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Users Guide to POST - Plant Operations Simulation Template

George E. Kelly
Daniel R. Clark

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
National Engineering Laboratory
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ABSTRACT

A non-proprietary simulation template program named POST (Plant Operations Simulation Template) has been developed for use with the Lotus 1-2-3* spreadsheet. The template provides for mathematical simulation of central heating/cooling plant equipment including boilers, cooling towers, and centrifugal chillers. It provides methods for configuring a simulation of a specific physical plant, defining operating conditions and time-dependent boundary conditions, running simulations, and graphing simulation results. POST is a flexible and highly portable analytical tool for plant equipment operators and engineers concerned with efficient operation of physical plant systems.

This Users Guide provides an overview of POST and its companion template program SETUP, which is used to define the characteristics of component models. Information is presented on the menu commands used in POST and three examples are provided. The examples show how the template program may be used to simulate the performance of a three-boilers heating plant and a central cooling plant consisting of two chillers and a cooling tower. Listings of the actual keystrokes for setting up and running both simulations are included.

* Release 2 of Lotus 1-2-3 is required. Lotus and 1-2-3 are registered trademarks of Lotus Development Corporation and are used in this report as a means of clear identification and neither constitute nor imply endorsement by the National Bureau of Standards.

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CONVERSION FACTORS FROM ENGLISH TO METRIC (SI) UNITS

Physical Characteristic	To convert from	To	Multiply by
Length	ft	m	0.3048
Area	ft^2	m^2	0.0929
Velocity	m/s	mph	0.447
Temperature	^oF	^oC	$t_C = (t_F - 32)/1.8$
Temperature difference	^oF	^oC	0.55555
Energy	Btu	J	$1/055 \times 10^3$
Power	Btu/hr	W	0.293
U-value	Btu/hr $ft^{2o}F$	$W/m^{2o}C$	5.678
Thermal resistance	hr $ft^{2o}F$/BTu	$m^{2o}C/W$	0.1761
Pressure	in Hg 60^oF	KPa	3.376

ACKNOWLEDGMENTS

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DISCLAIMER

The template programs POST and SETUP described in this report are furnished by the government and are accepted and used by any recipient with the express understanding that the United States Government makes no warranty, expressed or implied, concerning the accuracy, completeness, reliability, usability, or suitability for any particular purpose of the information and data contained in these programs or furnished in connection therewith, and the United States Government shall be under no liability whatsoever to any person by reason of any use made thereof. These programs belong to the U.S. Government. Therefore, the recipient further agrees not to assert any proprietary rights therein or to represent their programs to anyone as other than government programs.

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1. INTRODUCTION

Recent years have seen a tremendous increase in the quantity and quality of computer programs available to design engineers in all fields. In the HVAC industry, computer simulation and energy analysis programs have proven to be valuable tools for improving energy efficiency and comfort levels, reducing operating costs, and promoting the development of better heating and cooling system designs and control strategies. Unfortunately, such programs are often fairly complicated, requiring a long and difficult learning period to develop the expertise necessary for effective use. Furthermore, efforts to improve efficiency should not end with system design. Even the most carefully designed system can be operated inefficiently. However, little or no assistance has been available to equipment operators who must make the day-to-day and hour-to-hour decisions on just how to run a system. Even in large central heating and cooling plants, where minor inefficiencies can be relatively costly, most decisions still rely heavily on rules of thumb.

This report describes a computer methodology developed to help central heating and cooling plant personnel operate a plant more efficiently. Ideally, such a methodology should exhibit as many as possible of the following virtues:

1. It should operate on a variety of different microcomputers.
2. It should allow graphical output, so that the numbers generated can be readily visualized.
3. It should not attempt to take decision-making power out of the

plant operator's hands. Rather, it should allow questions to be posed concerning plant performance and the probable consequences of operating decisions and provide intelligible answers to these questions.

4. It should be flexible enough to model the equipment and the configuration of essentially any physical plant.

5. It should be simple enough to be learned quickly and used effectively by equipment operators with modest technical backgrounds and no computer experience.

6. It should be powerful enough to assist in the design of plant operating strategies.

The methodology described here is a preliminary attempt to meet these ambitious and sometimes conflicting goals. It is not a free-standing program, but a template or worksheet for use with a commercial spreadsheet program. In effect, the spreadsheet program provided a flexible problem-oriented language in which the modular simulation program could be represented easily and compactly (Johansson 1985; Haynes 1985).

Section 2 of this report provides an overview of the two template programs, SETUP and POST, which are used together to simulate the performance of heating and cooling plants. The SETUP program is used to tailor generic models to the specific performance characteristics of actual equipment. The POST worksheet, whose name stands for Plant Operations Simulation Template, is used to perform the actual plant systems simulation and to analyze the simulation results.

2. OVERVIEW

The simulation of a central heating/cooling plant involves the use of Release 2 of the spreadsheet program Lotus 1-2-3* and two worksheet files: a setup worksheet, called SETUP, and a simulation worksheet, called POST. The first is used to define the characteristics of the system components. This worksheet file need only be used once to set up models of the specific equipment found in a given plant. The resulting models are then moved to the POST worksheet, which is used to run the actual simulations of the system and to study its behavior under various operating conditions and strategies.

The component models rely on steady-state equations using a combination of basic physical laws and polynomial representations. For each type of component selected, the user is guided through a process of entering data for a specific piece of equipment. The data required is generally in a form readily available from equipment manufacturers. For example, the centrifugal chiller model requires tables of full load capacity and power consumption at various chilled water and condenser water temperatures, and

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data representing a part-load performance curve. The SETUP worksheet then uses the spreadsheet program (Lotus 1985) to perform regressions of the data, inserts the resulting coefficients into the appropriate equations, and generates "specific" equipment models that are tailored to the user's particular applications.

Once the component models, which represent the equipment in a particular plant, have been generated, they are transferred to the POST simulation worksheet. Next, the variables in the system must be identified and the connections between components must be specified. This is done by assigning a unique number to each variable in a given category, and the same number to any two or more variables which represent the same physical quantity. For example, each temperature has a name consisting of the characters "TEMP." followed by a number. The inlet and outlet water temperatures on the condenser side of a chiller might be assigned the numbers 1 and 2, making their names TEMP.1 and TEMP.2. If the condenser water flows directly into a cooling tower, the cooling tower inlet water temperature would also be assigned the number 2 and its name would also become TEMP.2. POST would then make the necessary connection to pass information from the chiller model to the cooling tower model.

When all connections between components have been assigned numbers, POST names all the variables and generates two lists of variables in alphabetical order. One is a list of all the simulation inputs or variables which may be changed freely by the user. This list typically includes weather conditions, setpoint temperatures, and on/off control settings. The other list contains all the simulation outputs, or quantities which are calculated by the system model.

The simulation worksheet provides a fairly large set of commands in the nested menu form, some of which are shown in Figure 1. These allow the user to examine the simulation outputs at a single operating point, or under a range or series of input conditions. Up to five inputs may be varied simultaneously, and POST provides assistance in setting up columns of input values. New outputs may be defined by the user in terms of existing variables, and added to the list of simulation outputs. Graphs of simulation results can be generated to illustrate the effects of a given set of inputs or to compare the results of several different operating strategies.

Section 3 discusses the SETUP and POST template programs in more detail, while sections 4, 5 and 6 contain actual examples of how these worksheets may be used to simulate central heating/cooling plants. Section 4 models the performance of three identical boilers run at the same part load factor to meet the heating requirements of a building. Section 5 is the same heating plant with the boilers run sequentially. A central cooling plant containing two identical centrifugal chillers and a cooling plant is simulated in Section 6. Keystroke by keystroke listings are provided in Sections 4 and 6 to aid the user in learning how to use the SETUP and POST worksheets.

A brief summary of how well POST meets the design goals described above is presented in Section 7, entitled Conclusion.

3. SETUP AND POST

The SETUP and POST template programs are used together to model and simulate the performance of plant systems. SETUP is first used to generate specific component models which match the performance data supplied by the user. POST is then employed to link these component models together into a system, perform one or a series of simulations, and display the results graphically. Both of these worksheets are described below.

3.1 SETUP Worksheet

The SETUP worksheet is initially provided with a set of "generic" mathematical models for a fossil fuel fired boiler, a centrifugal chiller, a two-cell cooling tower, and several merge/control models. Each model consists of a page of descriptive information which identifies the inputs and outputs of the component and displays their current values. In addition, each model includes a region of the worksheet where equations are stored for calculating the outputs from the inputs. These equations initially contain parameter values and coefficients which were drawn from various sources and are unlikely to represent the equipment in any particular plant. To generate models of specific pieces of equipment, data characterizing the performance of the equipment must be supplied by the user.

The SETUP worksheet includes the generic models, storage space for a library of specific models, and menu-driven procedures for creating specific models from the generic models and user-supplied data. To illustrate the process of generating specific models, the setup procedures for the cooling tower and the centrifugal chiller are described in detail below.

Figure 2 shows the geography or layout of the SETUP worksheet. Regions will be referred to by their starting points which correspond to their upper left-hand corner on the spreadsheet. For example, the index of previously created specific models starts at region Q1; it extends to the right to X1 and down as far as required to list all the specific component models. The generic library, which contains general models of heating/cooling plant equipment, starts at AA1, while the specific component model library starts at EA1. Other regions of the spreadsheet include regions containing text which describes the information needed to generate specific models from general models (e.g., the region starting at CA41), work areas for intermediate calculations (e.g., the region starting at A1001), and an area containing macros (region starting at A1). Macros are small spreadsheet programs which contain sequences of keystrokes and commands which are performed when an item (or command) in a menu is selected.

The SETUP worksheet begins by displaying an index of any previously created specific models (region Q1) and a menu for selecting a component whose characteristics are to be specified. When a component (e.g., a boiler) is selected, the worksheet displays a page of text summarizing the information required to define the component characteristics, and a menu allowing the user to either proceed or return to the index menu. If the user elects to proceed, the general model, stored in region AA1, is copied to a transition region starting at CA1. It is then tailored to match the performance information which the user supplies (e.g., steady state and part lead efficiency) and the resulting specific model is copied to the specific library region starting at EA1. The user is also prompted for a name for this new specific component model which is added to the index in region Q1. This process may then be repeated for as many specific component models as the user wishes to generate.

3.2 POST Worksheet

After a suitable library of specific components has been generated using the SETUP worksheet, the POST worksheet is used to assemble the components into a model representing a specific plant system. The first step is to select the desired components by pointing to entries in the library of specific component models. Models may be used more than once when two or more identical components occur in the system. As each component is selected, it is copied from the library on the SETUP worksheet into a region starting at FA1 of the POST simulation worksheet layout shown in Figure 3.

The next step is to identify the connections among the components of the system. This is done by assigning numbers (in column EZ) to all the variables involved in connections, using the same number for any two or more variables which represent the same physical quantity. For example, in a system consisting of one chiller and one cooling tower, three connections need to be identified. The water temperature leaving the condenser side of the chiller is assumed to be the same as the water temperature entering the cooling tower (i.e., piping heat gains are neglected), and these two variables could both be given the number 1. The water temperature entering the condenser is the same as the water temperature leaving the cooling tower, and these temperatures could both be numbered 2. The condenser water flow rate is the same as the tower water flow rate, and both could be numbered 3. Alternatively both could be numbered 1. POST equates variables only when they have the same category name (e.g., TEMP, FLOW, etc.) as well as the same connection number, so a temperature will not be equated to a flow rate.

Finally, POST performs an initialization procedure to prepare for carrying out simulations. Before this procedure, each variable was associated with a category name consisting of four letters (such as CTRL, FLOW, MISC, POWR, PRES, TEMP, etc.) followed by a period. During initialization, POST names each variable by appending a number to the category name, so that each unique variable has a unique name and variables marked as connections share the same name. The number supplied by POST is not necessarily the same as the user-supplied connection number, due to the sorting procedure that POST uses to assign variable names. POST also generates two lists of variables, alphabetized by assigned name. One list consists of all the Simulation Inputs (the region starting at A1), which act as boundary conditions and may be changed freely by the user. The other list consists of all the Simulation Outputs (the region starting at I1), which are calculated from the input values by the component models. In addition, the initialization procedure includes some operations required for internal bookkeeping purposes.

The Main Menu in Post

The menu commands in POST (see Figure 1) include all the procedures needed after a system description has been set up and initialized. It allows one to define sets of varying boundary conditions for driving a simulation, to run a simulation, to display various categories of information about a simulation, to define new simulation outputs as functions of existing variables, and to prepare graphs of simulation results. The top-level simulation menu of POST is referred to as the main menu. The choices available from the main menu are Display, Change, Run, Print, Quit, Setup, and Initialize. These options are discussed, in slightly different order, in the sections which follow.

Change

In POST, the word "change" refers to modifying the specification of operating conditions for a simulation. The menu choices under Change are ErrorTolerance, Linear_Input, Periodic_Input, Output, and Report.

When component connections are specified in a system containing one or more closed loops, iterative calculations are required. In the chiller and cooling tower example discussed previously, the loop involves the condenser inlet and outlet temperatures of the chiller and the water inlet and outlet temperatures of the cooling tower. To achieve a self-consistent solution, the worksheet must be recalculated repeatedly. Before each recalculation, the current values of all outputs are stored. After each calculation, the relative change in each variable is computed. Iteration continues until the largest relative change (Max.Err) is less than the convergence tolerance (Err.Tol) specified with the Change Error Tolerance command. A convergence tolerance of 0.01, for example, means that the largest relative change in any variable from one iteration to the next must be less than one percent.

The Linear_Input and Periodic_Input commands are used to create columns of values of selected input variables. In both cases, up to five inputs may be varied simultaneously. The Linear_Input command generates a column of values which increase or decrease linearly for each specified variable. The user must select the inputs to be varied, supply starting and ending values for each, and set the number of steps from start to end. In addition to the columns of data, the command writes a column of row numbers ranging from zero to the number of steps.

The Periodic_Input command differs from the Linear_Input command in several respects. First, it generates a column of "time" values in addition to the column of row numbers. Second, it generates values which vary sinusoidally rather than linearly,. The characteristics of each sinusoid are determined by the maximum and minimum values and the time at which the maximum occurs. A period of twenty-four hours is assumed. Third, it also allows values to be entered manually. In the latter case, for each of the selected input variables, the user can choose either automatic generation of sinusoidal data or manual data entry. This feature can be used, for example, to specify sinusoidal air temperature fluctuations in parallel with scheduled setpoint changes and a user-defined load profile or to specify a set of discrete input values, such as different control options, that the user wants to evaluate.

With either command, an output region number must also be specified. The columns of input data generated by these commands are stored in one of six regions of the worksheet, determined by a number from 1 to 6.

When a simulation is run in Linear_Input or Periodic_Input mode, each row of inputs is used to calculate all simulation outputs, and some or all of the output values are written beside the corresponding inputs. The Report command in the Change submenu is used to specify which outputs are reported. This command permits the use of "wildcards," so that the entry TEMP* would cause all temperatures to be reported. The default setting after initialization is the single entry "*", which causes all the outputs in the simulation to be reported.

The Output command is used to assist the user in processing simulation results. Its command definitions follow the same form as existing outputs, consisting of a mnemonic, a name, a formula which generates the value, and labels representing the units and a verbal definition of the variable. The Output command provides space for these entries and checks for missing or illegal entries before adding the new variable to the list of simulation outputs.

For example, in the single chiller and single cooling tower system discussed previously, one might wish to use the Output feature to determine the system coefficient of performance (COP) under various operating conditions. System COP can be defined as the cooling power output of the chiller divided by the total power required to run the chiller, the cooling tower fan, and the pumps implicitly associated with the system. Suppose that the cooling power, chiller input power, and cooling tower fan power have the names POWR.1, POWR.2, POWR.3, respectively, and that pumps on the evaporator and condenser water lines consume 24 and 20 kilowatts, respectively. The cooling power is given in tons whereas all other powers are in kilowatts, so a conversion factor is required for consistent units. The following spreadsheet expression evaluates to the system COP:

```
+POWR.1*3.516/(POWR.2+POWR.3+24+20)
```

The leading plus sign is required to indicate that the expression is a formula rather than an alphanumeric label. When this formula is entered into a cell of the worksheet, the cell stores the formula but displays its current value. The Output option allows such a formula to be entered as the value of a new variable, together with suitable labels describing the new variable, and takes care of the bookkeeping required to incorporate the variable into the simulation. Use of this command allows data analysis to be performed as a simulation is run, rather than after.

Run

The Run command invokes a menu of three additional choices: Single_Point, Linear_Range, or Periodic_Range. The Single_Point option simply iterates on the current set of simulation inputs until the convergence tolerance is met. The Linear_Range and Periodic_Range commands iterate on each set of input values in the appropriate output region, and write the corresponding output values to the right of the input values.

Display

The Display command is used to bring various portions of the worksheet into view. The menu choices under Display are Variables, Component, Linear_Input, Periodic_Input, Output_Region, and Graph. Graph is used for viewing graphs generated with the Graph command, discussed in a separate section. The remaining choices are discussed below.

