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POWER PLANT SIMULATION AND CONTROLLER DESIGN  
USING MODULAR MODELING SYSTEM SOFTWARE

A Thesis  
Presented for the  
Master of Science  
Degree  
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Roger D. Painter  
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## ABSTRACT

The primary objective of the work being done by The University of Tennessee Space Institute (UTSI) at the Coal-Fired Flow Facility (CFFF) is to prove the concept of operating a coal-fired power plant equipped with a magneto-hydrodynamic MHD topping cycle. The ultimate goal of the MHD power generation program is to bring the MHD process into commercial use. This would involve the design of a full-scale commercial coal-fired power plant with a MHD topping cycle.

The group responsible for the MHD program at UTSI is the Energy Conversion Research and Development Programs (ECP). ECP personnel, anticipating the design effort for a commercial MHD power plant, decided that computer simulation of conventional power plant components subjected to MHD conditions would be useful. To facilitate this simulation, a pre-release version of the Modular Modeling System (MMS) was acquired from The Electric Power Research Institute.

This work involves the development of a MMS model of the three superheater test-sections (TS1, TS2, and TS3) at the CFFF. The dynamic model was then used to design Proportional Integral (PI) controllers for the superheater test-section. It is hoped that this effort will lay the groundwork for future applications of MMS by ECP staff and UTSI students.

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## LIST OF SYMBOLS

|                 |                                            |
|-----------------|--------------------------------------------|
| $C(t)$          | System response in the time domain         |
| $F(t)$          | Function of time                           |
| $H$             | Enthalpy, Btu/lbm                          |
| $IX$            | Initial value of $X$                       |
| $K$             | Overall gain constant                      |
| $K_I$           | Integral gain                              |
| $K_p$           | Proportional gain                          |
| $P$             | Pressure, psia                             |
| $S$             | Laplas domain variable                     |
| $S_i$           | Complex eigenvalues                        |
| $t$             | Time, min                                  |
| $T$             | Temperature, K                             |
| $W$             | Flowrate, lbm/hr                           |
| $X$             | Dependent variable                         |
| $XD, \dot{X}$   | 1st derivative of $X$ with respect to time |
| $XDD, \ddot{X}$ | 2nd derivative of $X$ with respect to time |

### Greek Letters

|                |                                |
|----------------|--------------------------------|
| $\theta$       | Angle for calculation of $\xi$ |
| $\lambda_{IM}$ | Imaginary part of complex root |
| $\lambda_{RE}$ | Real part of the complex root  |
| $\xi$          | Damping coefficient            |
| $\tau$         | Time constant, min             |
| $\omega_n$     | Natural undamped frequency     |

## INTRODUCTION

Conventional fossil-fuel steam power plants are limited to about 40-percent overall efficiency. Several binary systems which consist of a conventional steam cycle downstream and some other enthalpy extraction process (topping cycle) upstream have been proposed to boost the efficiency of converting fossil fuels to electricity. For example, the gas-steam binary cycle, which uses a high temperature gas turbine topping cycle to extract enthalpy from the combustion gases before the gases enter the steam cycle, has been proven at plant efficiencies up to 40-percent.

Another topping cycle which has been proposed is the magnetohydrodynamic (MHD) cycle. The MHD generator converts the kinetic energy of the combustion gases directly into electrical energy with the aid of a magnetic field and electrodes placed in the walls of the combustion gas channel. The MHD generator requires an electrically conductive gas. With fossil fuels, it is generally necessary to add "seed" (salt of an alkali metal such as potassium) to the stream to make it conductive to electric current (Haywood and Womack, 1969).

A project is underway at The University of Tennessee Space Institute (UTSI) involving the development and testing

of a prototype open-cycle coal-fired MHD power system. Funding for the project is provided by a contract with the Department of Energy (DOE). The group within UTSI responsible for the MHD project is the Energy Conversion Research and Development Programs (ECP). This prototype, the coal-fired flow facility (CFFF) has now been operated for hundreds of hours. The CFFF uses pulverized coal as fuel and potassium salt as seed. The fuel/seed mixture is burned with preheated enriched air.

The primary objective of the work being done by ECP at the CFFF is to prove the concept of operating a coal-fired power plant equipped with a MHD topping cycle. This would involve the design of a full-scale coal-fired power plant with a MHD topping cycle. This could be accomplished by building a new plant equipped with the MHD topping cycle or by retrofitting an existing coal-fired power plant with a MHD topping cycle.

Whether the eventual scale-up of the MHD plant comes by a new plant construction or by a retrofit to an existing plant, there are unique characteristics of the MHD power plant which should be considered in the design phase of the scale-up. Specifically, the higher-than-conventional plant temperatures (2300°F at the superheater inlet) and the need to feed and recover the "seed" are the unique areas of concern in the eventual design effort (ECP, 1984).

ECP personnel anticipating the design effort for a commercial MHD plant decided that computer simulation of the conventional plant components, subjected to MHD conditions, would be useful. To facilitate this simulation, a pre-release version of the Modular Modeling System (MMS) was acquired.

MMS is a computer code developed by the Electric Power Research Institute (EPRI) to facilitate modeling the dynamics of electric power plants. The developers of MMS claim that the engineering time for producing a power plant simulation is greatly reduced by the use of MMS. The developers further claim that the program is "user friendly" to the extent that a plant model could be simulated by a process engineer with no more computer skills than a thorough knowledge of FORTRAN.

One objective of this work is to assist ECP in the evaluation of MMS. The development of a complete MMS plant model will require more than a man-year (W. R. Barcelo, et. al., 1985) of engineering time. Before undertaking such an effort, ECP would like to evaluate the applicability of MMS in the development of the power plant model.

Another objective of this work is to design the optimum controller gains for the Proportional Integral (PI) controllers controlling steam flow to the superheater

test-sections at the CFFF. The superheater test-sections are shown on Figure 1 and will be referred to as TS1, TS2, and TS3. The scope of the MMS model relative to the CFFF components, is discussed in detail in Chapter III.

The model required one man-month of engineering time and about \$800 in computer expenditures (excluding the installation of the system). This includes the time and expense used in the design of the PI controllers using the Root Locus Method (see Chapter II).

MMS allowed for the integration of the complex model. As a result, system interactions were well represented. The linear analysis routines in the software package provided the optimum gain for the controller after only two iterations of the model. The optimum gains for the PI controllers were found to be proportional gain ( $K_p$ ) = .05 and integral gain ( $K_I$ ) = .005 for all three superheater test-sections.

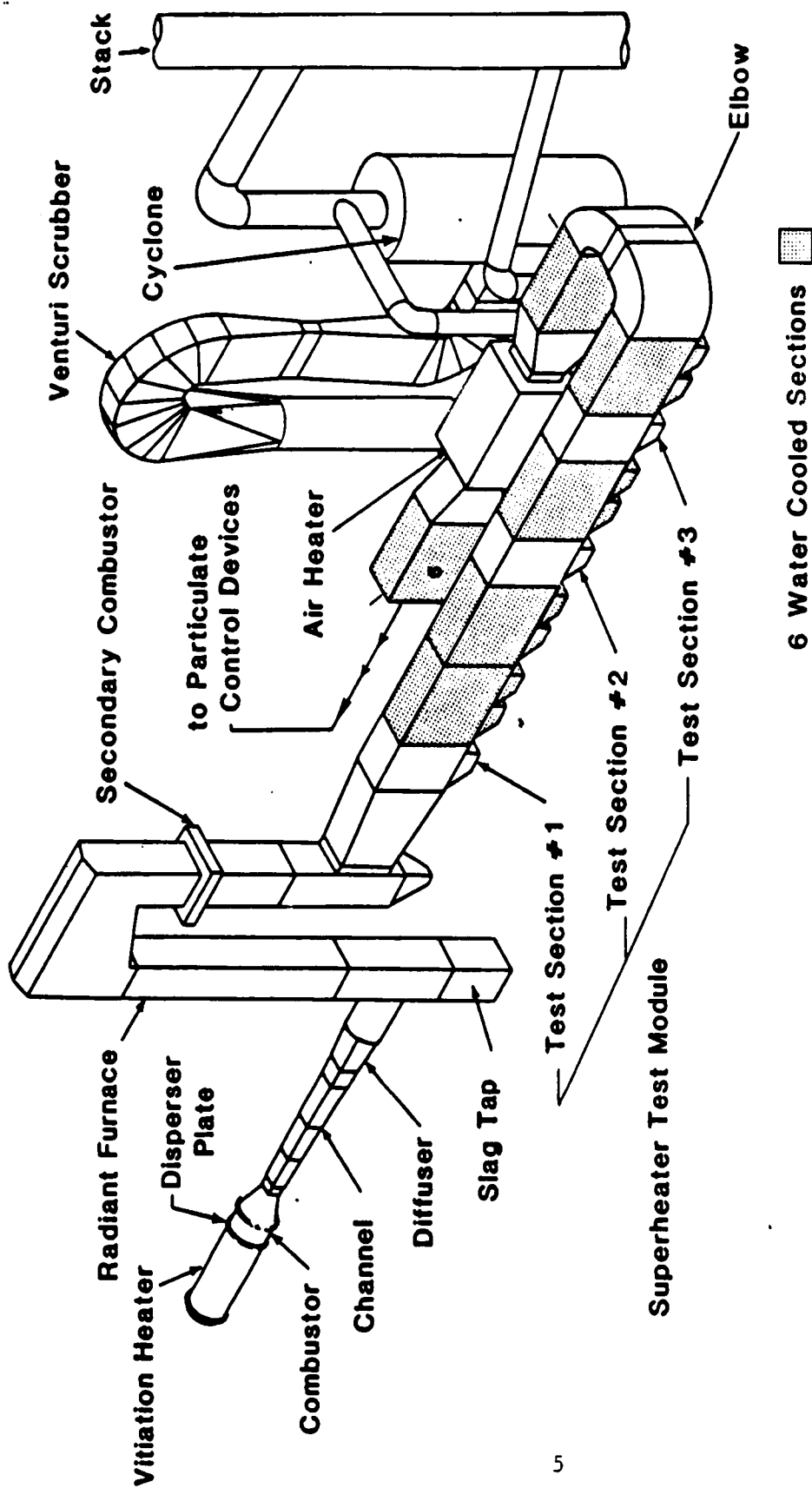


FIGURE 1 Coal-Fired Flow Facility at The University of Tennessee  
Space Institute

## CHAPTER I

### MODULAR MODELING SYSTEM SOFTWARE

The Modular Modeling System (MMS) is a computer code developed by the Electric Power Research Institute (EPRI) to facilitate modeling the dynamics of fossil fuel and nuclear steam electric power plants. It is intended to assist in the power plant design process and, during later operation, for troubleshooting, setting controller system gains, and forecasting the consequences of severe transient tests before they are actually run. The MMS provides preprogrammed modules that represent power plant components. These are automatically interconnected in the arrangement determined by the user by the Advanced Continuous Simulation Language (ACSL), which is an integral part of MMS. ACSL not only interconnects the preprogrammed modules in the order determined by the user but also sorts the equations into an executable sequence. The language also provides a run time executive, the integration algorithm, and the linear analysis routines (EPRI, 1987).

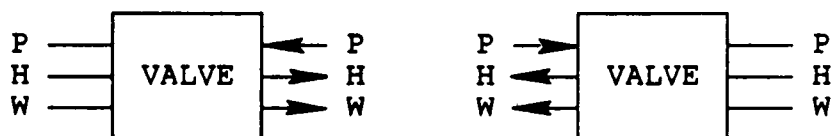
This chapter contains a brief description of the important elements of MMS. For a more complete description of MMS refer to the ACSL-Based MMS User's Manual (EPRI; Volume 3, 1983).

