-N}, \tag{31}$$

$$\dot{Q}_{cw} = h_{cw} \, A_{surf,c} \, \Delta T_{lm}, \tag{32}$$

where

$$\Delta T_{lm} = (T_{out,cw} - T_{in,cw}) \, / \, \ln[(T_{surf,c} - T_{in,cw}) \, / \, (T_{surf,c} - T_{out,cw})], \tag{33}$$

$$h_{cw} = Nu_{cw} \, k_{cw} \, / \, d_c, \tag{34}$$

$$N = h_{cw} \, A_{surf,c} \, / \, (\dot{m}_{cw} \, C_{pcw}), \tag{35}$$

and the subscript cw denotes the water in the tankless coil.

3.1.3. Boiler Control

The burner and the space heating water circulating pump are controlled by on/off control at upper/lower setpoints. A high/low temperature limit switch for space heating load control governs the circulating pump with an option of manual override. When the boiler water temperature was greater than, or equal to, the upper setpoint, the burner was turned off. When the boiler water temperature was less than, or equal to, the lower setpoint, then the burner was turned on. Similarly, when the space load-side temperature was greater than, or equal to, the upper limit, the pump was turned off. When the temperature was less than, or equal to, the lower limit, the pump was turned on. In addition, in order to achieve better convergence of computer simulations with the HVACSIM$^+$ program, a very small amount (typically 0.7 % of the total flow rate) of circulating water was allowed to flow through the pump even if the limit controller called for no water flow.

3.2. Computer Simulation Procedures

3.2.1. Source Program

The boiler component models described previously were coded in the Fortran 77 language as subroutines bearing names as:

TYPE62 for hot water boiler

TYPE63 for domestic hot water heating coil

TYPE64 for boiler control

The subroutine TYPE62 calls many routines as shown in Figure 9. Brief descriptions of these routines are given below.

BLINIT: setting initial conditions at full load

BLFLD: boiler heat exchanger performance at full load

BLHX: boiler heat exchanger performance at part load

BLFON: boiler fire-box performance during the on-period of the burner

BLOFF: boiler fire-box performance during the off-period of the burner

CPF: specific heat of the combustion products

GEF: gas emissivity

GS: radiation exchange area

HCOF: convective heat transfer coefficient

PRDPP: mass ratios of combustion product

PRDPR: viscosity and thermal conductivity of combustion product

TAFF: adiabatic flame temperature

CPCVA: specific heat of air

WCP: specific heat of water

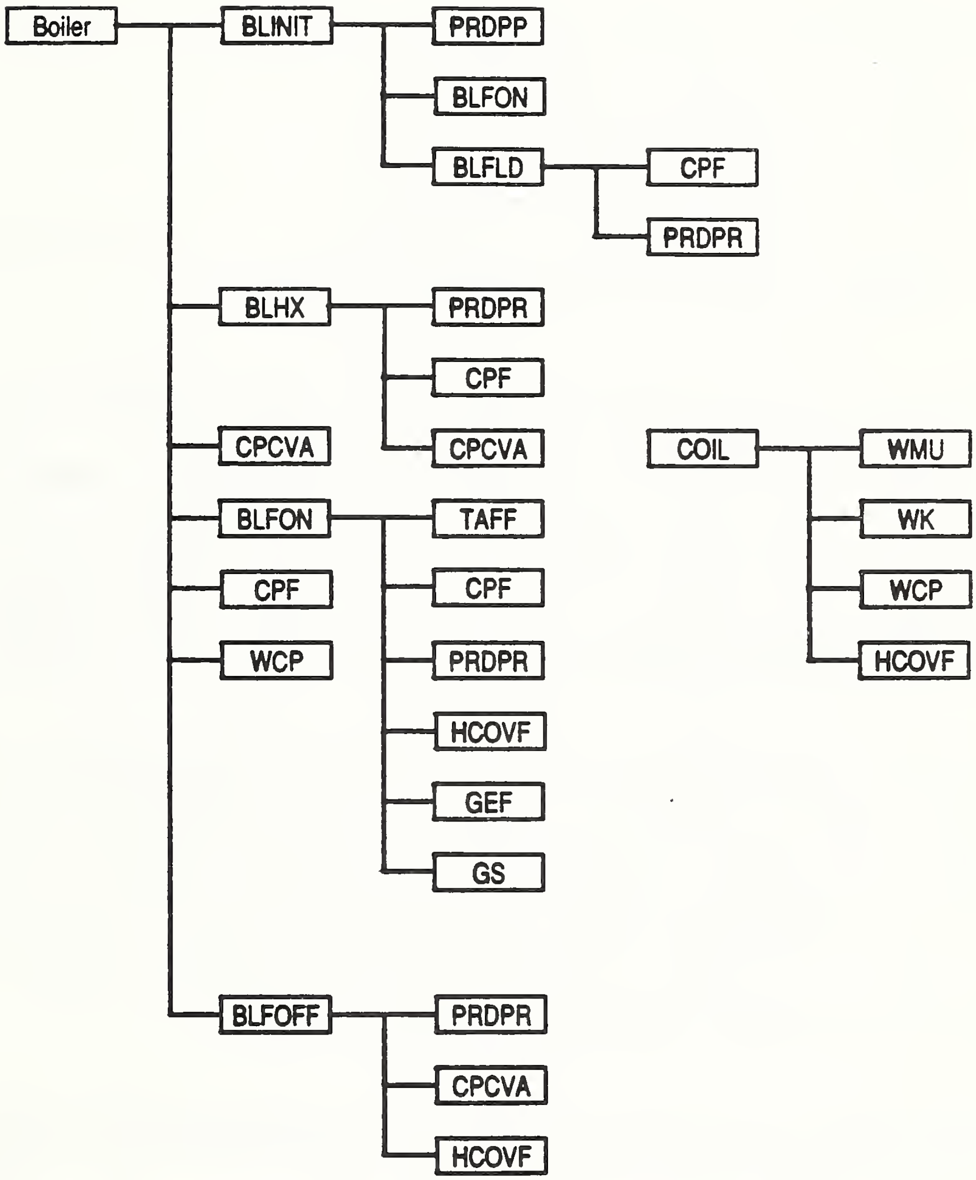

Figure 9 The routines called by the subroutines, TYPE62 and TYPE63

All routines called by the TYPE62 subroutine are included in Appendix A, except for CPCVA and WCP, which are part of the TYPES subroutine in the $HVACSIM^+$ program.

The subroutine TYPE63 needs four routines:

- WMU: viscosity of water,
- WK: thermal conductivity of water,
- WCP: specific heat of water, and
- HCOVF: convective heat transfer coefficient.

The subroutine TYPE64 does not call any other routine. The WMU and WK routines are also included in the $HVACSIM^+$ TYPES subroutine. The TYPE63 and TYPE64 are included in Appendix A.

3.2.2. Input Data Preparation

As shown in Figure 10, UNIT numbers were assigned to three component models (TYPE62, TYPE63, and TYPE64) and index numbers were assigned to state variables according to the $HVACSIM^+$ program documentation [15,16,17]. The characters, P, M, T, and C, in Figure 10 represent pressure, mass flow rate, temperature, and control variables, respectively.

The simulation setup was accomplished by invoking the front end program HVACGEN, which is included in the $HVACSIM^+$ program package. A simulation work file was generated. The hierarchical structure of the simulation work file contains SUPERBLOCK, BLOCK, and UNIT. In this boiler simulation, however, there is only one SUPERBLOCK that has only one BLOCK containing three

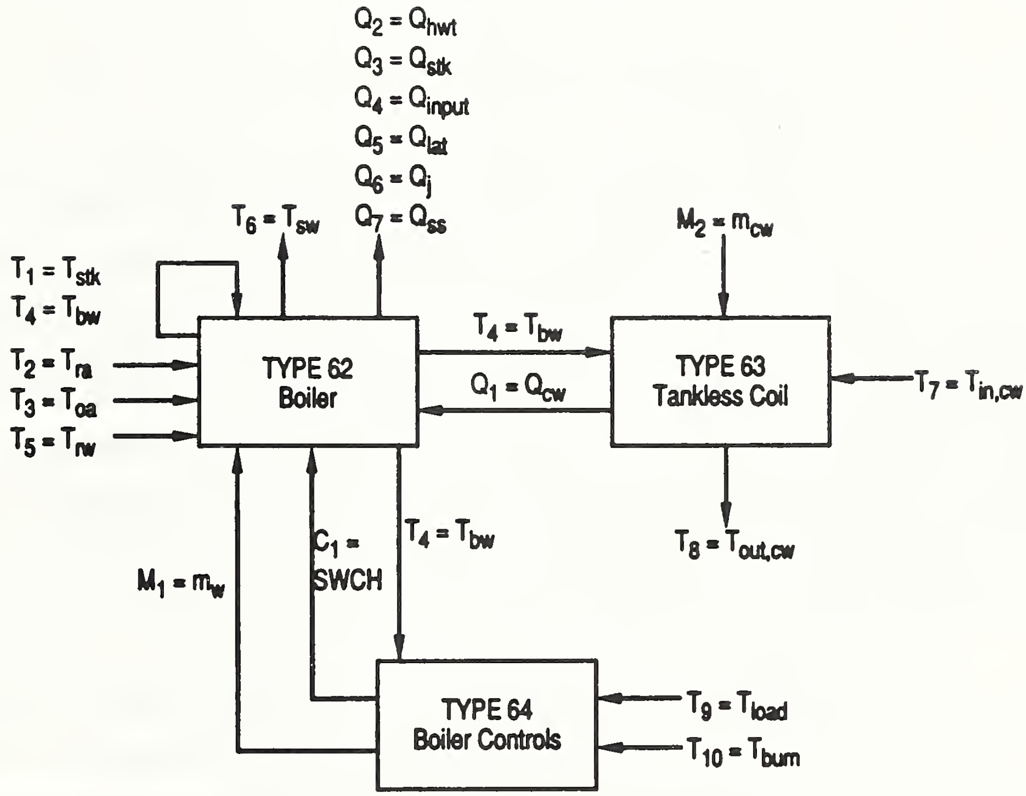

Figure 10 Block diagram of the boiler model for use with HVACSIM+

UNITS. This simulation setup is shown in Appendix B. It was generated using the "View All" command in HVACGEN.

The model definition file, which is required as an input file to the main program MODSIM, is created by the program SLIMCON. Whenever information required for the simulation work file is changed, the work file and the model definition file are updated.

A boundary data file, whether used or not, must be provided prior to a simulation along with the model definition file. The boundary data file may, however, be empty. For the simulations in this study, the on- and off-times of the water pump and the flow rate of domestic hot water drawn were included in the boundary data file. Because large step changes of a variable in the boundary data file often induce instability in a simulation, all large step changes were approximated by a number of small incremental changes. A program, CRBND, generating such incremental step changes in a boundary data file is listed in Appendix C.

The process of making a boundary data file is reasonably simple using the program CRBND, when either space water heating only or domestic hot water heating only is being performed,. However, when space heating and domestic water heating are combined, the output of CRBND must be manually edited with great care.

3.2.3. Execution of the Simulation

The main simulation program, MODSIM, was compiled using an optimized Fortran

77 compiler and was linked with necessary library routines on a mini-computer. The MODSIM program calls the equation solver routine that uses the Newton-Gauss method. With this method, good estimation of initial conditions is essential to achieve good convergence of the solution. Simulations were performed using two input files: the model definition file and boundary data file. The minimum and maximum time steps for simulations were assigned 0.5 sec and 200 sec, respectively. The MODSIM program automatically chooses the time step and order of integration between these two limits.

3.2.4. Analysis of Simulation Outputs

Computer simulation results were analyzed using a number of small programs. During this post-processing phase, the simulation output files were reformatted to be usable by a graphics routine, the heat transfer rates were integrated to obtain energy values, and the load factors and fuel utilization efficiencies were calculated. When interpolation of data was needed, a routine implementing a cubic B-spline method was employed. In addition, a commercial spreadsheet program was also used to analyze some of the simulation outputs.

4. RESULTS AND DISCUSSION

Using laboratory test results, the boiler model with the tankless coil was simulated and tuned. The tuned model was then verified with additional laboratory measurements. After verification, the computer model was used to simulate the boiler operation in both the summer and winter seasons.

4.1 Computer Model Verification

Computer simulations for heat-up and cool-down operations were repeated without an external load until reasonably good agreement was reached between computer simulation results and experimental measurements. Figure 11 shows the stack gas and boiler water temperatures of the computer simulation and the laboratory measurements during the heat-up and cool-down periods. The integration constants I_{cfw}, $I_{cfg,on}$, and $I_{cfg,off}$ used in equations (26), (29), and (30) were determined as a part of this process.

Figure 12 shows a simulation of part-load operation in space heating only mode. Cyclic stack gas and boiler water temperatures are compared. In this case, space heating water was circulated continuously and no domestic hot water was withdrawn. The burner was turned on or off depending upon the boiler water temperature. It should be noted that the measured boiler water temperature was not an average boiler water temperature but a local temperature measured at the location of the temperature sensor. The boiler temperature predicted by the computer simulations represented the average temperature throughout the boiler. From the cyclic operation simulations, some further adjustment were made to the time constants for the stack gas and boiler water during burner on- and off-periods.

The simulated pattern of domestic hot water use was investigated following the test procedure in the ANSI/ASHRAE 124P proposed standard [1]. An 18-hour standby period followed by a 6-hour draw period were studied using laboratory tests and computer simulations. The stack gas and boiler water temperatures are compared in Figure 13. Figure 14 depicts the boiler water

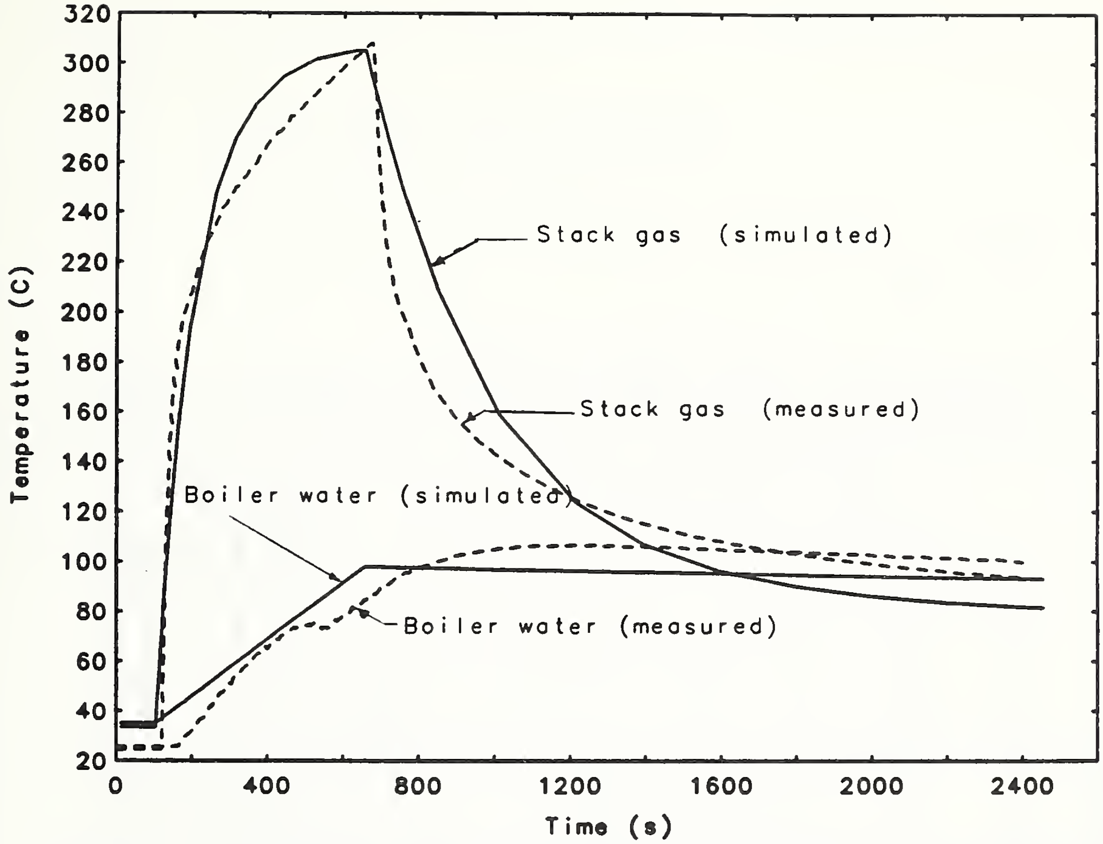

Figure 11 The stack gas and boiler water temperatures during the heat-up and cool-down periods