The Display Variables command brings the alphabetical listing of Simulation Inputs into view (region starting at A1). The user can then examine and change the current values of one or more inputs, and examine the current values of the simulation outputs. By "paging right" the user can also display the Simulation Outputs stored in the region starting at I1.

The Component option is used to present the descriptions of the components which make up the system. Each component is identified by a "page number" (e.g., *1, *2, etc.) in the top left corner. On selecting Display Component, the component on page 1 is displayed, and the user is given the opportunity to enter the page number of any other component in the system.

The Display Linear_Input and Display Periodic_Input commands show the areas where the characteristics of variable inputs are specified when the corresponding Setup commands are used. Display Output_Region presents an area where the actual values of inputs and outputs for a specific simulation are stored. Output region 1, 2, 3, and n start, respectively, at A1000, A1250, A1500, and AX where X=1000 + (n-1)250.

Graph

Graphs of simulation data are invaluable aids to understanding simulation results and visualizing system behavior. The Graph command yields a subset of the graph menu options in the host spreadsheet program, with a number of choices made automatically by default. It generates X-Y graphs from columns of data stored in one or more output regions. The menu choices under Graph are Use, Edit, Create, SavePic, View, Delete, and Quit.

The Create command sets up a new graph. The user chooses an output region, and selects columns of data by moving the cell pointer to the column headings of the independent (X-axis) variable and one or more dependent (Y-axis) variables. Up to six dependent variables can be selected, drawing up to six lines on a single graph. Default titles and legends for the graph are supplied automatically. Two titles appear above the graph: the title of the simulation, and the output region number. The X-axis is labeled with the description of the independent variable.

Legends below the graph identify each line on the graph by the assigned name of the dependent variable.

A name for the new graph must also be entered. Any number of graphs can be created, each with its own name. The Use command allows a graph already created to be selected by name, and that graph becomes the current graph. The View command displays the current graph.

The Display command in the Graph menu, mentioned in a previous section, is equivalent to a combination of the Graph Use and View commands. It requires a graph to be selected by name before the graph is displayed.

The Edit command allows an existing graph to be modified. The default titles and legends can be replaced, a Y-axis label can be added, lines can be erased from a graph or added to a graph, and grid lines can be added to or removed from a graph.

When a graph is created, all the data must reside in a single output region. However, the Edit command allows lines to be added using data from any output region. To compare simulation results stored in different output regions, the first dependent variable can be selected with Create and subsequent dependent variables in other output regions can be added with Edit. This feature could be used, for example, to plot system COP as a function of wet bulb temperature for two or more simulations involving different fan speed settings.

SavePic stores the current version of the current graph in a file with the default extension "PIC" for later printing. Delete is used to erase a graph and its name. Quit returns control to the main menu.

Print

This command causes the spreadsheet program to list the names, values and definitions of all the simulation input and output variables on a printer. The user can thus change one or more input values, perform a Single-Point Run as described above, and use the Print command to obtain a hard copy of the simulation inputs and outputs.

Setup

The Setup command allows the user to import specific component models (e.g., boiler, chiller, cooling tower) from the Setup worksheet and to connect them together to define the desired system simulation model.

Initialize

This command initializes the simulation. It appends a number to each variable's category name and copies all the input variables to the region of the spreadsheet containing Simulation Inputs and all the output variables to the region called Simulation Outputs.

Quit

This command on the main menu moves the cell pointer to a page of text and terminates POST menu control, leaving the user in the host spreadsheet program "Ready" mode. The page of text provides instructions for restarting the main menu of POST, summarizes a few other available POST commands, and gives the addresses of several regions of potential interest on the worksheet. Users familiar with the spreadsheet program can then take advantage of the full set of commands it provides, including graph options not available in the POST graph menu structure.

4. EXAMPLE 1: THREE GAS-FIRED BOILERS OPERATING AT IDENTICAL PART LOAD FACTORS

In this example, three identical gas-fired boilers are operated in parallel to meet a hypothetical building load. Each of the boilers operates at the same part load factor, which is defined as the boiler's output divided by its full load capacity or 1, whichever is smaller. All of the keystrokes required for setting up and running this example are provided in Listing 4-1 along with brief comments. Listings 4-2 through 4-7 provide supplemental information to further assist the user.

4.1 The Component Models

There are only two models used in the simulation--a gas-fired boiler model and a combination 3-way merge and heating load model. These models are described below.

4.1.1 The Boiler Model

As explained previously, the SETUP spreadsheet contains a number of "generic models" which can be tailored to model the performance of specific equipment. In the case of the Boiler Model, it is assumed that the boiler runs continuously (does not cycle on and off) during part load operation. This is equivalent of assuming that the output of the boiler is reduced from its full load value by reducing the rate at which fuel, and possibly combustion air, is supplied to the burner. The user must supply information on the properties of the fuel, the entering combustion air temperature, and between three and six sets of CO_2 and flue temperature data at various part load factors. The combustion efficiency at each of these part load factors is then calculated and the results used to determine the efficiency versus part load factor performance curve for the particular boiler being simulated.

In specifying the fuel, the user is asked to give the atomic ratios of the following elements making up the fuel: carbon, hydrogen, oxygen, nitrogen, and sulfur. Letting 1:h:o:n:s stand for these respective atomic ratios, normalized to the carbon atomic ratio, the following equations are used to model the combustion efficiency of the boiler at each of the user supplied part load factors.

The ratio, RT, of total combustion air to stoichiometric air is given by (Kelly, 1978):

$$RT = A + B/XCO_2,$$

where XCO_2 is the concentration of Carbon Dioxide (CO_2) in dry flue gas, and

$$A = 1 - BB/(4.76AA),$$

$$B = 100/(4.76AA),$$

$$AA = 1 + 0.25h + s - 0.5o,$$

$$BB = 1 + s + 0.5n + 3.76AA.$$

The latent heat loss, QL, in percent, is then:

$$QL = (100)(9488.4)h/((12.011 + 1.008h + 16o + 14.008n + 32.066s)HHV)$$

where HHV is the higher heating value of the fuel in units of Btu/lb.

The mass ratio of stoichiometric air to fuel, A/F, is:

$$A/F = 137.355AA/(12.011 + 1.008h + 16o + 14.008n + 32.066s).$$

This ratio is used to find the sensible heat loss, QS, given in percent by:

$$QS = (100/HHV) \sum_{j=1}^{5} [(1 + A/F)CF_j + (A/F)(RT - 1)CA_j](T_{ss}^{j} - T_{rm}^{j}),$$

where CA_j and CF_j are temperature coefficients for the heat capacity at constant pressure for air and the products of combustion. They are calculated using:

$$CA_j = \frac{\bar{R}}{(1.8)^{j-1}(j)} \sum_{k=1}^{N_a} a_{k,j} \frac{mf_k}{M_k}$$

$$CF_j = \frac{\bar{R}}{(1.8)^{j-1}(j)} \sum_{k=1}^{N_m} a_{k,j} \frac{mf_k}{M_k}$$

where mf_k is the mass fraction of the kth constituent, M_k is the molecular weight of the kth constituent $\bar{R}$ is the Universal Gas Constant = 1.98726 Btu/(lb-mole R), N_m is the number of constituents in the fuel mixture, N_a is the number of constituents in the entering combustion air, and $a_{k,j}$ are constants given in Table 1 for each of the different constituents, k.

Once the latent heat loss, QL, and the sensible heat loss, QS, are determined, the combustion efficiency, in percent, at a given part load factor is found using:

$$Eff = 100 - QL - QS.$$

After the combustion efficiency of the boiler is found for each of the part load factors for which the user has supplied CO_2 and flue temperature data, the efficiency versus part load factor curve for the boiler is determined. A second order polynomial of the form:

$$Y = a_1 + a_2X + a_3X^2,$$

where Y = 1/Eff and X = (1/load factor), is put through the 3 to 6 sets of Eff versus part load factor data using a least square fit method. This results in the following equations for the regression coefficients a_1, a_2, and a_3:

$$a_1 = \frac{1}{b} \begin{vmatrix} c_1 & b_{12} & b_{13} \\ c_2 & b_{22} & b_{23} \\ c_3 & b_{32} & b_{33} \end{vmatrix},$$

$$a_2 = \frac{1}{b} \begin{vmatrix} b_{11} & c_1 & b_{13} \\ b_{21} & c_2 & b_{23} \\ b_{31} & c_3 & b_{33} \end{vmatrix},$$

$$a_3 = \frac{1}{b} \begin{vmatrix} b_{11} & b_{12} & c_1 \\ b_{21} & b_{22} & c_2 \\ b_{31} & b_{32} & c_3 \end{vmatrix},$$

$$b = \begin{vmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{vmatrix},$$

where $b_{jk} = \sum_{i=1}^{T} X_i^{k+j-2}$, $c_k = \sum_{i=1}^{T} Y_i X_i^{k-1}$, T is the number of (X,Y) data sets, and Z indicates the determinate of the Z matrix = $Z_{11}Z_{22}Z_{33} + Z_{12}Z_{23}Z_{31} + Z_{13}Z_{32}Z_{21} - Z_{13}Z_{22}Z_{31} - Z_{23}Z_{32}Z_{11} - Z_{33}Z_{21}Z_{12}$ for a 3x3 matrix

Since the part load boiler performance curve which results from this process is a second order polynomial in the variable X, which is 1/(load factor)$^{-1}$, the user should try to provide CO_2 and flue temperature data over the entire range of load factors of interest. This will minimize the possibility that the resulting efficiency versus part load performance curve could take on some unusual and erroneous shape outside the range of data provided (e.g., go up instead of down as the part load factor goes to zero). In addition, the user must not provide fictitious data for a load factor identically equal to zero, since this will result in a divide by zero error in the spreadsheet. (Use instead a partload factor equal to a very small value, say 0.001).

4.1.2 N-Way Merge [1<N<6] with Heating Load Control Model

The N-Way Merge with Heating Load Control Model is a very simple model which assumes that there are N boilers, where N equals 2, 3, 4, or 5, connected in parallel. Since the total output from the merge is the sum of the individual boiler outputs, the average load factor for the boiler system, PLFavg, is given by:

$$PLFavg = \frac{LOAD}{\sum_i FLOutput_i}$$

where LOAD is the total heating load on the boiler system and $FLOutput_i$ is the full load output or capacity of the ith boiler. Assuming the loads on all of the inlet ports, except the port that is to be controlled, are known, the boiler corresponding to this controlled inlet port (cp) must have a part load factor, PLFcalc, given by:

$$PLFcalc = \frac{LOAD - \sum_i Output_i + Output_{cp}}{FLOutput_{cp}}$$

$$= \frac{LOAD - \sum_i{}' Output_i}{FLOutput_{cp}}$$

where " ' " indicates that the sum is over all inlet ports except the controlled port and $Output_{cp}$ and $FLOutput_{cp}$ are the output and full load output, respectively, of the boiler corresponding to the central port cp. This follows from the requirement that the total output from the merge must equal the Load imposed upon the boiler system by the building.

The user specifies the number of inlet ports corresponding to the number of boilers in the simulation in order to generate a specific Merge and Heating Load Control Model for a given simulation. For the example being considered in this section, N equals 3 and the specific model of interest becomes a 3-Way Merge with Heating Load Control Model.

When identical boilers are operated at the same part load factor (as in this example), the output PLFcalc from the N-Way Merge with Heating Load Control Model should be connected to the part load factor, PLF, input on one and only one boiler. For all the other boilers, the single PLFavg output from the merge/load model should be connected to the PLF inputs on these boilers. In addition, the Ctrl Mod(e) parameters for all the boilers should be set to 0 in the Simulation Inputs region of the spreadsheet. This causes the boilers to use the PLF as their part load factor and not the fixed parameter PLF set. The use of these simulation input parameters and the proper connections for PLFcalc and PLFavg will allow the simulation to converge to the proper solution.

4.2 Setting Up and Running Example 1

Listing 4-1 contains all the keystrokes necessary to setup and run the sample simulation entitled "Three Gas-Fired Boilers Operating At Identical Part Load Factors." Groups of keystrokes will be referred to as steps, which are numbered and shown on the left-hand side of this listing. Setting up and running a simulation involves the following tasks:

- Using the SETUP worksheet to generate specific component models from generic component models and then saving this new worksheet, preferably with a different name - say SETUP1. This task corresponds to steps 1 through 11 in Listing 4-1. Listing 4-2 shows typical natural gas fuel composition data and six sets of CO_2 and flue temperature data.

- Using the Setup command in the main menu of the POST worksheet, retrieve the specific component models needed. Make a sketch on paper (see Figure 4) showing how the inputs and outputs on the various components are connected to form the desired simulation and transfer this information to the POST spreadsheet by assigning unique connection numbers to any two or more variables which represent the same physical or calculated quantity (i.e., the output of one component is the input to another). Use the Initialize command in the main menu of POST to generate unique variable names, which depend upon the variable's category and connection number, and to copy all the input variables to the region of the spreadsheet containing Simulation Inputs and all the outputs to the region called Simulation

Outputs. This task is contained in steps 12 through 30 in Listing 4-1. The connection between the input and output variables in the various component models comprising this particular simulation are shown in Listing 4-3 and are partially discussed in section 4.1.2.

- Use the Change command in the main menu followed by the Output command in the submenu to enter a user-defined variable which may be useful for analyzing simulation results. Enter an Alt-V to incorporate this new variable in to the list of Simulation Outputs. Repeat this process for all additional user-defined variables. Steps 31 through 44 in Listing 4-1 and Listing 4-4 illustrate the setting up the user-defined outputs SysCap and SysEff.

- Change one or more input variables or parameters in the section containing Simulation Inputs. Be sure that the Ctrl Mod(e) parameters for all the boilers are set to 0 as discussed in section 4.1.2. Listing 4-5 contains a list of Simulation Outputs and Inputs printed with the Print command in the main menu. Carry out a simulation with these new inputs by selecting Run in the main menu and Single_Point in the resulting submenu. Alternatively, use Change in the main menu and then either Linear_Input or Periodic_Input to setup ranges over which one or more input variables are to be varied in either a linear or periodic manner and an Output_Region (e.g., 1, 2, 3, etc.) on the spreadsheet in which the results are to be stored. After completing this, select Run in the main menu followed by Linear_Range or Periodic_Range to carry out multiple simulations using the specified variables and ranges. Steps 45 through 51 and Listing 4-6 show how to setup a Linear_Input range and to carry out the multiple simulations specified in this Linear_Range. Part of the results which are written to Output Region 1 are displayed in Listing 4-7.

- Use the Graph command in the main menu and the commands in the various submenus to plot the results. You may also edit a graph to add or erase lines, change titles and legends, or add grid lines. When you are satisfied with the looks of a graph(s), it should be saved for later printing. Before quitting 1-2-3, the spreadsheet should be saved under a new name, BOILEXP1.WK1 for example. This task is carried out in steps 52 through 78 in Listing 4-1.

4.3 Simulation Results

GRAPH 1 in figure 5 contains a plot of System Efficiency versus Building Load for the three gas-fired boilers running at the same part load factors. Since all three gas-fired boilers are identical and are running at identical part load factors, this is the same part load performance curve for each boiler individually. This would not be the case if another boiler operating strategy, such as sequential operation, were selected. The operating strategy and its effect on system efficiency is discussed in the next section.

Listing 4-1 COMPLETE PROCEDURE FOR CREATING BOILEXP1.WK1 IN EXAMPLE 1

BOILEXP1 simulates the use of 3 boilers all operating together at the same part load to meet the building load.