### Modularity Concept

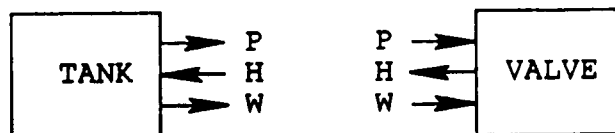
Each program module represents a unit operation. The module contains all the codes needed to represent the unit operation in the model. Streams of information are passed to and from the program module in the same way process streams are passed to and from unit operations in the plant. There are some rules to follow when connecting the program modules in order to satisfy the information requirements of the modules.

If two modules are to be interconnected, then they must satisfy requirements for information transfer, for example:

two valve modules cannot be directly connected.



Both modules call for P as an input and both output W. The tank and the valve can be connected.



The software provides a connection module (CONNI,C and CONNC,I) for the connection of otherwise incompatible modules.



### Nomenclature

MMS will automatically name each variable other than initial conditions. The first one or two characters indicate the general nature of the variable. Figure I.1 shows the first character identifiers for variables in the ACSL version of MMS.

Variables passed between modules, like flow rates, temperatures or pressures are identified using one to four character stream identifiers supplied by the user. Referring to Figure I.2, the temperature of the flue gas leaving TS1 would be TGL1. This name is arrived at by taking the general variable first character for temperature "T", and combining it with the user-supplied stream identifier for the flue gas leaving TS1 "GL1".

Variables associated with a unit operation which are not passed between components are named by using a user-supplied one to three character module identifier. Again referring to Figure I.2, the flow conductance for TS1 is KCFS1. This name is constructed by combining the general

|   |                                                               |
|---|---------------------------------------------------------------|
| C | Control System Variable                                       |
| D | Derivative                                                    |
| E | Electrical                                                    |
| F | Neutron Flux                                                  |
| G | Concentration, Ratio, Efficiency                              |
| H | Enthalpy                                                      |
| I | Initial Condition                                             |
| J | Power                                                         |
| K | Miscellaneous Coefficients and Constants                      |
| L | Level                                                         |
| M | Mass                                                          |
| N | Speed                                                         |
| O | Validity Flags                                                |
| P | Pressure                                                      |
| Q | Heat Flux                                                     |
| R | Density ( $\rho$ )                                            |
| S | Entropy                                                       |
| T | Temperature                                                   |
| U | Internal Energy                                               |
| V | Viscosity                                                     |
| W | Flow                                                          |
| X | Steam Quality                                                 |
| Y | Position/Stroke                                               |
| Z | Reserved for internal uses. Cannot be used for variable name. |

FIGURE I.1 Reserved First Character Identifiers

USER WORKSHEET: SPRHTR

MACRO INVOCATION:

SPRHTR ('S1', 'GE1', 'LN2', 'GL1', 'SL1')  
          ID      GE      SE      GL      SL

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

|                                                            |                              |
|------------------------------------------------------------|------------------------------|
| Flow Conductance                                           | (pph/ pcf.psi): KCFS1 = 2828 |
| Heat Exchanger Arrangement Parameter                       | (Integer): KKTS1 = 1         |
| (1: Counterflow, 2: Parallel Flow)                         |                              |
| Moisture Fraction of Flue Gas                              | : KMFS1 = .05                |
| Mass of Metal                                              | : KMMS1 = .32                |
| Slagging Factor (Fractional Reduction in HX Effectiveness) | : KSGS1 = .15                |
| Gas Convective H-T Parameter                               | : KUCS1 = .70                |
| Steam H-T Parameter                                        | : KUSS1 = 30                 |
| Volume of Gas                                              | : KVGS1 = 5184               |
| Volume of Steam                                            | : KVSS1 = 1.64               |

FIGURE I.2 USER WORKSHEET for Superheater Module  
in TS1

variable for the flow conductance "+KCF" with the user-supplied module identifier for TS1 "S1".

### Advanced Continuous Simulation Language

The version of MMS used in this work is based on the simulation language, Advanced Continuous Simulation Language (ACSL pronounced "AXLE"), developed by Mitchell and Gauthier, Assoc. (Mitchell and Gauthier, 1981). ACSL serves as a precompiler for the model. The ACSL precompiler constructs a complete FORTRAN program by replacing each one line module call in the model description with the complete set of equations for that module, generating all variable names, setting up FORTRAN common blocks, and sorting the equations into compatible order. The output of the ACSL precompiler is a FORTRAN source code which can be modified by the user. ACSL also provides for the integration of the model (see Chapter II).

ACSL also provides linear analysis capability. It linearizes the model around a user-specified operating point. This makes it possible to calculate eigenvalues for the model. More is said about the linear analysis routines in Chapter II.

### Steam Property Algorithms

Polynomial or tabular representations of various steam property relations are built into the system. These

routines are coded as FORTRAN FUNCTION Subroutines and may be called by the User in his MMS program like any FORTRAN subprogram. These routines are called internally from many of the MMS modules. The User may also call them in any MMS program.

## CHAPTER II

### THEORY

#### Model Integration

ACSL provides for the integration of the model. The simulation is performed by integrating state variables (e.g., enthalpy, pressure) with respect to time. This work uses Gear's stiff integration algorithm (EPRI; Volume 1, 1983). Gear's stiff algorithm uses as arguments, the values of the state variables at the end of the integration step rather than at the beginning; iterating until the difference between the results of successive calculations falls below an acceptable limit. Gear's stiff algorithm employs steps of variable length, automatically increasing the step size as the model approaches steady state.

The MMS modules are based on the conservation of mass, energy, and momentum equations. A complete derivation of the equation for a superheater is included in Appendix A. They are represented by ordinary differential equations in time. All computer solutions of differential equations are finite difference methods.

$$X_n = F(X_{n-1}, \text{Constants}, \text{Boundary Conditions}) \quad (\text{II.1})$$

$$X_{n+1} = X_n + \dot{X}_n h \quad (\text{II.2})$$

Instead of writing Equation 2 directly into the model, MMS replaces Equation II.2 with:

$$X = \text{INTEG} (X, IX) \quad (\text{II.3})$$

INTEG is an operator which calculates the time integral of X starting from the initial condition IX. MMS then allows the user to select the integration algorithm by setting a parameter which points INTEG to the selected program block. Gear's stiff integration algorithm is used in this work.

Equation II.3 implies

$$X = IX + \int_0^T \dot{X} dt \quad (\text{II.4})$$

In building the model, it is necessary to change differential operators into integration operators and this is accomplished by expressing the highest derivative of a variable in terms of lower derivatives and other variables. For example, consider the second-order system

$$\ddot{X} + 2 \xi \omega_n \dot{X} + \omega_n^2 X = F(t) \quad (\text{II.5})$$

where  $\omega_n$  is a natural undamped frequency and  $\xi$  is the damping ratio. Expressing this equation in terms of  $\ddot{X}$ , we have

$$\ddot{X} = F(t) - 2 \xi \omega_n \dot{X} - \omega_n^2 X \quad (\text{II.6})$$

$$\text{let } \ddot{X} = XDD \text{ and } \dot{X} = XD. \quad (II.7)$$

Now X is the second integral of XDD

$$X = \text{INTEG}(\text{INTEG}(XDD, XDIC), XIC). \quad (II.8)$$

These results can be generalized for a derivative of nth order (Mitchell and Gauthier, 1981).

### Control Theory

MMS provides design values for control loop gain without the usual trial and error approach to controller gain selection. The root locus method is used to specify the control gains after only one or two runs of the model. Traditionally, the model would be run many times, adjusting the gain after each run, until the desired response is achieved. MMS utilizes the ACSL linear analysis routines to calculate the model eigenvalues directly. The program output gives the value of the damping coefficient ( $\xi$ , discussed later in this section) along with each complex eigenvalue. The eigenvalues and values for  $\xi$  are all that is needed for the construction of the root locus plot and the determination of the optimum control loop gains.

The strategy used for the controller gain design is as follows:

1. Calculate all eigenvalues for the models while varying the proportional gain  $K_p$ .
2. Plot the less damped complex eigenvalues on the S-plane.
3. Select the value of  $K_p$  which predicts 10% overshoot.
4. Run the model again with the design value of  $K_p$  while varying the integral gain.  
Plot the response of the model to a step change in TGE1 at various values for  $K_I$ .
6. Select the value for  $K_I$  which minimizes overshoot and response time.

The linear analysis routines are activated from the run-time file, e.g.

```
ANALYZ 'LIST' = .T., 'NITRMX' =10, 'FRACOL' = .2, 'TRIM'
ANALYZ 'FRACDL' = .9, 'TRIM'
ANALYZ ' EIGEN'
```

'ANALZ' =                    calls the ACSL linear analysis routines.

'LIST' = .T.                causes all the states and their  
derivatives to be printed out for review  
on each iteration.

'NITRMX' = 10            limits the number of steps taken by the  
Newton Raphson routine to 10.

'FRACDL' = .2, .9       multiplies the step size for each state  
calculated by the Newton Raphson by .2  
in the first invocation of ANALYZ and by  
.9 in the second invocation. The value  
of 'FRACDL' compensates for the  
nonlinearity of the model. FRACDL is  
given a small value for highly nonlinear  
models. The first invocation of ANALYZ  
is intended to get close to the steady  
state and the second invocation is  
intended to zero in on the steady state.

'TRIM'                   calculates new state values that will  
decrease the residuals of all the model  
derivatives toward zero using a Newton  
Raphson Method.

'EIGEN'                  calculates the Jacobian about the  
current point having been specified by  
the proceeding 'TRIM' (Subcommand) by  
numerical perturbation. The linearized  
model is represented to the computer as  
the Jacobian Matrix and all subsequent  
linear model calculations are performed

on the Jacobian. The eigenvalues are the result of a diagonalization of the Jacobian into an equivalent complex diagonal matrix. Each of the complex diagonal elements is an eigenvalue and describes one response mode of the system. The system response to a real eigenvalue is a first-order response and the response to a complex eigenvalue is a damped second-order response.

In higher order systems, with many roots, the model response depends essentially on the "least damped complex roots". For the ACSL solution in particular, the model response is dominated by the least damped of the second-order response modes. Furthermore, for this particular application, the state variables associated with the "least damped complex roots" specify the response mode of the separate superheater test-sections in the model.

The root locus method depicts the entire system's transient behavior. The location of the system eigenvalues on the S-plane is related to the system response in time domain in the following way.

The response mode of the system can be described in terms of the characteristic equation for the second-order system of Equation II.5.

$$s^2 + \frac{1}{\tau} s + \frac{K}{\tau} = 0 \quad (\text{II.9})$$

where  $\tau$  is a constant,  $K$  is a variable gain.

The roots of this equation determine the transient behavior of the system. Solving for  $S$  with the binomial expression

$$S_i = -\frac{1}{2\tau} \pm \sqrt{\frac{1}{4\tau^2} - \frac{K}{\tau}} \quad (\text{II.10})$$

If  $S_1$  and  $S_2$  are real and negative, the response is first-order with no oscillary nature.

If  $S_1$  and  $S_2$  are complex with real part positive, the response is second-order and unstable. In the time domain, the response is of the form

$$C(t) = e^{\alpha t} (A \sin \omega t + B \cos \omega t) \quad (\text{II.11})$$

which characterizes an oscillatory response with increasing amplitude.

If the roots have no real part (lie on the imaginary axis) the system response is again unstable. The response in the

time domain is of the form

$$C(t) = A \sin \omega t + B \cos \omega t \quad (II.12)$$

which characterizes an undamped sinusoidal response.

If the roots are complex with real part negative, the system response is stable and is of the form

$$C(t) e^{-\alpha t} (A \sin \omega t + B \cos \omega t) \quad (II.13)$$

which is a damped sinusoidal or "damped second-order" response.

It follows that a complex eigenvalue with real part negative and near the imaginary axis will be characterized by greater oscillation and subsequently greater setpoint overshoot and a complex eigenvalue with real part negative and near the real axis will display little oscillatory behavior and experience less setpoint overshoot.