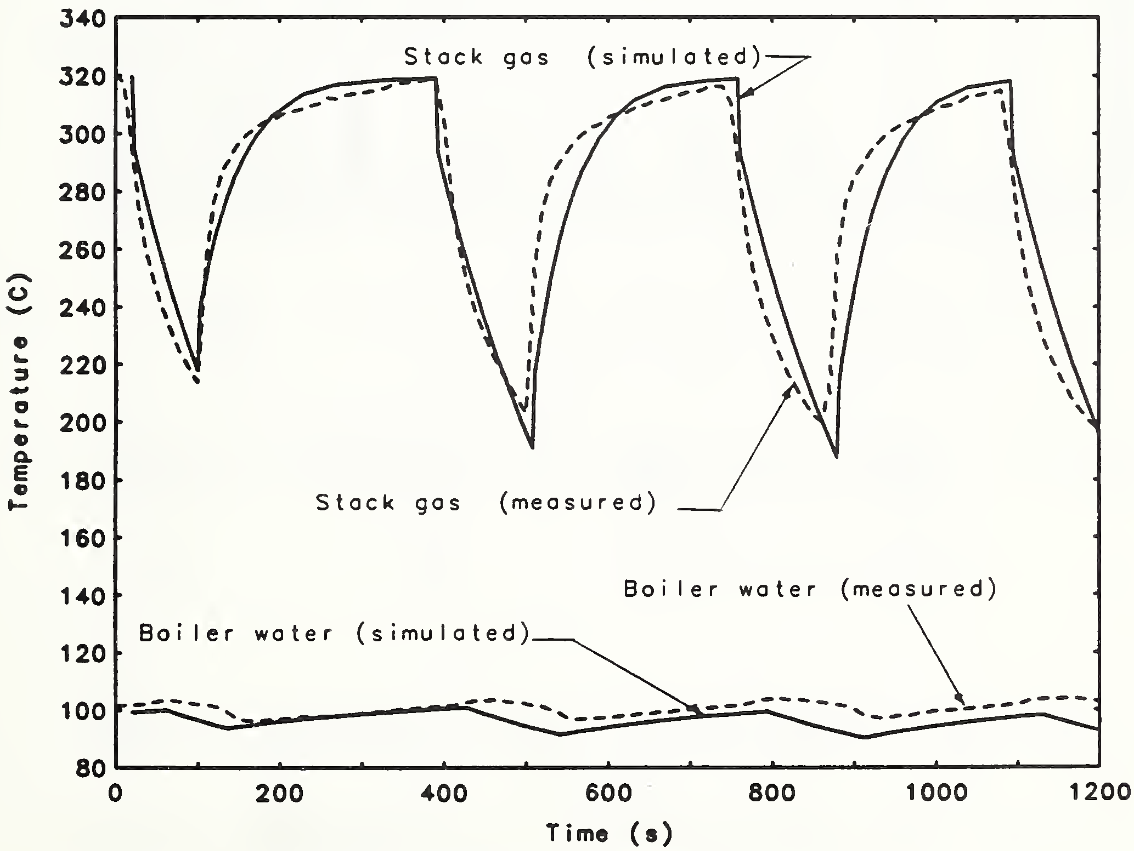

Figure 12 Part-load operation in space heating only

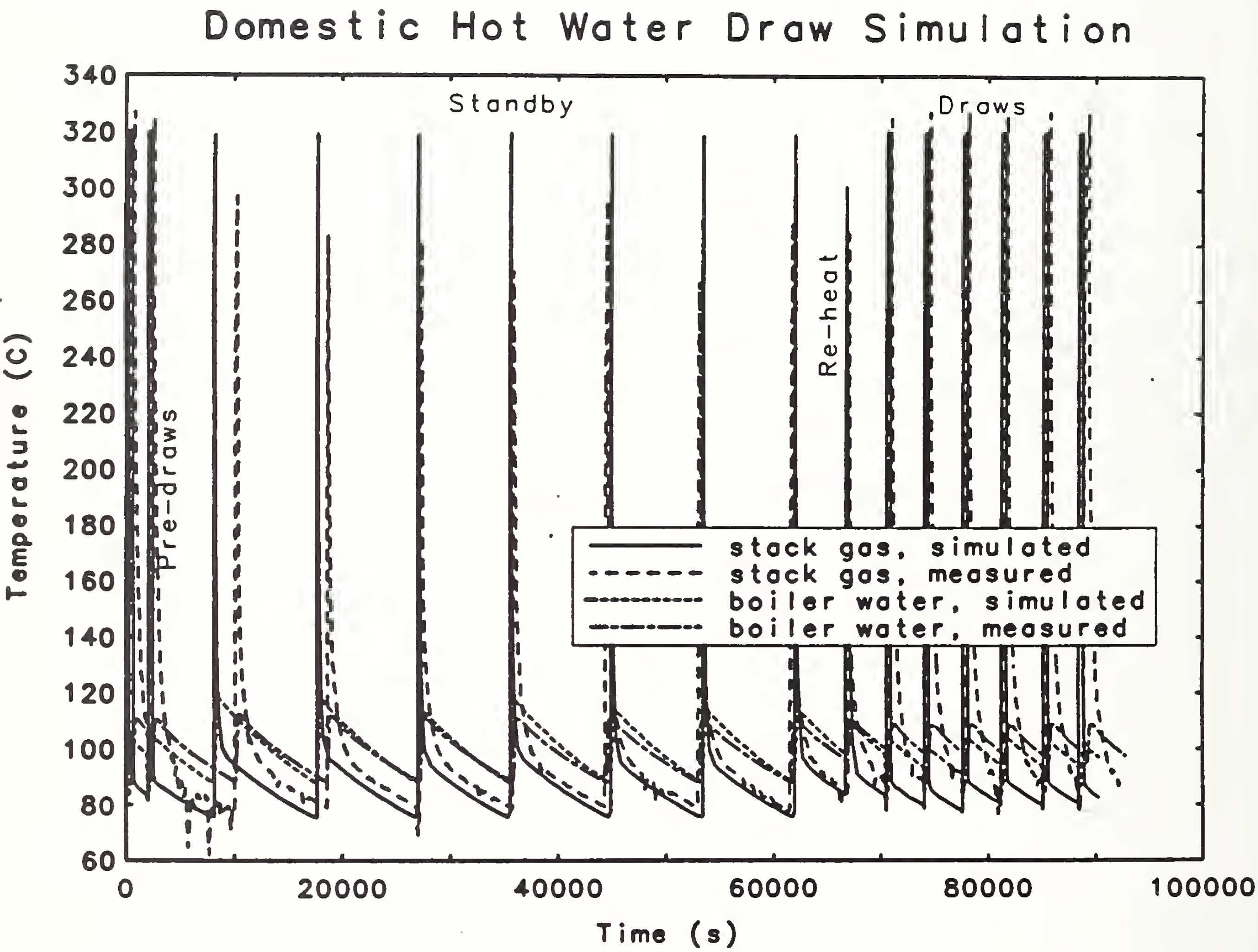

Figure 13 The stack gas and boiler water temperatures of a domestic hot water draw simulation

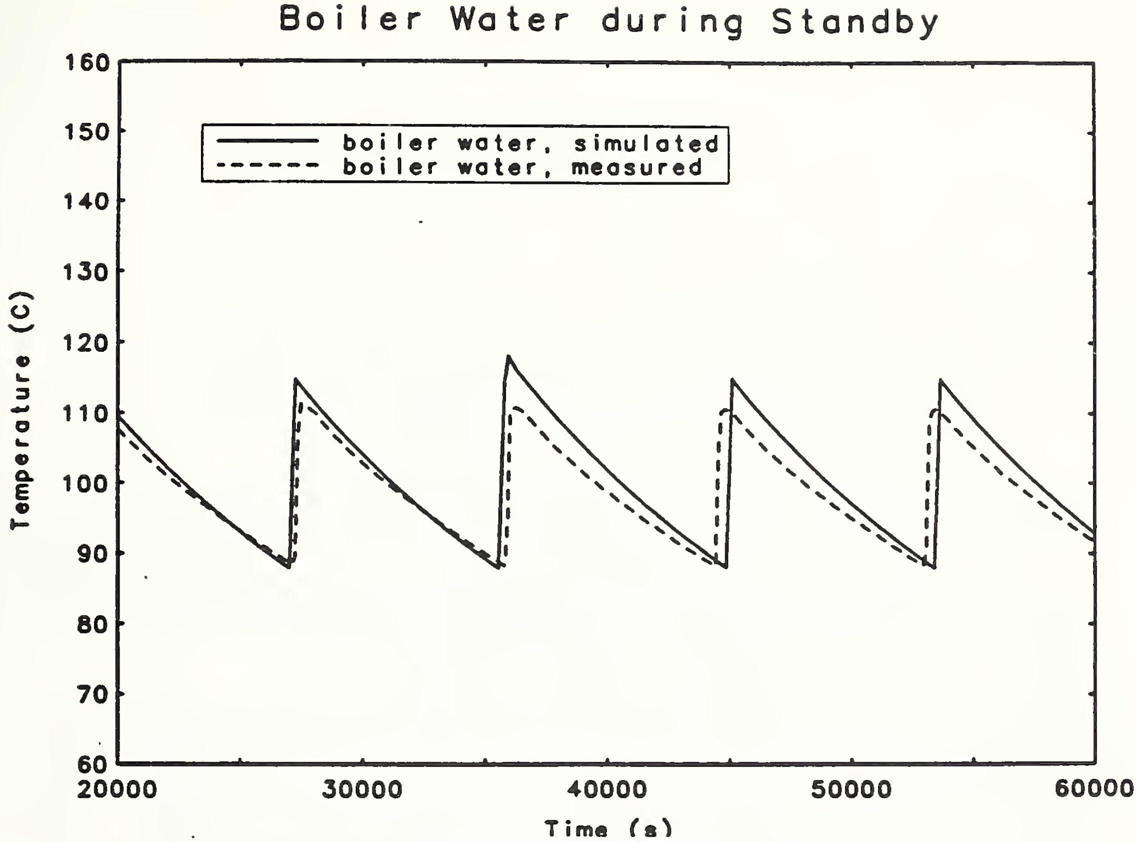

Figure 14 The boiler water temperature changes during a part of the standby period

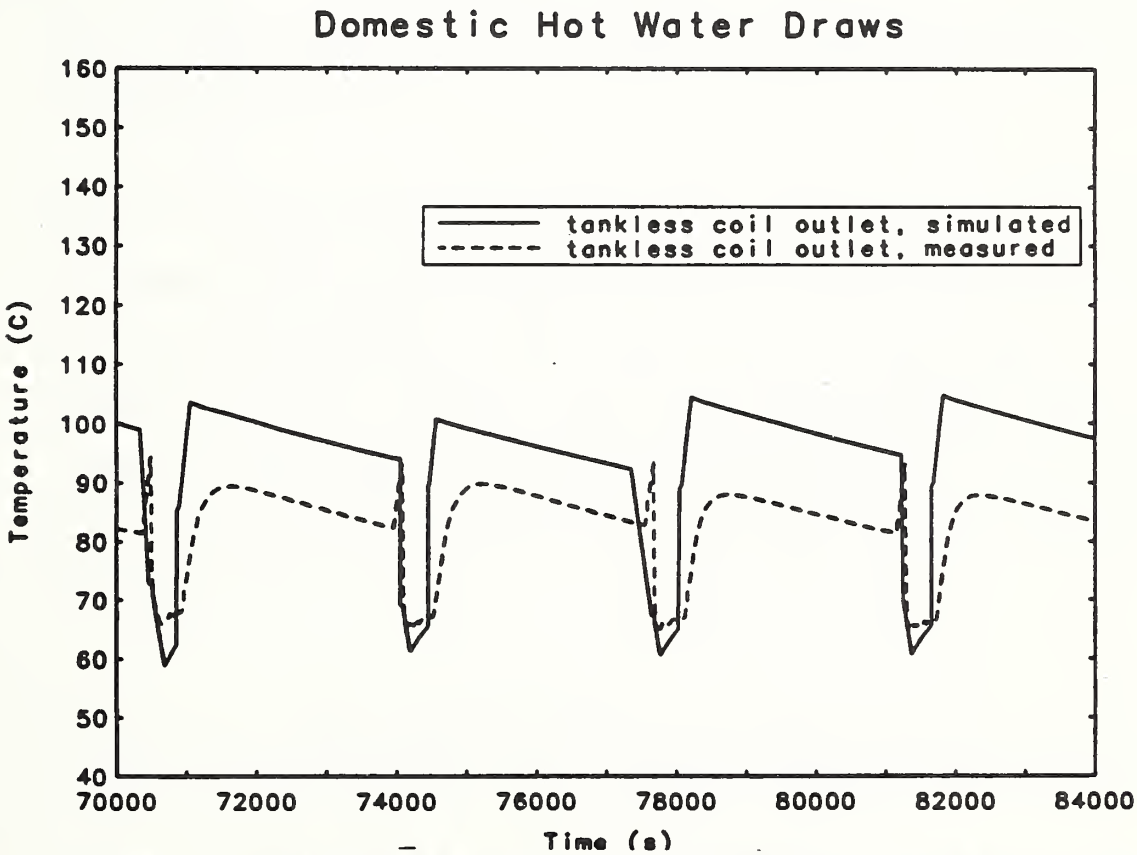

Figure 15 The tankless coil outlet temperatures during a part of the draw period

Table 1 24-hour Draw Test

EVENT	OIL (kg)	Qinp,exp (kJ)	Qinp,sim (kJ)	ELECTRIC (Wh)	Qele,exp (kJ)
Standby	1.455	65389	67310	78.1	281.2
Reheat	0.140	6292	6714	7.2	25.9
Draw 3	0.500	22471	22800	27.1	97.6
Draw 4	0.550	24718	22800	29.8	107.3
Draw 5	0.540	24268	22800	29.5	106.2
Draw 6	0.555	24942	22800	29.5	106.2
Draw 7	0.545	24493	22800	29.9	107.6
Draw 8	0.545	24493	22800	29.4	105.8
Total	4.83	217065	210824	260.5	937.8

Ratio of electricity to oil = 0.004320

temperature changes with respect to time during a part of the 18-hour standby period, while Figure 15 shows the tankless coil output temperatures during a part of the 6-hour draw period. The results of computer simulations and experiments agree reasonably well. Fuel input energy consumption was used as one of the key variable in the comparison of the laboratory measurements and the computer model simulation outputs. Table 1 shows fuel consumption figures.

4.2. Simulations of Summer Operating Mode

Using the verified computer model, simulations of summer operation were performed to determine input energy consumptions at various water loads and to evaluate the effect of boiler room temperature on the standby loss. Integration of power to obtain energy was achieved using a utility program, ENERGY. This program used a simple trapezoidal integration routine and is included in Appendix D.

Figure 16 shows the energy factor defined as the ratio of output energy to input energy without space heating, as a function of the domestic hot water load. The values appearing in this figure, however, were calculated without taking into account the electrical energy consumption. According to laboratory measurements, the electrical energy consumed by the oil burner represented approximately 0.43 % of the total energy input for a 24-hour test period (see Table 1).

Standby loss variation due to boiler room air temperature was also studied. A series of computer simulations were made with different room air temperatures.

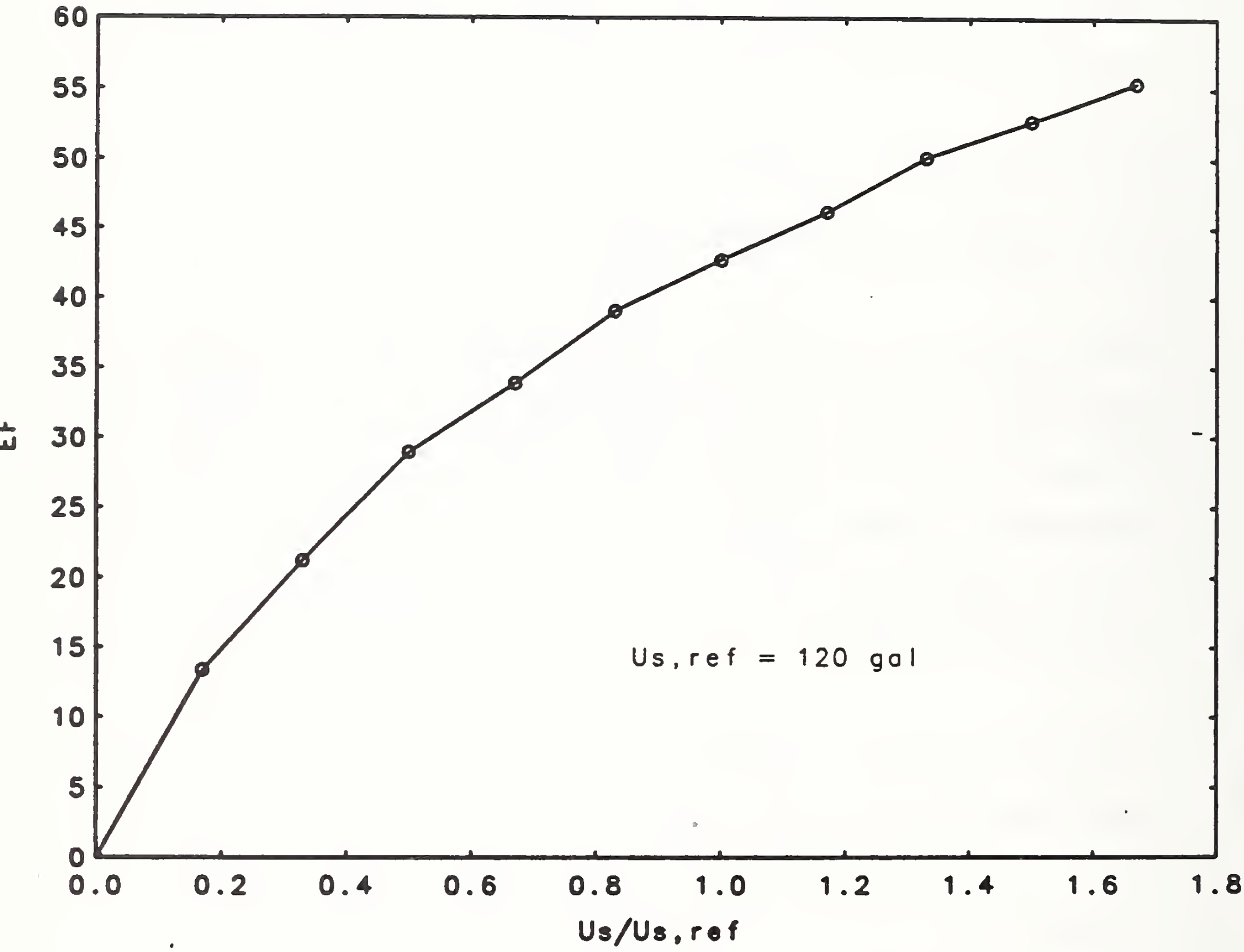

Figure 16 Energy factor for different domestic hot water use level. Note that typical average daily water use specified by DOE Test Procedure for water heaters is 64.3 gal/day.

The ratio, in percent, of the energy consumption for maintaining the boiler water temperature within the specified range during the standby period to the fuel input energy, $\dot{Q}_{input,sb}/Q_{input}$, is shown in Figure 17. The ratio is plotted against a dimensionless parameter that is the difference of room air temperature and boiler water temperature normalized by the boiler water temperature, $(T_{bw} - T_{ra})/T_{bw}$. Also Figure 18 shows the ratio, in percent, of jacket loss to input energy against the same dimensionless parameter. Figures 17 and 18 show that the room air temperature does affect boiler standby loss. Laboratory tests were attempted to confirm these simulation results, but no conclusion reached due to difficulty in maintaining the laboratory room air temperature constant for an 18-hour standby period.

4.3. Simulations of Winter Operating Mode

The effect of a combined space heating and domestic hot water heating load on boiler performance was also studied using computer simulations. Prior to the simulations, a typical thermostat cycle rate curve to meet space heating loads was selected from the report by Kao, Mastascusa, and Chi [18]. The circulating pump on- and off-periods were determined for various cycle rates using this curve. A boundary data file was generated, which incorporated the pump on/off periods used in the simulations.

The space load factor is given by:

$$x_{space} = \dot{Q}_{s,out} \;/\; (\eta_{ss}\,\dot{Q}_{input}), \tag{36}$$

where $\dot{Q}_{s,out}$ is the average delivered heat flow rate to the space during the simulation period.