STEP	KEYSTROKE ENTRY	COMMENT
1	/fcce {esc 5}	Entering ccs {esc 5} speeds up loading of spreadsheets. The notation {esc 5} means to press the esc key 5 times.
2	r SETUP ~	Load SETUP.WK 1. The symbol ~ should be entered as ~ and is interpreted as a carriage return.
3	B	Select boiler model and read screen.
4	C	continue
5	(input/change fuel data, see Listing 4-3)	Information containted in ( ) are instructions to be followed and should not be interpreted as literal key strokes. Use only arrow keys to input data.
6	~	
7	(enter combustion air temperature, TRA, and up to 6 sets of PLF, XCO_2 and TSS, use proper units)	
8	~	
9	New Gas Boiler	name of specific model
10	q	quit
11	/fs SETUP1	save file as SETUP1.WK1
12	/fr POST ~	retrieve POST.WK1
13	Alt-M	call up main menu
14	S	set up new simulation
15	SETUP1	use models in SETUP1.WK1
16	(move cell pointer to cell with *7)~	select boiler model
17	~~	to place boiler model at FA1

18	(move cell pointer to cell with *7)~	select boiler model
19	~(pgdn)~	to place second boiler model at FA21
20	(move cell pointer to cell with *7)~	select boiler model
21	~{pgdn}{pgdn}~	to place third boiler model at FA41
22	(move cell pointer to cell with *6)~	to select 3-way Merge w. Heating Load Control Model
23	~{pgdn}{pgdn}{pgdn}~	to place model at FA61
24	~(with cell pointer over a cell without an *)	to end setup mode
25	Three Gas-Fired Boilers S ~	simulation title
26	Ctrl-right arrow	Ctrl-right arrow means to press the right arrow key while holding down the control key.
27	(enter connection numbers, see Listing 4-3)	to specify how component models are connected
28	(It is recommended that you also customize the Mnemonics at this point to reflect the fact that there are multiple boilers. For example: change PLF to PLF1 in first boiler model, to PLF2 in second boiler model, to PLF3 in third boiler model.)	
29	Alt-M	to recall main menu
30	I	Initialize simulation
31	CO	Change Output
32	~ (enter a single user-defined variable, see Listing 4-4	enter Mnemonic, Name, Value, Units, Definition and use a formula for Value entry
33	Alt-V	to add user-defined variable to simulation
34	{esc}	to accept list of reported variables and return to main menu
35	CO	Change Output

36	~ (enter 2nd user-defined variable, see Listing 4-4)	enter 2nd user-defined variable
37	Alt-V	to add user-defined variable to simulation
38	{esc}	to accept list of reported variables and return to main menu
39	D V ~	Display variables
40	(enter/change value of input variables using only arrow keys to enter data, see Listing 4-5)	
41	~	carriage return when done
42	r s	run single point to smooth feathers ruffled by insertion
43	D V ~ Ctrl-right arrow	display output variables (see Listing 4-5)
44	~	carriage return when done
45	c L	change linear_range
46	e	edit
47	(enter linear input data, see Listing 4-6)	
48	~D	carriage return when done
49	r L	run linear_range
50	DO ~~	to display output region 1 (see Listing 4-7)
51	~	carriage return when done
52	g	graph
53	C	create
54	~	to use data set number 1
55	~	
56	↑↓	to see Mnemonics associated with the variable names

57	(position cell pointer over POWR.4)~	to select POWR.4 at x-variable
58	~	
59	(position cell pointer over USER.2)~	to select USER.2 as first y-variable
60	x ~	enter x to end selection of y-variable
61	GRAPH1	name of graph
62	V	View graph
63	E L	Edit graph legend
64	A	select first data range
65	All at Same Load ~	enter A legend
66	T	Title
67	Y	Y-axis title
68	System Efficiency (%) ~	
69	T	
70	X	X-axis title
71	Building Load (kBtu/h)~	
72	q	quit
73	~	to use GRAPH1 for graph name
74	V	view
75	q	quit graph submenu
76	q	quit main menu
77	/fs BOILEXP1 ~	same spreadsheet in BOILEXP1.WK1
78	(r)	(replace old file if one exists)
79	/fcce {esc 6}	to get main spreadsheet menu program and allow for rapid file loading

Listing 4-2 FUEL AND BOILER PERFORMANCE DATA USED IN EXAMPLE 1

	FI	FJ	FK	FL	FM	FN	FO	FP
1		BOILER						
2							Constants	
3		Fuel Data					==========	==========
4		==========	==========	==========	==========		MO2	32
5		atomic ratio H/C		h	3.6246		MN2	28.016
6		atomic ratio O/C		o	0.01896		MCO2	44.011
7		atomic ratio N/C		n	0.15545		MH2O	18.016
8		atomic ratio S/C		s	0		MSO2	64.066
9		HHV (BTU/lb)		HHV	20120		mfO2	0.233
10							mfN2	0.767
11							R	1.98726
12		Performance	TRA=	70	F	(530	R)	
13		==========	==========	==========	==========	==========	==========	==========
14		PLF	0.01	0.2	0.4	0.6	0.8	1
15		XCO2 (%)	1	4	6	8	9.5	11
16		TSS (F)	500	400	425	450	475	500
17		RT	11.16717	2.859827	1.936788	1.475268	1.256654	1.097661
18		QL (%)	9.420113	9.420113	9.420113	9.420113	9.420113	9.420113
19		QS (%)	85.17809	17.42050	13.05976	10.94253	10.13493	9.583106
20		EFF (%)	5.401794	73.15938	77.52011	79.63735	80.44494	80.99677

Listing 4-3 SIMULATION CONNECTION NUMBERS IN BOILEXP1.WK1, FROM EXAMPLE 1

```
  *1  Boiler
      New Gas Boiler                          Max.Err:       0
  I/O Mnemonic Name         Value Units       Definition
  === ======== =======  ======== ========  ==================
6  I  FLOutpt1 POWR.12      1000 kBtu/hr   Full Load Output
   I  PumpPwr1 POWR.6          5 kw        Pump Power
   I  CtrlMod1 CTRL.4          0 --        0=>use PLF;  1=>use PLFset
   I  PLFset1  CTRL.6          1 --        Setpoint part-load ratio
1  I  PLF1     CTRL.8          1 --        Part-load factor

3  0  Output1  POWR.9       1000 kBtu/hr   Boiler Output
   0  EFF1     MISC.2   80.79380 --        Boiler Efficiency
   0  Input1   POWR.8   1237.718 kBtu/hr   Boiler Input


  *2  Boiler
      New Gas Boiler                          Max.Err:       0
  I/O Mnemonic Name         Value Units       Definition
  === ======== =======  ======== ========  ==================
7  I  FLOutpt2 POWR.13      1000 kBtu/hr   Full Load Output
   I  PumpPwr2 POWR.2          5 kw        Pump Power
   I  CtrlMod2 CTRL.3          0 --        0=>use PLF;  1=>use PLFset
   I  PLFset2  CTRL.5          1 --        Setpoint part-load ratio
2  I  PLF2     CTRL.9          1 --        Part-load factor

4  0  Output2  POWR.10      1000 kBtu/hr   Boiler Output
   0  EFF2     MISC.3   80.79380 --        Boiler Efficiency
   0  Input2   POWR.5   1237.718 kBtu/hr   Boiler Input


  *3  Boiler
      New Gas Boiler                          Max.Err:       0
  I/O Mnemonic Name         Value Units       Definition
  === ======== =======  ======== ========  ==================
8  I  FLOutpt3 POWR.14      1000 kBtu/hr   Full Load Output
   I  PumpPwr3 POWR.1          5 kW        Pump Power
   I  CtrlMod3 CTRL.7          0 --        0=>use PLF;  1=>use PLFset
   I  PLFset3  CTRL.1          1 --        Setpoint part-load ratio
2  I  PLF3     CTRL.9          1 --        Part-load factor

5  0  Output3  POWR.11      1000 kBtu/hr   Boiler Output
   0  EFF3     MISC.1   80.79380 --        Boiler Efficiency
   0  Input3   POWR.3   1237.718 kBtu/hr   Boiler Input
```

Listing 4-3 SIMULATION CONNECTION NUMBERS IN BOILEXP1.WK1, FROM EXAMPLE 1 (Continued)

```
   *4  3-Way Merge Boiler Load Merge
       3-Way Merge w. Load Control         Max.Err:        0
   I/O Mnemonic Name         Value Units    Definition
   === ======== =======  ======== ======== ==================
    I  Nset     CTRL.2           1 --       Control Inlet Numb
3   I  Output1  POWR.9        1000 kBtu/hr  Output of Boiler 1
4   I  Output2  POWR.10       1000 kBtu/hr  Output of Boiler 2
5   I  Output3  POWR.11       1000 kBtu/hr  Output of Boiler 3


6   I  FLOutpt1 POWR.12       1000 kBtu/hr  Boiler1 Full Load Capacity
7   I  FLOutpt2 POWR.13       1000 kBtu/hr  Boiler2 Full Load Capacity
8   I  FLOutpt3 POWR.14       1000 kBtu/hr  Boiler3 Full Load Capacity


    I  Load     POWR.4        3000 kBtu/hr  Building Load
    I  LdPumpPr POWR.7         7.5 kW       Load Pump Power

2   0  PLFavg   CTRL.9           1 --       Avg System PLF
1   0  PLFcalc  CTRL.8           1 --       Calc PLF for control inlet
```

Listing 4-4   USER-DEFINED VARIABLES IN BOILEXP1.WK1, FROM EXAMPLE 1

```
       EZ    FA     FB       FC        FD        FE        FF        FG
81           *5  Additional Outputs                        Max.Err:          0
82
83           I/O Mnemonic Name          Value Units    Definition
84           === ======== =======  ======== ======== ======================
85            0  SysCap   USER.1          †   kBtu/hr  Total System Output
86            0  SysEff   USER.2          ‡   --       Total System Efficiency
87
88
89
90
91
92
93
94
95
96
79
98
99
100
```

† + FD11 + FD31 + FD51

‡ + ((FD11 + FD31 + FD51)/(FD13 + FD33 + FD53))*100

Listing 4-5 SAMPLE SIMULATION OUTPUTS AND INPUTS IN BOILEXP1.WK1, FROM EXAMPLE 1

```
POST     Three Gas-Fired Boilers                               Err.Tol =    0.001
                                                                Max.Err =        0
Simulation Outputs                       (Page Left for Inputs)
===================================================================================
Mnemonic Name          Value Units       Definition
PLFcalc  CTRL.8            1 --          Calc PLF for control inlet
PLFavg   CTRL.9            1 --          Avg System PLF
EFF3     MISC.1     80.79380 --          Boiler Efficiency
EFF1     MISC.2     80.79380 --          Boiler Efficiency
EFF2     MISC.3     80.79380 --          Boiler Efficiency
Input3   POWR.3     1237.718 kBtu/hr     Boiler Input
Input2   POWR.5     1237.718 kBtu/hr     Boiler Input
Input1   POWR.8     1237.718 kBtu/hr     Boiler Input
Output1  POWR.9         1000 kBtu/hr     Boiler Output
Output2  POWR.10        1000 kBtu/hr     Boiler Output
Output3  POWR.11        1000 kBtu/hr     Boiler Output
SysCap   USER.1         3000 kBtu/hr     Total System Output
SysEff   USER.2     80.79380 --          Total System Efficiency


Simulation Inputs                        (Page Right for Outputs)
===================================================================================
Mnemonic Name          Value Units       Definition
PLFset3  CTRL.1            1 --          Setpoint part-load ratio
Nset     CTRL.2            1 --          Control Inlet Number
CtrlMod2 CTRL.3            0 --          0=>use PLF;  1=>use PLFset
CtrlMod1 CTRL.4            0 --          0=>use PLF;  1=>use PLFset
PLFset2  CTRL.5            1 --          Setpoint part-load ratio
PLFset1  CTRL.6            1 --          Setpoint part-load ratio
CtrlMod3 CTRL.7            0 --          0=>use PLF;  1=>use PLFset
PumpPwr3 POWR.1            5 kW          Pump Power
PumpPwr2 POWR.2            5 kW          Pump Power
Load     POWR.4         3000 kBtu/hr     Building Load
PumpPwr1 POWR.6            5 kW          Pump Power
LdPumpPr POWR.7          7.5 kW          Load Pump Power
FLOutpt1 POWR.12        1000 kBtu/hr     Full Load Output
FLOutpt2 POWR.13        1000 kBtu/hr     Full Load Output
FLOutpt3 POWR.14        1000 kBtu/hr     Boiler3 Full Load Capacity
```

Listing 4-6 LINEAR INPUT DATA IN BOILEXP1.WK1, FROM EXAMPLE 1

```
Edit  View  Quit  Done
Edit linear input settings
          AG          AH          AI          AJ          A          B            C      D
1   Linear Input Settings                             5   Mnemonic Name          Value Units
2   ====================                              6   PLFset3  CTRL.1            1 --
3   Number of variable inputs:                     1 7   Nset     CTRL.2            1 --
4   Number of steps for each:                     19 8   CtrlMod2 CTRL.3            0 --
5   Output Data Set Number:                        1 9   CtrlMod1 CTRL.4            0 --
6                                                 10  PLFset2  CTRL.5            1 --
7   Var.      Variable      First        Last     11  PLFset1  CTRL.6            1 --
8   No.       Name          Value        Value    12  CtrlMod3 CTRL.7            0 --
9   ===       =======       =====        =====    13  PumpPwr3 POWR.1            5 kW
10  1         POWR.4          150         3000    14  PumpPwr2 POWR.2            5 kW
11  2                                             15  Load     POWR.4         3000 kBtu/hr
12  3                                             16  PumpPwr1 POWR.6            5 kW
13  4                                             17  LdPumpPr POWR.7          7.5 kW
14  5                                             18  FLOutpt1 POWR.12        1000 kBtu/hr
15                                                19  FLOutpt2 POWR.13        1000 kBtu/hr
16  Current Mode:       Line Input                20  FLOutpt3 POWR.14        1000 kBtu/hr
17                                                21
18                                                22
19                                                23
20                                                24
```

Listing 4-7 OUTPUT DATA SET 1 IN BOILEXP1.WK1, FROM EXAMPLE 1

	B	C	D	E	F	G	H	I
999	0	PLFcalc	PLFavg	EFF3	EFF1	EFF2	Input3	Input2
1000	POWR.4	CTRL.8	CTRL.9	MISC.1	MISC.2	MISC.3	POWR.3	POWR.5
1001	150	0.05	0.05	43.67350	43.67350	43.67350	114.4858	114.4858
1002	300	0.1	0.1	62.42117	62.42117	62.42117	160.2020	160.2020
1003	450	0.15	0.15	69.49426	69.49426	69.49426	215.8451	215.8451
1004	600	0.2	0.2	73.00070	73.00070	73.00070	273.9699	273.9699
1005	750	0.25	0.25	75.05535	75.05535	75.05535	333.0874	333.0874
1006	900	0.3	0.3	76.39393	76.39393	76.39393	392.7013	392.7013
1007	1050	0.35	0.35	77.33117	77.33117	77.33117	452.5988	452.5988
1008	1200	0.4	0.4	78.02235	78.02235	78.02235	512.6735	512.6735
1009	1350	0.45	0.45	78.55233	78.55233	78.55233	572.8664	572.8664
1010	1500	0.5	0.5	78.97120	78.97120	78.97120	633.1421	633.1421
1011	1650	0.55	0.55	79.31037	79.31037	79.31037	693.4779	693.4779
1012	1800	0.6	0.6	79.59049	79.59049	79.59049	753.8588	753.8588
1013	1950	0.65	0.65	79.82565	79.82565	79.82565	814.2745	814.2745
1014	2100	0.7	0.7	80.02584	80.02584	80.02584	874.7174	874.7174
1015	2250	0.75	0.75	80.19827	80.19827	80.19827	935.1821	935.1821
1016	2400	0.8	0.8	80.34833	80.34833	80.34833	995.6646	995.6646
1017	2550	0.85	0.85	80.48009	80.48009	80.48009	1056.161	1056.161
1018	2700	0.9	0.9	80.59670	80.59670	80.59670	1116.670	1116.670
1019	2850	0.95	0.95	80.70062	80.70062	80.70062	1177.190	1177.190
1020	3000	1	1	80.79380	80.79380	80.79380	1237.718	1237.718

5. EXAMPLE 2: SEQUENTIAL OPERATION OF THREE GAS-FIRED BOILERS

In this example, three identical gas-fired boilers are operated sequentially to meet a hypothetical building load. As the building load increases from zero, the first boiler is operated at higher and higher part load factors to meet the load, while boilers 2 and 3 remain off. As the building load increases past the point where the part load factor of boiler 1 becomes equal to 1.0, then boiler 2 is fired. Finally, boiler 3 is fired when the building load has increased to the point where boilers 1 and 2 running at full capacity (i.e., both have part load factors equal to 1.0) cannot provide enough heat output to meet the load.

Listing 5-1 provides an outline of the steps necessary to setup, run, and analyze the results from this example, while Listings 5-2 through 5-6 provide supplemental information. Individual keystrokes are <u>not</u> provided, since it is expected that a user who has worked through Example 1 successfully should not encounter serious difficulty.

5.1 The Component Models

The component models in this example are the same as those described in section 4.1 for Example 1. The only difference that occurs is how they are linked together and the parameters chosen for some of the Simulation Inputs.

When the boilers are operated sequentially, PLFavg in the N-Way Merge with Heating Load Control model is not used. Instead, PLFcalc is connected to the PLF inputs on all the boilers. For a boiler operating at part load, the CtrlMod(e) parameter in the Simulation Inputs is set to 1 and the full load output FLOutpt is set to full load capacity of the boiler. For boilers which are not operating, the CtrlMod(e) should be set to 1, the PLFset parameters should be set to a very small value (e.g., 0.00001, but never 0) and the FLOutpt variable should be given the value 0.0. A boiler that is running at full load should have CtrlMod(e) and PLFset both set to 1 and FLOutpt should be set equal to the full load capacity of the boiler.

5.2 Setting Up and Running Example 2

The starting point for Example 2 is the spreadsheet (BOILEXP1.WK1) created and saved in Example 1. This spreadsheet should be retrieved and the connection numbers changed as described in the previous section and as illustrated in Listing 5-2. The Initialize command in the main menu should then be used to reinitialize the simulation. The user-defined variables created in Example 1 will be automatically incorporated into the Simulation Outputs.

In order to consider the three cases of interest:

- Boiler 1 operates at part load to meet the building load with Boilers 2 and 3 off,

- Boiler 1 runs at full load, boiler 2 operates at part load, and boiler 3 is off, and

- Boilers 1 and 2 operate at full load while boiler 3 operates at part load,

the Simulation Inputs and the Linear Input ranges must be changed and the simulation Run for each of these cases. Listing 5-3 gives sample inputs for each case, while Listing 5-4 shows how to setup a Linear_Input range for case 1. The results of cases 1, 2, and 3 should be copied to Output Regions 2, 3, and 4, respectively. After all three cases have been run, the results should be combined in Output Region 5 (using the menu commands in 1-2-3) to give a continuous set of system performance data for all building loads between 150 and 3000 kBtu/h. Listing 5-5 shows the Simulation Outputs and Inputs for case 3 and a building load of 3000 kBtu/h, while Listing 5-6 displays part of the combined performance data from Output Region 5.