The damping coefficient  $\xi$  is an indication of the position of the roots in the S-plane (see Figure II.1). For roots on the real axis  $\xi$  is 1 and  $\xi$  is 0 for roots on the imaginary axis. The magnitude of  $\xi$  for any root location is then given by Equation II.14.

$$\xi = \frac{\text{RE}}{\sqrt{\lambda_{\text{RE}}^2 + \lambda_{\text{IM}}^2}} \quad \text{or} \quad \xi = \cos \theta \quad (\text{II.14})$$

where  $\theta$  is the angle between the real axis on Figure II.1 and a straight line intersecting the root locus and the origin.

In addition to setpoint overshoot characterized by  $\xi$ , system response speed must also be considered in the controller design. The response speed of the system refers to how much time it takes the control variable to reach the setpoint after an initial disturbance. The response speed of the system is characterized by the undamped natural frequency ( $\omega_n$ ) for the response mode. The undamped natural frequency ( $\omega_n$ ) and  $\xi$  are inversely proportional to one another

$$\omega_n \propto \frac{1}{\xi}. \quad (\text{II.15})$$

In other words, a relatively large value for  $\xi$  produces a system which is characterized by minimal overshoot and a sluggish response and a relatively small value for  $\xi$  produces a system characterized by quick response time and an unacceptable degree of setpoint overshoot. The selection of controller gains by specifying the value for  $\xi$ , represents a trade-off between controller response time and setpoint overshoot (Savant, 1964).

The selection of the design value for the damping coefficient is to some extent a matter of engineering judgement. By this stage in the design of the controller gains, it should be known that the process is stable and that it can operate at steady state sufficiently close to setpoint. Figure II.2 gives the percent overshoot for values of  $\xi$ . Other works (Armor, Divakaran, et. al., 1983) involving power plant simulation using MMS have selected the design point  $\xi = .6$ , which gives approximately 10% overshoot, as a target for control system optimization. This work uses  $\xi = .6$  as a target for control gain optimization (EPRI; Volume 1, 1983).

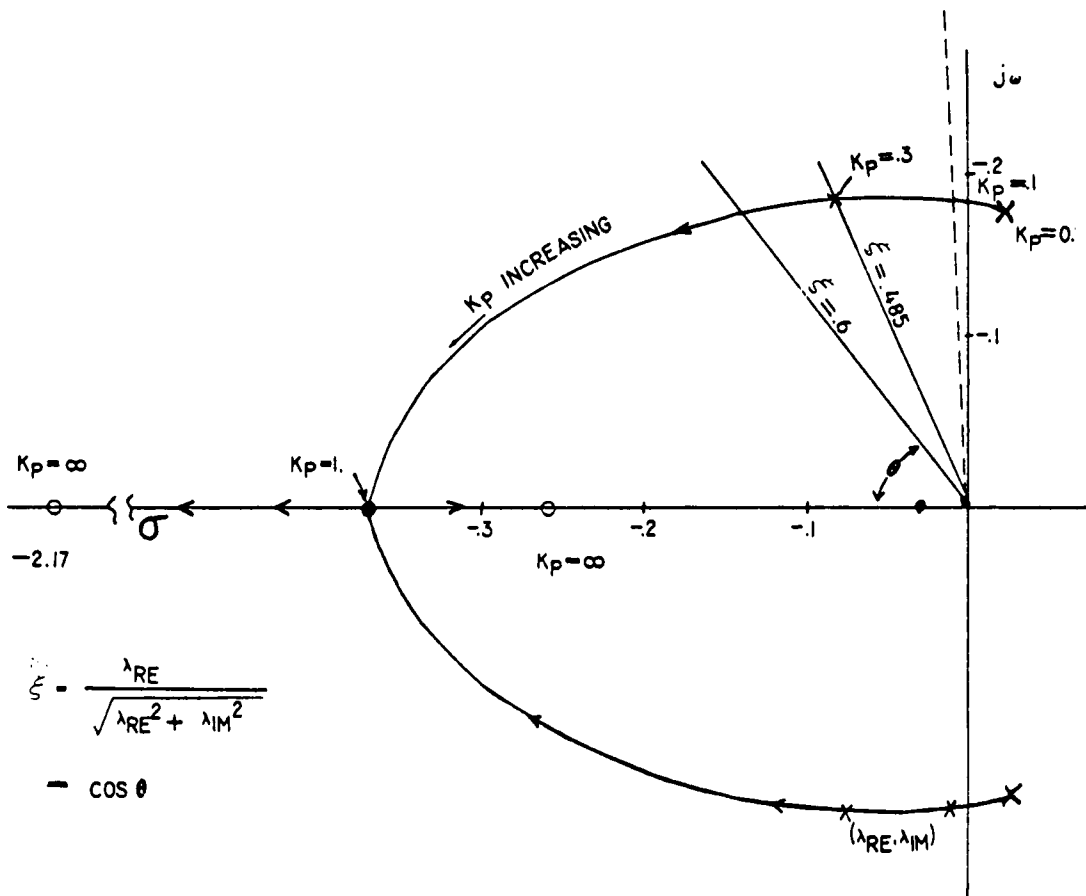


FIGURE II.1 Example of a Root Locus Plot

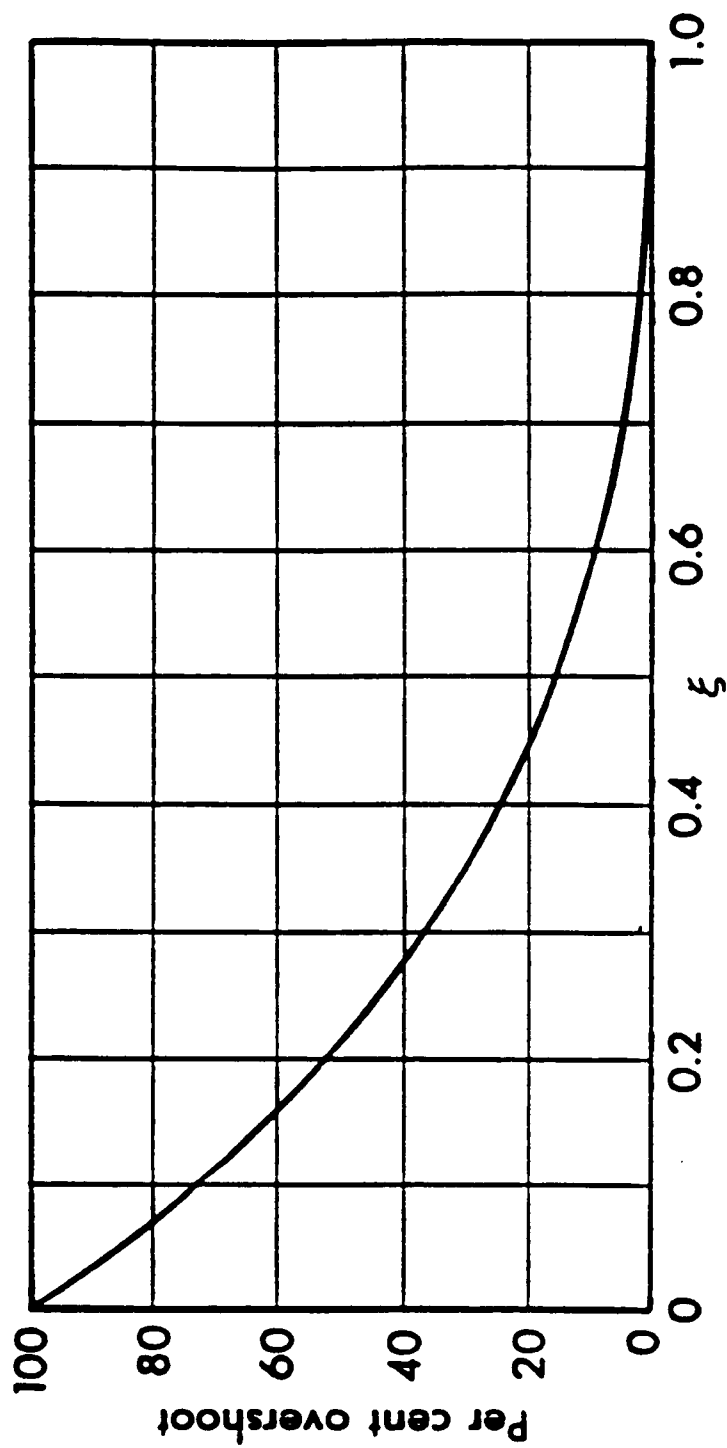


FIGURE II.2 Percent Overshoot Versus  $\xi$

## CHAPTER III

### BUILDING THE SUPERHEATER TEST-SECTION MODEL

In this chapter, all the necessary information needed to simulate the superheater test-section model is accumulated and assembled onto User Worksheets. The model is coded directly from the user worksheets to avoid repetition of effort (EPRI; Volume 3, 1983).

#### Deciding the Scope of the Model

Figure III.1 is a simplified process schematic showing all plant components and process paths to be modeled. Notice the cooling water paths for the economizers (cooling sections) are not shown. Constant flowrate of economizer cooling water is assumed. The controllers compare the temperature of the steam leaving the superheater test sections to a setpoint and act on the error.

Figure III.2 is the MMS representation of Figure III.1. This drawing defines the scope of the model. The denote the boundaries of the model. The boundary conditions must be specified by the user. The boundary condition "TEMP GAS ENTERING SUPERHEATER 1" (TGE1) is the variable which is perturbed to exercise the model. The steam into the superheaters is from a common header. The condition of the steam is assumed to be the same for all three superheaters. Notice that 6 "CONNC" modules had to be added to allow proper interconnections of the modules.