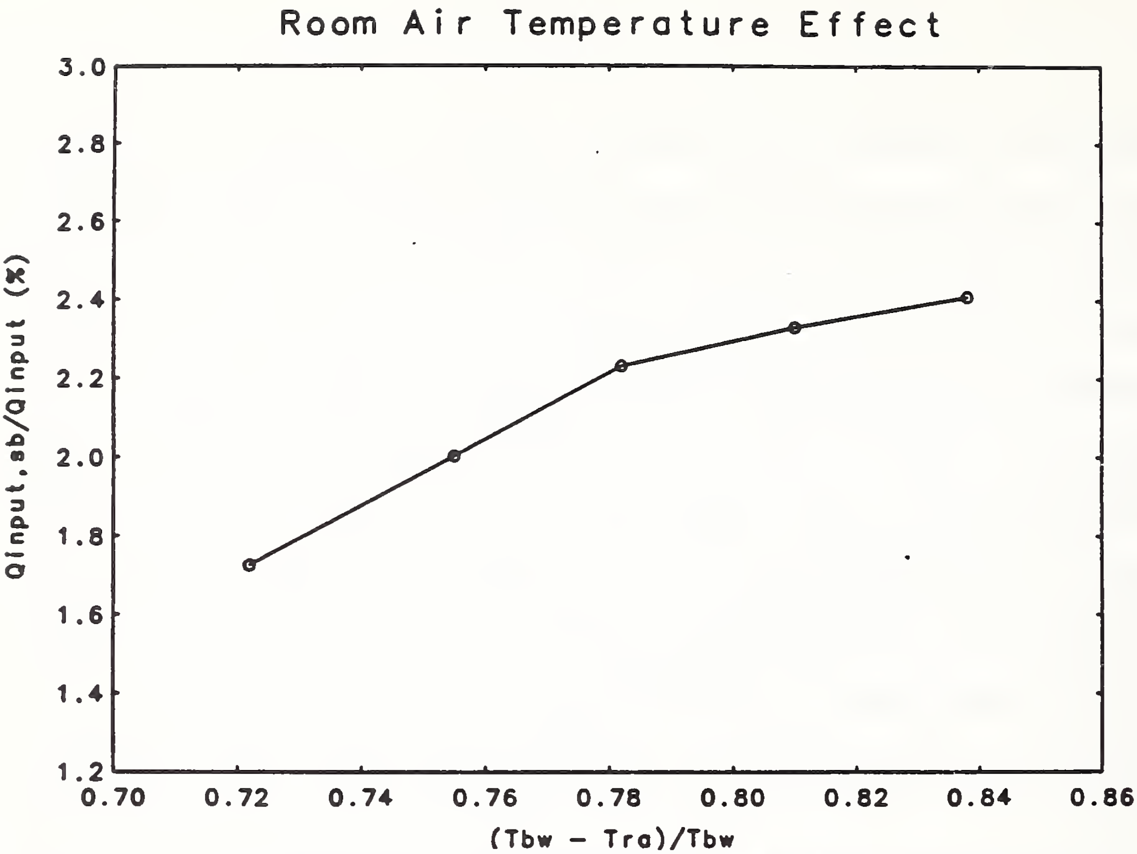

Figure 17 The energy consumption during the standby period showing the room temperature effect

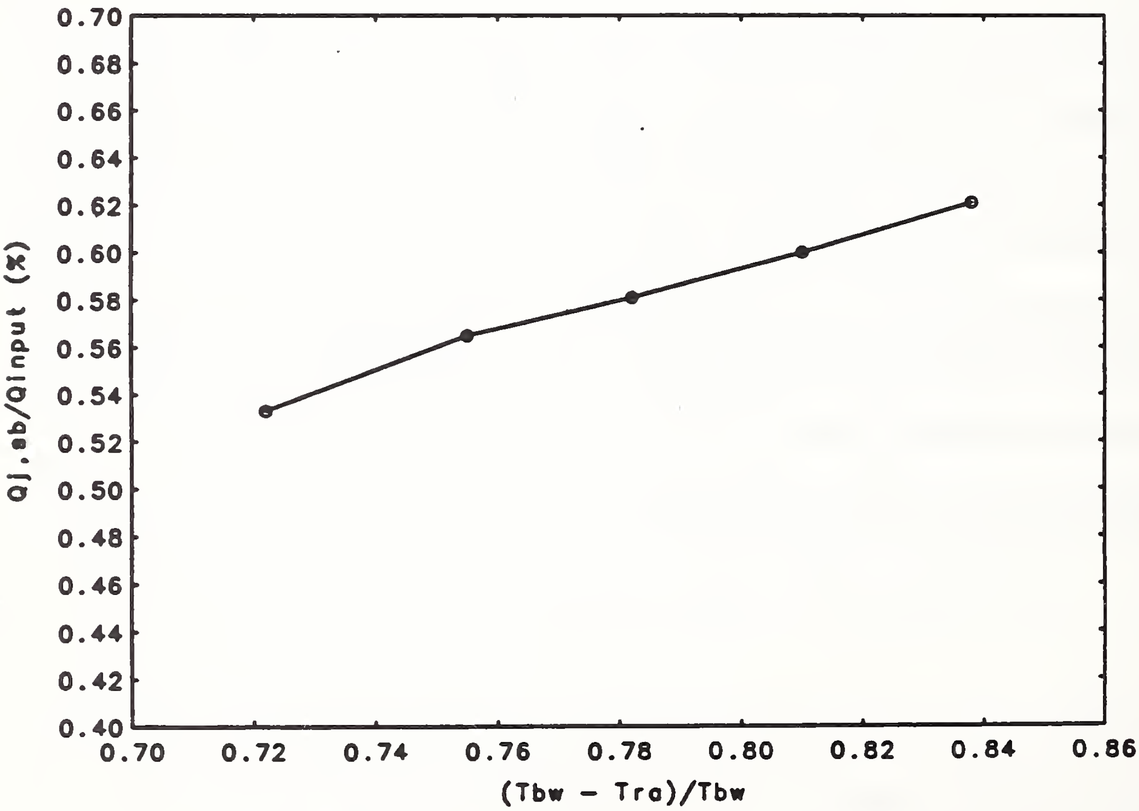

Figure 18 The jacket loss during the standby period showing the room temperature effect

Figure 19 represents a curve of fuel utilization efficiency, η_u, with respect to space load factor, x_{space}, for space heating only. This curve was created by smoothing raw simulation outputs of MODSIM by using the program SPLINE (see Appendix E).

With combined loads of space heating and water heating, computer simulations were carried out for 12 instead of 24 hours to save computational time. The first 6-hour period was for space heating only, while the second 6-hour period was for combined space and water heating. The energy outputs of the first period were then multiplied by a factor of three to obtain the energy values during the 18-hour period during which there is no water heating load. Since the room air temperature was assumed to be constant, this multiplication is justified. In addition, the boiler inlet water temperature (returning from the heated space) and the tankless coil inlet water temperature were modelled as remaining constants in the simulations.

The fuel utilization efficiency for combined loads is plotted against the space load factor in Figure 20. The amount of hot water drawn daily is shown as a parameter. At $x_{space} = 0$, the efficiency is the energy factor, EF. From this figure, we can see that the water load causes the efficiency to increase when the space load is low. This efficiency increase diminishes, however, as the space load increases.

5. A METHOD FOR DETERMINING THE COMBINED SEASONAL EFFICIENCY

On the basis of computer simulations and laboratory experiments, a simple method for determining the combined seasonal efficiency of Type I appliances

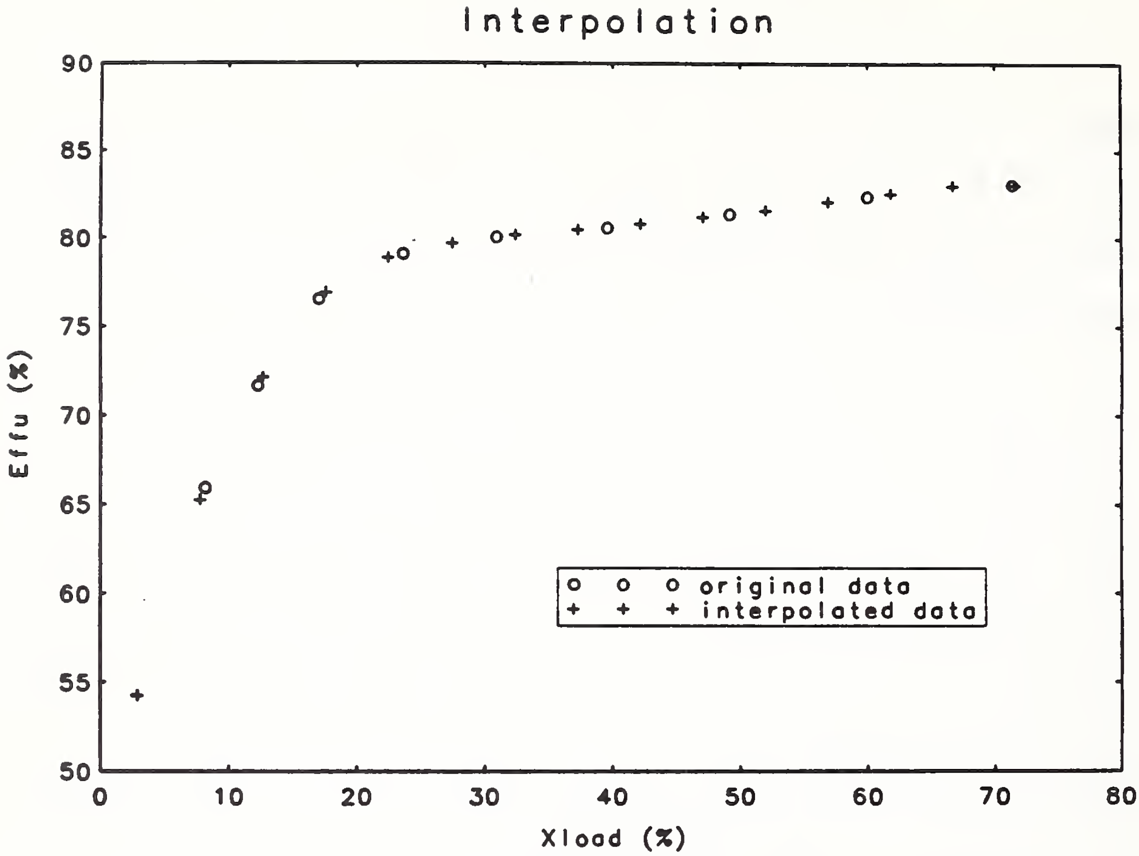

Figure 19 Fuel utilization efficiency with respect to the space load factor for space heating only

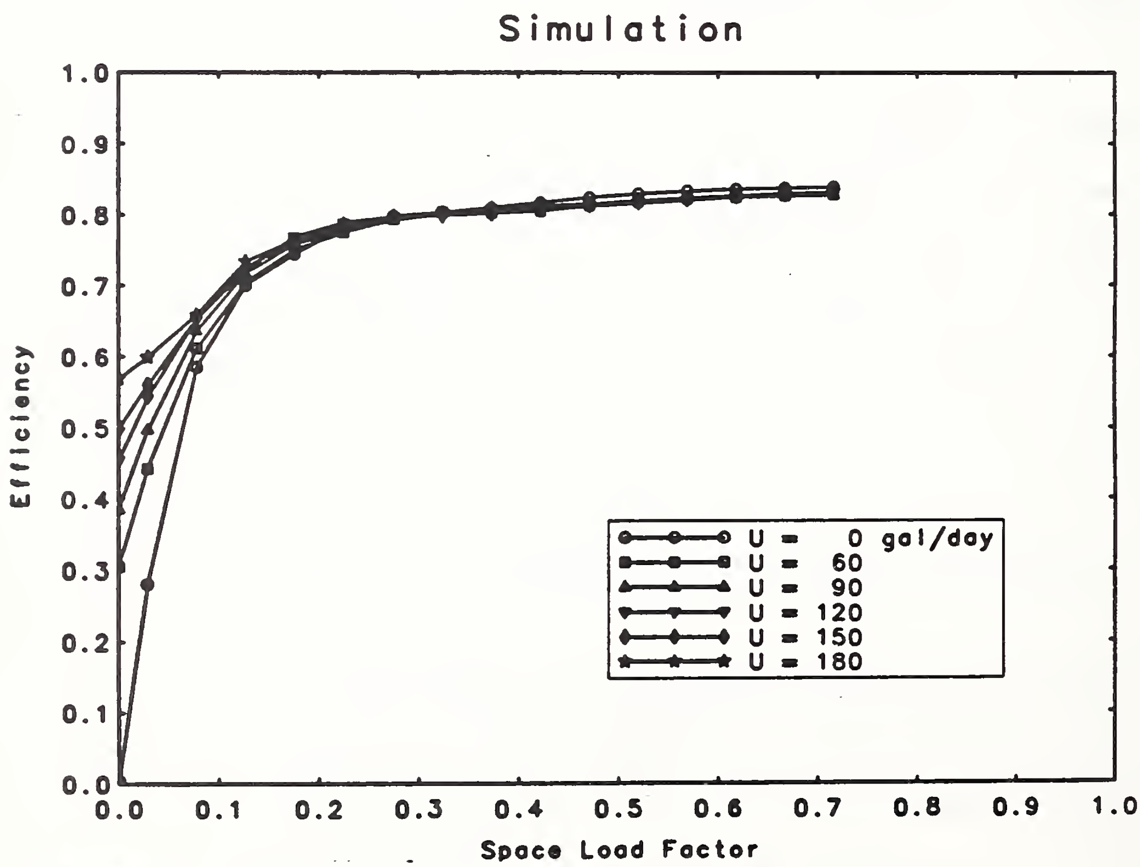

Figure 20 **Fuel utilization efficiency for combined loads**

is presented here. The primary design function of Type I appliances is space heating and the secondary function is domestic water heating.

Step 1: Generate a fuel utilization part-load efficiency curve as a function of space heating loads for zero domestic water load having the form:

$$\eta = (a\ x\ /\ (x + b)) + c, \tag{37}$$

and satisfying the following conditions:

$$\eta = 0.0 \quad \text{at } x = 0$$

$$\eta = \eta_{225} \quad \text{at } x = 0.225$$

$$\eta = \eta_{ss} \quad \text{at } x = 1.0.$$

In equation (37), x is the space load factor, η_{225} is the part-load efficiency at 22.5 % load obtained using ANSI/ASHRAE 103 Standard, η_{ss} is the steady-state efficiency, and a, b, and c are constants. For Type I appliances these constants can be calculated as follows:

$$a = (\eta_{ss} - c)\ (1 + b)$$

$$b = -0.225\ (\eta_{ss} - \eta_{225})\ /\ (0.225\ \eta_{ss} - \eta_{225} + 0.775)$$

$$c = 0$$

Figures 21 and 22 show efficiency curves resulting from the computer simulation and the equation (37) at 60 and 120 gallons of daily domestic hot water use, respectively.

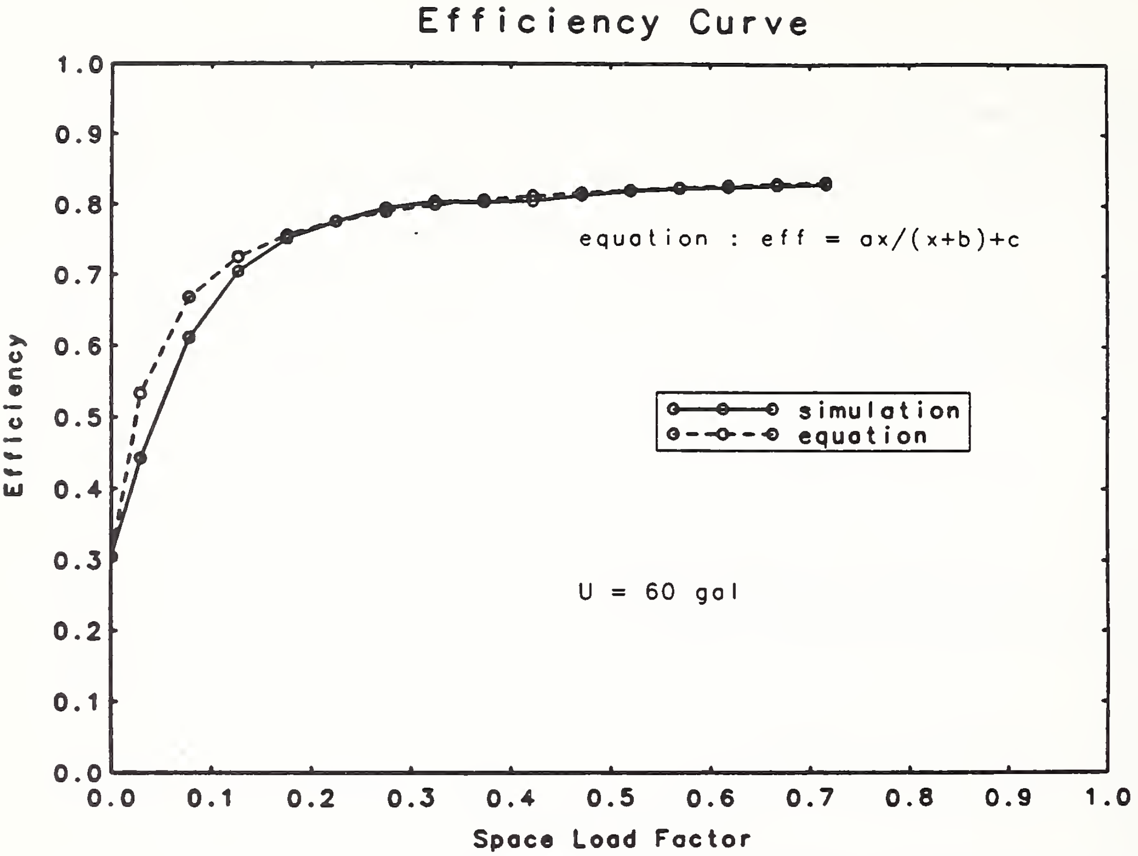

Figure 21 Efficiency curves from computer simulation and the equation at U = 60 gal

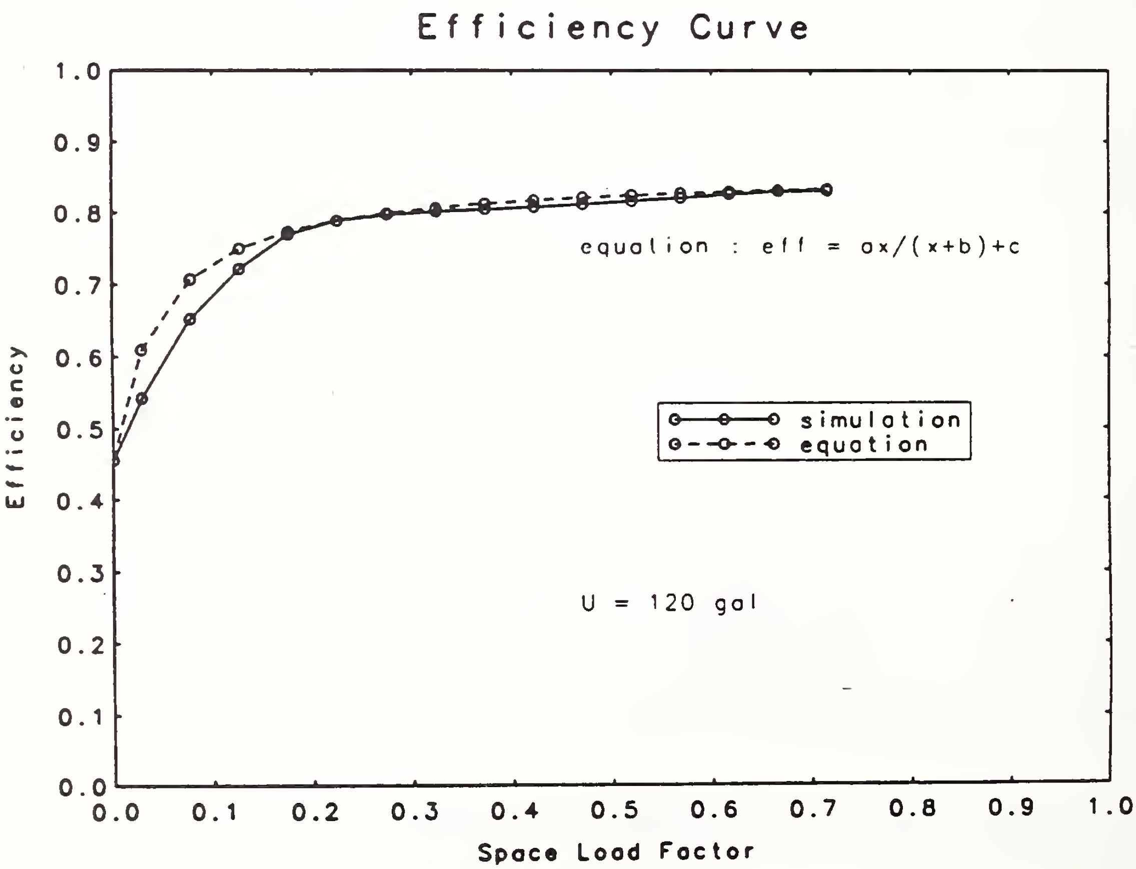

Figure 22 Efficiency curves from computer simulation and the equation at U = 120 gal

Step 2: Using the equation (37), find the efficiency, η_c^*, at the load $x=0.225 + x_{water}$, where the average domestic water load factor, x_{water}, is given by:

$$x_{water} = \dot{Q}_{w,out} / (\eta_{ss}\ \dot{Q}_{input}), \tag{38}$$

where $\dot{Q}_{w,out}$ is the average heat flow rate for domestic water heating.