5.3 Simulation Results

The combined system performance data in Output Region 5 were used to generate the graph shown in Figure 6 which shows the effect of sequential boiler operation on System Efficiency. It is interesting to note how the system efficiency drops as each successive boiler is fired up. Figure 7 is a combination plot showing System Efficiency versus Building Load for the case where all boilers operate at the same part load factor (the data in Output Region 1 from Example 1) and the case where the boilers are operated sequentially (same as Figure 6 using Output Region 5). It is clear that for these particular gas-fired boilers it is much more efficient to operate them sequentially at building loads below 2000 kBtu/h.

Listing 5-1 OUTLINE OF PROCEDURE FOR GENERATING BOILEXP2.WK1 IN EXAMPLE 2

BOILEXP2 uses BOILEXP.1 and adds three more cases

- o boiler #1 operates at part load to meet low building loads
- o boiler #1 runs at full load and boiler operates at part load
- o boiler #1 and #2 run at full load and boiler #3 operates at part load.

Load Spreedsheet Program and then retrieve BOILEXP1

Change connection numbers between component models (see Attachment 1)

Initialize simulation

Change Simulation Inputs so only boiler #1 operates at part load, other boilers are off
(see Listing 5-3b)

Change Linear_range so that:

Number of variable inputs = 1
Number of steps for each = 5
Output data set = 2
The variable POWR.5 goes from a first value of 150 to a last value of 900
(see Listing 5-4)

Run Linear_range

Change Simulation Inputs so that boiler #1 runs at full load while #2 operates at part load
(see Listing 5-3b)

Change Linear_range (use output data set = 3, 6 steps, POWR.5 goes from 1050 to 1950)

Run Linear_range

Change Simulation Input so that boilers #1 and #2 run at full load while #3 operates at part load
(see Listings 5-3c and 5-5)

Change Linear_range (use output data set = 4, 6 steps, POWR.5 goes from 2100 to 3000)

Run Linear_range

Use 1-2-3 menu to move data in output region #2 to region #5. Append data from region #3 and region #4 to it so that the building load, POWR.5, goes from 150 to 3000 kBtu/h in one data set (see Listing 5-6)

Plot system efficiency vs. building load for data region #5 in GRAPH2

Edit GRAPH1 to include the same results plotted in GRAPH2 and save in GRAPH3

Use Spreadsheet menu commands to change the Y-scale in GRAPH3 and save in GRAPH4

Save GRAPH1, GRAPH2 and GRAPH3 using SAVEPIC in Graph menu for later printing

Save spreadsheet as BOILEXP2.WK1

Listing 5-2 SIMULATION CONNECTION NUMBERS IN BOILEXP2.WK1, FROM EXAMPLE 2

```
  *1  Boiler
      New Gas Boiler                                 Max.Err:        0
  I/O Mnemonic Name        Value Units    Definition
  === ======== =======  ======== ======== =================
6  I  FLOutpt1 POWR.12      1000 kBtu/hr  Full Load Output
   I  PumpPwr1 POWR.1          5 kW       Pump Power
   I  CtrlMod1 CTRL.6          0 --       0=>use PLF;  1=>use PLFset
   I  PLFset1  CTRL.5          1 --       Setpoint part-load ratio
1  I  PLF1     CTRL.9          1 --       Part-load factor

3  O  Output1  POWR.9       1000 kBtu/hr  Boiler Output
   O  EFF1     MISC.2   80.79380 --       Boiler Efficiency
   O  Input1   POWR.3   1237.718 kBtu/hr  Boiler Input


  *2  Boiler
      New Gas Boiler                                 Max.Err:        0
  I/O Mnemonic Name        Value Units    Definition
  === ======== =======  ======== ======== =================
7  I  FLOutpt2 POWR.13         0 kBtu/hr  Full Load Output
   I  PumpPwr2 POWR.8          5 kW       Pump Power
   I  CtrlMod2 CTRL.7          1 --       0=>use PLF;  1=>use PLFset
   I  PLFset2  CTRL.8    0.00001 --       Setpoint part-load ratio
1  I  PLF2     CTRL.9          1 --       Part-load factor

4  O  Output2  POWR.10         0 kBtu/hr  Boiler Output
   O  EFF2     MISC.3   0.000006 --       Boiler Efficiency
   O  Input2   POWR.7          0 kBtu/hr  Boiler Input


  *3  Boiler
      New Gas Boiler                                 Max.Err:        0
  I/O Mnemonic Name        Value Units    Definition
  === ======== =======  ======== ======== =================
8  I  FLOutpt3 POWR.14         0 kBtu/hr  Full Load Output
   I  PumpPwr3 POWR.4       1000 kW       Pump Power
   I  CtrlMod3 CTRL.1          1 --       0=>use PLF;  1=>use PLFset
   I  PLFset3  CTRL.2    0.00001 --       Setpoint part-load ratio
1  I  PLF3     CTRL.9          1 --       Part-load factor

5  O  Output3  POWR.11         0 kBtu/hr  Boiler Output
   O  EFF3     MISC.1   0.000006 --       Boiler Efficiency
   O  Input3   POWR.6          0 kBtu/hr  Boiler Input
```

Listing 5-2 SIMULATION CONNECTION NUMBERS IN BOILEXP2.WK1, FROM EXAMPLE 2 (continued)

```
   *4  3-Way Merge Boiler Load Merge
       3-Way Merge w. Load Control              Max.Err:        0
   I/O Mnemonic Name          Value Units       Definition
   === ======== =======    ======== ========  ==================
    I  Nset     CTRL.4            1 --          Control Inlet Numb
3   I  Output1  POWR.9         1000 kBtu/hr     Output of Boiler 1
4   I  Output2  POWR.10           0 kBtu/hr     Output of Boiler 2
5   I  Output3  POWR.11           0 kBtu/hr     Output of Boiler 3


6   I  FLOutpt1 POWR.12        1000 kBtu/hr     Boiler1 Full Load Capacity
7   I  FLOutpt2 POWR.13           0 kBtu/hr     Boiler2 Full Load Capacity
8   I  FLOutpt3 POWR.14           0 kBtu/hr     Boiler3 Full Load Capacity


    I  Load     POWR.5         1000 kBtu/hr     Building Load
    I  LdPumpPr POWR.2          7.5 kW          Load Pump Power

    O  PLFavg   CTRL.3            1  --         Avg System PLF
1   O  PLFcalc  CTRL.9            1  --         Calc PLF for control inlet
   *5  Additional Outputs                       Max.Err:        0

   I/O Mnemonic Name          Value Units       Definition
   === ======== =======    ======== ========  ==================
    O  SysCap   USER.1         1000 kBtu/hr     Total System Output
    O  SysEff   USER.2     80.79380 --          Total System Efficiency
```

Listing 5-3a SAMPLE INPUTS IN BOILEXP2.WK1, FROM EXAMPLE 2

	A	B	C	D	E	F	G	H
1	POST	Three Gas-Fired Boilers					Err.Tol =	0.001
2							Max.Err =	0
3	Simulation Inputs[1]				(Page Right for Outputs)			
4	==							
5	Mnemonic	Name	Value	Units	Definition			
6	CtrlMod3	CTRL.1	1	--	0=>use PLF; 1=>use PLFset			
7	PLFset3	CTRL.2	0.00001	--	Setpoint part-load ratio			
8	Nset	CTRL.4	1	--	Control Inlet Number			
9	PLFset1	CTRL.5	1	--	Setpoint part-load ratio			
10	CtrlMod1	CTRL.6	0	--	0=>use PLF; 1=>use PLFset			
11	CtrlMod2	CTRL.7	1	--	0=>use PLF; 1=>use PLFset			
12	PLFset2	CTRL.8	0.00001	--	Setpoint part-load ratio			
13	PumpPwr1	POWR.1	5	kW	Pump Power			
14	LdPumpPr	POWR.2	7.5	kW	Load Pump Power			
15	PumpPwr3	POWR.4	5	kW	Pump Power			
16	Load	POWR.5	1000	kBtu/hr	Building Load			
17	PumpPwr2	POWR.8	5	kW	Pump Power			
18	FLOutpt1	POWR.12	1000	kBtu/hr	Full Load Output			
19	FLOutpt2	POWR.13	0	kBtu/hr	Full Load Output			
20	FLOutpt3	POWR.14	0	kBtu/hr	Full Load Output			

[1] Boiler 1 operates at part-load. Boilers 2 and 3 are off.

Listing 5-3b SAMPLE INPUTS IN BOILEXP2.WK1, FROM EXAMPLE 2

	A	B	C	D	E	F	G	H
1	POST	Three Gas-Fired Boilers					Err.Tol =	0.001
2							Max.Err =	0
3	Simulation Inputs[2]				(Page Right for Outputs)			
4	==							
5	Mnemonic	Name	Value	Units	Definition			
6	CtrlMod3	CTRL.1	1	--	0=>use PLF; 1=>use PLFset			
7	PLFset3	CTRL.2	0.00001	--	Setpoint part-load ratio			
8	Nset	CTRL.4	2	--	Control Inlet Number			
9	PLFset1	CTRL.5	1	--	Setpoint part-load ratio			
10	CtrlMod1	CTRL.6	1	--	0=>use PLF; 1=>use PLFset			
11	CtrlMod2	CTRL.7	0	--	0=>use PLF; 1=>use PLFset			
12	PLFset2	CTRL.8	1	--	Setpoint part-load ratio			
13	PumpPwr1	POWR.1	5	kW	Pump Power			
14	LdPumpPr	POWR.2	7.5	kW	Load Pump Power			
15	PumpPwr3	POWR.4	5	kW	Pump Power			
16	Load	POWR.5	2000	kBtu/hr	Building Load			
17	PumpPwr2	POWR.8	5	kW	Pump Power			
18	FLOutpt1	POWR.12	1000	kBtu/hr	Full Load Output			
19	FLOutpt2	POWR.13	1000	kBtu/hr	Full Load Output			
20	FLOutpt3	POWR.14	0	kBtu/hr	Full Load Output			

[2] Boiler 1 operates at full load. Boiler 2 operates at part-load. Boiler 3 is off.

Listing 5-3c SAMPLE INPUTS IN BOILEXP2.WK1, FROM EXAMPLE 2

	A	B	C	D	E	F	G	H
1	POST	Three Gas-Fired Boilers					Err.Tol =	0.001
2							Max.Err =	0
3	Simulation Inputs[3]				(Page Right for Outputs)			
4	==========	==========	==========	==========	==========	==========	==========	==========
5	Mnemonic	Name	Value	Units	Definition			
6	CtrlMod3	CTRL.1	0	--	0=>use PLF; 1=>use PLFset			
7	PLFset3	CTRL.2	1	--	Setpoint part-load ratio			
8	Nset	CTRL.4	3	--	Control Inlet Number			
9	PLFset1	CTRL.5	1	--	Setpoint part-load ratio			
10	CtrlMod1	CTRL.6	1	--	0=>use PLF; 1=>use PLFset			
11	CtrlMod2	CTRL.7	1	--	0=>use PLF; 1=>use PLFset			
12	PLFset2	CTRL.8	1	--	Setpoint part-load ratio			
13	PumpPwr1	POWR.1	5	kW	Pump Power			
14	LdPumpPr	POWR.2	7.5	kW	Load Pump Power			
15	PumpPwr3	POWR.4	5	kW	Pump Power			
16	Load	POWR.5	3000	kBtu/hr	Building Load			
17	PumpPwr2	POWR.8	5	kW	Pump Power			
18	FLOutpt1	POWR.12	1000	kBtu/hr	Full Load Output			
19	FLOutpt2	POWR.13	1000	kBtu/hr	Full Load Output			
20	FLOutpt3	POWR.14	1000	kBtu/hr	Full Load Output			

[3]Boilers 1 and 2 operate at full load. Boiler 3 operates at part-load.

Listing 5-4   LINEAR RANGE FOR DATA SET 1 IN BOILEXP2.WK1, FROM EXAMPLE 2

```
Edit  View  Quit  Done
Edit linear input settings
        AG        AH        AI        AJ           A         B          C        D
1   Linear Input Settings                     5   Mnemonic Name        Value Units
2   ====================                      6   CtrlMod3 CTRL.1          1 --
3   Number of variable inputs:              1 7   PLFset3  CTRL.2    0.00001 --
4   Number of steps for each:               5 8   Nset     CTRL.4          1 --
5   Output Data Set Number:                 2 9   PLFset1  CTRL.5          1 --
6                                             10  CtrlMod1 CTRL.6          0 --
7   Var.      Variable    First      Last     11  CtrlMod2 CTRL.7          1 --
8   No.       Name        Value      Value    12  PLFset2  CTRL.8    0.00001 --
9   ===       =======     =====      =====    13  PumpPwr1 POWR.1          5 kW
10  1         POWR.5        150        900    14  LdPumpPr POWR.2        7.5 kW
11  2                                         15  PumpPwr3 POWR.4          5 kW
12  3                                         16  Load     POWR.5        900 kBtu/hr
13  4                                         17  PumpPwr2 POWR.8          5 kW
14  5                                         18  FLOutpt1 POWR.12      1000 kBtu/hr
15                                            19  FLOutpt2 POWR.13         0 kBtu/hr
16  Current Mode:      Line Input             20  FLOutpt3 POWR.14         0 kBtu/hr
17                                            21
18                                            22
19                                            23
20                                            24
```

Listing 5-5 EXAMPLE 2 SAMPLE SIMULATION OUTPUTS AND INPUTS IN BOILEXP2.WK1 WITH ALL THREE BOILERS AT FULL LOAD

```
POST     Three Gas-Fired Boilers                        Err.Tol =   0.001
                                                        Max.Err =       0
Simulation Outputs                (Page Left for Inputs)
============================================================================
Mnemonic Name        Value Units     Definition
PLFavg   CTRL.3          1 --        Avg System PLF
PLFcalc  CTRL.9          1 --        Calc PLF for control inlet
EFF3     MISC.1   80.79380 --        Boiler Efficiency
EFF1     MISC.2   80.79380 --        Boiler Efficiency
EFF2     MISC.3   80.79380 --        Boiler Efficiency
Input1   POWR.3   1237.718 kBtu/hr   Boiler Input
Input3   POWR.6   1237.718 kBtu/hr   Boiler Input
Input2   POWR.7   1237.718 kBtu/hr   Boiler Input
Output1  POWR.9       1000 kBtu/hr   Boiler Output
Output2  POWR.10      1000 kBtu/hr   Boiler Output
Output3  POWR.11      1000 kBtu/hr   Boiler Output
SysCap   USER.1       3000 kBtu/hr   Total System Output
SysEff   USER.2   80.79380 --        Total System Efficiency


Simulation Inputs                 (Page Right for Outputs)
============================================================================
Mnemonic Name         Value Units    Definition
CtrlMod3 CTRL.1           0 --       0=>use PLF;  1=>use PLFset
PLFset3  CTRL.2           1 --       Setpoint part-load ratio
Nset     CTRL.4           3 --       Control Inlet Number
PLFset1  CTRL.5           1 --       Setpoint part-load ratio
CtrlMod1 CTRL.6           1 --       0=>use PLF;  1=>use PLFset
CtrlMod2 CTRL.7           1 --       0=>use PLF;  1=>use PLFset
PLFset2  CTRL.8           1 --       Setpoint part-load ratio
PumpPwr1 POWR.1           5 kW       Pump Power
LdPumpPr POWR.2         7.5 kW       Load Pump Power
PumpPwr3 POWR.4           5 kW       Pump Power
Load     POWR.5        3000 kBtu/hr  Building load
PumpPwr2 POWR.8           5 kW       Pump Power
FLOutpt1 POWR.12       1000 kBtu/hr  Full Load Output
FLOutpt2 POWR.13       1000 kBtu/hr  Full Load Output
FLOutpt3 POWR.14       1000 kBtu/hr  Full Load Output
```

Listing 5-6 DATA SET 5 IN BOILEXP2.WK1, FROM EXAMPLE 2

	B	C	D	E	F	G	H	I
1999	0	PLFavg	PLFcalc	EFF3	EFF1	EFF2	Input1	Input3
2000	POWR.5	CTRL.3	CTRL.9	MISC.1	MISC.2	MISC.3	POWR.3	POWR.6
2001	150	0.15	0.15	0.000006	69.49426	0.000006	215.8451	0
2002	300	0.3	0.3	0.000006	76.39393	0.000006	392.7013	0
2003	450	0.45	0.45	0.000006	78.55233	0.000006	572.8664	0
2004	600	0.6	0.6	0.000006	79.59049	0.000006	753.8588	0
2005	750	0.75	0.75	0.000006	80.19827	0.000006	935.1821	0
2006	900	0.9	0.9	0.000006	80.59670	0.000006	1116.670	0
2007	1050	0.525	0.05	0.000006	80.79380	43.67350	1237.718	0
2008	1200	0.6	0.2	0.000006	80.79380	73.00070	1237.718	0
2009	1350	0.675	0.35	0.000006	80.79380	77.33117	1237.718	0
2010	1500	0.75	0.5	0.000006	80.79380	78.97120	1237.718	0
2011	1650	0.825	0.65	0.000006	80.79380	79.82565	1237.718	0
2012	1800	0.9	0.8	0.000006	80.79380	80.34833	1237.718	0
2013	1950	0.975	0.95	0.000006	80.79380	80.70062	1237.718	0
2014	2100	0.7	0.1	62.42117	80.79380	80.79380	1237.718	160.2020
2015	2250	0.75	0.25	75.05535	80.79380	80.79380	1237.718	333.0874
2016	2400	0.8	0.4	78.02235	80.79380	80.79380	1237.718	512.6735
2017	2550	0.85	0.55	79.31037	80.79380	80.79380	1237.718	693.4779
2018	2700	0.9	0.7	80.02584	80.79380	80.79380	1237.718	874.7174
2019	2850	0.95	0.85	80.48009	80.79380	80.79380	1237.718	1056.161
2020	3000	1	1	80.79380	80.79380	80.79380	1237.718	1237.718

6. EXAMPLE 3: TWO CHILLERS AND A COOLING TOWER

This example consists of a central cooling plant containing a cooling tower, two identical chillers connected in parallel, and two flow merge components. Two control strategies are considered--both chillers running at the same part load factor and sequential operation of the chillers to meet the cooling load on the plant.