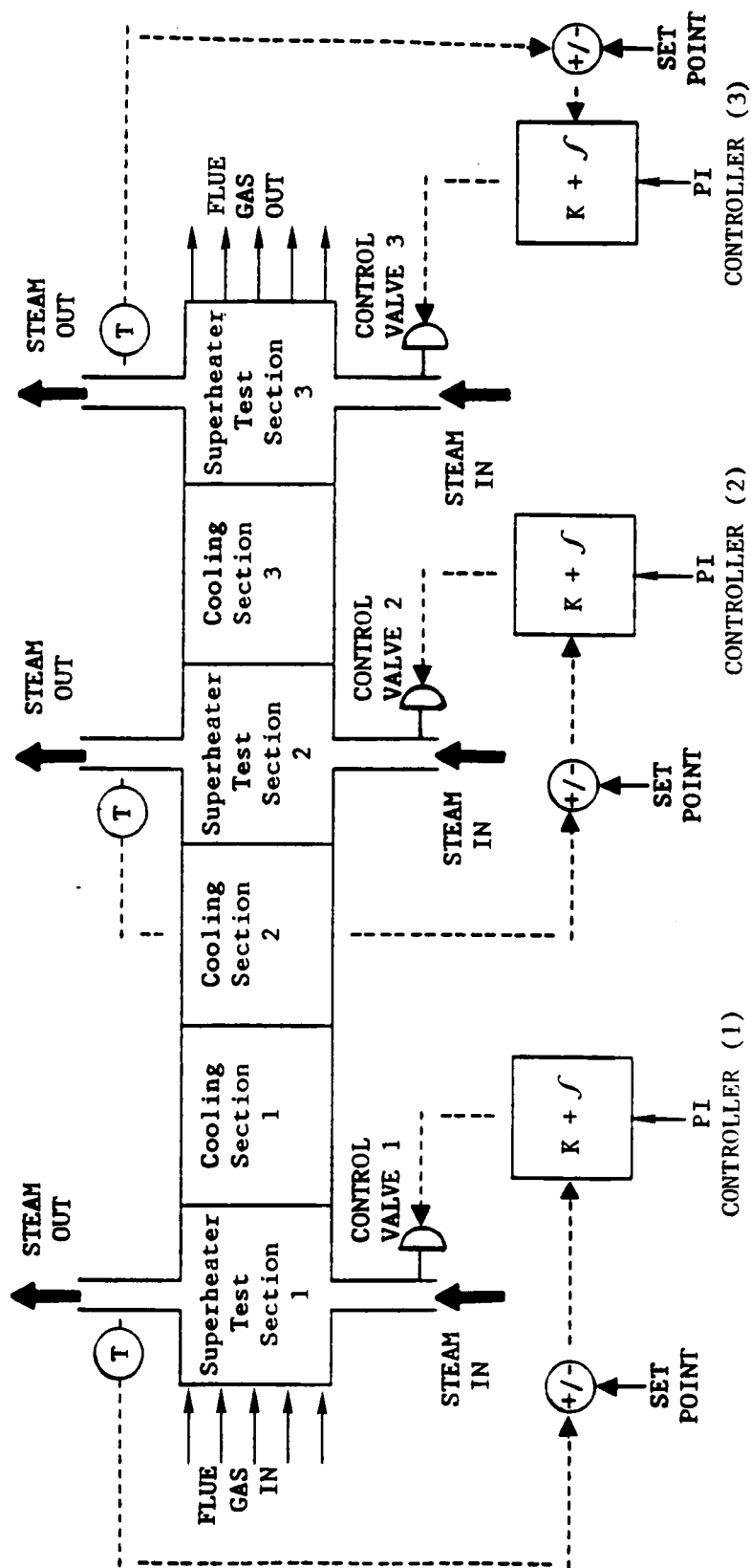


FIGURE III.1 Simplified Model Schematic for Superheater Test-Section Model

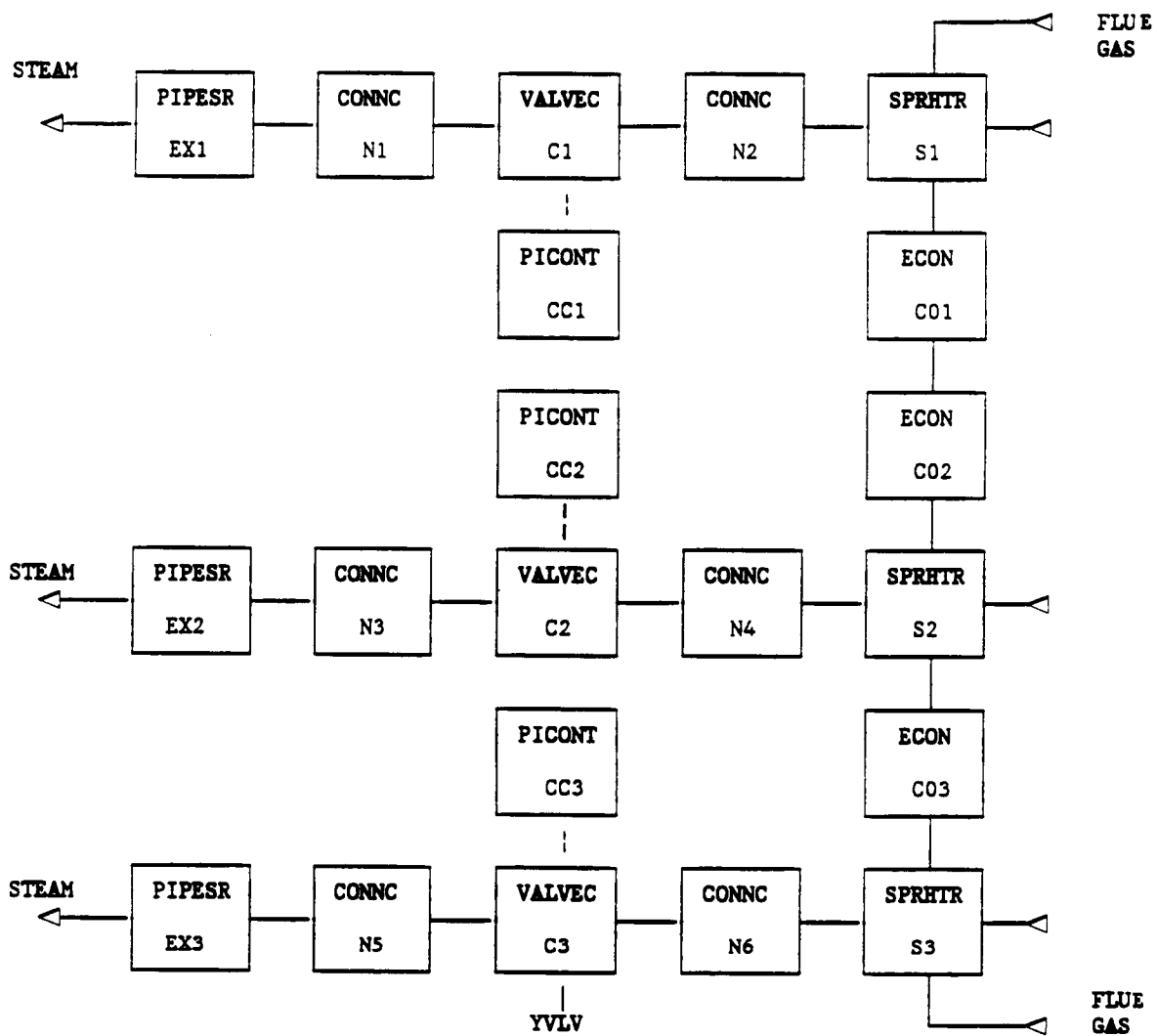


FIGURE III.2 Connection Schematic for Superheater Test Section Model

### Model Parameterization

The correlations and physical property data in Appendix A were used to calculate the system parameters.

### Complete User Worksheets

A User Worksheet is completed for each module in the interconnection schematic. Constant parameters and boundary conditions are included on the worksheets. The transfer of interconnection variables is specified in the Macro Invocation on the User Worksheets. Figure III.3 is an example of a completed User Worksheet. The balance of the User Worksheets for the model are included in Appendix B.

USER WORKSHEET: SPRHTR

MACRO INVOCATION:

SPRHTR ('S1', 'GE1', 'LN2', 'GL1', 'SL1')  
ID GE SE GL SL

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

|                                                            |                              |
|------------------------------------------------------------|------------------------------|
| Flow Conductance                                           | (pph/ pcf.psi): KCFS1 = 2828 |
| Heat Exchanger Arrangement Parameter                       | (Integer): KKTS1 = 1         |
| (1: Counterflow, 2: Parallel Flow)                         |                              |
| Moisture Fraction of Flue Gas                              | : KMFS1 = .05                |
| Mass of Metal                                              | : KMMS1 = .32                |
| Slagging Factor (Fractional Reduction in HX Effectiveness) | : KSGS1 = .15                |
| Gas Convective H-T Parameter                               | : KUCS1 = .70                |
| Steam H-T Parameter                                        | : KUSS1 = 30                 |
| Volume of Gas                                              | : KVGS1 = 5184               |
| Volume of Steam                                            | : KVSS1 = 1.64               |

FIGURE III.3 Example of a Completed User Worksheet

## CHAPTER IV

### EXECUTING THE MMS MODEL

This chapter gives a brief overview of the procedure for executing the MMS model. No attempt is made to describe the many runtime commands or the selection of integration criterion. The MMS manuals will provide that information.

The original ACSL model needs to be translated into executable FORTRAN. Before the model can be translated, the MMS system subroutines must be combined with the ACSL system subroutines. This is accomplished by:

Copy ACSLMAC MACRO.BIN

MACRO.BIN now contains all the ACSL macros. It is now necessary to place the MMS module macros into MACRO.BIN. To do this, the "SAVE" keyword must be placed into the file containing the MMS macros (MMS.MAC). After "SAVE" is typed into MMS.MAC, the MMS macros are added by:

ACSL:MMS.MAC/M = MACRO.BIN

Now that MACRO.BIN contains all the necessary macros, the model file (MMS.MOD) can be translated by:

ACSL:MMS.MOD/M = MACRO.BIN

The FORTRAN source is then compiled by:

FORTRAN:MMS

to generate a FORTRAN object code. The object code is ready to be input to the link/loader. At this step, all the

necessary routines must be linked together to create an executable binary code. This includes standard system routines such as math and outputting routines, as well as precompiled MMS routines such as steam property algorithms (Crawford, 1987). The exact link command will vary depending on the system. It is at the linking stage where a less experienced user is likely to make mistakes.

After the link is accomplished, the executable binary is a complete plant model ready to be exercised by the runtime executive. The runtime command file is created by:

```
EDIT MMS.RT
```

After the runtime file is completed, it can be assigned to the screen by:

```
ASSIGN MMS.RT FOR005
```

and the file is executed by:

```
RUN MMS
```

Figure IV.1 gives a graphical representation of the MMS system structure.

## MMS STRUCTURE

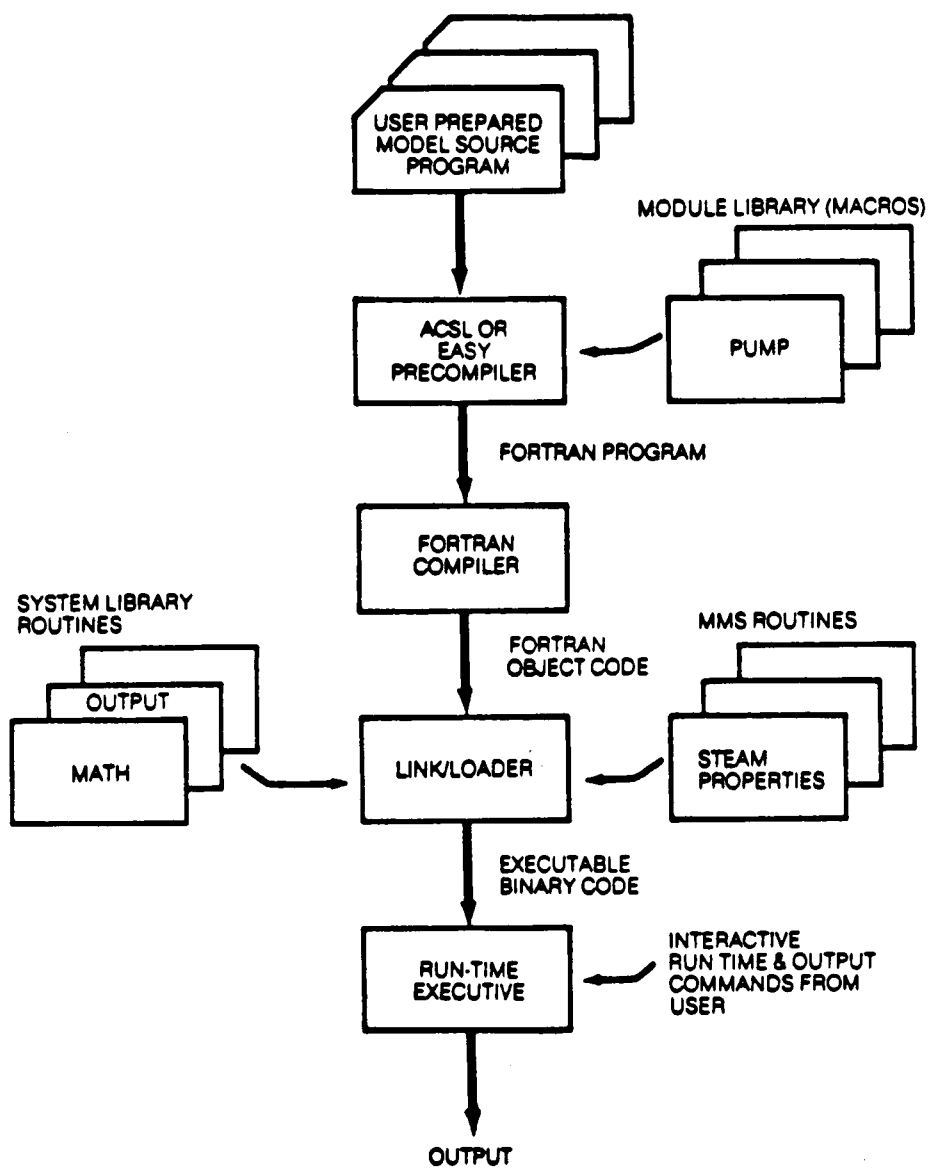


FIGURE IV.1 MMS System Structure

## CHAPTER V

### VALIDATION OF THE SUPERHEATER TEST-SECTION MODEL

Open-loop (control gains = 0) plant data were not available for the model validation. Validation was achieved by mimicking the closed loop response of the plant. The controller modules were incorporated to control the temperature of steam leaving the test-sections to the corresponding plant data. To thoroughly exercise the model, a period of plant operation was chosen which saw a dramatic transient in the temperature of the flue gas into the first superheater. This transient occurred between 14:00 and 16:00 hours on February 19, 1988 during the LMF4M test in CFFF.