Step 3: Use the same form of equation (37) to generate a curve of the form:

$$\eta' = (a'x / (x + b')) + c', \tag{39}$$

which satisfies three conditions:

$\eta' = EF$ at $x = 0$

$\eta' = \eta_c^*$ at $x = 0.225$

$\eta' = \eta_{ss}$ at $x = 1.0$

This curve represents the combined efficiency of the boiler as function of space heating load for a daily water usage corresponding to a domestic water load factor of x_{water}.

Step 4: It is needed to bin on equation (37) to find a correction factor that relates the trimmed result to the value $\eta 22.5$ found by the ASHRAE 103 test procedure. Using the hourly bin data given in the report by Parken, Kelly, and Didion [19], apply the bin method on the curve represented by equation (39) to find a combined heating seasonal efficiency for the appliance.

Figure 23 illustrates Step 1 through Step 3, and Table 2 shows the output of a spreadsheet program for the boiler with a tankless coil when the daily usage of hot water is 120 gal.

6. CONCLUSION

A residential, fossil fuel-fired, hot water boiler model with a tankless domestic water heating coil was developed based upon laboratory tests, and used with the HVACSIM$^+$ program. The computer model was verified with some of the experimental data and used to evaluate the boiler performance through simulations.

Laboratory tests were performed mainly to obtain parameter values used in the computer model verification. The computer model can also be used to simulate other residential boilers with/without domestic water heating coils.

A method utilizing a curve-fitted equation and the bin method is proposed to determine the combined efficiency of a Type I integrated appliance of which primary function is space heating. No comparison was, however, made between this procedure and draft ASHRAE 124P Standard [1]. Thus, there is a need for additional research on combined space and domestic water heating appliances, especially Type II appliances whose primary functions are domestic water heating.

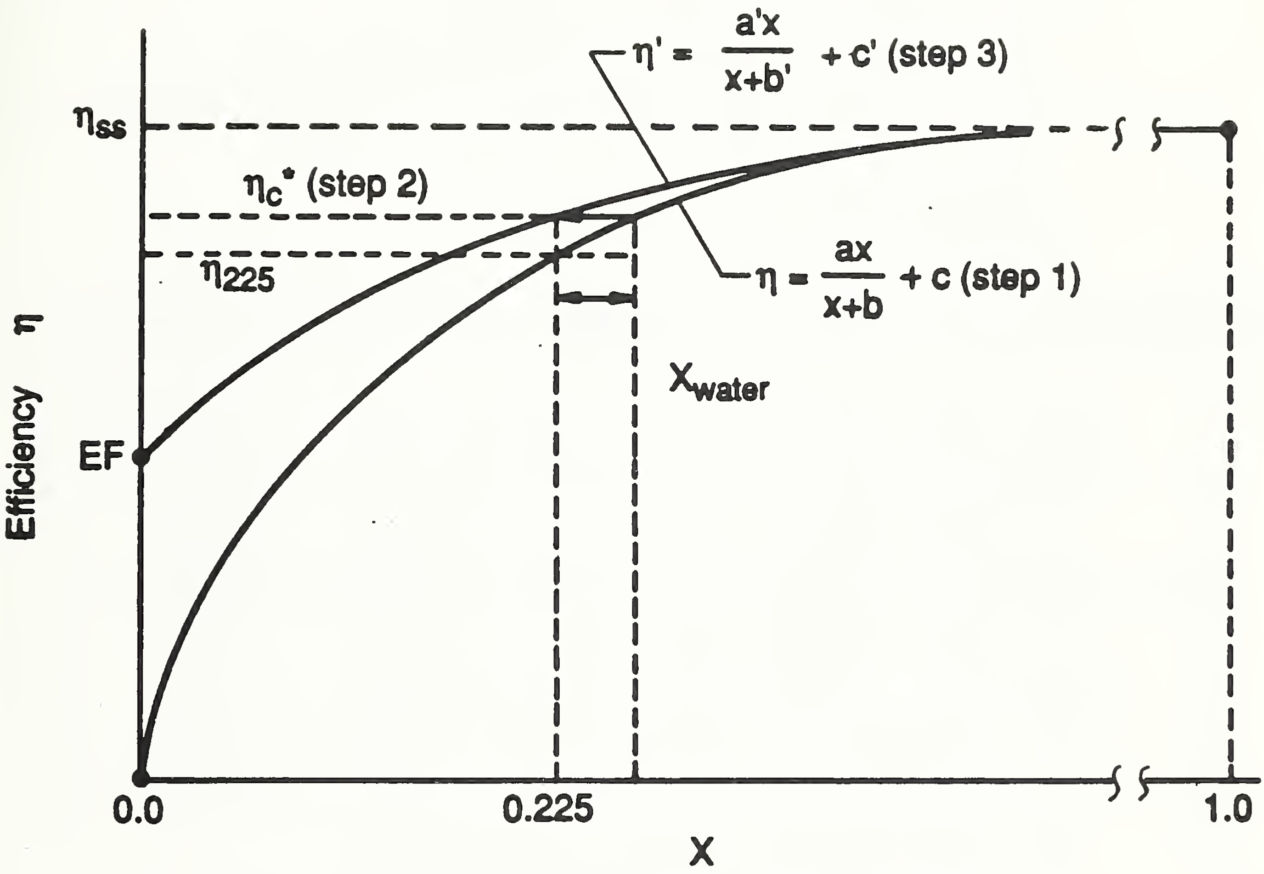

Figure 23 Illustration of Steps 1 through 3 of the NIST's recommended procedure

Table 2 Bin Data Analysis

BIN DATA ANALYSIS

Region IV
Design outdoor temperature = 5 °F
Oversizing factor = 0.7
Daily domestic hot water use = 120 gal
Tj : Bin temperature
Nj : Fractional hours
Xspace : Space heating load factor
Xwater : Domestic water heating load factor
Xload : Combined load factor (= Xspace + Xwater)
Effu : Part-load efficiency
Bin on Xspace
Effu computed by EFFSPWT program

Bin #	Tj (F)	Nj	Xspace	Xload	Nj*Xload	Nj*Xload/Effu	Xwater	Effu
			0	0			0.0231	0.4550
1	62	0.132	0.0294	0.0525	0.0039	0.0064	0.0231	0.6085
2	57	0.111	0.0784	0.1015	0.0087	0.0123	0.0231	0.7055
3	52	0.103	0.1275	0.1506	0.0131	0.0175	0.0231	0.7483
4	47	0.093	0.1765	0.1996	0.0164	0.0213	0.0231	0.7723
5	42	0.100	0.2255	0.2486	0.0225	0.0286	0.0231	0.7878
6	37	0.109	0.2745	0.2976	0.0299	0.0375	0.0231	0.7985
7	32	0.126	0.3235	0.3466	0.0408	0.0506	0.0231	0.8064
8	27	0.087	0.3725	0.3956	0.0324	0.0399	0.0231	0.8125
9	22	0.055	0.4216	0.4447	0.0232	0.0284	0.0231	0.8173
10	17	0.036	0.4706	0.4937	0.0169	0.0206	0.0231	0.8212
11	12	0.026	0.5196	0.5427	0.0135	0.0164	0.0231	0.8244
12	7	0.013	0.5686	0.5917	0.0074	0.0089	0.0231	0.8271
13	2	0.006	0.6176	0.6407	0.0037	0.0045	0.0231	0.8294
14	-3	0.002	0.6667	0.6898	0.0013	0.0016	0.0231	0.8314
15	-8	0.001	0.7157	0.7388	0.0007	0.0009	0.0231	0.8331
SUM					0.234558	0.295306		

Seasonal Efficiency = 0.794289

7. REFERENCES

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C**********************************************************************
C
      SUBROUTINE TYPE62(XIN,OUT,PAR,SAVED,IOSTAT)
C
C----------------------------------------------------------------------
C
C     TYPE 62: HOT WATER BOILER WITH A DOMESTIC HOT WATER HEATING COIL
C
C     January 21, 1988      Cheol Park
C     Revised:     June 22, 1988
C
C     INPUTS:
C       TSTK    Stack gas temperature (C)
C       TRA     Room air temperature (C)
C       TOA     Outdoor air temperature (C)
C       TBLW    Boiler water temperature (C)
C       PSW     Supply boiler water pressure (kPa)
C       WSW     Supply boiler water flowrate (kg/s)
C       TRW     Return boiler water temperature (C)
C       QCW     Heat flow rate to the tankless coil (kW)
C       SWCH    Switch for controlling on/off
C               1 for burner on and 0 for burner off
C
C     OUTPUTS:
C       TSTK    Stack gas temperature (C)      --- Diff. eq.
C       TBLW    Boiler water temperature (C)   --- Diff. eq.
C       TSW     Supply water temperature (C)
C       QHWT    Heat flow to water (kW)
C       QSTK    Heat loss from the stack (kW)
C       QINPUT  Input heat flow (kW)
C       QLTNT   Latent heat loss (kW)
C       QJAKT   Heat loss from the boiler jacket (kW)
C       QSS     Heat flow to boiler water (kW)
C
C     PARAMETERS:
C
C       VGF     Volume of gas in the boiler fire-box (m3)
C       ASF     Boiler fire-box effective radiation heat transfer area (m2)
C       ARF     Boiler fire-box refractory surface area (m2)
C       LGPF    Gas-path length in the fire-box (m)
C       EMISF   Fire-box surface emissivity in fraction
C       VWB     Volume of water in the boiler (m3)
C       AJAKT   Boiler jacket surface area (m2)
C       UJAKT   Boiler jacket U-factor (kW/m2-C)
C       CARB    Atomic ratio of carbon in fuel
C       HYDR    Atomic ratio of hydrogen in fuel
C       OXYG    Atomic ratio of oxygen in fuel
C       XNTR    Atomic ratio of nitrogen in fuel
C       SULF    Atomic ratio of sulfur in fuel
C       HFUEL   Fuel higher heating value (kJ/kg)
C       CPFUEL  Fuel specific heat value (kJ/kg-C)
C       WFUEL   Fuel supply rate (kg/s)
C       TFUEL   Fuel temperature (C)
C       XAIR    Excess air for combustion (-)
C       EFFYSS  Steady-state boiler efficiency in fraction (-)
C       TBLWS   Boiler water temperature at steady state (C)
C       TSGS    Stack gas temperature at full load (C)
C       ICFGON  Integration control factor for on-period stack gas temp.
C       ICFGOF  Integration control factor for off-period stack gas temp.
C       ICFW    Integration control factor for water temperature
C       DTFG    Short start period for burner on/off cycle (s)
C       ICFGNS  Integration control for short start on-period
C       ICFGFS  Integration control for short start off-period
C       DTBW    Minimum time interval for updating QSS (s)
C
C**********************************************************************
C
      PARAMETER (NSAVED=5,NDE=2,NIN=9,NOUT=9,NPAR=28)
C
      LOGICAL   COMINT
      REAL      LGPF,ICFGON,ICFGOF,ICFW,ICFGNS,ICFGFS
      DIMENSION XIN(NIN),OUT(NOUT),PAR(NPAR),IOSTAT(NOUT),SAVED(NSAVED)
      COMMON    /CHRONO/ TIME,TSTEP,TTIME,TMIN,ITIME
```

```
      COMMON    /PRODCT/ PT,PCO2,PH2O,PN2,PO2,PSO2,RATF,RWTF,RPTF
      COMMON    /CONFIG/ VGF,ASF,ARF,LGPF,EMISF,VWB,AJAKT,UJAKT
      COMMON    /FUEL/   HFUEL,CPFUEL,WFUEL,TFUEL
      COMMON    /FULLD/  CNTU,TSGS,QINP,TAUG,TAUW

      DATA      COMINT/.TRUE./
      DATA      WTFAC /0.8/,TBLREF/97.5/
C*      DATA      WTFAC /0.8/,TRAREF/23.0/,TBLREF/97.5/

C*      NAMELIST  /NAM1/ QINP
C*      NAMELIST  /NAM2/ TIME,SWCH,QSS,TSTK,TBLW,QF,QHXC,
C*     &                   DTSTK,DTBLW,TEXGF,WGOFF,WTTL
C*      NAMELIST  /NAM3/ TIME,IONOFF,TIME0,DELT,ICFGON,ICFGOF
C*      NAMELIST  /NAM4/ TIME,TIME1,DELTB,QSS,QSS1
C*      NAMELIST  /NAM5/ TIME,TBLW,TSTK,QCW
C*      NAMELIST  /NAM6/ TIME,QINPUT,QLTNT,QSTK,QJAKT,QHWT,QSS

C
C     Inputs:
C
      TSTK    =XIN(1)
      TRA     =XIN(2)
      TOA     =XIN(3)
      TBLW    =XIN(4)
      PSW     =XIN(5)
      WSW     =XIN(6)
      TRW     =XIN(7)
      QCW     =XIN(8)
      SWCH    =XIN(9)
C
C     Parameters:
C
      VGF     =PAR(1)
      ASF     =PAR(2)
      ARF     =PAR(3)
      LGPF    =PAR(4)
      EMISF   =PAR(5)
      VWB     =PAR(6)
      AJAKT   =PAR(7)
      UJAKT   =PAR(8)
      CARB    =PAR(9)
      HYDR    =PAR(10)
      OXYG    =PAR(11)
      XNTR    =PAR(12)
      SULF    =PAR(13)
      HFUEL   =PAR(14)
      CPFUEL  =PAR(15)
      WFUEL   =PAR(16)
      TFUEL   =PAR(17)
      XAIR    =PAR(18)
      EFFYSS  =PAR(19)
      TBLWS   =PAR(20)
      TSGS    =PAR(21)
      ICFGON  =PAR(22)
      ICFGOF  =PAR(23)
      ICFW    =PAR(24)

      DTFG    =PAR(25)
      ICFGNS  =PAR(26)
      ICFGFS  =PAR(27)

      DTBW    =PAR(28)

C     Assume that the boiler supply water temperature is the same
C     as the boiler water temperature, i.e. TSW=TBLW.
C
      TSW=TBLW
C
C     Initial conditions at steady state.   Input data at
C     beginning of simulation  must be entered using a steady-state
C     values.
C
      IF(ITIME.EQ.1 .AND. COMINT) THEN
```

```
          PT=1.
          TSTK=TSGS
          TBLW=TBLWS
          TSWS=TBLWS
          CALL  BLINIT(CARB,HYDR,OXYG,XNTR,SULF,XAIR,
     &      TRA,TBLWS,TSWS,EFFYSS,WGON)
          COMINT=.FALSE.
          SAVED(1)=TIME
          SAVED(2)=WGON
          SAVED(3)=0.0
          SAVED(4)=1
C*          PRINT NAM1
        ELSE
          WGON=SAVED(2)
        ENDIF
C
C       Burner off
C
        IF(TIME .GT. SAVED(1)) THEN

        IF(SWCH.LE.0.5) THEN
          CALL BLFOFF(TSTK,TRA,TBLW,WGON,WGOFF,QFC,TEXGF)
          CALL BLHX(TSW,TEXGF,TSTK,WGOFF,QHXC)
          CALL CPCVA(TRA,CPA,DUMMY,DUMMY,DUMMY)
          QF=QFC
          IONOFF=0
          CAPG=WGOFF*CPA
C
C       Burner on
C
        ELSE
          CALL BLFON(TRA,TBLW,WGON,QFCR,TAFC,TEXGF)
          CALL BLHX(TSW,TEXGF,TSTK,WGON,QHXC)
          QF=QFCR
          IONOFF=1
          CAPG=WGON*CPF(TRA,TSTK)
        ENDIF

        ENDIF
C
C       Heat fluxes
C
        CAPW=WSW*WCP(TBLW)

        QINPUT=WFUEL*HFUEL*IONOFF
        QLTNT=2442.*WFUEL*RWTF*IONOFF
        QJAKT=AJAKT*UJAKT*(TBLW-TRA)
        QHWT=CAPW*(TSW-TRW)+QCW
        QSTK=QINPUT-QLTNT-QF-QHXC
        QSS=QF+QHXC-QJAKT-QCW
        QSS1=SAVED(3)


C       Setting up a short time interval of rapid change of gas
C       temperature  and  using different integration constants

        IF(TIME .GT. SAVED(1)) THEN
          IBURN=SAVED(4)+0.001
          IF(IONOFF .NE. IBURN) THEN
            TIME0 = TIME
          ELSE
            DELT = TIME-TIME0
          ENDIF
          SAVED(4) = IONOFF
        ENDIF

        IF(DELT .LT. DTFG) THEN
          ICFGON = ICFGNS
          ICFGOF = ICFGFS
        ENDIF

C       Introducing time-delay to the boiler water temperature,
C       QSS is updated every time-interval of DELTB, if DELTB is
```

```
C     greater than or equal to the specified minimum value of DTBW.
C     At the same time, the reference time,TIME1,
C     is also changed.  It is assumed that QSS holds a steady value
C     in the time-interval.

C     NOTE that DELTB depends upon the specified maximum time step,
C     TMAX.  Due to this fact, the use of different TMAX's could result
C     in different simulation results.