6.1 The Component Models

For the cooling tower, the user must first enter the number of cells in the tower, the volumetric flow rate per fan at each of three settings (off, low speed, and high speed), and the power consumption per fan at low and high speeds. A data entry form is provided for this information.

A second data form is then displayed for entry of initial values of the inputs to the model. These are the water flow rate and temperature entering the cooling tower, the off/low/high settings of the fans, the entering air dry bulb and wet bulb temperatures, and the barometric pressure. The volumetric air flow rate is determined by the fan settings and the previously entered fan data. The dry bulb temperature is used only in converting the volumetric flow rate to a mass flow rate. The barometric pressure is also used in this conversion and in psychrometric calculations.

Cooling tower performance is characterized by a single fixed parameter called the "factor of merit," F (Whillier 1967). After initial values of the input variables are supplied, the user is given three choices for specifying F. First, a value of F may be entered. Second, F may be calculated from a single operating point. In this case the input variables are used in conjunction with a single value of the water outlet temperature to determine F. Third, performance data may be entered. In this case a value of F is calculated for each data point, and the average is used. The standard deviation of F is also displayed.

When the performance data option is selected, the nature of the available data may be specified. Values of the entering air wet bulb temperature and the water inlet and outlet temperatures are always required. The default assumes that all other inputs, including the volumetric air flow rate calculated from the fan settings, are fixed at their initial values. A format option permits the data to be entered either as a table of water outlet temperatures versus a row of wet bulb temperatures and a column of water inlet temperatures, or as three columns of data. The former is more convenient for manufacturer's data which is already in tabular form, while the latter is usually needed for experimental data.

Alternatively, other inputs may be identified as additional variables. For example, if data are available at more than one air flow rate, this input may be marked as a variable rather than a constant. Columns of data would then be entered for each of the four variables. The tabular format option is not available when additional variables are specified.

The centrifugal chiller model is similar to the one recommended by Stoecker (1975), the major difference being that capacity and power are correlated with evaporator and condenser inlet temperatures rather than with the evaporator outlet (chilled water) temperature and the condenser water inlet temperature. This is to eliminate the need for an iterative solution under conditions where the chilled water outlet temperature is not immediately known. When outlet temperatures are provided as performance data, the inlet temperatures are calculated during the setup procedure.

The centrifugal chiller requires three sets of performance data: full load capacity versus evaporator and condenser temperatures, and power ratio (actual power consumption divided by full load capacity). As with the cooling tower, the procedure begins with a page of text summarizing the performance data requirements and a menu allowing the user to either proceed or return to the menu. The next step requires entry of initial values for the inputs to the model and then performance data is requested. The nature of the available data can again be specified. Evaporator and condenser temperatures are required, but in both cases either inlet or outlet temperatures may be entered. Either a tabular format or a columnar format for data entry may be chosen.

Once the performance data have been entered, linear regression is used to generate coefficients for the correlation equations. The resulting coefficients are inserted into the model in place of the generic coefficients. A label identifying the specific chiller is requested before the model is stored in the specific components library.

The merge component model simply mixes flow streams having different flow rates and temperatures to find the mixed flow rate and temperature leaving the merge. The merge with control is a little more complicated and is discussed below in the context of setting up the two chillers/cooling tower simulation.

6.2 Setting Up and Running Example 3

Figure 8 is a block diagram of the central cooling plant. All variables which represent connections between components are identified on this diagram. For example, the temperatures labeled T_1 and T2 are outputs from the two chillers and inputs to the flow merge. T_3 is an output from the merge and an input to the cooling tower, while T_4 is an output from the cooling tower and an input to both chillers. Since no load model is used in this example, the return temperature from the load, T_5, is a boundary condition. Temperatures T_8 and T_9 are setpoints for the two chillers.

The chiller model has two modes of operation, selected by means of the input called CtrlMode. When CtrlMode = 0, the chilled water temperature is controlled to a specified setpoint temperature and any value entered for the part load ratio setpoint, PLRset, is ignored. When CtrlMode = 1, the chiller operates at a specified part load ratio setpoint, PLRset, and any value entered for the setpoint temperature is ignored. With the CtrlMode for the first chiller set equal to 0, this chiller is in the temperature setpoint mode. If the CtrlMode for the second chiller were 1, it would operate in a part load setpoint mode at full capacity (with PLRset = 1). The "Flow Merge with Setpoint Control" component, which controls the mixed water temperature downstream from the merge, would then calculate the setpoint temperature Tset for the first chiller such that the mixed water temperature after the merge will equal the overall setpoint temperature after mixing, TsetAvg. In this case, the second chiller would cool the water as long as it could, say to about 38.5 F (13.1°C) at full capacity, and the first chiller would cool the water to a Tset = 43.5 F (15.8°C) if the mixed water supply temperature setpoint, TsetAvg, was 41 F (14.4°C). If the chilled water return temperature or the ambient wet bulb temperature is changed, the second chiller will still operate at full capacity but the chilled water supply temperature will change. The merge and control component will automatically adjust the temperature setpoint Tset of the second chiller to maintain the mixed water temperature at the overall setpoint, TsetAvg.

An alternative control strategy is to operate both chillers with a chilled water outlet temperature equal to the overall setpoint. Since the two chillers in this example are identical, this means both will run at the same part load ratio. The simulation can be switched to this strategy simply by changing the control mode of the second chiller, CtrlMode, from 1 to 0.

Listing 6-1 is a keystroke-by-keystroke procedure for setting up and running a simulation which examines how best to operate the cooling tower (i.e., number of fans on high and low speeds) and compares sequential operation of the chillers with operation of the chillers at identical part-load factors. Listings 6-2 through 6-6 provide the user with supplemental information. The System COP, which is a useful measure of system performance, is added as a user defined output for comparing the different control strategies.

6.3 Simulation Results

Figure 9 is a graph of System COP as a function of the chilled water temperature returning from the load. The line denoted by crosses was generated with the second chiller at full capacity and the first chiller operating in the temperature setpoint mode. The line denoted by squares was produced with both chillers operating at the same capacity to meet the setpoint temperature. The figure shows that for this system under these operating conditions, the later strategy is slightly more efficient over most but not quite all of the range of loads examined. The chiller performance at low return water temperature (below 48 F (8.7°C) results in unrealistic by low part load factors for chiller 1, and thus the results shown for these low temperature conditions are questionable. To create this figure, the following steps were taken:

1. The Setup Linear_Input command was used to generate a column of values of chilled water return temperature from 46 F (17.2°C) to 51 F (20°C) in half-degree intervals in output region 1.

2. The Setup Report command was used to specify a few outputs to be reported.

3. The Run Linear_Input command was used to run a simulation using these temperatures.

4. The Graph Create command was used to generate a graph of System COP as a function of chilled water return temperature.

5. The variable CtrlMode for the second chiller was changed from 1 to 0 on the Simulation Input portion of the worksheet.

6. The Setup Linear_Input command was used again to store the same temperatures in output region 2, and another simulation was run as before.

7. The Graph Edit command was used to add the second line to the graph, and to modify the titles and legends on the graph.

8. The Graph SavePic command was used to store the graph in a file for later printing.

Listing 6-1 COMPLETE PROCEDURE FOR CREATING CHILLEXP.WK1 IN EXAMPLE 3

STEP	KEYSTROKE ENTRY	COMMENTS
1	/f cce {esc 5} r SETUP ~	Load SETUP.WK1. If already loaded, use Alt M to obtain MENU (note: cce {esc 5} speeds up loading process. Also ~ indicates a carriage return)
2	t	tower
3	C	continue
4	~	fan data
5	~	initial input values
6	V 0.6~	Value of F
7	Tower w. F = 0.6~	Specific name
8	{right}~	Chiller
9	C	continue
10	~	initial input values
11	3~	will supply Tevap.out and Tcond.in
12	C	columns
13	20~	# rows of data
14	~	use default ASHRAE data
15	11~	# rows part load data
16	~	use default data
17	400 ton (from ASHRAE data)~	specific name
18	{right 2} ~ C	Merge, continue
19	2~	# of flowstreams
20	~ ~	use existing units label (gpm) and default input values
21	Condenser Water Merge~	specific name

22	{right 3} ~ C	Ctrl Merge, continue
23	2~	# of flowstreams
24	~ ~	use existing units label (gpm) and default input values
25	Chilled water merge/control~	specific name
26	q	Quit
27	/fsSETUP1~	File save SETUP1 (extension .WK1 supplied by Lotus)
28	r	replace existing copy of SETUP1.WK1
29	/frpost ~	retrieve POST.WK1
30	Alt-M S	Begin procedure to copy components from setup worksheet
31	SETUP1~	Enter name of setup worksheet
32	{down 2}~	Select Chiller
33	~ ~	Make it 1st page of simulation
34	{down 2}~	Select Chiller again
35	~{pgdn}~	Make it 2nd page of simulation
36	{down}~	Select Cooling Tower
37	~{pgdn 2}~	Make it 3rd page of simulation
38	{down 3}~	Select Merge
39	~{pgdn 3}~	Make it 4th page of simulation
40	{down 4}~	Select Merge/Control
41	~{pgdn 4}~	Make it 5th page of simulation
42	~	Quit component entry
43	Cooling Tower and Two Chillers~	Enter simulation title
44	Ctrl-right arrow	Enter connection numbers (see Listing 6-2)
45	Alt-M I	Initialize simulation

46	CO~	Change Output and enter a single user-defined variable (Mnemonic, Name, Value, Units, and Definition. Enter Formula for Value)
47	Alt-V	Incorporate System COP into simulation
48	R~	Run in single point mode to smooth feathers ruffled by insertion
49	CRE	Change Reported variables list, Edit
50	flow.1 {down}	Report air flow thru cooling tower
51	misc.3 {down}	Report PLR of 1st chiller
52	misc.6 {down}	Report System COP
53	powr.4 {down}	Report chiller #1 cooling power output
54	powr.5 {down}	Report chiller #2 cooling power output
55	temp.3 ~	Report chilled water temp. supplied to load
56	~	End editing
57	D	Done
58	{esc}	Return to Main Menu
59	CP	Setup Periodic Inputs for a quick look at effects of cooling tower fan speed and chiller control mode
60	E 3{down}9{down}1{down}9{right} ctrl.2{down}ctrl.8{down}ctrl.6{right} L{up}L{up}L~~	Fill in input settings
61	C	Continue
62	{pgdn} (enter data)	enter data (see Listing 6-3)

63	Alt-M	Fire up the Main Menu again
64	RP	Run simulation with Periodic input

Conclusions from this simulation:
With this particular load and weather =
1) System COP is highest when both cooling tower fans run at low speed.
2) System COP is highest when both chillers run at same PLR (CTRL.6=0) rather than one chiller at full capacity and one at part load (CTRL.6=1).

65	~ ~ ~ (Change NFanHi (CTRL.2) to 0) (Change NFanLo (CTRL.8) to 2) (Make sure CTRL.3=0 and CTRL.6=1)	Display Variables, enable arrow keys
66	~	Back to Main Menu
67	CLE	Change Line_Inputs, Edit
68	1{down}10{down}2{right} temp.8{right}47{right}5~~ D	Vary Tchwi, the temp. returning from load, from $47^{\circ}F$ to $52^{\circ}F$ in 10 steps (half-degree intervals)
69	RL	Simulation stored at A2000
70	CLE	Prepare to run another Line_Input Simulation
71	{down} {down}3 ~~ D	Write output to Region 3 (A3000)
72	~ ~ ~	Display Variables, enable arrow keys
73	(Change CTRL.6 from 1 to 0)	
74	RL	Simulation stored at A3000
75	GC~	Create Graph, data in Region 3
76	~{right}~	x-axis variable = temp.8 = Tchwi
77	~{right 3}~	y-axis variable = misc.6 = SysCOP
78	x~	exit

79	graph 1~	enter graph name
80	v	view (see how graph looks)
81	e	edit graph
82	ts Effect of Chiller Control Strategy~	
83	LA CTRL.6 = 0 ~	
84	ty System COP ~	
85	ab	Add a second line to graph
86	2~	Data in Region 2
87	~{right 4}~	2nd y-variable = misc.6
88	LB CTRL.6 = 1 ~	
89	q ~ V	 to use GRAPH 1 and View[1]
90	S GRAPH 1.PIC r Q Q	replace GRAPH 1 and Quit
91	/	to bring up Lotus 1-2-3 menu

[1]COMMENTS ON GRAPH 1:

1) At the highest temp. (largest load), the chillers no longer meet load and the chilled water supply temp. rises
2) At the lowest temp. when CTRL.6=1, Chiller #1 is operating at ridiculously low capacity (PLR~ 5%), which is way outside the range of data used for chiller correlation. Thus, the rise in COP may be an artifact.

Listing 6-2 SIMULATION CONNECTION NUMBERS IN CHILLEXP.WK1, FROM EXAMPLE 3

---

*1 Centrifugal Chiller
400 ton (from ASHRAE data) Max.Err: 251.5882

	I/O	Mnemonic	Name	Value	Units	Definition
	===	========	=======	========	========	==================
4	I	FLwChw	FLOW.5	1000	gpm	Chilled water flow rate
1	I	FlwCdw	FLOW.2	1200	gpm	Condenser water flow rate
5	I	Tchwi	TEMP.8	52	F	Ch.w. return (inlet) temp.
4	I	Tcdwi	TEMP.7	87.64629	F	Entering cond. water temp.
9	I	Tchset	TEMP.12	41.58992	F	Setpoint chilled water temp.
	I	PLRset	CTRL.1	1	KW/kW	Setpoint part-load ratio
	I	CtrlMode	CTRL.3	0	--	0=>use Tset; 1->use PLRset
6	O	Tchwo	TEMP.9	42.41007	F	Chilled water outlet temp.
1	O	Tcdwo	TEMP.4	97.68915	F	Condenser water outlet temp.
	O	Qact	POWR.4	400.1588	tons	Actual cooling power output
	O	Pact	POWR.7	361.2212	kW	Actual input power
	O	Qcond	POWR.8	1768.521	kW	Condenser heat rej. rate
	O	COP	MISC.2	3.895949	kW/kW	COP: Qact/Pact
	O	PLRout	MISC.3	1	kW/kW	Part-load Ratio: Qact/Qfull

*2 Centrifugal Chiller
400 ton (from ASHRAE data) Max.Err: 251.5882

	I/O	Mnemonic	Name	Value	Units	Definition
	===	========	=======	========	========	==================
5	I	FlwChw	FLOW.6	1000	gpm	Chilled water flow rate
2	I	FlwCdw	FLOW.3	1200	gpm	Condenser water flow rate
5	I	Tchwi	TEMP.8	52	F	Ch.w. return (inlet) temp.
4	I	Tcdwi	TEMP.7	87.64629	F	Entering cond. water temp.
8	I	Tchset	TEMP.11	42	F	Setpoint chilled water temp.
	I	PLRset	CTRL.7	1	kW/kW	Setpoint part-load ratio
	I	CtrlMode	CTRL.6	0	--	0=>use Tset; 1=>use PLRset
7	O	Tchwo	TEMP.10	42.41007	F	Chilled water outlet temp.
2	O	Tcdwo	TEMP.5	97.68915	F	Condenser water outlet temp.
	O	Qact	POWR.5	400.1588	tons	Actual cooling power output
	O	Pact	POWR.6	361.2212	kW	Actual input power
	O	Qcond	POWR.3	1768.521	kW	Condenser heat rej. rate
	O	COP	MISC.4	3.895949	kW/kW	COP: Qact/Pact
	O	PLRout	MISC.5	1	kW/kW	Part-load Ratio: Qact/Qfull

Listing 6-2 SIMULATION CONNECTION NUMBERS IN CHILLEXP.WK1, FROM EXAMPLE 3 (continued)