To duplicate the plant test, a two-hour-long history of TGE1, which closely resembled the plant data, had to be fed into the model. The model was integrated in three minute intervals with the corresponding value from the plant data specified at the beginning of each interval. The set point for the controllers was updated at the beginning of each three minute interval. The resulting input from this process is compared to the plant data in Figure V.1. The discrepancy between the two curves is one source of error in the responses which follow.

# MODEL VALIDATION INPUT

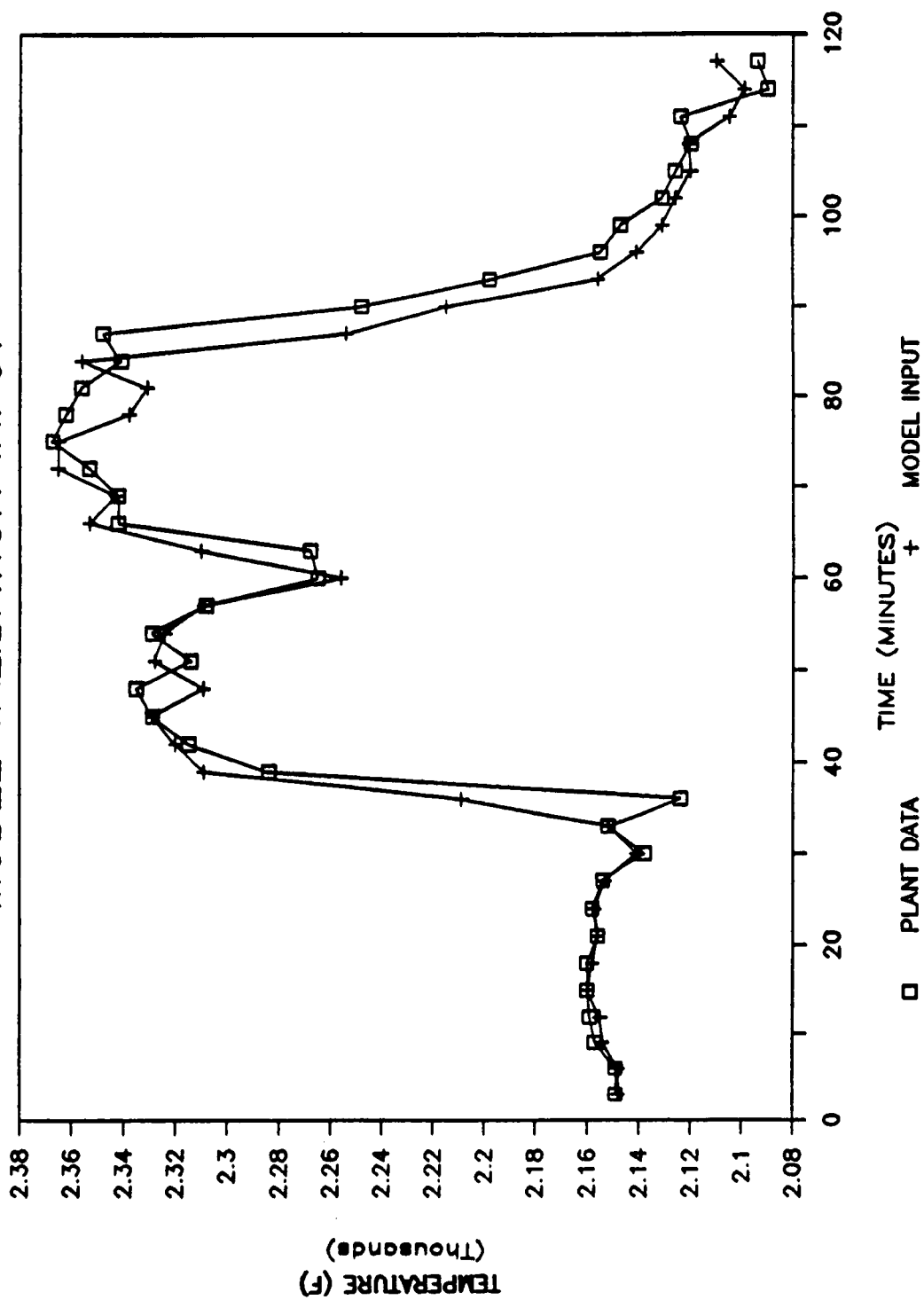


FIGURE V.1 Temperature of Flue Gas Into TS1

A review of Figures V.2 through V.10 gives a comparison of the model response to the actual plant. For the most part, the correlation between the plant and model is excellent. There are a couple of areas which need discussion.

The first area of discrepancy between the model and plant response is apparent in the relatively large difference in the values for steam flow from the first superheater (Figure V.7). This discrepancy was most apparent after  $t = 40$  (minutes). After an exhaustive effort to make the model conform, the possibility that some physical phenomenon was responsible for the discrepancy was explored. It was found that the system had been operating for hours before the transient at TGE1 near or below the melting point of  $K_2SO_4$  (1956°F). During the excursion, temperatures in the superheater rose well above the melting point of  $K_2SO_4$ . It is possible that the unexpected increase in heat transfer displayed by the plant was due to the running-off of a molten coating of slag from the front of the superheater tubes. To simulate this, the slagging coefficient KSGS1 was decreased soon after the temperature increase. Figure V.8 shows an improved response after (KSGS1) was adjusted. No effort was made to validate the reasoning leading up to reducing KSGS1. Considering the overall adherence of the model to the plant response, the