      IF(ITIME .EQ. 1) THEN
        TIME1=TIME
        SAVED(5`=TIME1
      ENDIF

      IF(TIME .GT. SAVED(1)) THEN
        TIME1=SAVED(5)
        DELTB = TIME-TIME1
        IF(DELTB .GE. DTBW) THEN
          SAVED(3)=QSS
          TIME1=TIME
          SAVED(5)=TIME1
        ENDIF
      ENDIF

C
C     Derivatives  of stack gas and boiler water temperatures
C
      IF(IONOFF .EQ. 1) THEN
        DTSTK=(TSGS-TSTK)/(ICFGON*TAUG)
      ELSEIF(IONOFF .EQ. 0) THEN
        TINF=WTFAC*TBLREF+(1.-WTFAC)*TRA
        DTSTK=(TINF-TSTK)/(ICFGOF*TAUG)
      ENDIF

      DTBLW=(CAPW*(TRW-TSW)+QSS1)/(ICFW*TAUW)
C
C     Outputs
C
      OUT(1)  =DTSTK
      OUT(2)  =DTBLW
      OUT(3)  =TSW
      OUT(4)  =QHWT
      OUT(5)  =QSTK
      OUT(6)  =QINPUT
      OUT(7)  =QLTNT
      OUT(8)  =QJAKT
      OUT(9)  =QSS

      IF(TIME. GT. SAVED(1)) THEN
C*        PRINT NAM2
C*        PRINT NAM3
C*        PRINT NAM4
C*        PRINT NAM5
C*        PRINT NAM6
      ENDIF
      SAVED(1)=TIME
C
      IOSTAT(1)=0
      IOSTAT(2)=0
      IOSTAT(3)=0
      IOSTAT(4)=1
      IOSTAT(5)=1
      IOSTAT(6)=1
      IOSTAT(7)=1
      IOSTAT(8)=1
      IOSTAT(9)=1
C
      RETURN
      END
C
C*************************************************************************
C
      SUBROUTINE BLINIT(CARB,HYDR,OXYG,XNTR,SULF,XAIR,
```

```
     &  TRA,TBLW,TSW,EFFYSS,WGON)
C
C ------------------------------------------------------------------------
C
C       CNTU     Modified boiler HX heat transfer number at full load
C       TAUG     Modified boiler stack gas time constant
C       TAUW     Modified boiler water time constant
C
C************************************************************************
C
      REAL      LGPF
      COMMON    /PRODCT/ PT,PCO2,PH2O,PN2,PO2,PSO2,RATF,RWTF,RPTF
      COMMON    /CONFIG/ VGF,ASF,ARF,LGPF,EMISF,VWB,AJAKT,UJAKT
      COMMON    /FUEL/   HFUEL,CPFUEL,WFUEL,TFUEL
      COMMON    /FULLD/  CNTU,TSGS,QINP,TAUG,TAUW
C*      NAMELIST  /NAMINI/ WGON,QFCR,TAFC,TEXGF,QJAKT,QFNS,TAUG,TAUW
C
C     Combustion gas properties
C
      CALL PRDPP(CARB,HYDR,OXYG,XNTR,SULF,XAIR)
C
C     Estimate the gas path lenth in the boiler fire-box by matching
C     the calculated and the measured gas temperatures at the exit of
C     the fire-box.
C
      CALL BLFON(TRA,TBLW,WGON,QFCR,TAFC,TEXGF)
C
C     Steady-state condition
C
      QJAKT=AJAKT*UJAKT*(TBLW-TRA)
      TINHX=TEXGF
      QFNS=QFCR-QJAKT
      CALL BLFLD(WGON,QFNS,TINHX,EFFYSS,TSW)
C
C     Time constants of gas and water
C
      IF(TAUG.LT.1.E-10) THEN
        T1G=(TFUEL+RATF*TRA)/RPTF
C*        T1G=(CPFUEL*TFUEL+RATF*TRA)/RPTF
        T2G=TSGS
        CPG=CPF(T1G,T2G)
        CAPG=CPG*WGON
        TAUG=1.0/CAPG
      ENDIF
      IF(TAUW.LE.1.E-10) THEN
        TAUW=4200.*VWB
      ENDIF
C*      PRINT NAMINI
C
      RETURN
      END
C
C************************************************************************
C
      SUBROUTINE BLFLD(WGON,QFNS,TINHX,EFFYSS,TSW)
C
C------------------------------------------------------------------------
C
C     Boiler heat exchanger performance at full load.  Calculation
C     of the number of heat transfer unit.
C
C************************************************************************
C
      REAL      K,MU,NTU
      COMMON    /FULLD/  CNTU,TSGS,QINP,TAUG,TAUW
C*      NAMELIST  /NAMFLD/ QHXSS,NTU,CNTU
C
C     The specific heat of gas passing through the heat
C     exchanger by using the measured stack gas temperature at
C     a steady state.
C
      CP=CPF(TINHX,TSGS)
C
```

```
C      The number of transfer units at full load
C
       QHXSS=EFFYSS*QINP-QFNS
       ENTU=1.-QHXSS/(CP*WGON*(TINHX-TSW))
       IF(ENTU.GT.1.E-20) THEN
         NTU=LOG(1./ENTU)
       ELSE
         NTU=50.
         CP=CPF(TINHX,TSW)
         TAVE=0.5*(TINHX+TSW)
         PRINT *,' —— TOO LARGE EFFICIENCY VALUE ——'
       ENDIF
       CALL PRDPR(TAVE,MU,K)
       CNTU=NTU*WGON**0.2*MU**0.4*(CP/K)**0.6
C*       PRINT NAMFLD
C
       RETURN
       END
C
C*************************************************************************
C
       SUBROUTINE BLHX(TSW,TINHX,TEXHX,WG,QHXC)
C
C-------------------------------------------------------------------------
C
C       Boiler heat-exchanger part load performance
C
C*************************************************************************
C
       REAL       K,MU,NTU
       COMMON     /FULLD/  CNTU,TSGS,QINP,TAUG,TAUW
C
C      The number of transfer unit for boiler heat exchanger
C      at part load condition.
C
       TAVE=0.5*(TINHX+TEXHX)
       IF(ABS(TINHX-TEXHX) .GT. 0.001) THEN
         CP=CPF(TINHX,TEXHX)
       ELSE
         CALL CPCVA(TAVE,CPA,DUMMY,DUMMY,DUMMY)
       ENDIF
C
       CALL PRDPR(TAVE,MU,K)
C
C      Convective heat transfer rate
C
       IF(WG.GT. 1.0E-6) THEN
         NTU=CNTU/(WG**0.2*MU**0.4*(CP/K)**0.6)
         QHXC=CP*WG*(TINHX-TSW)*(1.-EXP(-NTU))
       ELSE
         QHXC=CP*WG*(TINHX-TSW)
       ENDIF
C
       RETURN
       END
C
C*************************************************************************
C
        SUBROUTINE BLFON(TRA,TBLW,WGON,QFCR,TAFC,TEXGF)
C
C-------------------------------------------------------------------------
C
C      Simulation of boiler fire-box performance during on-period
C
C        PT      Gas pressure (atm)
C        PCO2    Number of moles of CO2
C        PH2O    Number of moles of H2O
C        PSO2    Number of moles of SO2
C        PO2     Number of moles of O2
C        PN2     Number of moles of N2
C        RATF    Mass ratio of air to fuel
C        RWTF    Mass ratio of water to fuel
```

```
C        RPTF    Mass ratio of combustion product to fuel
C        TS      Fire-box surface temperature (C)
C        QFCR    Fire-box heat transfer rate (kW)
C        TAFC    Adiabatic flame temperature (C)
C        TEXGF   Fire-box exit gas temperature (C)
C
C*************************************************************************
C
      REAL       K,MU,LGPF
      COMMON     /PRODCT/ PT,PCO2,PH2O,PN2,PO2,PSO2,RATF,RWTF,RPTF
      COMMON     /CONFIG/ VGF,ASF,ARF,LGPF,EMISF,VWB,AJAKT,UJAKT
      COMMON     /FUEL/   HFUEL,CPFUEL,WFUEL,TFUEL
      COMMON     /FULLD/  CNTU,TSGS,QINP,TAUG,TAUW
      DATA       SIGMA/5.670E-11/, CKELVN/273.15/, PI/3.14159/

C
C     Fuel input
C
      HHV=HFUEL+CPFUEL*(TFUEL-TRA)
      QINP=WFUEL*HHV
C
C     Set the fire-box surface tmperature to be the same as the boiler
C     water temperature.
C
      TS=TBLW
C
C     Convert temperature unit into absolute unit
C
      TKS=TS+CKELVN
      TKA=TRA+CKELVN
C
C     The gas and water vapor flow rates during on-cycle
C
      WGON=WFUEL*RPTF
      WH2O=WFUEL*RWTF
C
      HF=WFUEL*HHV-2442.*WH2O
      ATOTAL=ASF+ARF
      CS=ASF/ATOTAL
      AL=3.5*VGF/ATOTAL
C
C     Adiabatic flame temperature
C
      TAFC=TAFF(HHV,TRA)
      TAF=TAFC+CKELVN
C
C     The heat transfer rate due to radiation and
C     convection using the well-stirred furnace theory
C
      TG2=TAF-250
      ITR=0
10    ITR=ITR+1
      TG2C=TG2-CKELVN
      TGAVE=0.5*(TAF+TG2)
      CPOE=CPF(TRA,TG2C)
      CPAE=CPF(TG2C,TAFC)
      CPOA=CPF(TRA,TAFC)
      TT=TGAVE-CKELVN
      CALL PRDPR(TT,MU,K)
      PR=MU*CPAE/K
      AC=VGF/LGPF
      DH=SQRT(4.0*AC/PI)
      RE=WGON*DH/(MU*AC)
      HCOV=HCOVF(RE,PR,K,DH)
      GE=GEF(PCO2,PH2O,AL,TT)
      AGS=GS(ATOTAL,CS,GE,EMISF)
      TRATIO=TKS/TGAVE
      AGS=AGS*(1.-TRATIO**3)/(1.-TRATIO**4)
      AGS=AGS+2.*ASF*HCOV/(SIGMA*(TGAVE+TKS)**3)
      QFCR=AGS*SIGMA*(TGAVE**4-TKS**4)
C
C     A new estimate of gas temperature by using Newton's method
C
```

```
      CAPWOE=CPOE*WGON
      CAPWOA=CPOA*WGON
      CCOAT=CAPWOA*(TAF-TKA)*(HF-QFCR)
      CCOE=CAPWOE*HF
      TGCAL=CCOAT/CCOE+TKA
      DTG2=TGCAL-TG2
      IF(ABS(DTG2).GT.10.) THEN
        IF(ITR.GT.1) THEN
          TG=TG1-DTG1*(TG2-TG1)/(DTG2-DTG1)
          IF(ABS(DTG1).GT.ABS(DTG2)) THEN
            DTG1=DTG2
            TG1=TG2
          ENDIF
          TG2=TG
        ELSE
          DTG1=DTG2
          TG1=TG2
          TG2=TG2+100.
          IF(DTG1.LT.0.) THEN
            TG2=TG2-200.
          ENDIF
        ENDIF
        GOTO 10
      ENDIF
C
C     Gas temperature at boiler fire-box during on-period
C
      TEXGF=TG2-CKELVN
C
      RETURN
      END
C
C*********************************************************************
C
      SUBROUTINE BLFOFF(TSTK,TRA,TBLW,WGON,WGOFF,QFC,TEXGF)
C
C---------------------------------------------------------------------
C
C     Boiler fire-box performance during off-period
C
C*********************************************************************
C
      REAL      K,MU,NTU,LGPF
      COMMON    /CONFIG/ VGF,ASF,ARF,LGPF,EMISF,VWB,AJAKT,UJAKT
      COMMON    /FULLD/  CNTU,TSGS,QINP,TAUG,TAUW
      DATA      CKELVN/273.15/, PI/3.14159/
C
C     Mass flow rate of air during off-period
C
      IF(TSTK-TRA .GT. 0.01) THEN
C*      IF(ABS(TSTK-TRA) .GT. 0.01) THEN
        WGOFF=WGON*((TSTK-TRA)/(TSGS-TRA))**0.56
     &         *((TSGS+CKELVN)/(TSTK+CKELVN))**1.19
C*        DS=0.4
C*        WGOFF=DS*WGOFF
      ELSE
        WGOFF=0.0
      ENDIF
C
C     The properties of gas in the boiler fire-box:
C     The dynamic viscosity, thermal conductivity, specific heat
C     capacity, Prantl number, and Reynolds number based on the
C     hydraulic diameter.
C
      TAVE=0.5*(TRA+TEXGF)
      CALL PRDPR(TAVE,MU,K)
      CALL CPCVA(TEXGF,CPA,DUMMY,DUMMY,DUMMY)
      PR=MU*CPA/K
      AC=VGF/LGPF
      DH=SQRT(4.0*AC/PI)
      RE=WGOFF*DH/(MU*AC)
C
C     The convective heat transfer coefficient.
```

```
C
      HCOV=HCOVF(RE,PR,K,DH)
C
C     The off-cycle heat transfer rate using the
C     effectiveness method of a heat exchanger.
C     The gas temperature at the exit of the boiler fire-box.
C
      CAPA=CPA*WGOFF
      IF(WGOFF .GT. 0.001) THEN
        NTU=ASF*HCOV/CAPA
        QFC=CAPA*(TRA-TBLW)*(1.-EXP(-NTU))
        TEXGF=TRA-QFC*(1./CAPA)
      ELSE
        QFC=0.0
        TEXGF=(TRA+TBLW)/2.
      ENDIF
C
      RETURN
      END
C
C*********************************************************************
C
        SUBROUTINE TYPE63(XIN,OUT,PAR,SAVED,IOSTAT)
C
C---------------------------------------------------------------------
C
C     TYPE 63: HOT WATER COIL WITH CONSTANT WALL TEMPERATURE
C
C     February 16, 1988 Cheol F rk
C     Revised : April 15, 1988
C
C     INPUTS:
C       TBLW   Boiler water temperature (C)
C       WCW    Water flow rate through the coil (kg/s)
C       TICW   Inlet coil water temperature (C)
C
C     OUTPUTS:
C       TOCW   Outlet coil water temperature (C)
C       QCW    Heat flow rate from boiler water to coil water (kW)
C
C     PARAMETERS:
C       DCOIL  Diameter of coil
C       LCO L  Length of coil
C
C*********************************************************************
C
      PARAMETER (NSAVED=2,NDE=0,NIN=3,NOUT=2,NPAR=2)
C
      REAL       K,LCOIL,LMTD,MU
      DIMENSION XIN(NIN),OUT(NOUT),PAR(NPAR),IOSTAT(NOUT),SAVED(NSAVED)
      COMMON     /CHRONO/ TIME,TSTEP,TTIME,TMIN,ITIME
      DATA       PI/3.14159/
C*      NAMELIST /NAM1/ HCOV,TOCW,LMTD,QCW
C*      NAMELIST /NAM2/ TIME,TBLW,WCW,TICW,TOCW,QCW
C
C     Inputs:
C
      TBLW   =XIN(1)
      WCW    =XIN(2)
      TICW   =XIN(3)
C
C     Parameters:
C
      DCOIL  =PAR(1)
      LCOIL  =PAR(2)
C
C     Temporally set the wall temperature of the water coil equal to
C     the boiler water temperature.
C
      TS=TBLW
C
C     Water properities:  dynamic viscosity, thermal conductivity, and
C     specific heat of water from the subroutine WATPR with average
```

```
C      temperature except at the beginning.
C
       IF(ITIME.EQ.1) THEN
         TAVE=0.5*(TBLW+TICW)
         SAVED(1)=TIME
         SAVED(2)=TICW
       ELSE
         TOCW=SAVED(2)
         TAVE=0.5*(TOCW+TICW)
       ENDIF
       MU=WMU(TAVE)
       K=WK(TAVE)
       CP=WCP(TAVE)
C
C      The coil surface area, and wetted cross-sectinal area.
C
       AS=PI*DCOIL*LCOIL
       AC=PI*DCOIL*DCOIL/4.0
C
C      Reynolds number and Prandltl number of the coil water
C
       RE=WCW*DCOIL/(AC*MU)
       PR=MU*CP/K
       HCOV=HCOVF(RE,PR,K,DCOIL)
C
C      The outlet temperature and the heat flow rate when
C      the coil surface temperature is constant.
C
       IF(WCW.GT. 0.0001) THEN
         A=HCOV*AS/(WCW*CP)
         TOCW=TS-(TS-TICW)*EXP(-A)
         LMTD=(TOCW-TICW,/LOG((TS-TICW)/(TS-TOCW))
         QCW=HCOV*AS*LMTD
       ELSE
         TOCW=TS
         QCW=0.0
       ENDIF
C
C      Outputs:
C
       OUT(1)  =TOCW
       OUT(2)  =QCW
       SAVED(2)=TOCW
C
       IF(TIME .GT. SAVED(1)) THEN
C*         PRINT NAM1
C*         PRINT NAM2
       ENDIF
       SAVED(1)=TIME
C
       IOSTAT(1)=0
       IOSTAT(2)=0
C
       RETURN
       END
C
C**********************************************************************
C
         SUBROUTINE TYPE64(XIN,OUT,PAR,SAVED,IOSTAT)
C
C----------------------------------------------------------------------
C
C      TYPE 64: BOILER BURNER AND CIRCULATING PUMP CONTROLS
C
C      February 17, 1988 Cheol Park
C      Revised : June 6, 1988
C
C      INPUTS:
C        TBURN  Burner control temperature (C)
C        TBLW   Boiler water temperature (C)
C        TLOAD  Load temperature (C)
C        CTHERM Thermostat control indicator for the burner
C                1 for thermostat control, 0 for manual control (-)
```

```
C       WCW    Domestic hot water flow rate (kg/s)
C
C     OUTPUTS:
C       SWCH   Burner control on/off signal (-)
C       WSW    Boiler circulating water flow rate (kg/s)
C
C     PARAMETERS:
C       TBURON Boiler burner-on temperature (C)
C       TBUROF Boiler burner-off temperature (C)
C       TPMPON Boiler water circulating pump-on temperature (C)
C       TPMPOF Boiler water circulating pump-off temperature (C)
C       WPUMP  Circulating wcter flow rate (kg/s)
C       RATEOF Minimum water flow rate ratio
C                                      during off-period of pump (-)
C
C*****************************************************************
C
      PARAMETER (NSAVED=1,NDE=0,NIN=5,NOUT=2,NPAR=6)
C
      DIMENSION XIN(NIN),OUT(NOUT),PAR(NPAR),IOSTAT(NOUT),SAVED(NSAVED)
      COMMON    /CHRONO/ TIME,TSTEP,TTIME,TMIN,ITIME

C*      NAMELIST  /NAM1/ TIME,TBUROF,TBURON,TBLW,SWCH,WCW
C
C     Inputs:
C
      TBURN  =XIN(1)
      TBLW   =XIN(2)
      TLOAD  =XIN(3)
      CTHERM =XIN(4)
      WCW    =XIN(5)
C
C     Parameters:
C
      TBURON =PAR(1)
      TBUROF =PAR(2)
      TPMPON =PAR(3)
      TPMPOF =PAR(4)
      WPUMP  =PAR(5)
      RATEOF =PAR(6)
C
      IF(ITIME .EQ. 1) THEN
        SAVED(1)=TIME
      ENDIF
C
C     Boiler burner control
C
C     The burner is controlled by the thermostat sensing the boiler
C     water temperature if the indicator, CTHERM, is greater than or
C     equal to 0.5.  Otherwise TBURN controls the burner.
C     The values of CTHERM and TBURN must be present in the boundary
C     data file.

      IF(CTHERM .GE. 0.5) THEN
        TBURN=TBLW
      ENDIF

C     Turn on and off the burner and the pump only when the time step
C     varies to prevent false action due to numerical instability
C     during the large change of a variable.