---

*3 Cooling Tower

F = 0.6 Max.Err: 251.5882

	I/O	Mnemonic	Name	Value	Units	Definition
	I	Pbaro	PRES.1	14.696	psia	Barometric Pressure
3	I	FlwCdw	FLOW.4	2400	gpm	Total water flow rate
	I	Tdb	TEMP.1	86	F	Entering air dry bulb temp.
	I	Twb	TEMP.2	77	F	Entering air wet bulb temp.
3	I	Twi	TEMP.6	97.68915	F	Entering hot water temp.
	I	NFanHi	CTRL.2	0	--	# cells on high fan speed
	I	NFanLo	CTRL.8	2	--	# cells on low fan speed
	O	NFanOff	CTRL.4	0	--	# cells with fan off
4	O	Two	TEMP.7	87.64629	F	Leaving cooled water temp.
	O	FlwA	FLOW.1	162000	cfm	Air flow rate
	O	FanPowr	POWR.1	14	kW	Fan power consumption
	O	Qtower	POWR.2	3536.366	kW	Tower heat rejection rate
	O	RelHum	MISC.1	0.670716	--	Ambient air Relative Humidity

*4 2-Way Flow Merge

Condenser water merge Max.Err: 251.5882

	I/O	Mnemonic	Name	Value	Units	Definition
1	I	Flow1	FLOW.2	1200	gpm	Flow rate at first inlet
2	I	Flow2	FLOW.3	1200	gpm	Flow rate at second inlet
1	I	Temp1	TEMP.4	97.68915	F	Temperature at first inlet
2	I	Temp2	TEMP.5	97.68915	F	Temperature at second inlet
3	O	FlowOut	FLOW.4	2400		Flow rate at outlet
3	O	TempOut	TEMP.6	97.68915		Temperature at outlet

Listing 6-2 SIMULATION CONNECTION NUMBERS IN CHILLEXP.WK1, FROM EXAMPLE 3 (continued)

```
   *5  2-Way Merge with Setpoint Control
       Chilled water merge/control           Max.Err: 251.5882
   I/O Mnemonic Name        Value Units      Definition
   === ======== =======  ======== ========  ==================
    I  Nset     CTRL.5          1 --         Controlled Inlet Number
4   I  Flow1    FLOW.5       1000 gpm        Flow rate at first inlet
5   I  Flow2    FLOW.6       1000 gpm        Flow rate at second inlet

6   I  Temp1    TEMP.9   42.41007 F          Temperature at first inlet
7   I  Temp2    TEMP.10  42.41007 F          Temperature at second inlet

8   I  TsetAvg  TEMP.11        42 F          Overall Setpoint Temp.

6   O  FlowOut  FLOW.7       2000 gpm        Flow rate at outlet
    O  TempOut  TEMP.3   42.41007 F          Temperature at outlet
9   O  Tset     TEMP.12  41.58992 F          Setpoint for Inlet # 1


   *6  Additional Outputs                    Max.Err:  251.5882

   I/O Mnemonic Name        Value Units      Definition
   === ======== =======  ======== ========  ==================
    O  SysCOP   MISC.6   3.407330 --         System COP
```

Listing 6-3 PERIODIC INPUT RANGE AND OUTPUT FOR DATA SET 1 IN CHILLEXP.WK1, FROM EXAMPLE 3

```
        AG        AH        AI        AJ        AK        AL        AM        AN
21   Periodic Input Settings
22   (PERIOD=24 hours assumed)
23   ==========================
24   Number of variable inputs:        3
25   Number of steps for each:         9
26   Output Data Set Number:           1
27   Stopping Time (hours):            9
28
29            Var.     Variable   Form
30            No.      Name       (S or L)
31            ===      =======    ========
32            1        ctrl.2     L
33            2        ctrl.8     L
34            3        ctrl.6     L
35            4
36            5
37    (S=sinusoidal, L=piecewise linear)
38
39   Current Mode:     Line Input
40
```

OUTPUT DATA SET 1 IN CHILLEXP.WK1

	A	B	C	D	E	F	G	H
1000	ROW #	TIME	ctrl.2	ctrl.8	ctrl.6			MISC.6
1001	0	0	2	0	0	320000	0.803233	3.225087
1002	1	1	1	1	0	241000	0.817282	3.323167
1003	2	2	0	2	0	162000	0.838406	3.392976
1004	3	3	0	1	0	97000	0.919391	3.076503
1005	4	4	0	0	0	32000	1	2.243687
1006	5	5	0	0	1	32000	1	2.242043
1007	6	6	0	1	1	97000	0.842351	3.045848
1008	7	7	0	2	1	162000	0.678799	3.302174
1009	8	8	1	1	1	241000	0.636020	3.223694
1010	9	9	2	0	1	320000	0.606935	3.125238
1011								
1012								
1013								
1014								
1015								
1016								
1017								
1018								
1019								

Listing 6-4 SAMPLE OUTPUTS AND INPUTS IN CHILLEXP.WK1, FROM EXAMPLE 3

POST Cooling Tower and Two Chillers Err.Tol = 0.001
Max.Err =251.5882

Simulation Outputs (Page Left for Inputs)

Mnemonic	Name	Value	Units	Definition
NFanOff	CTRL.4	0	--	# cells with fan off
FlwA	FLOW.1	162000	cfm	Air flow rate
FlowOut	FLOW.4	2400		Flow rate at outlet
FlowOut	FLOW.7	2000	gpm	Flow rate at outlet
RelHum	MISC.1	0.670716	--	Ambient air Relative Humidity
COP	MISC.2	3.895949	kW/kW	COP: Qact/Pact
PLRout	MISC.3	1	kW/kW	Part-Load Ratio: Qact/Qfull
COP	MISC.4	3.895949	kW/kW	COP: Qact/Pact
PLRout	MISC.5	1	kW/kW	Part-Load Ratio: Qact/Qfull
SysCOP	MISC.6	3.407330	--	System COP
FanPowr	POWR.1	14	kW	Fan power consumption
Qtower	POWR.2	3536.366	kW	Tower heat rejection rate
Qcond	POWR.3	1768.521	kW	Condenser heat rej. rate
Qact	POWR.4	400.1588	tons	Actual cooling power output
Qact	POWR.5	400.1588	tons	Actual cooling power output
Pact	POWR.6	361.2212	kW	Actual input power
Pact	POWR.7	361.2212	kW	Actual input power
Qcond	POWR.8	1768.521	kW	Condenser heat rej. rate
Tchwo	TEMP.10	42.41007	F	Chilled water outlet temp.
Tset	TEMP.12	41.58992	F	Setpoint for Inlet # 1
TempOut	TEMP.3	42.41007	F	Temperature at outlet
Tcdwo	TEMP.4	97.68915	F	Condenser water outlet temp.
Tcdwo	TEMP.5	97.68915	F	Condenser water outlet temp.
TempOut	TEMP.6	97.68915		Temperature at outlet
Two	TEMP.7	87.64629	F	Leaving cooled water temp.
Tchwo	TEMP.9	42.41007	F	Chilled water outlet temp.

Listing 6-4 SAMPLE OUTPUTS AND INPUTS IN CHILLEXP.WK1, FROM EXAMPLE 3 (continued)

Simulation Inputs (Page Right for Outputs)

Mnemonic	Name	Value	Units	Definition
PLRset	CTRL.1	1	kW/kW	Setpoint part-load ratio
NFanHi	CTRL.2	0	--	# cells on high fan speed
CtrlMode	CTRL.3	0	--	0=>use Tset; 1=>use PLRset
Nset	CTRL.5	1	--	Controlled Inlet Number
CtrlMode	CTRL.6	0	--	0=>use Tset; 1=>use PLRset
PLRset	CTRL.7	1	kW/kW	Setpoint part-load ratio
NFanLo	CTRL.8	2	--	# cells on low fan speed
FlwCdw	FLOW.2	1200	gpm	Condenser water flow rate
Flow2	FLOW.3	1200	gpm	Flow rate at second inlet
Flow1	FLOW.5	1000	gpm	Flow rate at first inlet
Flow2	FLOW.6	1000	gpm	Flow rate at second inlet
Pbaro	PRES.1	14.696	psia	Barometric Pressure
Tdb	TEMP.1	86	F	Entering air dry bulb temp.
Twb	TEMP.2	77	F	Entering air wet bulb temp.
Tchwi	TEMP.8	52	F	Ch.w. return (inlet) temp
Tchset	TEMP.11	42	F	Setpoint chilled water temp.

Listing 6-5 LINEAR INPUT RANGE IN CHILLEXP.WK1, FROM EXAMPLE 3

```
         AG        AH        AI        AJ        AK        AL       AM      AN
1   Linear Input Settings
2   ====================
3   Number of variable inputs:          1
4   Number of steps for each:          10
5   Output Data Set Number:             3
6
7   Var.      Variable     First     Last
8   No.       Name         Value     Value
9   ===       =======      =====     =====
10  1         TEMP.8          47        52
11  2
12  3
13  4
14  5
15
16  Current Mode:      Line Input
17
18
19
20
```

Listing 6-6 OUTPUT REGIONS IN CHILLEXP.WK1, FROM EXAMPLE 3

	A	B	C	D	E	F	G	H
1000	ROW #	TIME	ctrl.2	ctrl.8	ctrl.6	FLOW.1	MISC.3	MISC.6
1001	0	0	2	0	0	320000	0.803233	3.225087
1002	1	1	1	1	0	241000	0.817282	3.323167
1003	2	2	0	2	0	162000	0.838406	3.392976
1004	3	3	0	1	0	97000	0.919391	3.076503
1005	4	4	0	0	0	32000	1	2.243687
1006	5	5	0	0	1	32000	1	2.242043
1007	6	6	0	1	1	97000	0.842351	3.045848
1008	7	7	0	2	1	162000	0.678799	3.302174
1009	8	8	1	1	1	241000	0.636020	3.223694
1010	9	9	2	0	1	320000	0.606935	3.125238

	A	B	C	D	E	F	G	H
1250	ROW #	TEMP.8	FLOW.1	MISC.3	MISC.6	POWR.4	POWR.5	TEMP.3
1251	0	47	162000	0.054520	2.999102	21.57314	395.6922	42.00005
1252	1	47.5	162000	0.159560	2.952600	63.15725	395.8195	42.00024
1253	2	48	162000	0.264272	2.974857	104.6635	396.0435	42.00020
1254	3	48.5	162000	0.368379	3.038046	146.0286	396.4080	42.00017
1255	4	49	162000	0.471933	3.123506	187.2935	396.8639	42.00024
1256	5	49.5	162000	0.575129	3.216370	228.5290	397.3524	42.00028
1257	6	50	162000	0.678233	3.302918	269.8047	397.8051	42.00026
1258	7	50.5	162000	0.781343	3.370238	311.1339	398.2039	42.00025
1259	8	51	162000	0.884666	3.406227	352.5517	398.5136	42.00025
1260	9	51.5	162000	0.988439	3.400861	394.0916	398.7007	42.00025
1261	10	52	162000	1	3.408575	400.2757	400.2757	42.40727

	A	B	C	D	E	F	G	H
1500	ROW #	TEMP.8	FLOW.1	MISC.3	MISC.6	POWR.4	POWR.5	TEMP.3
1501	0	47	162000	0.527972	2.814210	208.6351	208.6351	42
1502	1	47.5	162000	0.579572	2.951709	229.4986	229.4986	42
1503	2	48	162000	0.631595	3.074360	250.3621	250.3621	42
1504	3	48.5	162000	0.683474	3.181964	271.2256	271.2256	42
1505	4	49	162000	0.735228	3.272224	292.0891	292.0891	42
1506	5	49.5	162000	0.786907	3.342945	312.9526	312.9526	42
1507	6	50	162000	0.838563	3.392285	333.8161	333.8161	42
1508	7	50.5	162000	0.890254	3.418931	354.6796	354.6796	42
1509	8	51	162000	0.942043	3.422221	375.5432	375.5432	42
1510	9	51.5	162000	0.993994	3.402220	396.4067	396.4067	42
1511	10	52	162000	1	3.408641	400.2819	400.2819	42.40712

7. CONCLUSION

Of the six program design goals listed in the introduction, the first two, limited hardware dependence and graphical output capabilities, were achieved by basing the method on an existing spreadsheet program which already has these features. The third, not usurping the decision-making power of a plant operator, was met by developing a simulation methodology which makes no attempt to optimize system performance of its own accord but instead encourages the user to evaluate different alternatives and to select what he believes is the best mode of plant operation. The fourth, flexibility, was achieved by using a modular method with provisions for linking components together into the configuration of a specified plant. The fifth, simplicity, was partially achieved by developing procedures for turning general-purpose component modules into models for specific equipment without demanding that the user understand the mathematics behind the models.

It should be noted that these last two goals of flexibility and simplicity are not independent and tend to conflict. The tradeoffs made in developing POST have tended to favor flexibility at the expense of simplicity. The developers of the spreadsheet program upon which POST relies have attempted to make their program both flexible and easy to use, and POST owes its existence to the success of their efforts. Hopefully, POST will be judged easy to use for the same reasons that spreadsheet programs are, since it takes advantage of the same menu-driven command structure.

Finally, the sixth design goal was to produce a powerful method which would be useful to persons with a wide range of technical sophistication. The authors believe that the power of the technique has been demonstrated, but its usefulness will depend largely on its success in actual plant applications. At present, the utility of POST in an actual heating/cooling plant environment remains to be tested.

8. REFERENCES

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Stoecker, W.F., ed. 1975. Procedures for simulating the performance of components and systems for energy calculation. New York; American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Whillier, A., 1967. "A fresh look at the calculation of performance of cooling towers." ASHRAE Transactions, Vol. 82, pt. 1, p. 269.

Table 1. Contants for Determining Temperature Coefficients for the Heat Capacity of Air and the Products of Combustion at Constant Pressure

j.	$a_{O_2,j}$	$a_{N_2,j}$	$a_{H_2O,j}$	$a_{SO_2,j}$	$a_{CO_2,j}$
1.	3.7189946	3.6916148	4.1565016	3.2257132	2.1701000
2.	$-2.5167288 \times 10^{-3}$	$-1.3332552 \times 10^{-3}$	$-1.7244334 \times 10^{-3}$	5.6551207×10^{-3}	1.0378115×10^{-2}
3.	8.5837353×10^{-6}	2.6503100×10^{-6}	5.6982316×10^{-6}	$-2.4970208 \times 10^{-7}$	$-1.0733938 \times 10^{-5}$
4.	$-8.2998716 \times 10^{-9}$	$-9.7688341 \times 10^{-10}$	-4.593004×10^{-9}	$-4.2206766 \times 10^{-9}$	6.3459175×10^{-9}
5.	$2.7082180 \times 10^{-12}$	$-9.9772234 \times 10^{-14}$	$1.4233654 \times 10^{-12}$	$2.1392733 \times 10^{-12}$	$-1.6280701 \times 10^{-12}$