# MODEL VALIDATION

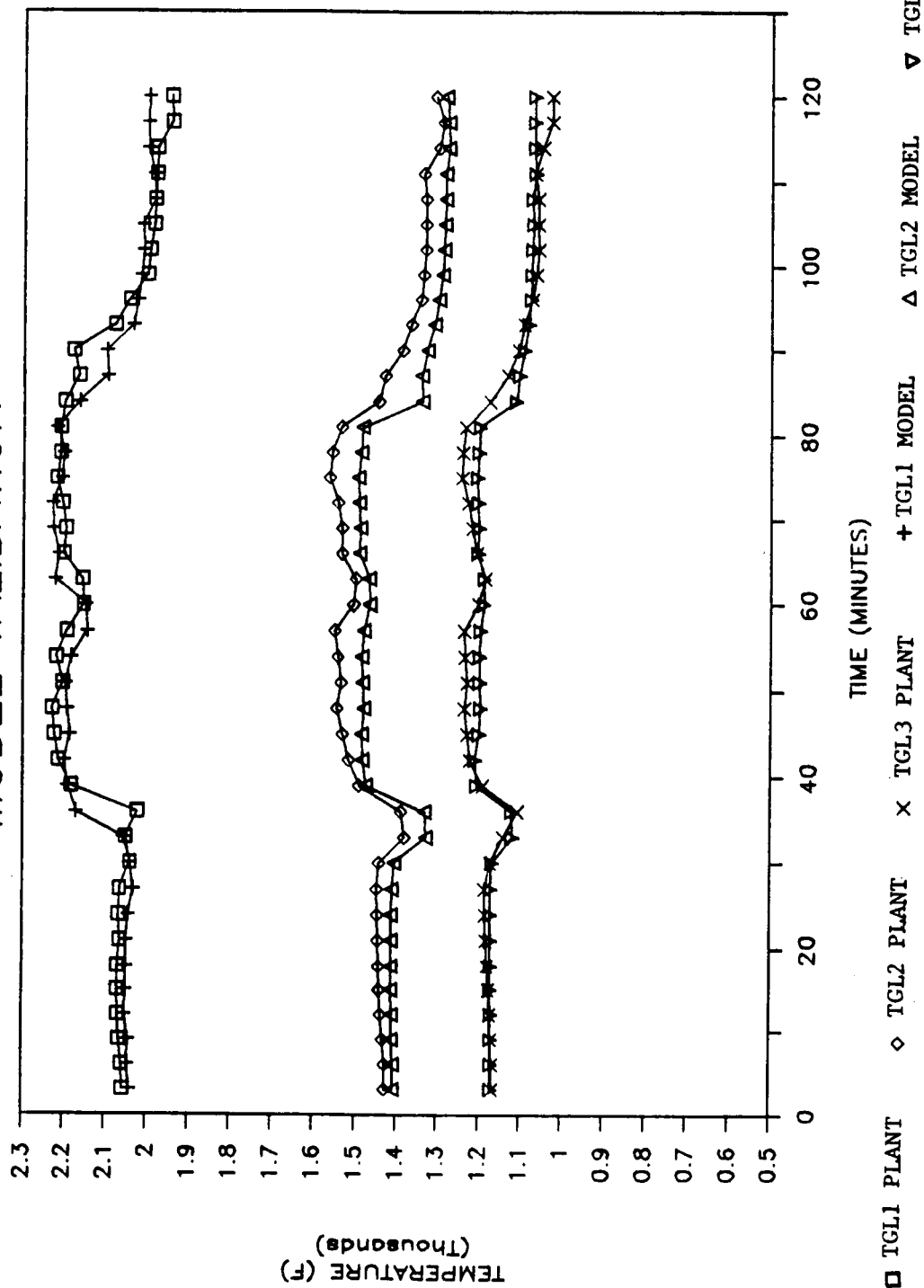


FIGURE V.2 Temperature of Gas Leaving TS1, TS2, and TS3

# MODEL VALIDATION

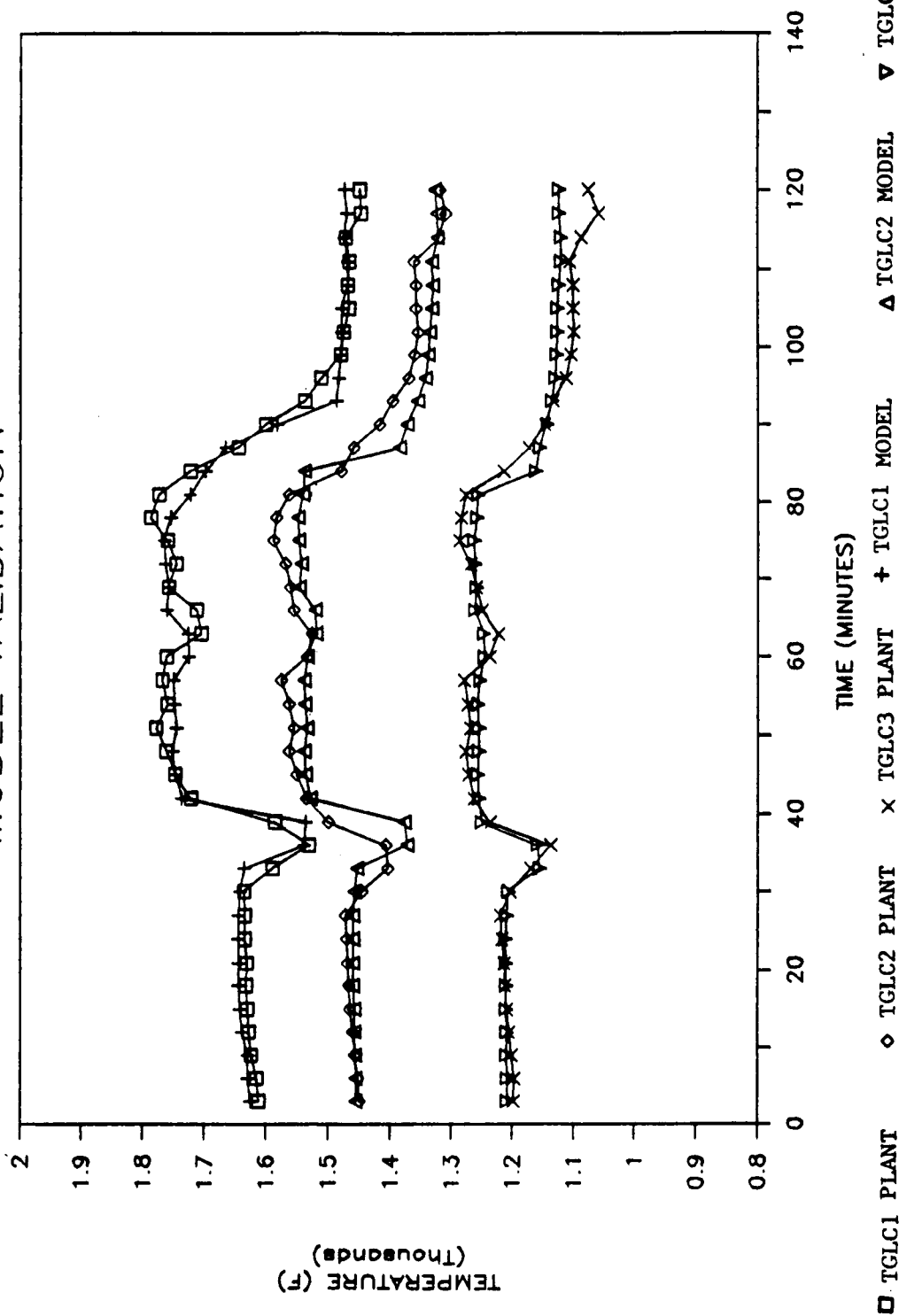


FIGURE V.3 Temperature of the Gas Leaving Economizers 1 - 3

## MODEL VALIDATION

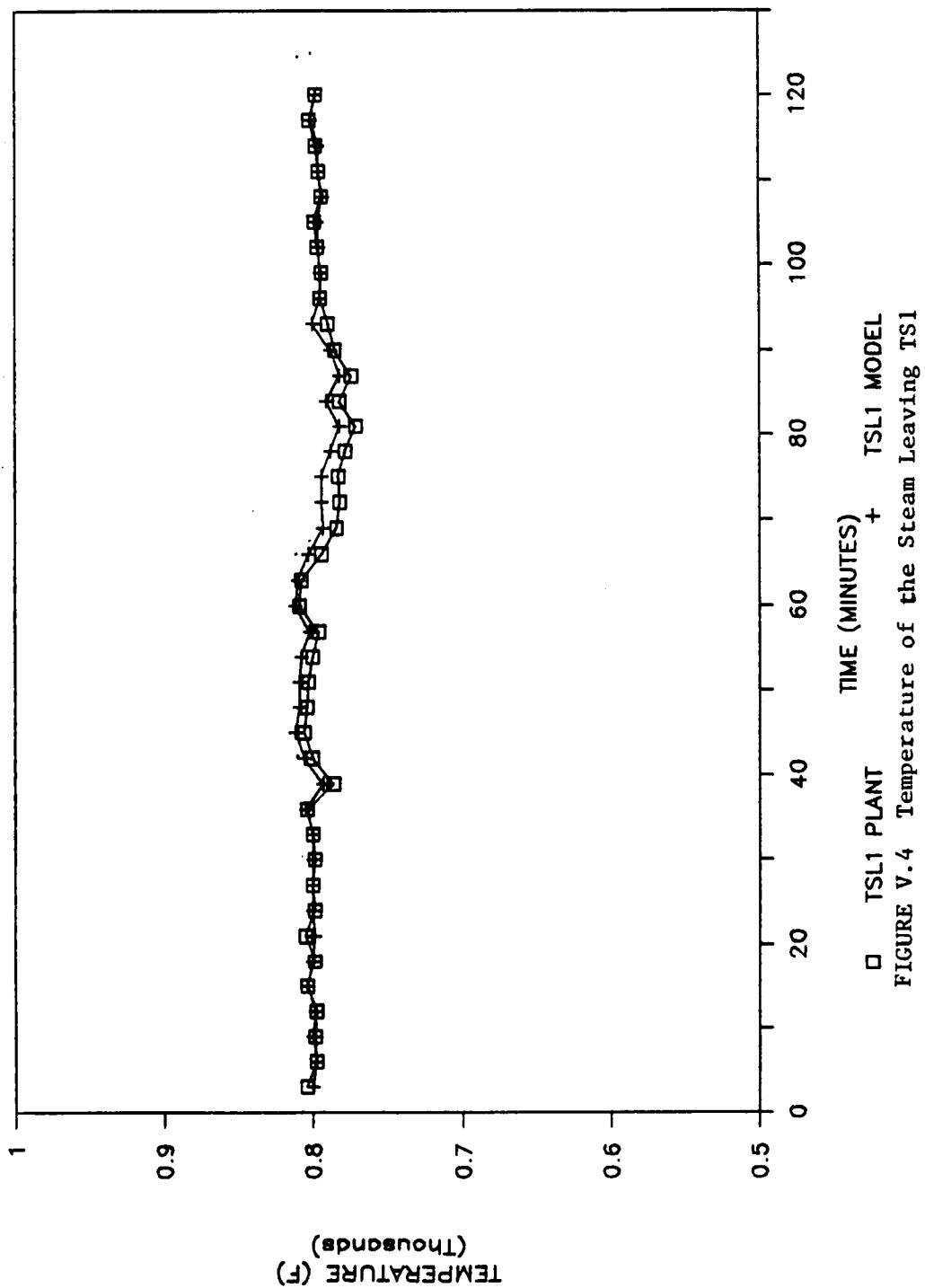


FIGURE V.4 Temperature of the Steam Leaving TSL1

# MODEL VALIDATION

## TEMP STEAM LEAVING SUPERHEATER 2 (F)

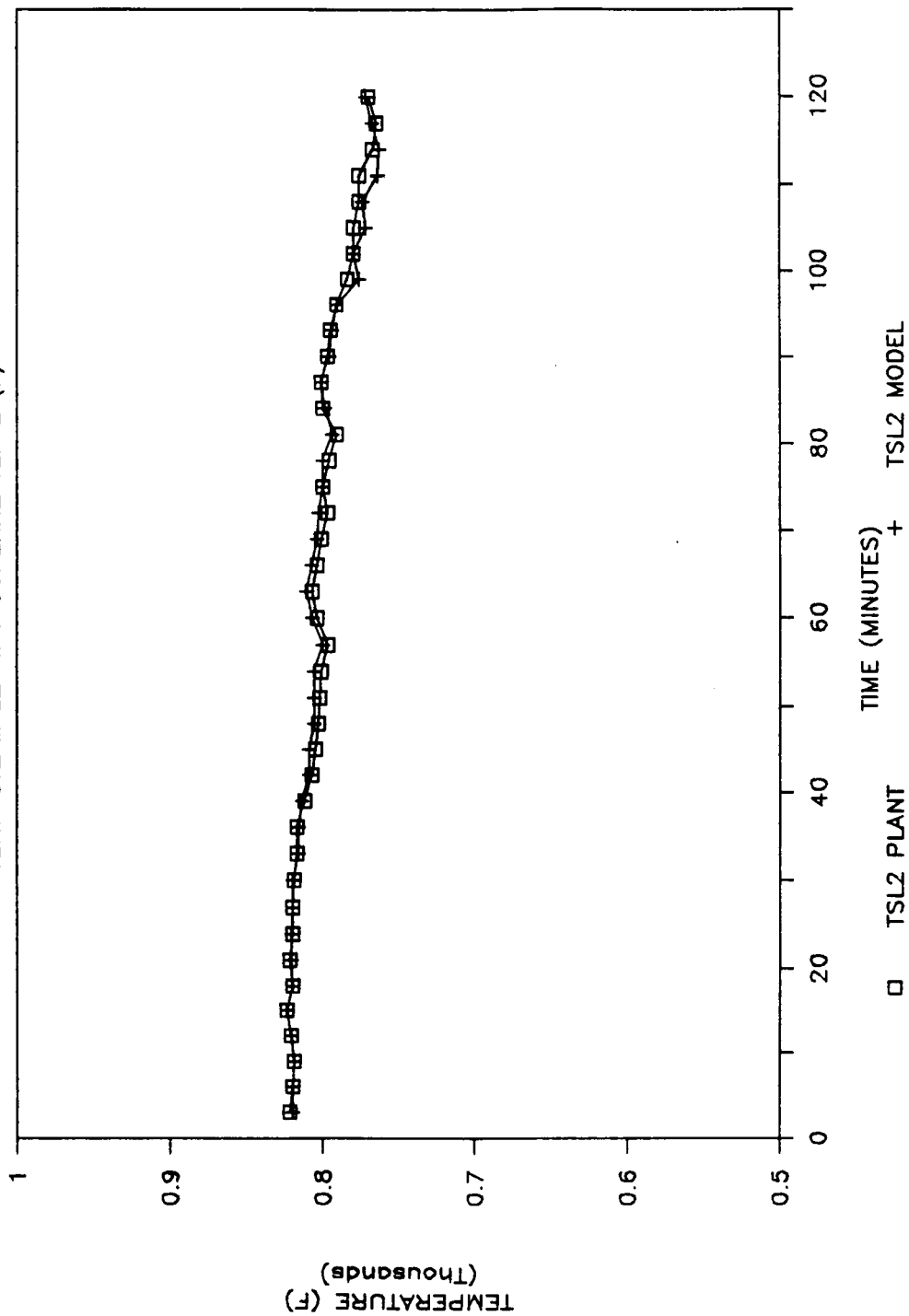


FIGURE V.5 Temperature of the Steam Leaving TS2

# MODEL VALIDATION

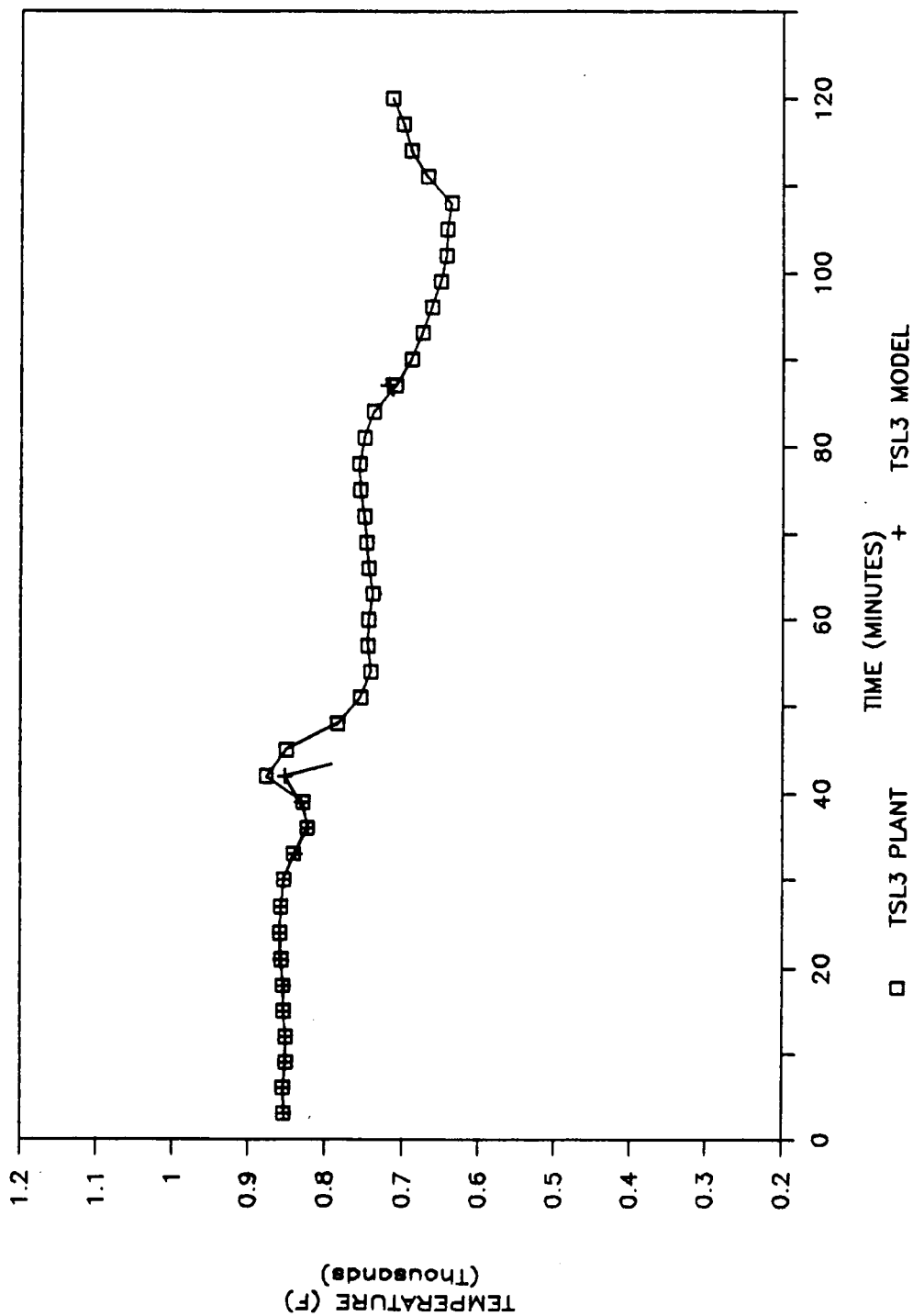


FIGURE V.6 Temperature of the Steam Leaving TS3

# MODEL VALIDATION

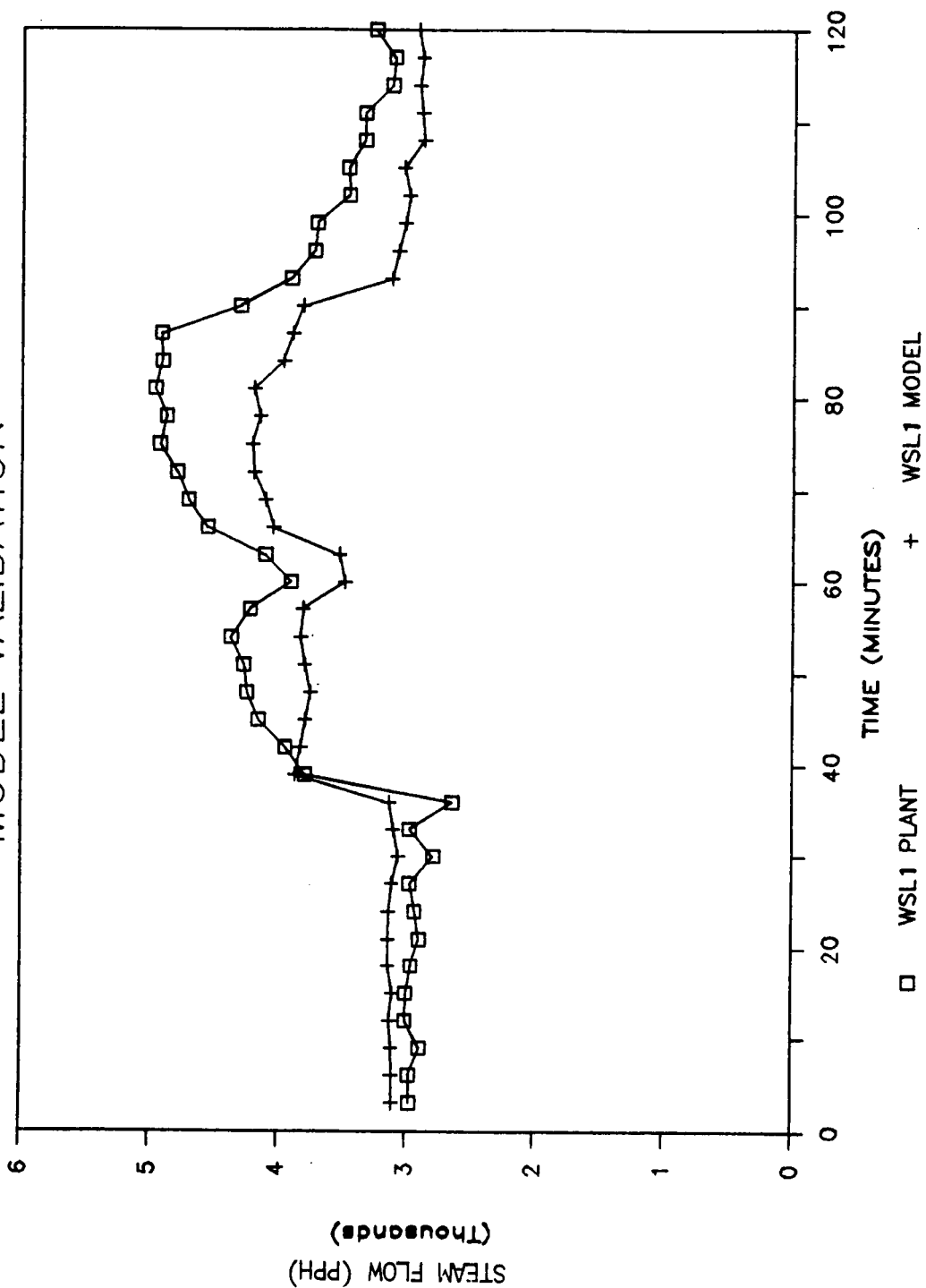


FIGURE V.7 Flow of Steam Leaving TS1 Before Reducing KSGS1

# MODEL VALIDATION

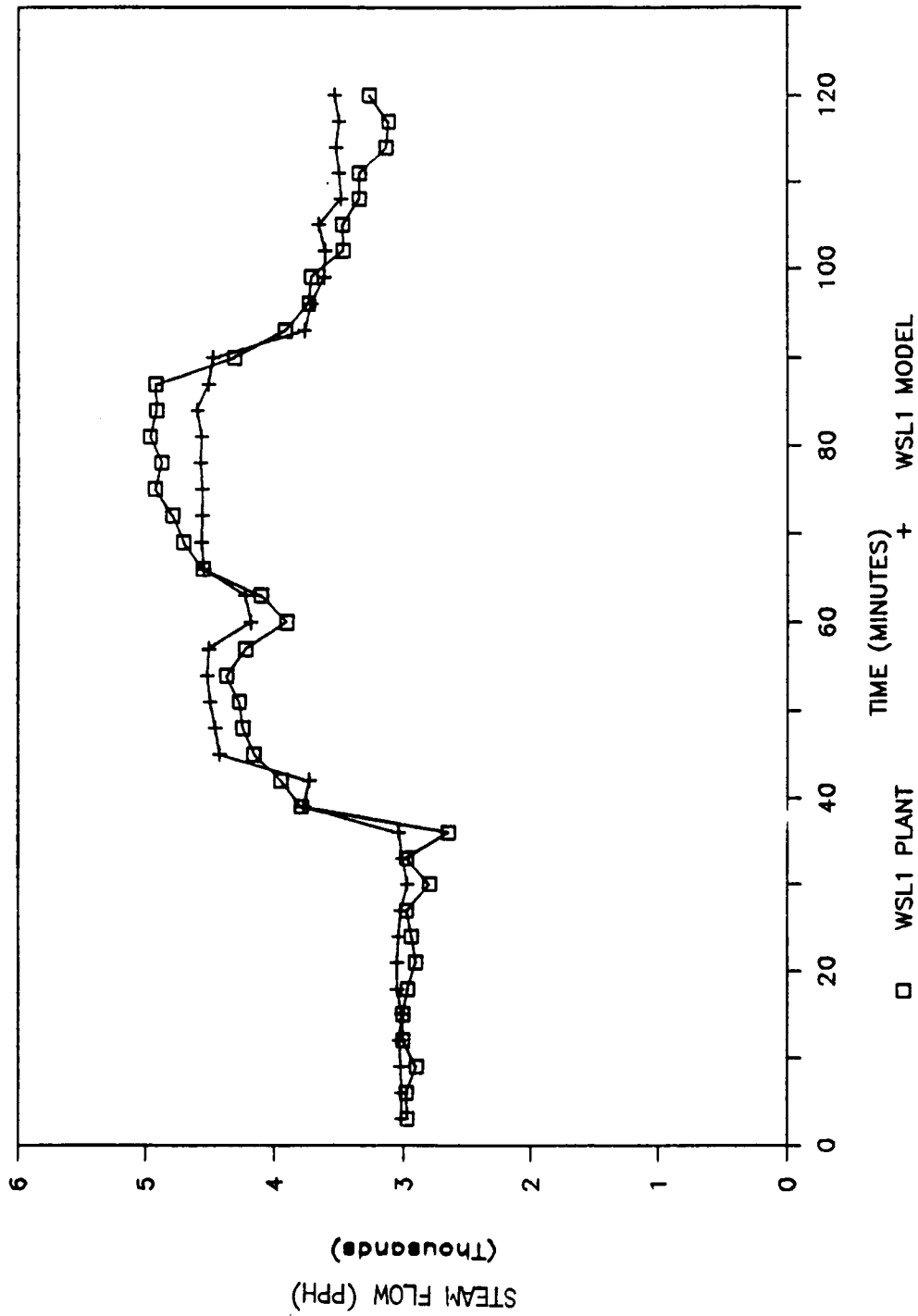


FIGURE V.8 Flow of Steam Leaving TS1 After Reducing KSGS

# MODEL VALIDATION

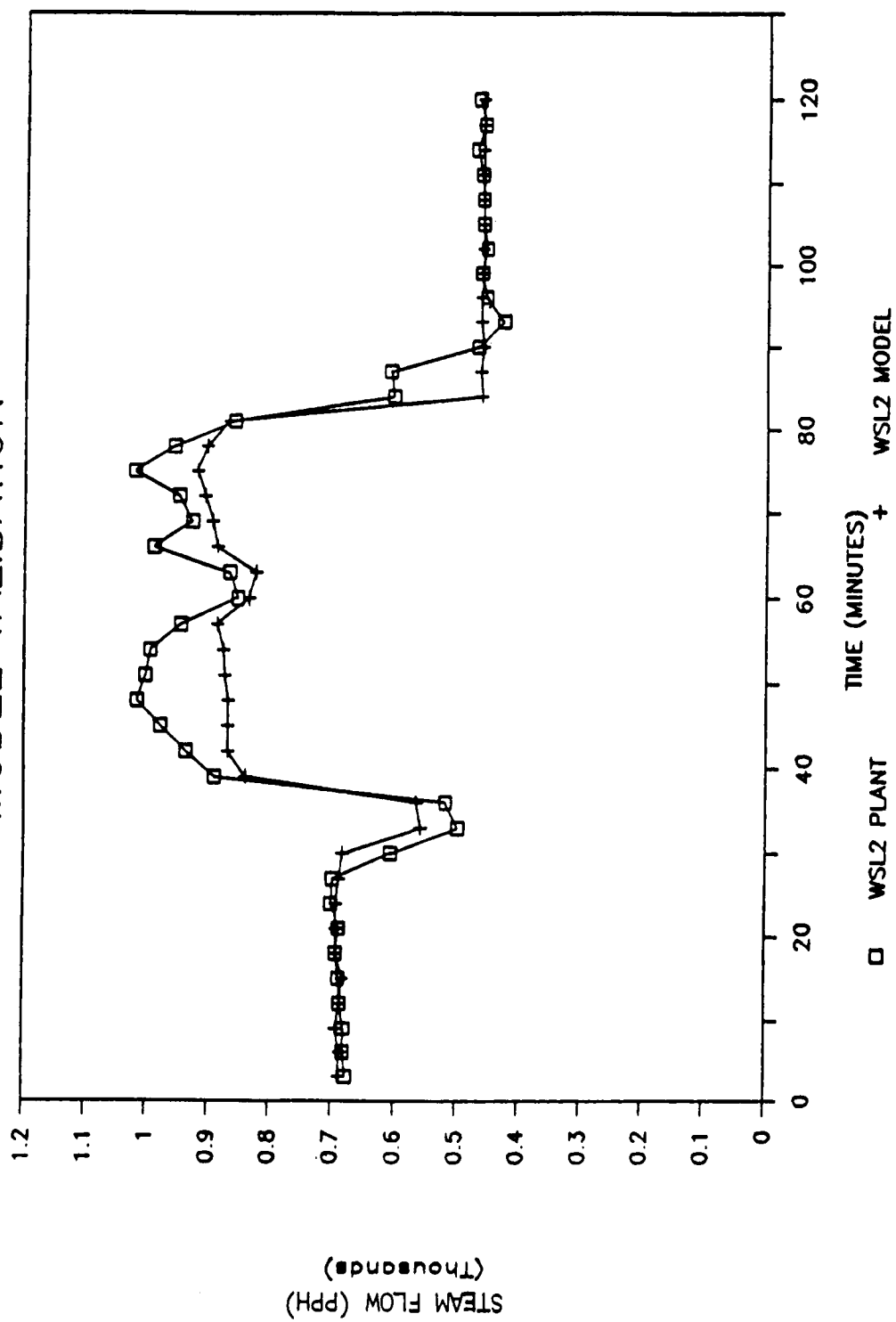


FIGURE V.9 Flow of Steam Leaving TS2

# MODEL VALIDATION

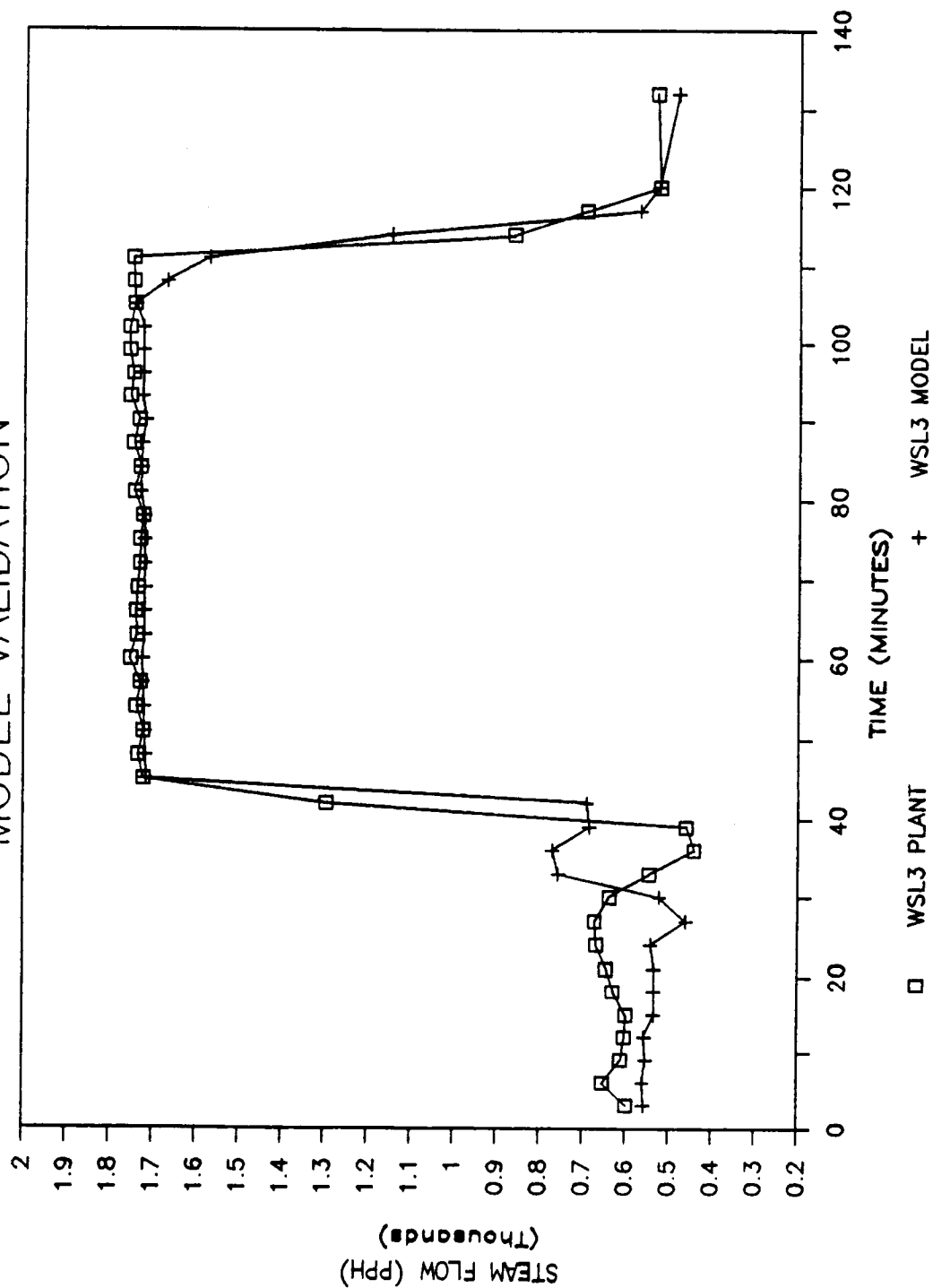


FIGURE V.10 Flow of Steam Leaving TS3

leading up to reducing KSGS1. Considering the overall adherence of the model to the plant response, the discrepancy in the steam flow from TS1 in its original condition would not invalidate the model.