      IF(TIME .GT. SAVED(1)) THEN
        IF(TBURN .GE. TBUROF) THEN
          SWCH=0.0
        ELSEIF(TBURN .LE. TBURON) THEN
          SWCH=1.0
        ENDIF

C     Boiler water circulating pump control

        IF(TLOAD .LE. TPMPON) THEN
          WSW=WPUMP
        ELSEIF(TLOAD .GE. TPMPOF) THEN
```

```
            WSW=RATEOF*WPUMP
          ENDIF
        ENDIF
C
C       Outputs:
C
        OUT(1)  =SWCH
        OUT(2)  =WSW
C
        IOSTAT(1)=0
        IOSTAT(2)=0
C
C*        IF(TIME .GT. SAVED(1)) THEN
C*          PRINT NAM1
C*        ENDIF
        SAVED(1)=TIME
C
        RETURN
        END
```

```
C*****************************************************************
C
      FUNCTION CPF(TC1,TC2)
C
C-----------------------------------------------------------------
C
C     Combustion product specific heat
C
C     INPUTS:
C        TC1     Air temperature (C)
C        TC2     Combustion product temperature (C)
C        PCO2    Number of moles of CO2
C        PH2O    Number of moles of H2O
C        PO2     Number of moles of O2
C        PSO2    Number of moles of SO2
C        PN2     Number of moles of N2
C
C     OUTPUT:
C        CPF     Specific heat of combustion product (kJ/(kg-C))
C
C*****************************************************************
C
      COMMON/PRODCT/PT,PCO2,PH2O,PN2,PO2,PSO2,RATF,RWTF,RPTF
C
      DIMENSION C(6,2)
      DIMENSION A(30),B(30)
      DATA A/4.2497678,-6.912652E-3,3.1602134E-5,-2.9715432E-8,
     &9.510358E-12,2.1701,1.0378115E-2,-1.0733938E-5,6.3459175E-9,-1.628
     &0701E-12,4.1565016,-1.7244334E-3,5.6982316E-6,-4.5930044E-9,1.4233
     &654E-12,3.6916148,-1.3332552E-3,2.65031E-6,-9.768834E-10,-9.977223
     &4E-14,3.7189946,-2.5167288E-3,8.5837353E-6,-8.2998716E-9,2.708218E
     &-12,3.2257132,5.6551207E-3,-2.4970208E-7,-4.2206766E-9,2.1392733E-
     &12/
      DATA B/1.1795744,1.0950594E-2,-4.062213E-6,7.1370281E-10,
     &-4.7490353E-14,4.4129266,3.1922896E-3,-1.297823E-6,2.4147446E-10
     &,1.6742986E-14,2.6707532,3.0317115E-3,-8.535157E-7,1.1790853E-10,
     &-6.1973568E-15,2.8545761,1.5976316E-3,-6.2566254E-7,1.1315849E-
     &10,-7.689707E-15,3.5976129,7.8145603E-4,-2.238667E-7,4.2490159E
     &-11,-3.3460204E-15,5.1982451,2.0595095E-3,-8.6254450E-7,
     &1.6636523E-10,-1.1847837E-14/
C
C     Set T1 and T2 in degree K
C
      T1=273.15+TC1
      T2=273.15+TC2
      TM=1000.
      DO 10 I=1,6
      DO 10 J=1,2
      C(I,J)=0.
10    CONTINUE
C
      IF(T1.LT.1000.) THEN
        IF(T2.LT.1000.) THEN
          DO 30 I=1,6
          M=5*(I-1)
          DO 20 J=1,5
          JJ=M+J
          C(I,1)=C(I,1)+A(JJ)*(T2**J-T1**J)/J
20        CONTINUE
          C(I,1)=C(I,1)*8.32066/(T2-T1)
30        CONTINUE
          CPF=(PCO2*C(2,1)+PH2O*C(3,1)+PN2*C(4,1)
     &         +PO2*C(5,1)+PSO2*C(6,1))/(PCO2*44.
     &         +PH2O*18.+PN2*28.+PO2*32.+PSO2*64.)
        ELSE
          DO 50 I=1,6
          M=5*(I-1)
          DO 40 J=1,5
          JJ=M+J
          C(I,1)=C(I,1)+A(JJ)*(TM**J-T1**J)/J
          C(I,2)=C(I,2)+B(JJ)*(T2**J-TM**J)/J
40        CONTINUE
          C(I,1)=(C(I,1)+C(I,2))*8.32066/(T2-T1)
```

```
50        CONTINUE
          CPF=(PCO2*C(2,1)+PH2O*C(3,1)+PN2*C(4,1)
     &        +PO2*C(5,1)+PSO2*C(6,1))/(PCO2*44.
     &        +PH2O*18.+PN2*28.+PO2*32.+PSO2*64.)
        ENDIF
      ELSE
        IF(T2.GT.1000.) THEN
          DO 70 I=1,6
          M=5*(I-1)
          DO 60 J=1,5
          JJ=M+J
          C(I,2)=C(I,2)+B(JJ)*(T2**J-T1**J)/J
60        CONTINUE
          C(I,2)=C(I,2)*8.32066/(T2-T1)
70        CONTINUE
          CPF=(PCO2*C(2,2)+PH2O*C(3,2)+PN2*C(4,2)
     &        +PO2*C(5,2)+PSO2*C(6,2))/(PCO2*44.
     &        +PH2O*18.+PN2*28.+PO2*32.+PSO2*64.)
        ELSE
          DO 90 I=1,6
          M=5*(I-1)
          DO 80 J=1,5
          JJ=M+J
          C(I,1)=C(I,1)+A(JJ)*(TM**J-T2**J)/J
          C(I,2)=C(I,2)+B(JJ)*(T1**J-TM**J)/J
80        CONTINUE
          C(I,1)=(C(I,1)+C(I,2))*8.32066/(T1-T2)
90        CONTINUE
          CPF=(PCO2*C(2,1)+PH2O*C(3,1)+PN2*C(4,1)
     &        +PO2*C(5,1)+PSO2*C(6,1))/(PCO2*44.
     &        +PH2O*18.+PN2*28.+PO2*32.+PSO2*64.)
        ENDIF
      ENDIF
      RETURN
      END
C
C***********************************************************************
C
      FUNCTION GEF(PPCO2,PPH2O,XL,TG)
C
C-----------------------------------------------------------------------
C
C     Gas emissivity
C
C     INPUTS:
C        PPCO2   Partial pressure of CO2 (atm)
C        PPH2O   Partial pressure of H2O (atm)
C        XL      Length of combustion (ft)
C        TG      Radiating gas temperature (C)
C
C     OUTPUT:
C        GEF     Gas emissivity
C
C***********************************************************************
C
C     Select gas emissivity constants C1 & C2
C
      XX=3.2808*XL*(PPCO2+PPH2O)
      IF(XX.GT.0.2) THEN
        C1=287.
        C2=0.4
      ELSE
        C1=406.9
        C2=0.62
      ENDIF
C
C     Compute gas emissivity
C
      TRG=1.8*(TG+273.15)
      GEX=XX**C2*C1/TRG
      GEF=GEX
      RETURN
      END
```

```
C
C-----------------------------------------------------------------------
C
      FUNCTION GS(AT,CS,GE,SE)
C
C-----------------------------------------------------------------------
C
C     Gos/Sink exchonge oreo
C
C     INPUTS:
C        AT     Totol oreo (m2)
C        CS     Rotio of octive furnoce surfoce oreo to totol oreo
C        GE     Gos emissivity
C        SE     Active surfoce emissivity
C
C     OUTPUT:
C        GS     Rodiotion exchonge oreo (m2)
C
C-----------------------------------------------------------------------
C
      GSX=1./GE+1./(CS*SE)-1.
      GSX=AT/GSX
      GS=GSX
      RETURN
      END
C
C-----------------------------------------------------------------------
C
      FUNCTION HCOVF(RE,PR,K,D)
C
C-----------------------------------------------------------------------
C
C     Convective heot tronsfer coefficient
C
C     INPUTS:
C       RE       Reynolds number
C       PR       Prondtl number
C       K        Thermol conductivity (kW/(m-C))
C       D        Hydoulic diometer (m)
C
C     OUTPUT:
C       HCOVF    Convective heot tronsfer coefficient (kW/(m2-C))
C
C-----------------------------------------------------------------------
C
      REAL    K,NSN
C
C     Test if the flow is lominor or turbulent bosed on Reynolds number.
C
      IF (RE.GE.2000.0) THEN
        NSN=0.023*RE**0.8*PR**0.4
      ELSE
        NSN=3.66
      ENDIF
C
C     Colculote the convective heot trorsfer coefficient using the
C     Nusselt number.
C
      HCOVF=NSN*K/D
C
      RETURN
      END
C
C***********************************************************************
C
      SUBROUTINE PRDPP(CARB,HYDR,OXYG,XNTR,SULF,XAIR)
C
C-------------------------------------------------------
C
C     Combustion products
C
C     INPUTS:
C       PT     Pressure (otm)
```

```
C         XAIR    Excess air fraction
C         CARB    Number of moles of carbon
C         HYDR    Number of moles of hydrogen
C         OXYG    Number of moles of oxygen
C         XNTR    Number of moles of nitrogen
C         SULF    Number of moles of sulfur
C
C       OUTPUTS:
C         PCO2    Partial pressure of CO2 (atm)
C         PH2O    Partial pressure of H2O (atm)
C         PSO2    Partial pressure of SO2 (atm)
C         PN2     Partial pressure of N2  (atm)
C         PO2     Partial pressure of O2  (atm)
C         RATF    Mass ratio of air to fuel (-)
C         RPTF    Mass ratio of product to fuel (-)
C         RWTF    Mass ratio of water in product to fuel (-)
C
C*************************************************************************
C
      COMMON/PRODCT/PT,PCO2,PH2O,PN2,PO2,PSO2,RATF,RWTF,RPTF
C
C     Moles of oxygen and nitrogen to be added
C
      R00=2.*CARB+0.5*HYDR+2.*SULF-OXYG
      RN0=3.76*R00
C
C     Moles of CO2, H2O, O2, SO2 and N2 in products
C
      PCO2=CARB
      PH2O=0.5*HYDR
      PO2=0.5*R00*XAIR
      PSO2=SULF
      PN2=0.5*XNTR+0.5*RN0*(1.+XAIR)
C
C     Weight of fuel, air, and products
C
      WTF=12.*CARB+HYDR+16.*OXYG+14.*XNTR+32.*SULF
      WTA=(16.*R00+14.*RN0)*(1.+XAIR)
      WTP=(44.*PCO2+18.*PH2O+32.*PO2+64.*PSO2+28.*PN2)
      WTW=18.*PH2O
C
C     Compute partial pressures and mass ratios
C
      AMULT=PT/(PCO2+PH2O+PO2+PSO2+PN2)
      PCO2=PCO2*AMULT
      PH2O=PH2O*AMULT
      PSO2=PSO2*AMULT
      PO2=PO2*AMULT
      PN2=PN2*AMULT
      RATF=WTA/WTF
      RPTF=WTP/WTF
      RWTF=WTW/WTF
      RETURN
      END
C
C*************************************************************************
C
      SUBROUTINE PRDPR(T,AMM,AKK)
C
C-----------------------------------------------------------------
C
C     Viscosity and conductivity of combustion product
C
C     INPUTS:
C       PCO2    Partial pressure of CO2 (atm)
C       PH2O    Partial pressure of H2O (atm)
C       PSO2    Partial pressure of SO2 (atm)
C       PN2     Partial pressure of N2  (atm)
C       PO2     Partial pressure of O2  (atm)
C
C     OUTPUTS:
C       AMM     Product dynamic viscosity (kg/(m-s))
C       AKK     Product thermal conductivity (kW.(m-C))
```

```
C
C*********************************************************************
C
      COMMON/PRODCT/PT,PCO2,PH2O,PN2,PO2,PSO2,RATF,RWTF,RPTF
      DIMENSION X(11),A(11),B(11),AM(5),AK(5)
      DATA X/-10.,260.,440.,620.,800.,1070.,
     &1520.,2420.,3140.,3500.,4160./
      DATA A/0.0387,0.0553,0.0646,0.073,0.0806,0.0911,
     &0.1062,0.1320,0.1500,0.1583,0.1710/
      DATA B/0.01287,0.01944,0.02333,0.02692,0.03022,
     &0.03483,0.04178,0.05348,0.0612,0.0646,0.0709/
      DATA AM/0.889,0.685,1.123,0.964,0.889/
      DATA AK/0.925,0.906,1.037,0.983,0.925/
C
      NP=11
      AMM=PCO2*AM(1)+PH2O*AM(2)+PO2*AM(3)+PN2*AM(4)+PSO2*AM(5)
      AKK=PCO2*AK(1)+PH2O*AK(2)+PO2*AK(3)+PN2*AK(4)+PSO2*AK(5)
      TF=32.+1.8*T
      AMM=(4.1333E-04)*AMM*TAB1(NP,X,A,TF)
      AKK=(1.731E-03)*AKK*TAB1(NP,X,B,TF)
      RETURN
      END
C
C
C*********************************************************************
C
      FUNCTION TAFF(HHV,TBS)
C
C---------------------------------------------------------------------
C
C     Adiabatic flame temperature
C
C     INPUTS:
C        HHV   Higher heating value of fuel (kJ/kg)
C        RWTF  Weight of H2O per kg of fuel (kg/kg)
C        RPTF  Weigth of product per kg of fuel (kg/kg)
C        PCO2  Number of moles of CO2
C        PH2O  Number of moles of H2O
C        PO2   Number of moles of O2
C        PSO2  Number of moles of SO2
C        PN2   Number of moles of N2
C        TBS   Base temperature (C)
C
C   . OUTPUT:
C        TAF   Adiabatic flame temperature (C)
C
C*********************************************************************
C
      COMMON/PRODCT/PT,PCO2,PH2O,PN2,PO2,PSO2,RATF,RWTF,RPTF
      ITR=0
      HVV=HHV-2442.*RWTF
      TAF1=0.995*HVV/RPTF+TBS
100   CP=CPF(TAF1,TBS)
      TAF2=HVV/RPTF/CP+TBS
      T=ABS(TAF1-TAF2)
      TAF1=TAF2
      ITR=ITR+1
      IF(ITR.LT.10 .AND. T.GT.0.1) THEN
        GOTO 100
      ENDIF
      TAFF =TAF1
      RETURN
      END
C
C*********************************************************************
C
      FUNCTION TAB1(NP,X,Y,X1)
C
C---------------------------------------------------------------------
C
C     Determine Y(X1) value from tabulated Y vs X values
C
C     INPUTS/OUTPUTS:
```