COMMAND MENU STRUCTURE

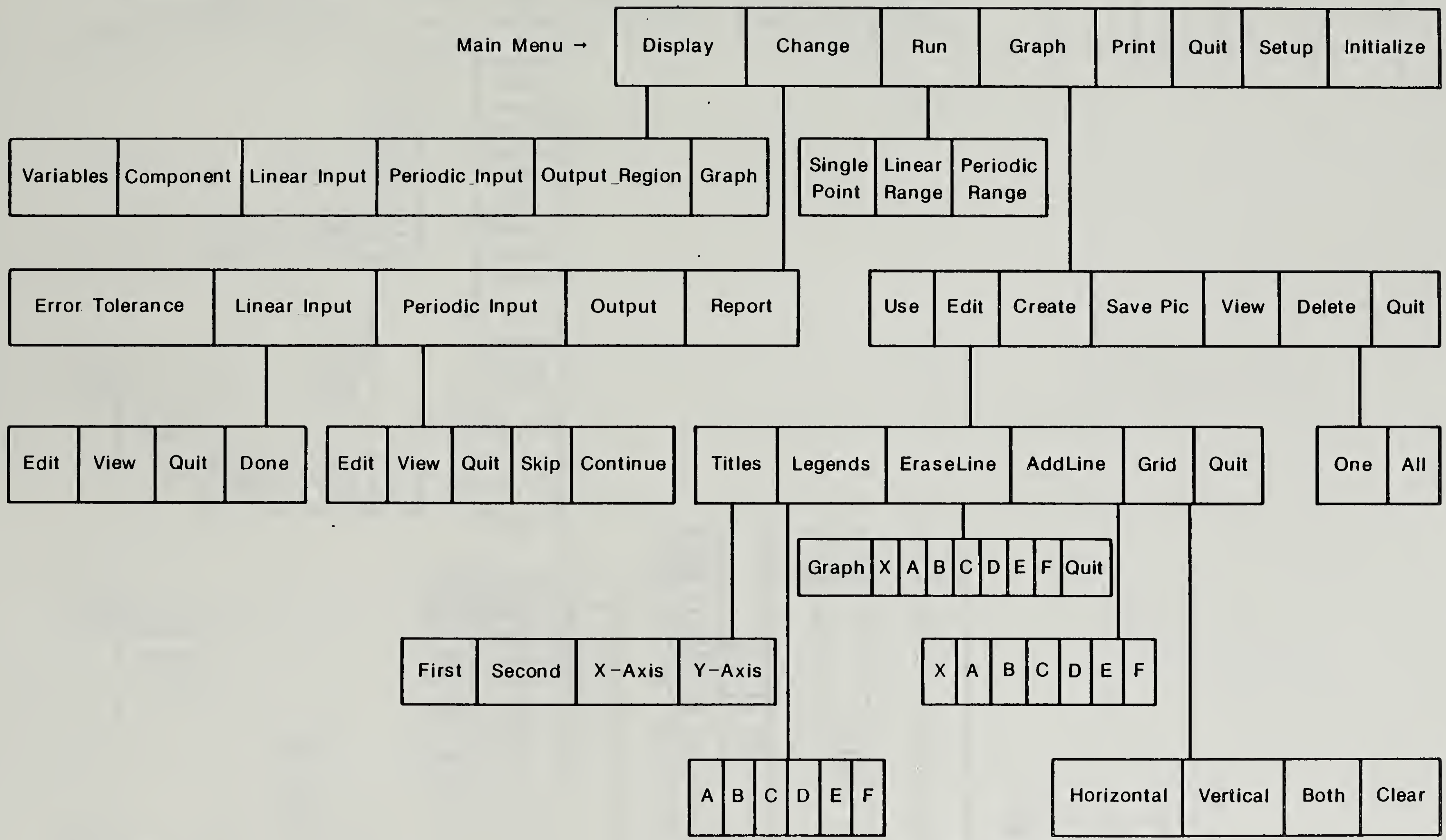

Figure 1. Command Menu Structure in POST Worksheet

SETUP WORKSHEET GEOGRAPHY

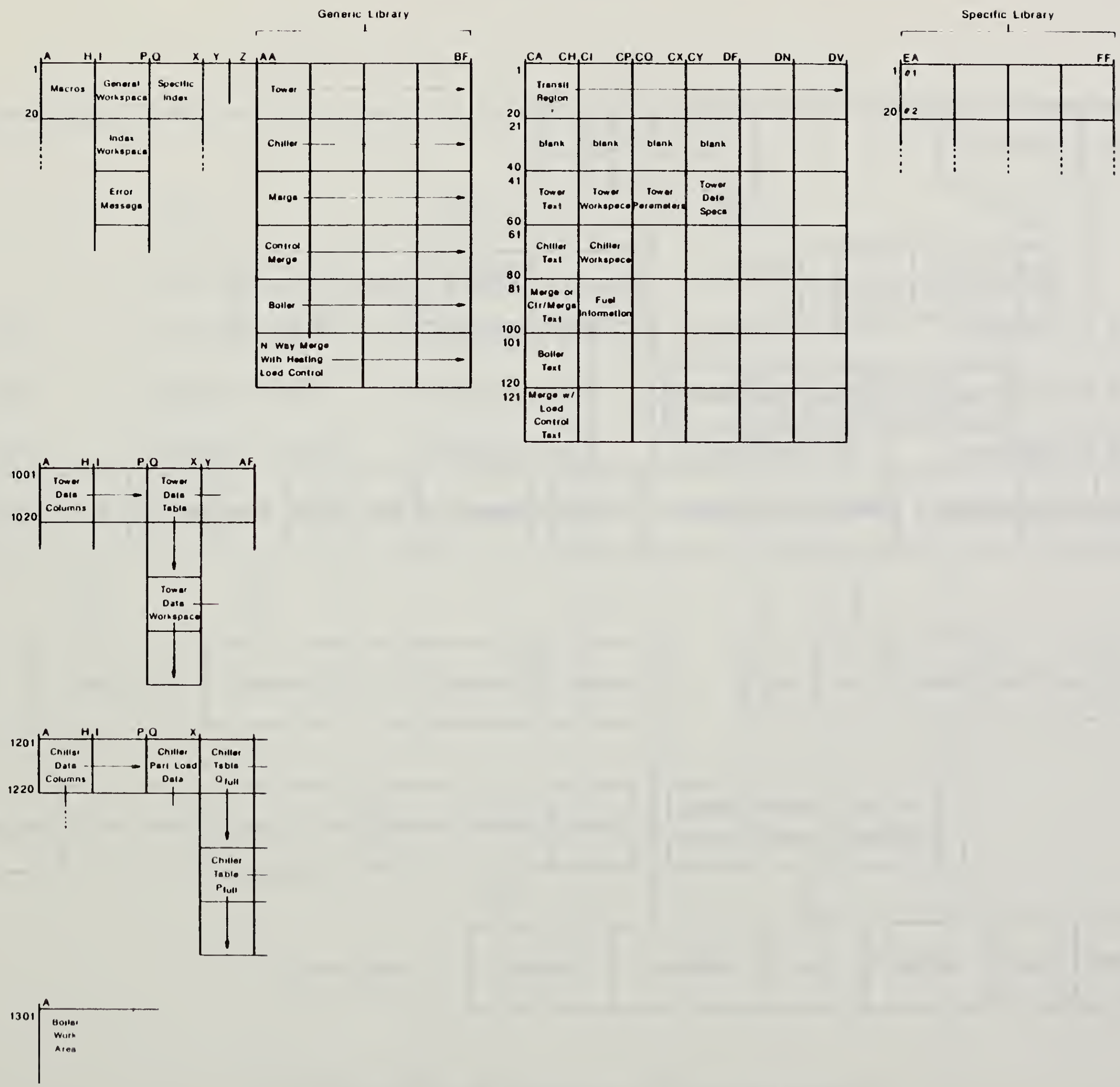

Figure 2. Layout of SETUP Worksheet

POST WORKSHEET GEOGRAPHY

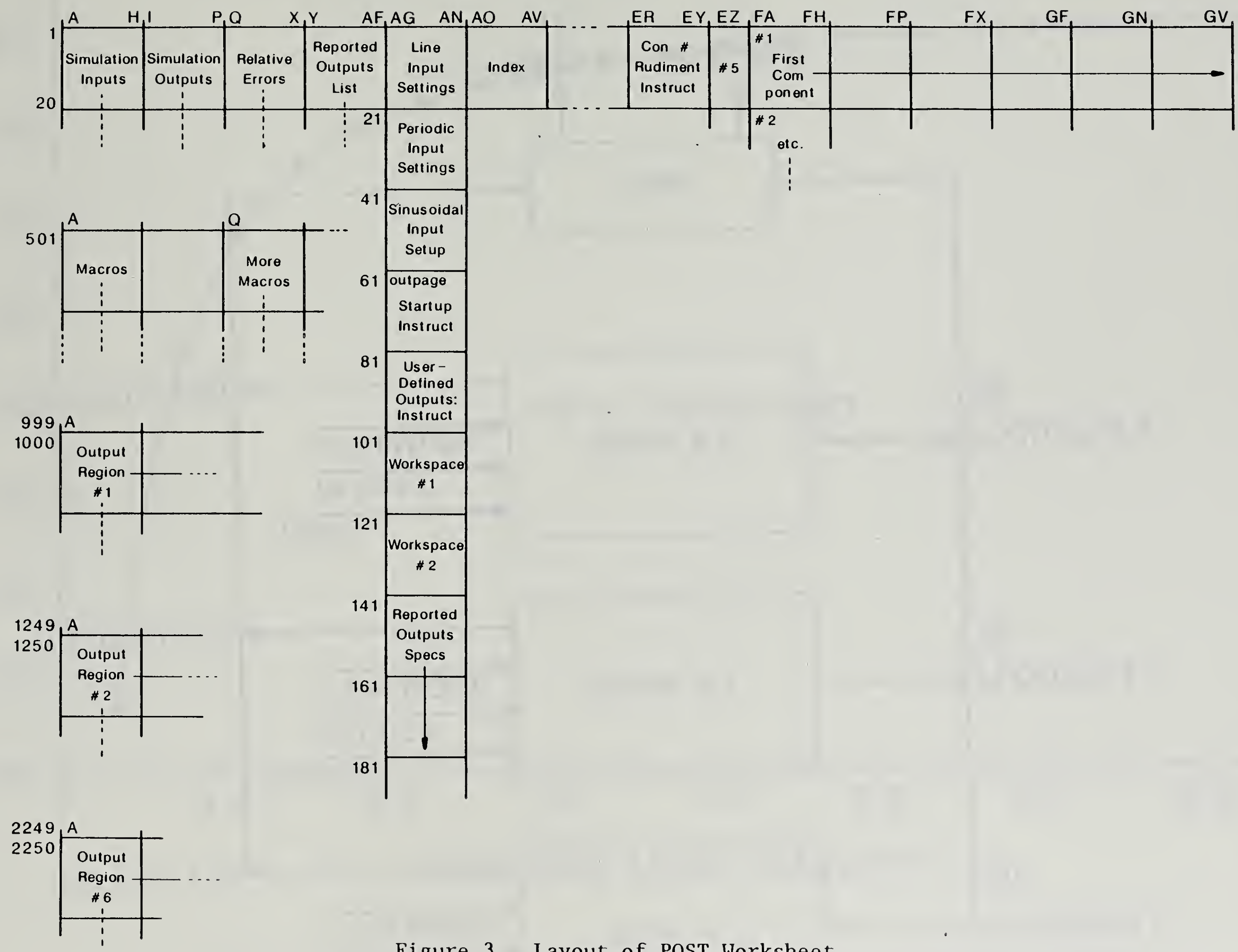

Figure 3. Layout of POST Worksheet

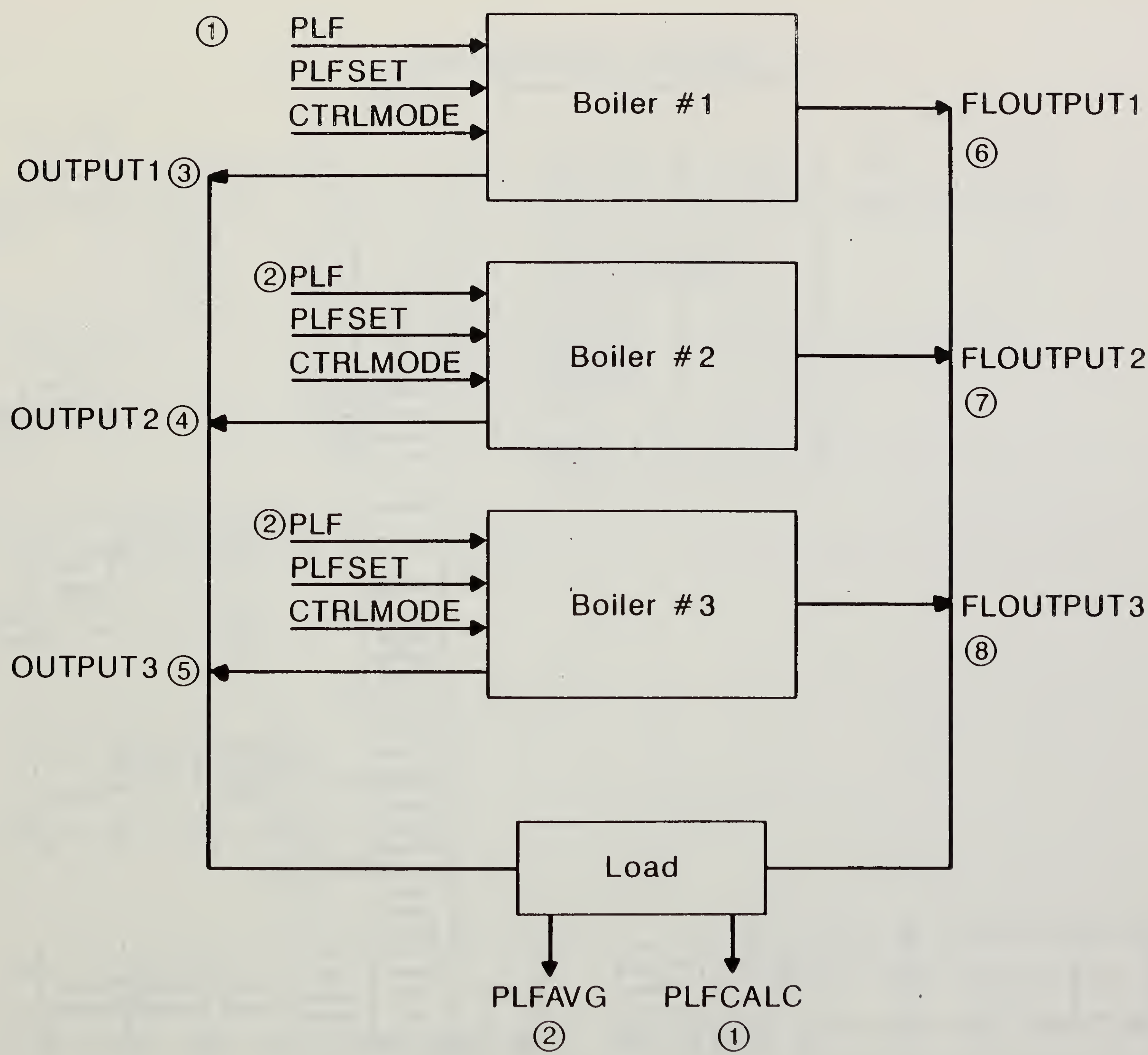

Figure 4. Component Connections for Example 1: Three Gas-Fired Boilers Operating at Identical Part Load Factors

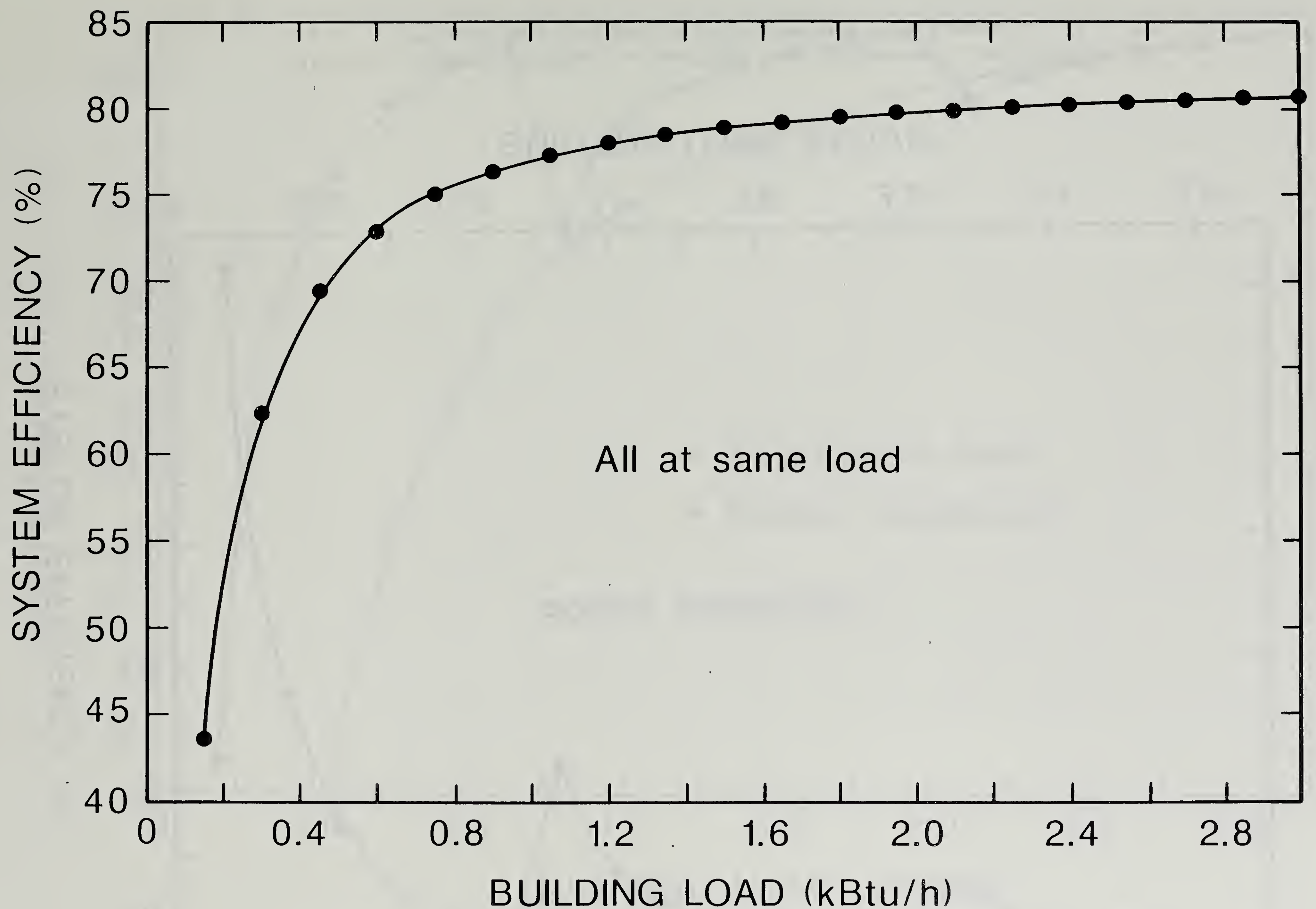

Figure 5. System Efficiency vs. Building Load for System of Three Gas-Fired Boilers Running at the Same Factors (Results in Example 1)