```
C        NP   Number of data points
C        X    Data points of independent variables
C        Y    Data points of dependent variables
C        TAB1 Output dependent variable
C        X1   Input independent variable
C
C*********************************************************************
C
      DIMENSION X(NP),Y(NP)
C
C     Set out the range Y1(X1) values
C
      XMIN=X(1)
      XMAX=X(NP)
      IF(X1.LE.XMIN) THEN
        Y1=Y(1)
      ELSEIF(X1.GT.XMAX) THEN
        Y1=Y(NP)
      ELSE
C
C     Interpolate for Y1(X1) value
C
        I=1
10      IF (X1.LE.X(I)) THEN
          DXT=X(I)-X(I-1)
          DYT=Y(I)-Y(I-1)
          RDXT=1./DXT
          DYODX=DYT*RDXT
          DX=X1-X(I-1)
          Y1=Y(I-1)+DX*DYODX
        ELSE
          I=I+1
          GOTO 10
        ENDIF
      ENDIF
      TAB1=Y1
      RETURN
      END
```

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al

BLC22D - Reduced number of reported variables to BLC22C    880628

SUPERBLOCK 1
     BLOCK 1
         UNIT  1      TYPE 62 - BOILER MODEL WITH A TANKLESS COIL
         UNIT  2      TYPE 63 -  DOMESTIC HOT WATER COIL
         UNIT  3      TYPE 64 -  BOILER BURNER AND WATER PUMP CONTROL
----------------------------------------------------

UNIT   1      TYPE  62
BOILER MODEL WITH A TANKLESS COIL

1      INPUTS:
        TEMPERATURE       1 - TSTK    : Stack gas temperature (DE)
        TEMPERATURE       2 - TRA     : Room air temperture
        TEMPERATURE       3 - TOA     : Outdoor air temperature
        TEMPERATURE       4 - TBLW    : Boiler water temperature
        PRESSURE          1 - PSW     : Supply water pressure
        FLOW              1 - WSW     : Supply water flowrate
        TEMPERATURE       5 - TRW     : Return water temp.
        POWER             1 - QCW     : Heat flowrate to domestic hot water coil
        CONTROL           1 - SWCH    : Control switch for on/off

2      OUTPUTS:
        TEMPERATURE       1 - TSTK    : Stack gas temperature (DE)
        TEMPERATURE       4 - TBLW    : Boiler water temp. (DE)
        TEMPERATURE       6 - TSW     : Supply water temp.
        POWER             2 - QHWT    : Heat gain of water
        POWER             3 - QSTK    : Heat loss from stack
        POWER             4 - QINPUT  : Heat input rate
        POWER             5 - QLTNT   : Latent heat loss
        POWER             6 - QJAKT   : Heat loss thru boiler jacket
        POWER             7 - QSS     : Heat flow rate to boiler water

3      PARAMETERS:
           0.736000E-01 VGF     : Volume of gas in the boiler fire-box (m3)
           0.175500     ASF     : Boiler fire-box effective radiation heat trans
           0.000000     ARF     : Boiler fire-box refractory surface area (m2)
           0.381000     LGPF    : Gas-path length in the boiler fire-box (m)
           0.800000     EMISF   : Fire-box surface emissivity value in fraction
           0.776000E-01 VWB     : Volume of water in the boiler (m3)
            2.60000     AJAKT   : Boiler jacket surface area (m2)
           0.169290E-02 UJAKT   : Boiler jacket U-factor (kW/m2-C)
            1.00000     CARB    : Atomic ratio of carbon in fuel
            1.84400     HYDR    : Atomic ratio of hydrogen in fuel
           0.000000     OXYG    : Atomic ratio of oxygen in fuel
           0.000000     XNTR    : Atomic ratio of nitrogen in fuel
           0.300000E-02 SULF    : Atomic ratio of sulfur in fuel
            45327.0     HFUEL   : Fuel higher heating value (kJ/kg)
           0.839000     CPFUEL  : Fuel specific heat value (kJ/kg-C)
           0.126600E-02 WFUEL   : Fuel supply rate (kg/s)
            26.5000     TFUEL   : Fuel temperature (C)
```

```
          0.200000      XAIR   : Execess combustion air (-)
          0.790000      EFFYSS : Boiler full load efficiency (-)
           95.0000      TBLWS  : Boiler water temp. at steady state (C)
           320.000      TSGS   : Stack gas temp. at full load (C)
          0.925000      ICFGON : Integration control for on-period stack gas
           3.14000      ICFGOf : Integration control for off-period stack gas
           1.38000      ICFW   : Integration control for boiler water temperatu
           3.00000      DTFG   : Short start period for burner on/off cycle (s)
          0.231250      ICFGNS : Integration control for short start on-period
          0.462500      ICFGFS : Integration control for short start off-period
           30.0000      DTBW   : Time interval for updating QSS (s)
----------------------------------------------------

UNIT   2      TYPE  63
 DOMESTIC HOT WATER COIL

1      INPUTS:
        TEMPERATURE       4 - TBLW   : Boiler water temperature
        FLOW              2 - WCW    : Water flowrate thru the coil
        TEMPERATURE       7 - TICW   : Coil inlet water temp.

2      OUTPUTS:
        TEMPERATURE       8 - TOCW   : Coil outlet water temperature
        POWER             1 - QCW    : Heat flowrate to the coil water

3      PARAMETERS:
          0.193000E-01 DCOIL  : Diameter of the coil (m)
           4.20600     LCOIL  : Length of the coil (m)
----------------------------------------------------

UNIT   3      TYPE  64
 BOILER BURNER AND WATER PUMP CONTROL

1      INPUTS:
        TEMPERATURE      10 - TBURN  : Burner control temperature
        TEMPERATURE       4 - TBLW   : Boiler water temperature
        TEMPERATURE       9 - TLOAD  : Load temperature
        CONTROL           2 - CTHERM : Thermostat control indicator 1/0 for auto/
        FLOW              2 - WCW    : Water flowrate thru the coil

2      OUTPUTS:
        CONTROL           1 - SWCH   : Burner control on/off signal
        FLOW              1 - WSW    : Boiler circulating water flowrate

3      PARAMETERS:
           85.0000     TBURON : Boiler burner-on temp. (C)
           98.9000     TBUROF : Boiler burner-off temp. (C)
           70.0000     TPMPON : Boiler water pump-on temperature (C)
           80.0000     TPMPOF : Boiler water pump-off temperature (C)
          0.286100     WPUMP  : Circulating water flowrate (kg/s)
          0.100000E-03 RATEOF : Minimum water flow rate ratio when pump off
(-
----------------------------------------------------
Initial Variable Values:
```

```
PRESSURE         1 ->    0.000000    (kPa)
FLOW             1 ->    0.000000    (kg/s)
FLOW             2 ->    0.000000    (kg/s)
TEMPERATURE      1 ->     315.000    (C)
TEMPERATURE      2 ->     26.5000    (C)
TEMPERATURE      3 ->     17.0000    (C)
TEMPERATURE      4 ->     30.0000    (C)
TEMPERATURE      5 ->     57.3800    (C)
TEMPERATURE      6 ->     30.0000    (C)
TEMPERATURE      7 ->     14.0000    (C)
TEMPERATURE      8 ->     28.0000    (C)
TEMPERATURE      9 ->     25.0000    (C)
TEMPERATURE     10 ->     80.0000    (C)
CONTROL          1 ->     1.00000    (-)
CONTROL          2 ->    0.000000    (-)
POWER            1 ->    0.000000    (kW)
POWER            2 ->    0.000000    (kW)
POWER            3 ->    0.000000    (kW)
POWER            4 ->    0.000000    (kW)
POWER            5 ->    0.000000    (kW)
POWER            6 ->    0.000000    (kW)
POWER            7 ->    0.000000    (kW)
----------------------------------------------------
Simulation Error Tolerances:

1      RTOLX=   0.100000E-03      ATOLX=   0.100000E-04
       XTOL=    0.200000E-03      TTIME=    1.00000

SUPERBLOCK 1
2      FREEZE OPTION 0      SCAN OPTION 0
----------------------------------------------------
The following are Boundary Variables in the simulation:

FLOW             2
TEMPERATURE      9
TEMPERATURE     10
CONTROL          2
----------------------------------------------------
The following are the reported variables:


SUPERBLOCK 1       REPORTING INTERVAL    120.000
TEMPERATURE      1
TEMPERATURE      4
TEMPERATURE      8
CONTROL          1
POWER            1
POWER            2
POWER            4
```

```
C******************************************************************
C
C       CRBND3 : Generation of boundary data file  for the boiler model
C                  when domestic hot water is drawn with space heating.
C
C                This program generates a set of data files or a file
C                for space loads at a given domestic hot water draw.
C
C ----------------------------------------------------------------
C
C        August 5, 1988  Cheol Park
C
C ******************************************************************

      PROGRAM CRBND3

      PARAMETER    (MAXN=15)
      REAL         XPUMP(MAXN),CYCLERT(MAXN),NCYCLE
      INTEGER      TSTOP,TPS,TPON(MAXN),TPOFF(MAXN),NCYPMP(MAXN)
      CHARACTER    BNDFILE*12, FILEXT(MAXN)*3,STEPPMP*11,ERRFILE*12
      CHARACTER    STEPOUT*12,ANSWER*1

      DATA         XPUMP/0.02, 0.05, 0.10, 0.15, 0.20, 0.225,0.30,
     &              0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 0.95, 0.975/
      DATA         CYCLERT/0.4, 0.6, 1.20, 1.40, 1.70, 1.80, 2.20,
     &               2.45, 2.5, 2.35, 2.20, 1.70, 0.90, 0.50, 0.40/

      DATA         TPS/12/

      DATA         FILEXT/'002','005','010','015','020','023','030',
     &               '040','050','060','070','080','090','095','098'/


      PRINT *,' Is this run STEP 1 or STEP 2 ?'
      READ *,ISTEP
      PRINT *,' ISTEP =  ', ISTEP

C     Determine the pump on/off-times and the number of cycles per
C     the period.

      PRINT 1000
      TSTOP=5000+TPS*3600
      DO 10 I=1,MAXN
      NCYCLE=CYCLERT(I)*TPS
      TPON(I)=3600*XPUMP(I)/CYCLERT(I)
      TPOFF(I)=3600*TPS/NCYCLE-TPON(I)
      IF(NCYCLE-INT(NCYCLE) .GT. 0.0) THEN
        NCYPMP(I)=INT(NCYCLE+1.0)
      ELSE
        NCYPMP(I)=NCYCLE
      ENDIF
      PRINT 2000, I,XPUMP(I),CYCLERT(I),NCYPMP(I),TPON(I),TPOFF(I),
     &           TSTOP

   10 CONTINUE

C     Create a boundary data files with different file extension

      IF(ISTEP .EQ. 1) THEN
        CALL STEPINA
      ENDIF

      PRINT *,' Are you processing a single file ? (N)'
      READ (*,FMT='(A1)') ANSWER
      IF(ANSWER .EQ. 'Y' .OR. ANSWER .EQ. 'y') THEN
        PRINT *,' What is the index number?'
        READ *, INDEX
        I=INDEX

        STEPPMP='STEPPMP.'//FILEXT(I)
        STEPOUT='STEPOUT.'//FILEXT(I)
        BNDFILE='BNDE000.'//FILEXT(I)
        ERRFILE='ERRE000.'//FILEXT(I)
```

```
          IF(ISTEP .EQ. 1) THEN
            CALL STEPIN(TPON(I),TPOFF(I),NCYPMP(I),STEPPMP)
            CALL STEPCOM(STEPOUT)
            PRINT *,' Edit STEPOUT:',FILEXT(I),' and perform STEP 2 '
          ELSEIF(ISTEP .EQ.2) THEN
            CALL STEPBND(BNDFILE,STEPOUT,NUMCOL)
            CALL CHEKBND(BNDFILE,ERRFILE,NUMCOL)
            PRINT *,' Edit BNDE000.',FILEXT(I)
            PRINT *,'       based on ERRE000.',FILEXT(I)
            PRINT *,' ================================================'
            PRINT *
          ENDIF
        ELSE

          PRINT *,' NOTE:  Excluded are Index 1 and 15. '

          DO 20 I=2,MAXN-1
C*          DO 20 I=1,MAXN
          STEPPMP='STEPPMP.'//FILEXT(I)
          STEPOUT='STEPOUT.'//FILEXT(I)
          BNDFILE='BNDE000.'//FILEXT(I)
          ERRFILE='ERRE000.'//FILEXT(I)

          IF(ISTEP .EQ. 1) THEN
            CALL STEPIN(TPON(I),TPOFF(I),NCYPMP(I),STEPPMP)
            CALL STEPCOM(STEPOUT)
            PRINT *,' Edit STEPOUT.',FILEXT(I),' and perform STEP 2 '
          ELSEIF(ISTEP .EQ.2) THEN
            CALL STEPBND(BNDFILE,STEPOUT,NUMCOL)
            CALL CHEKBND(BNDFILE,ERRFILE,NUMCOL)
            PRINT *,' Edit BNDE000.',FILEXT(I)
            PRINT *,'       based on ERRE000.',FILEXT(I)
            PRINT *,' ================================================'
            PRINT *
          ENDIF
20        CONTINUE
        ENDIF

1000    FORMAT(/79('*')/T3,'I',T8,'Xpump',T18,'Cycle Rate',T30,
     &  ' # cycles',T42,'Tp,on',T52,'Tp,off',T62,'Tstop'/79('*')//)
2000    FORMAT(I5,2F10.3,4I10)

        STOP
        END

C*********************************************************************
C
        SUBROUTINE STEPINA
C
C       STEPINA : Generation of input data to STEPBND.FTN
C                 when domestic hot water is drawn.
C
C *********************************************************************

        IMPLICIT        INTEGER(A-Z)
        CHARACTER*1     YESNO
        REAL            WCWON,WCWOFF,US

        DATA            TBURN/100/,CTHERM/1/
        DATA            YESNO/'y'/,TLDON,TLDOFF/68,85/

        OPEN(8,FILE='STEPINA2.DAT')

        PRINT *,' Enter the total amount of water drawn in Gal'
        READ *, US

        PRINT *,' How many cycles in 6-hour period?'
        READ *, NCYCLE

        PRINT *,' Start time of draw?'
        READ *, TSTART
```

```
      WCWON=0.1892
      WCWOFF=0.0
      DURATN=US*3.7854/(WCWON*NCYCLE)
      PRINT *,'  DURATION OF DRAW =',DURATN
      PRINT *,'  DRAW RATE (KG/S) =',WCWON

      DO 10 I=1,NCYCLE

        TIMEON=TSTART+(I-1)*3600*6/NCYCLE
        TIMEOF=TIMEON+DURATN

        WRITE(8,1000) YESNO
        WRITE(8,1100) TIMEON,WCWOFF,TLDOFF,TBURN,CTHERM
        WRITE(8,1100) TIMEON,WCWON, TLDOFF,TBURN,CTHERM
        WRITE(8,1000) YESNO
        WRITE(8,1100) TIMEOF,WCWON, TLDOFF,TBURN,CTHERM
        WRITE(8,1100) TIMEOF,WCWOFF,TLDOFF,TBURN,CTHERM

10    CONTINUE

      YESNO='n'

      WRITE(8,1000) YESNO

1000  FORMAT(A1)
1100  FORMAT(I10,F10.4,3I5)

      RETURN
      END
C*********************************************************************
C
      SUBROUTINE STEPIN(TPON,TPOFF,NCYPMP,STEPPMP)
C
C     STEPIN : Generation of input data to STEPBND.FTN
C              when the water pump is cycled.
C
C *********************************************************************
C

      IMPLICIT    INTEGER(A-Z)
      CHARACTER   STEPPMP*11
      CHARACTER*1 YESNO

      DATA        TSTART/5000/,WCW/0/,TBURN/100/,CTHERM/1/
      DATA        TLDON,TLDOFF/68,85/
C*      NAMELIST    /NAM2/ TPON,TPOFF,NCYPMP

      OPEN(7,FILE=STEPPMP)

C*      PRINT NAM2
      DO 10 I=1,NCYPMP
        YESNO='y'
        TIMEON=TSTART+(I-1)*(TPON+TPOFF)
        TIMEOF=TSTART+I*TPON+(I-1)*TPOFF

        WRITE(7,1000) YESNO
        WRITE(7,1100) TIMEON,WCW,TLDOFF,TBURN,CTHERM
        WRITE(7,1100) TIMEON,WCW,TLDON ,TBURN,CTHERM
        WRITE(7,1000) YESNO
        WRITE(7,1100) TIMEOF,WCW,TLDON ,TBURN,CTHERM
        WRITE(7,1100) TIMEOF,WCW,TLDOFF,TBURN,CTHERM

10    CONTINUE

      YESNO='n'
      TSTOP=TIMEOF+TPOFF

      WRITE(7,1000) YESNO
      WRITE(7,1100) TSTOP

1000  FORMAT(A1)
1100  FORMAT(I10,4I5)
```

```
      RETURN
      END
C*******************************************************************
C
      SUBROUTINE STEPCOM(STEPOUT)
C
C     STEPCOM : Combining outputs of STEPIN.FTN for space heating
C               and domestic hot water draw
C
C *******************************************************************
C

      PARAMETER     (MAXDAT=500)
      CHARACTER*1   YESNO
      CHARACTER*80  HEAD
      CHARACTER     STEPPMP*11,STEPOUT*11,FILEXT*3
      REAL          WCWS(MAXDAT,3),WCWD(MAXDAT,3)
      INTEGER       TIMES(MAXDAT),TLDS(MAXDAT,3),TLDD(MAXDAT,3)
      INTEGER       TBURN,CTHERM,TIMED(MAXDAT),TIME(MAXDAT),
     &              IWCWS(MAXDAT,3),TSTOP

      OPEN(9,FILE=STEPOUT)
      OPEN(10,FILE='STEPLEAD.DAT')
      REWIND 7
      REWIND 8
      REWIND 10

*     Read File 10 and write on File 9 ( Initialization heading )

      L=1
5     READ(10,1100,END=7) HEAD
      WRITE(9,1100)       HEAD
      GOTO 5

*     Read File 7 ( Output for space heating)

7     I=1
10    READ(7,1000) YESNO
      IF(YESNO .EQ. 'y') THEN
        READ(7,*) TIMES(I),IWCWS(I,1),TLDS(I,1),TBURN,CTHERM
        READ(7,*) TIMES(I),IWCWS(I,2),TLDS(I,2),TBURN,CTHERM
        I=I+1
        GOTO 10
      ENDIF
      READ(7,*) TSTOP
      NUMDAT7=I-1
      PRINT *,' Total number of time changes of file 7 = ', NUMDAT7

*     Read File 8 ( Output for domestic hot water draw)

      J=1
20    READ(8,1000) YESNO
      IF(YESNO .EQ. 'y') THEN
        READ(8,*) TIMED(J),WCWD(J,1),TLDD(J,1),TBURN,CTHERM
        READ(8,*) TIMED(J),WCWD(J,2),TLDD(J,2),TBURN,CTHERM
        J=J+1
        GOTO 20
      ENDIF
      NUMDAT8=J-1
      PRINT *,' Total number of time changes of file 8 = ', NUMDAT8

*     Combining two file with a kind of sorting

      TIMEMK=TIMED(1)
      ISTART=1
      JJ=1
      KK=0
      YESNO='y'

25    DO 40 I=ISTART,NUMDAT7
      IF(TIMES(I) .LT. TIMEMK) THEN
         K1=KK+I-ISTART+1
         TIME(K1)=TIMES(I)
```

```
          WCWS(I,1)=IWCWS(I,1)
          WCWS(I,2)=IWCWS(I,2)
          WRITE(9,1000) YESNO
          WRITE(9,1200) TIMES(I),WCWS(I,1),TLDS(I,1),TBURN,CTHERM
          WRITE(9,1200) TIMES(I),WCWS(I,2),TLDS(I,2),TBURN,CTHERM
C*          PRINT *,'I, K1,  TIME(K1)=',I,K1,TIME(K1)
        ELSE
          DO 30 J=1,NUMDAT8
          IF(TIMED(J) .GT. TIMES(I-1) .AND.
     &      TIMED(J) .LE. TIMES(I)) THEN
            K2=K1+J-JJ+1
            TIME(K2)=TIMED(J)
            WRITE(9,1000) YESNO
            WRITE(9,1200) TIMED(J),WCWD(J,1),TLDD(J,1),TBURN,CTHERM
            WRITE(9,1200) TIMED(J),WCWD(J,2),TLDD(J,2),TBURN,CTHERM
C*            PRINT *,'J, K2, TIME(K2)=',J,K2,TIME(K2)
          ELSEIF(TIMED(J) .GT. TIMES(I)) THEN
            JJ=J
            TIMEMK=TIMED(J)
            GOTO 50
          ENDIF
30        CONTINUE
        ENDIF
40      CONTINUE
50      KK=K2
        ISTART=I
        IF(ISTART .LT. NUMDAT7) THEN
          GOTO 25
        ENDIF

        DO 55 I=1,NUMDAT7
        IF(TIMES(I) .GE. TIMEMK) THEN
          K3=NUMDAT8+I
          TIME(K3)=TIMES(I)
          WCWS(I,1)=IWCWS(I,1)
          WCWS(I,2)=IWCWS(I,2)
          WRITE(9,1000) YESNO
          WRITE(9,1200) TIMES(I),WCWS(I,1),TLDS(I,1),TBURN,CTHERM
          WRITE(9,1200) TIMES(I),WCWS(I,2),TLDS(I,2),TBURN,CTHERM
C*          PRINT *,'I, K3, TIME(K3) =',I,K3,TIME(K3)
        ENDIF
55      CONTINUE
        YESNO='n'
        WRITE(9,1000) YESNO

*       Write output

C*        DO 60 I=1,NUMDAT7+NUMDAT8
C*        PRINT *,' I,   TIME(I) =', I, TIME(I)
C*        WRITE(9,1100) I, TIME(I)
C*60      CONTINUE
        CLOSE(9)

1000    FORMAT(A1)
1100    FORMAT(A80)
1200    FORMAT(I10,F10.4,3I10)

        RETURN
        END
*****************************************************************
*
        SUBROUTINE STEPBND(BNDFILE,STEPOUT,NUMCOL)
*
*       STEPBND : Stepwise changes in Boundary variables
*
*
*        t0   t1   t2   t3   t4   t5   t6   t7   t8   t9
*
*        |----|----|----|----|----|----|----|----|----|
*             ^
*             |
*       The step change occurs at t1.
*
```

```
*         NUMSUB : Number of subintervals in an interval (=5)
*         NUMINT : Number of intervals chosen (=9)
*         DELTSUB: Size of each subinterval in seconds
*         DELT   : Size of each interval in seconds
*         NUMCOL : Number of columns of Y-variables
*
*         In the figure shown above, there are 9 intervals, of which
*         size is DELT seconds, DELT = NUMSUB*DELTSB.
*
*
****************************************************************

      PARAMETER   (MAXCOL=30,MAXINT=20,MAXSUB=10)
      CHARACTER   ANSWER*1,BNDFILE*12,FILEXT*3,STEPOUT*12
      REAL        Y1(MAXCOL),Y2(MAXCOL),DELY(MAXCOL),YY(MAXCOL)
      REAL        TIME(0:MAXINT),TIME1(0:MAXINT,0:MAXSUB)
      REAL        Y(0:MAXINT,MAXCOL)
      INTEGER     TIME2

      OPEN(9, FILE=STEPOUT)
      OPEN(11,FILE=BNDFILE)
      CLOSE(11,STATUS='DELETE')

      OPEN(11,FILE=BNDFILE)
      REWIND 9

      PRINT *, '---   A boundary data is being generated ---'
C*      PRINT *, ' What is the number of columns for Y-values ?'
      READ(9,*) NUMCOL
C*      PRINT *,' Enter Subinterval size in seconds'
C*      PRINT *,' Number of Intervals?, and Number of Subintervals'
      READ(9,*) DELTSB,NUMINT,NUMSUB
      IF(NUMSUB .LT. 4) THEN
        PRINT *, ' --- NUMBER OF SUBINTERVALS MUST BE MORE THAN 4---'
        STOP '   MODIFIY YOUR INPUT DATA AND TRY AGAIN  '
      ENDIF
C*10    PRINT *,' Enter Step change time, and Y-values before change'
10      CONTINUE
      READ(9,*) TSTEP,(Y1(I),I=1,NUMCOL)
C*       PRINT *,' Enter Step change time, and Y-values after change'
      READ(9,*) TSTEP,(Y2(I),I=1,NUMCOL)

      DELT=NUMSUB*DELTSB
      TIME(0)=TSTEP-DELT

      DO 20 J=0,NUMINT
        TIME(J)=TIME(0)+REAL(J)*DELT
      DO 20 K=0,NUMSUB
        TIME1(J,K)=TIME(J)+REAL(K)*DELTSB
20    CONTINUE

      DO 30 I=1,NUMCOL
        DELY(I)=(Y2(I)-Y1(I))/(NUMINT-1)
        Y(0,I)=Y1(I)
      DO 30 J=0,NUMINT-1
        Y(J,I)=Y(0,I)+REAL(J)*DELY(I)
30    CONTINUE

      DO 60 J=0,NUMINT-1
      DO 40 I=1,NUMCOL
40      YY(I)=Y(J,I)+1.0E-10
      DO 50 K=0,NUMSUB
        TIME2=TIME1(J,K)+1.0E-10
        WRITE(11,1000) TIME2,(YY(L),L=1,NUMCOL)
50    CONTINUE
60    CONTINUE

C*       PRINT *,'Continue?'
      READ (9,FMT='(A1)') ANSWER
      IF(ANSWER .EQ.'Y'.OR. ANSWER .EQ. 'y') GOTO 10

1000  FORMAT(1X,I7,F10.4,6F10.2)
```

```
      RETURN
      END
C ************************************************************************
C
      SUBROUTINE CHEKBND(BNDFILE,ERRFILE,NUMCOL)
C
C       CHEKBND :  Check the boundary data file for proper sequence
C                  of the time data
C
C ************************************************************************
C
      PARAMETER  (MAXCOL=30)
      CHARACTER  ERRFILE*12,BNDFILE*12
      REAL       YY(MAXCOL)
      INTEGER    TIMENEW,TIMEOLD,TIME2

      OPEN(12,FILE=ERRFILE)
      CLOSE(12,STATUS='DELETE')
      OPEN(12,FILE=ERRFILE)

      OPEN(11,FILE=BNDFILE)
      REWIND 11

      TIMEOLD=0
10    READ(11,1000,END=20) TIME2,(YY(L),L=1,NUMCOL)
      TIMENEW=TIME2
      IF(TIMENEW .LT. TIMEOLD) THEN
C*        PRINT *,' Time is less than the previous value '
        PRINT *,' ERROR: ',TIMENEW,TIMEOLD
        WRITE(12,2000) TIMENEW,TIMEOLD
      ELSE
        TIMEOLD=TIMENEW
      ENDIF
      GOTO 10
20    CONTINUE

1000  FORMAT(1X,I7,F10.4,6F10.2)
2000  FORMAT(2X,2I12)

      RETURN
      END
```

```
C ****************************************************************
C
C       ENERGY : Integration by using traperzoidal method
C              Step change is considered  for the SB*.DAT files
C
C       May 10, 1988  C. P.
C       Revised :   July 15, 1988
C
C       NCOL    : Number of data columns per a record
C       NROW    : Number of data rows in a whole file
C       ISEL    : Index number of coulmn of selected data
C       NRPR    : Number of rows per a record
C       TBEGIN  : Begining time of integration (s)
C       TEND    : Ending time of integration (s)
C
C ****************************************************************
C
        PROGRAM   ENERGY

        PARAMETER (MAXCOL=30,MAXROW=15000)
        REAL      X(MAXCOL),Y(MAXROW),T(MAXROW)
        CHARACTER INPFIL*20,XX*80

C       DATA      NRPR/4/
        DATA      DTMIN/0.1/

C*        PRINT *,' Data File Name ?'
C*        READ(*,FMT='(A20)')  INPFIL
C*        PRINT 1000,  INPFIL
C*1000    FORMAT(10('*'),A20,5X,10('*'))
C*        OPEN(7,FILE=INPFIL)

5       OPEN(8,FILE='ENERGY8.OUT')
        READ(8,FMT='(A80)',END=7) XX
        GOTO 5

7       PRINT *,'  Total number of columns and rows ?'
        READ *,    NCOL, NROW
        PRINT *, ' Number of rows per a record in the file ?'
        READ *,    NRPR

        WRITE(8,1000)

10      REWIND 7
        PRINT *,'  Selected channel number ?'
        READ(*, *,END=50)    ISEL
        PRINT *, ' Selected channel number  ', ISEL
        PRINT *,'  Begining time, Ending time (s) ?'
        READ *,    TBEGIN, TEND
        PRINT *,'  TBEGIN  =  ',TBEGIN, '  TEND =  ',TEND
        PRINT *,'  Maximum time interval and change in value '
        READ *,    DTREF, DYREF
        PRINT *,'  DTREF =',DTREF,'   DYREF =',DYREF

        ICOUNT=1
20      READ(7,*,END=30) (X(J),J=1,NCOL)
        TIME = X(1)
        IF(TIME .GE. TBEGIN .AND. TIME .LE. TEND) THEN
          T(ICOUNT)=X(1)
          Y(ICOUNT)=X(ISEL)
          ICOUNT=ICOUNT+1
        ELSEIF(TIME .GT. TEND) THEN
          GOTO 30
        ENDIF

        IF(ICOUNT-1 .LT. NROW/NRPR) THEN
          GOTO 20
        ENDIF

30      NCOUNT=ICOUNT-1

        IF(NCOUNT .GE. MAXROW) THEN
          STOP ' ----- MAXROW IS GREATER THAN 15000 -----'
```

```
      ENDIF

      SUM=0.0
      DO 40 I=1,NCOUNT

C       Tropezoidol integration

      IF(I .GT. 1)  THEN

C         Step change

        IF((T(I)-T(I-1)) .GE. DTREF .AND.
     &                    (Y(I)-Y(I-1)) .GE. DYREF) THEN
          TR=T(I)-DTMIN
          S=Y(I-1)*(TR-T(I-1))
        ELSEIF((T(I)-T(I-1)) .GE. DTREF .AND.
     &                    (Y(I-1)-Y(I)) .GE. DYREF) THEN
          TR=T(I-1)+DTMIN
          S=Y(I)*(T(I)-TR)
        ELSE
          S=(Y(I)+Y(I-1))*(T(I)-T(I-1))/2.0
        ENDIF
      ELSE
        S=0.0
      ENDIF
C*      PRINT *,' I = ', I,'     S =',S
      SUM=SUM+S
40    CONTINUE

      AVE=SUM/(TEND-TBEGIN)

      PRINT *,'  TOTAL   =   ', SUM
      PRINT *,'  AVERAGE =   ', AVE
      PRINT *
      PRINT *,' ---------------------------------------------------------------'

      WRITE(8,2000) ISEL,TBEGIN,TEND,SUM,AVE,DTREF,DYREF

      IF(ISEL .EQ. 5) THEN
        TBON=SUM
        TBOFF=TEND-TBEGIN-TBON
      ELSEIF(ISEL .EQ. 7) THEN
        QHWT=SUM
      ELSEIF(ISEL .EQ. 8) THEN
        QINP=SUM
      ELSEIF(ISEL .EQ. 6) THEN
        QCW=SUM
      ENDIF

      GOTO 10

50    XBURN= TBON/(TBON+TBOFF)
      EF=  QCW/QINP*100.
      PRINT *,'  TBON =',TBON,'     TBOFF =',TBOFF
      PRINT *,'  XBURN =',XBURN, '      EF =',EF
      EFFU=  QHWT/QINP*100.
      PRINT *,'  XBURN =',XBURN, '      EFFU =',EFFU

1000  FORMAT(79('-'))
2000  FORMAT(I5,2F7.0,F12.1,3F10.4)

      CLOSE(8)
      STOP  '----- END OF JOB -----'
      END
```

```
C ********************************************************************
C
C     SPL : Interpolate the data points using B-spline method
C
C --------------------------------------------------------------------
C
C     August 22, 1988  Cheol Park
C
C ********************************************************************
C
      PROGRAM   SPL

      PARAMETER (NDATA=100,NSETMAX=10)

      CHARACTER TITLE(2)*80
      DIMENSION X(NDATA),Y(NDATA),FDP(NDATA),XX(NDATA),YY(NDATA)
      DIMENSION YNEW(NDATA,NSETMAX)

      DATA      N/12/,NSET/6/

      OPEN(7,FILE='SPL.INP')
      OPEN(8,FILE='SPL.X')
      OPEN(9,FILE='SPL.OUT')
      CLOSE(9,STATUS='DELETE')
      OPEN(9,FILE='SPL.OUT')

      REWIND 7
      REWIND 8
      REWIND 9

C     Read  the reference data file.
      DO 60 KK=1,NSET
      READ(7,2000,END=999) TITLE(1)
      READ(7,2000)         TITLE(2)

      DO 10 I=1,N
      READ(7,*) IXPUMP,XBURNER, X(I),Y(I)
10    CONTINUE

C     Calculate the derivatives at each of point (x,y)

      CALL SPLINE(N,X,Y,FDP)

C     Read the input file of XX.

      DO 30 J=1,NDATA
      READ(8,*,END=40) XX(J)
30    CONTINUE
40    NN=J-1
      REWIND 8

      DO 50 K=1,NN

C     Interpolate for given data.

      CALL SPEVAL(N,X,Y,FDP,XX(K),YY(K))

      PRINT *, K, XX(K), YY(K)
      YNEW(K,KK)=YY(K)

50    CONTINUE
60    CONTINUE

      DO 70 K=1,NN
      WRITE(9,1000) XX(K),(YNEW(K,KK),KK=1,NSET)
70    CONTINUE

1000  FORMAT(8F10.2)
2000  FORMAT(A80)

999   STOP
```

```
      END
C ********************************************************************
C
      SUBROUTINE SPLINE(N,X,Y,FDP)
C
C -------------------------------------------------------------------
C
C     SPLINE : computes the second derivatives needed in cubic
C              spline interpolation. The original program was written by
c               J. H. Ferziger Ref.[1]. A little modification is made.
C
C     July 18, 1984 C.P.
C
C     N:          Number of data points
C     X:          Array containing the values of the independent variable
C                 (Assume to be in ascending order)
C     Y:          Array containing the values of the function at the data
C                 points given in the X array
C
C     FDP:        Output array which contains the second derivatives of
C                 the interpolating cubic spline.
C
C     REFERENCE:
C       [1]  Joel H. Ferziger, "Numerical Methods for Engineering
C                 Application," John Wiley & Sons, 1981, pp.17-18.
C
C ********************************************************************
C
      REAL      LAMDA
      PARAMETER (NMAX=100)
      DIMENSION X(NMAX),Y(NMAX),A(NMAX),B(NMAX),C(NMAX),R(NMAX),
     &          FDP(NMAX)
C
C     Compute the coefficients and the RHS of the equations.
C     This routine uses the cantilever condition. The parameter
C     LAMDA is set to 1. But this can be user-modified.
C
C     A,B,C are the three diagonals of the tridiagonal system,
C     and R is the right hand side.
C
      LAMDA = 1.
      C(1)=X(2)-X(1)
      DO 10 I=2,N-1
      C(I)=X(I+1)-X(I)
      A(I)=C(I-1)
      B(I)=2.*(A(I)+C(I))
      R(I)=6.*((Y(I+1)-Y(I))/C(I)-(Y(I)-Y(I-1))/C(I-1))
10    CONTINUE
      B(2)=B(2)+LAMDA*C(1)
      B(N-1)=B(N-1)+LAMDA*C(N-1)
C
C     Tridiagonal solver subroutine.
C     But the notaion is clumsy so we will solve directly.
C
      DO 20 I=3,N-1
      T=A(I)/B(I-1)
      B(I)=B(I)-T*C(I-1)
      R(I)=R(I)-T*R(I-1)
20    CONTINUE
      FDP(N-1)=R(N-1)/B(N-1)
      DO 30 I=2,N-2
      FDP(N-I)=(R(N-I)-C(N-I)*FDP(N-I+1))/B(N-I)
30    CONTINUE
      FDP(1)=LAMDA*FDP(2)
      FDP(N)=LAMDA*FDP(N-1)
C
      RETURN
      END
C ********************************************************************
C
      SUBROUTINE SPEVAL(N,X,Y,FDP,XX,F)
C
C -------------------------------------------------------------------
```

```
C
C     SPEVAL : evoluotes the cubic spline for given the derivatives
C              computed by subroutine SPLINE.
C
C     XX:        Value of independent variable for which an interpolated
C                value is reqested
C     F:         The interpolated result
C
C ******************************************************************
C
      PARAMETER (NMAX=100)
      DIMENSION X(NMAX),Y(NMAX),FDP(NMAX)
C
C     Find the proper interval.
C
      DO 10 I=1,N-1
      IF(XX.LE.X(I+1)) GOTO 20
10    CONTINUE
C
C     Evaluate the cubic.
C
20    DXM=XX-X(I)
      DXP=X(I+1)-XX
      DEL=X(I+1)-X(I)
      F=FDP(I)*DXP*(DXP*DXP/DEL-DEL)/6.
     & +FDP(I+1)*DXM*(DXM*DXM/DEL-DEL)/6.
     & +Y(I)*DXP/DEL+Y(I+1)*DXM/DEL
C
      RETURN
      END
```

```
C *********************************************************************
C
C     EFFSPWT :  Efficiency  equation
C
C                 Eta = ax/(x+b) + c
C
C ---------------------------------------------------------------------
C
C     September 22, 1988  Cheol Park
C     Rev:  Septmeber 26, 1988
C
C *********************************************************************
C
      PROGRAM   EFFSPWT

      REAL      EF,EFMULT,ETA225,ETA225N,ETANEW,ETASS,ETAZERO,U,XDHW,
     &          XLOAD,XSPWT
      REAL      ETA
      INTEGER   I,IMAX,J,JMAX,NCASE,NDATA

      PARAMETER (IMAX=50,JMAX=20)

      DIMENSION XLOAD(IMAX),ETANEW(IMAX,JMAX),XDHW(JMAX)
      DIMENSION U(JMAX),EF(JMAX),ETA225N(JMAX)


      OPEN(7,FILE='EFFSPWT.INP')
      OPEN(8,FILE='EFFSPWT.OUT')
      CLOSE(8,STATUS='DELETE')
      OPEN(8,FILE='EFFSPWT.OUT')

      REWIND 7

C     Read the input data for zero-water-load.

      READ(7,*) ETAZERO,ETA225,ETASS,EFMULT

C     Read the number of cases, the water drawn per day in gallon, and
C     the energy factors(%), and  the load factor due to domestic hot water
C     draw(-).

      READ(7,*) NCASE
      DO 10 J=1,NCASE
      READ(7,*) U(J),EF(J),XDHW(J)
      EF(J)=EFMULT*EF(J)/100
10    CONTINUE

      DO 20 J=1,NCASE
      XSPWT=0.225+XDHW(J)
      ETA225N(J)=ETA(ETAZERO,ETA225,ETASS,XSPWT)
20    CONTINUE

C     Read the loads where the effciencies are calculated.

      READ(7,*) NDATA
      DO 30 I=1,NDATA
      READ(7,*) XLOAD(I)
      XLOAD(I)=XLOAD(I)/100
30    CONTINUE

      DO 40 J=1,NCASE
      DO 40 I=1,NDATA

      ETANEW(I,J)=ETA(EF(J),ETA225N(J),ETASS,XLOAD(I))

40    CONTINUE

      DO 50 I=1,NDATA
      WRITE(8,1000) XLOAD(I),(ETANEW(I,J),J=1,NCASE)
50    CONTINUE

1000  FORMAT(8F10.4)
```

```
      STOP
      END
C ********************************************************************
C
      FUNCTION ETA(ETAZERO,ETA225,ETASS,XLOAD)
C
C ********************************************************************
C
      REAL   A,B,C,ETA,ETA225,ETASS,ETAZERO,XLOAD

C     A curve-fit equation

      C=ETAZERO
      B=-0.225*(ETASS-ETA225)
     &            /(0.225*ETASS-ETA225+0.775*ETAZERO)
      A=(ETASS-C)*(1.+B)
      ETA=A*XLOAD/(XLOAD+B)+C

      RETURN
      END
```

```
C ************************************************************************
C
C     EQTBIN:  Efficiency equation and bin analysis
C
C                   Eta = ax/(x+b) + c
C
C ------------------------------------------------------------------------
C
C     September 22, 1988  Cheol Park
C     Rev:  January 27, 1989
C
C ************************************************************************
C
      PROGRAM   EQTBIN

      REAL      EF,ETA225,ETA225N,ETANEW,ETASS,ETAZERO,U,
     &          XDHW,XLOAD,XSPWT,ETAU,ETASBIN
      REAL      ETA
      INTEGER   I,IMAX,J,JMAX,NCASE,NDATA
      CHARACTER TITLE*80


      PARAMETER (IMAX=50,JMAX=20)

      DIMENSION XLOAD(IMAX),ETANEW(IMAX,JMAX),XDHW(JMAX)
      DIMENSION U(JMAX),EF(JMAX),ETA225(JMAX),ETA225N(JMAX)
      DIMENSION ETAU(IMAX),ETASBIN(JMAX)

      OPEN(7,FILE='EQTBIN.INP')
      OPEN(8,FILE='EQTBIN.OUT')
      CLOSE(8,STATUS='DELETE')
      OPEN(8,FILE='EQTBIN.OUT')

      REWIND 7

C     Read the input data for zero-water-load.

      READ(7,*) ETAZERO,ETASS

C     Read the number of cases, the water drawn per day in gallon, and
C     the energy factors(%), and  the load factor due to domestic hot water
C     draw(-).

      READ(7,*) NCASE
      DO 10 J=1,NCASE
      READ(7,*) U(J),EF(J),XDHW(J),ETA225(J)
      EF(J)=EF(J)/100.
10    CONTINUE

C     Find a new combined efficiency at the point where the space load
C     is 22.5 percent.

      DO 20 J=1,NCASE
      XSPWT=0.225+XDHW(J)
```

```
      ETA225N(J)=ETA(ETAZERO,ETA225(J),ETASS,XSPWT)
20    CONTINUE

C     Read the loads where the effciencies are calculated.

      READ(7,*) NDATA
      DO 30 I=1,NDATA
      READ(7,*) XLOAD(I)
      XLOAD(I)=XLOAD(I)/100
30    CONTINUE

      DO 50 J=1,NCASE
      DO 40 I=1,NDATA

      ETANEW(I,J)=ETA(EF(J),ETA225N(J),ETASS,XLOAD(I))
      IF(I .GT. 1) THEN
         ETAU(I-1)= ETANEW(I,J)
      ENDIF

40    CONTINUE

      CALL ESEASON( ETAU, ETAS)
      ETASBIN(J) =ETAS

50    CONTINUE

      TITLE='  ******    OUTPUT OF EQTBIN.FTN ******'
      WRITE(8,2000) TITLE
      WRITE(8,3000) (U(J),J=1,NCASE)
      WRITE(8,4000)
      DO 60 I=1,NDATA
      WRITE(8,1000) XLOAD(I),(ETANEW(I,J),J=1,NCASE)
60    CONTINUE
      WRITE(8,5000) (ETASBIN(J),J=1,NCASE)

1000  FORMAT(12F10.4)
2000  FORMAT(A80)
3000  FORMAT(' XLOAD  U =',12F10.1)
4000  FORMAT( )
5000  FORMAT(/' Eta,bin =',12F10.4)

      STOP
      END

C ************************************************************************
C
      FUNCTION ETA(ETAZERO,ETA225,ETASS,XLOAD)
C
C ************************************************************************
C
      REAL   A,B,C,ETA,ETA225,ETASS,ETAZERO,XLOAD

C     A curve-fit equation
```

```
      C=ETAZERO
      B=-0.225*(ETASS-ETA225)
     &             /(0.225*ETASS-ETA225+0.775*ETAZERO)
      A=(ETASS-C)*(1.+B)
      ETA=A*XLOAD/(XLOAD+B)+C

      RETURN
      END

c*****************************************************************************
c
c       ESEASON : seasonal efficiency for combined space and water loads
c
c        January 26, 1989       Cheol Park
c
c*****************************************************************************

       subroutine eseason(etau, etas)

       real      sum1, sum2, xspace, etau, etas, temp

       real      n

       integer   i, imax

       parameter ( imax= 15 )

       dimension xspace(imax), etau(imax), temp(imax),
     &            n(imax)

c       bin data for region IV

        data     n/0.132, 0.111, 0.103, 0.093, 0.100, 0.109, 0.126,
     &             0.087, 0.055, 0.036, 0.026, 0.013, 0.006, 0.002,
     &             0.001/

        data  temp/  62., 57., 52., 47., 42., 37., 32., 27., 22.,
     &               17., 12.,  7.,  2., -3., -8./

c       design condition

        data  tref/65.0/, tdesign/5.0/, oversize/0.7/


        sum1 = 0.0
        sum2 = 0.0

        do 10 i=1,imax

        xspace(i) = (tref-temp(i))/((tref-tdesign)*(1.+oversize))

        sum1 = sum1 + n(i)*xspace(i)
        sum2 = sum2 + n(i)*xspace(i)/etau(i)
        if (i .eq. imax) then
```

```
         print *, 'i,  xspace, sum1, sum2, etau =', i, xspace(i) ,sum1,
     &               sum2, etau(i)
        endif

10      continue

        etas = sum1/sum2
        print *
        print *, ' Seasonal Efficiency = ', etas

        return
        end
```

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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 residential boiler for space heating and domestic hot water heating was studied by conducting laboratory tests and computer simulations. A clam-shell, wet-base, oil-fired, residential boiler with a tankless coil for heating domestic water was selected for this research project.

The purpose of this study was to develop a method for evaluating the performance of an integrated space and water heating appliance. Based upon laboratory tests, a computer model was developed and used with the HVACSIM$^+$ building system simulation program to simulate the operation of the integrated appliance.

The model was verified for heat-up, cool-down, cyclic, and standby modes of operation, along with various domestic hot water draw cycles. Using the verified model, computer simulations were carried out for both summer and winter operations of the appliance. As a result of these simulation studies, a simple method for determining the combined, seasonal efficiency of Type I appliance, whose primary design function is space heating and secondary function is domestic water heating, is presented.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

computer simulation; domestic hot water heating; integrated appliance; performance test procedure; residential boiler, space heating.

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