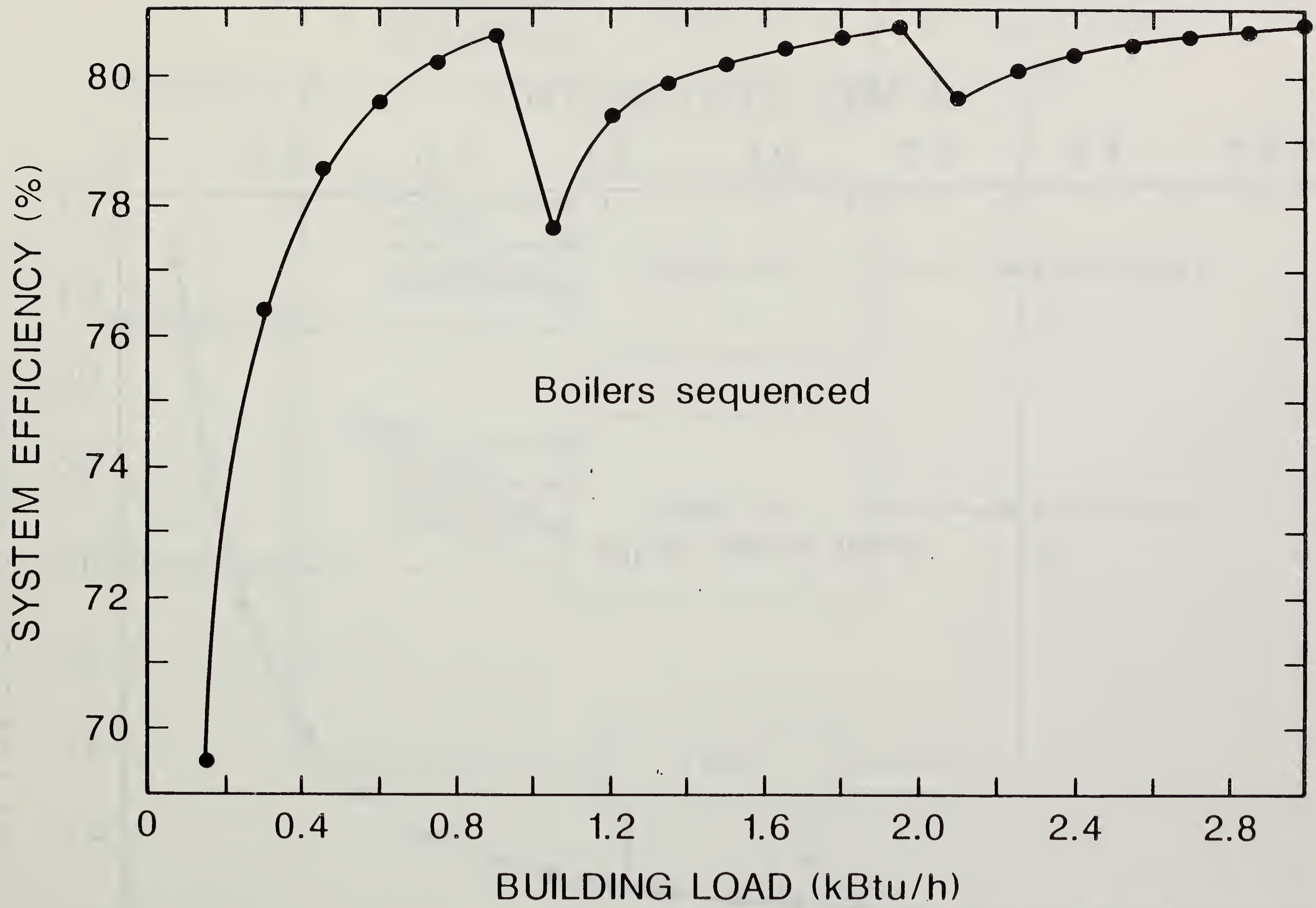

Figure 6. System Efficiency vs. Building Load for System of Three Gas-Fired Boilers Operating Sequentially (Results from Example 2)

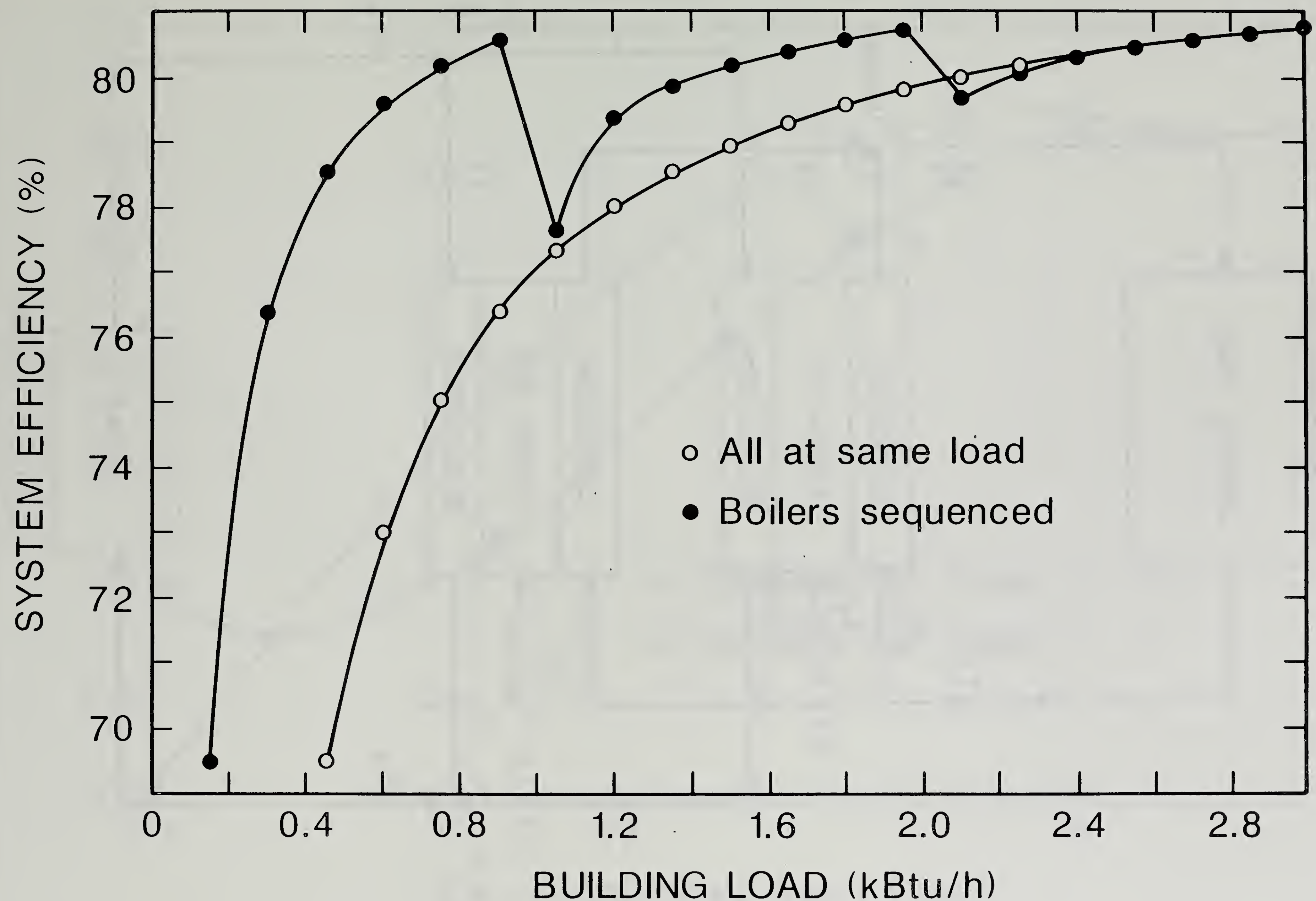

Figure 7. Comparison of Boiler System Performance for Both Parallel and Sequential Operation (Results from Examples 1 and 2)

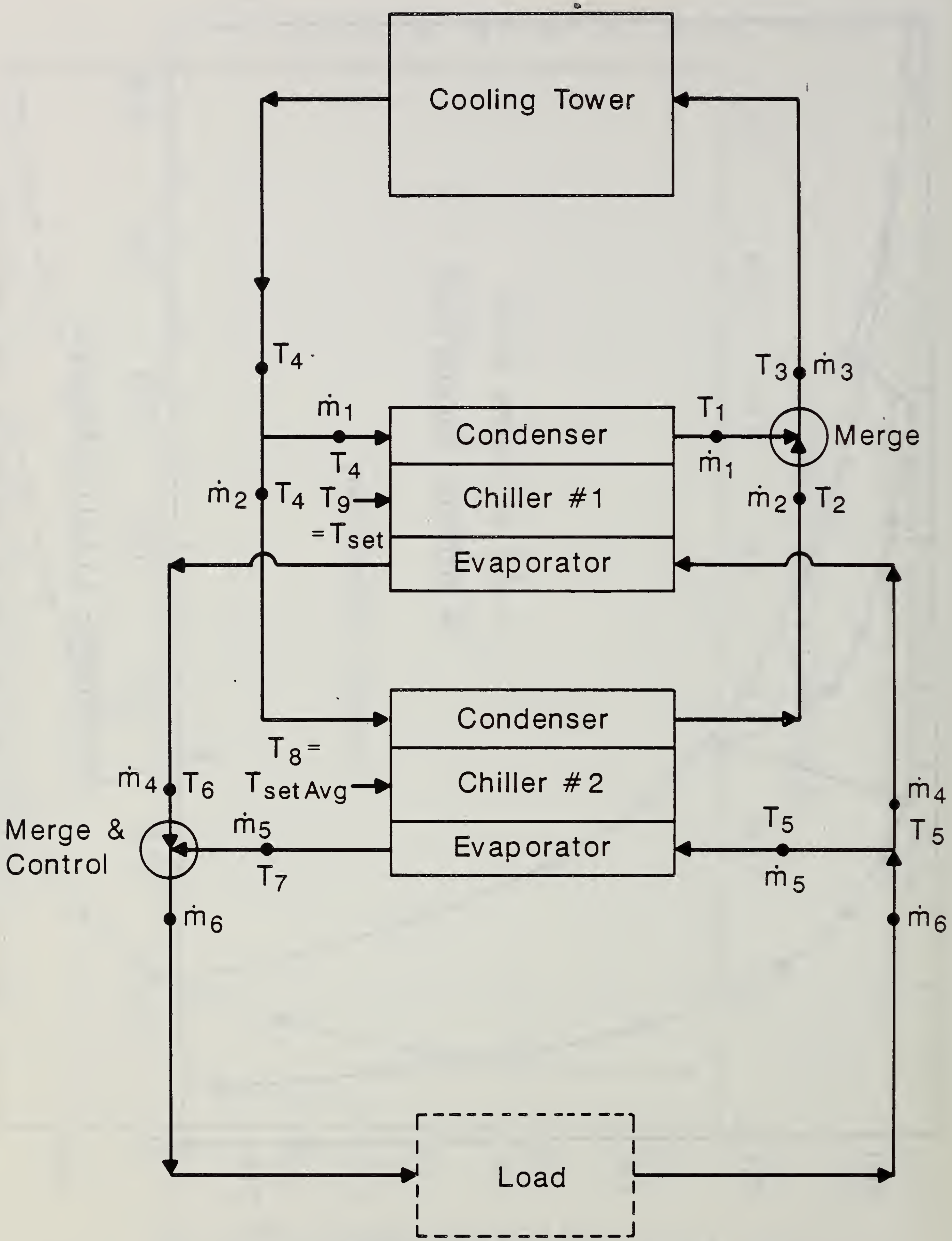

Figure 8. Component Connections for Example 3: Cooling Plant System Consisting of Two Chillers and a Cooling Tower

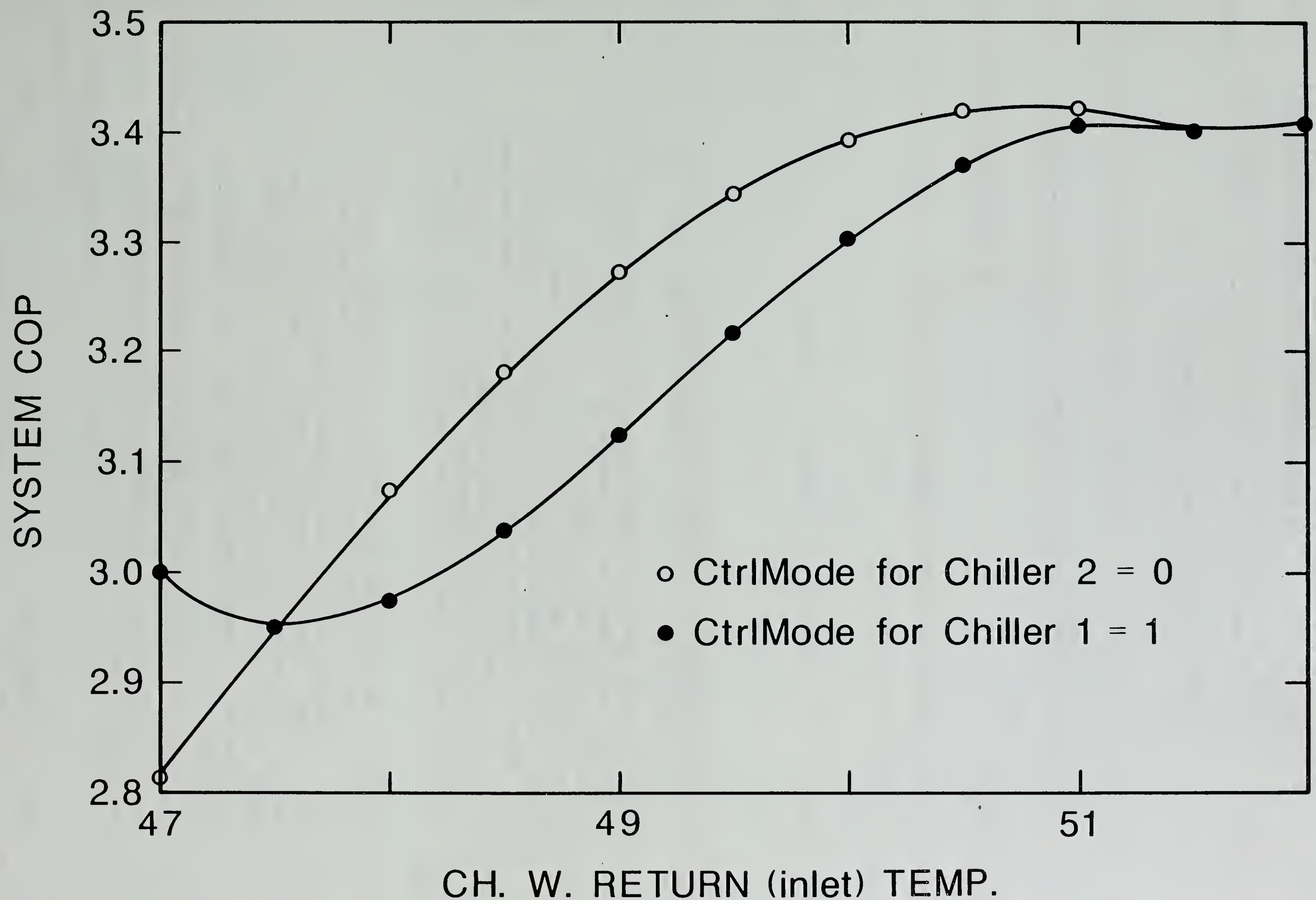

Figure 9. System COP vs. Chilled Water Temperature Returning from the Building Load for Two Different Chiller Operating Strategies (Results from Example 3)

NBS-114A (REV. 2-8C)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET** (See instructions)	1. PUBLICATION OR REPORT NO. NBSIR 88-3740	2. Performing Organ. Report No.	3. Publication Date MARCH 1988

4. TITLE AND SUBTITLE

Users Guide to Post - Plant Operations Simulation Template

5. AUTHOR(S)

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6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

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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 non-proprietary simulation template program named POST (Plant Operations Simulation Template) has been developed for use with the Lotus 1-2-3* spreadsheet. The template provides for mathematical simulation of central heating/cooling plant equipment including boilers, cooling towers, and centrifugal chillers. It provides methods for configuring a simulation of a specific physical plant, defining operating conditions and time-dependent boundary conditions, running simulations, and graphing simulation results. POST is a flexible and highly portable analytical tool for plant equipment operators and engineers concerned with efficient operation of physical plant systems.

This Users Guide provides an overview of POST and its companion template program SETUP, which is used to define the characteristics of component models. Information is presented on the menu commands used in POST and three examples are provided. The examples show how the template program may be used to simulate the performance of a three-boilers heating plant and a central cooling plant consisting of two chillers and a cooling tower. Listings of the actual keystrokes for setting up and running both simulations are included.

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

boilers; central heating/cooling plant; centrifugal chillers; cooling towers: equipment performance; heating/cooling equipment; operating strategies; simulation; spreadsheet template

13. AVAILABILITY

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