The other point to mention concerns the temperature of the steam leaving the third superheater. Control was terminated on the steam temperature leaving TS3 at  $t = 50$  (minutes) when the steam flow control valve on TS3 was suddenly opened full throttle. The valve was opened manually during the LMF4M run to help reduce flue gas temperatures in the downstream components.

## CHAPTER VI

### CONTROLLER GAIN DESIGN

A command file was created (Appendix E) that ran the validated model at various values of proportional gain ( $K_p$ ). Inspection of the program output showed that all the model eigenvalues except four were real and negative. Of the four complex eigenvalues, two were stationary and near the real axis. The other two complex roots were sensitive to change in proportional gain.

The response of TS1 is not affected by the presence of TS2 and TS3 downstream. No complex eigenvalue is associated with TS1. According to the principles in Chapter II, the response for TS1 is first-order. The response of TS2 is affected by the presence of TS1 and TS3 by the presence of TS2. The two variable complex roots were associated with TS2 and TS3. The principles in Chapter II predicted that the response of TS2 and TS3 would be damped second-order.

The complex eigenvalues were plotted on Figure VI.1 to demonstrate the behavior of the root locus. The real axis had to be expanded to show the mapping of the root locus. The arrows indicate the mapping of the root locus with increasing  $K_p$ . The root associated with TS2 is almost identical to the root associated with TS3 for all  $K_p$ . Figure VI.1 then represents the behavior of TS2 and TS3.

# ROOT LOCUS PLOT

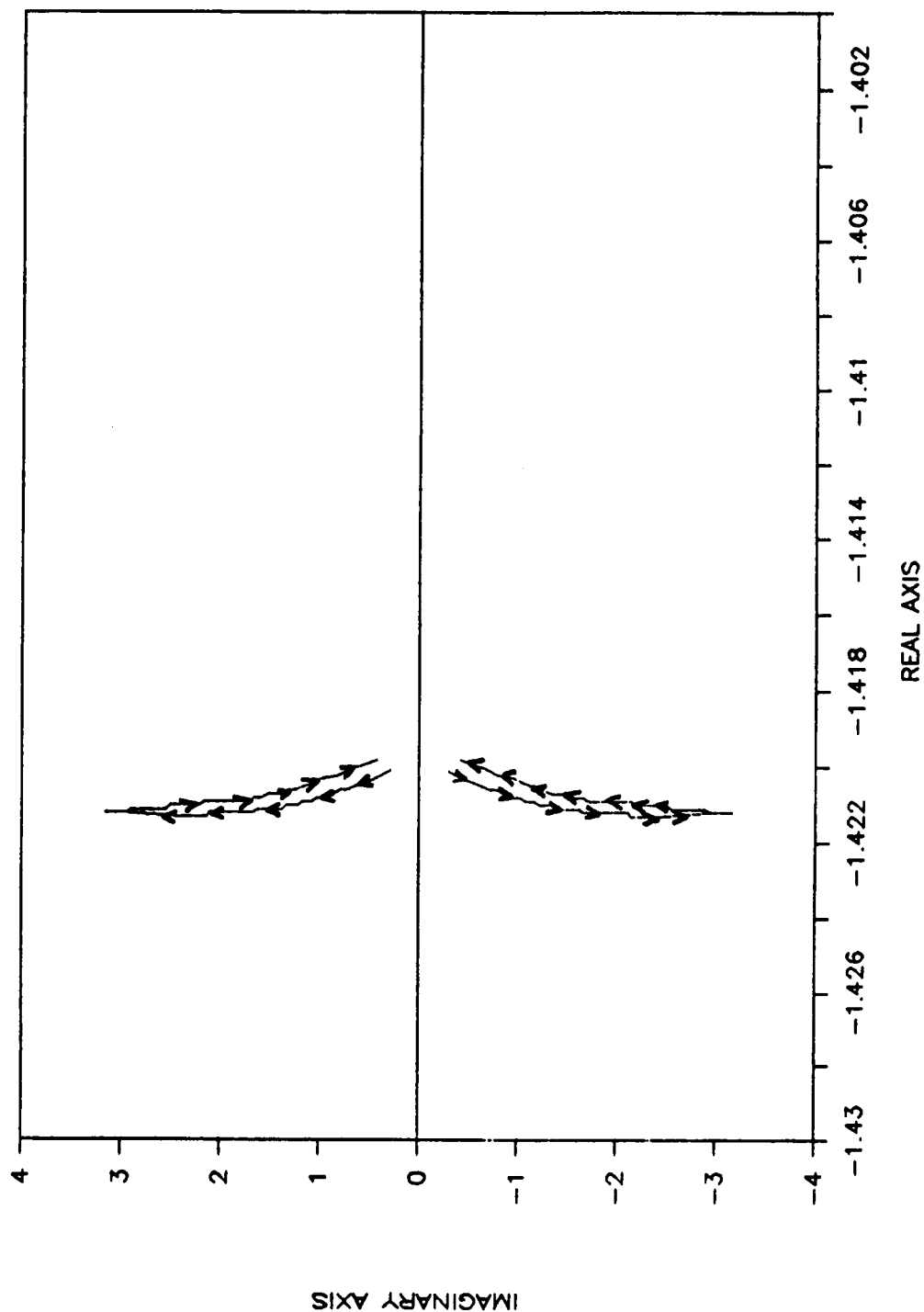


FIGURE VI.1 Mapping of Root Locus for Variable Proportional Gain ( $K_p$ )

The root locus does not cross the imaginary axis so the system is stable for all values of  $K_p$  considered.

Figure VI.2 is a plot of the same data shown in Figure VI.1. Figure VI.2 is the form of the root locus plot which is useful for the controller gain design. A line is drawn on Figure VI.2 corresponding to  $\xi = 0.6$ . The corresponding value of  $K_p$  is 0.05. This step specified  $K_p$  for TS2 and TS3.

Normally, the integral gain ( $K_I$ ) is adjusted with  $K_p$  until the design value of  $\xi$  is achieved. In this work, the root locus is not sensitive to changes in  $K_I$ . As an alternative method for selecting  $K_I$ , the model is run again with  $K_p = 0.05$  and variable values for  $K_I$ .

Figures VI.3 through VI.5 show the response of the steam flow controllers for TS1, TS2, and TS3, to a step change in TGE1. Each figure shows the response of the steam flow controllers at three values of  $K_I$  (0.0025, 0.0050, 0.0100).

As predicted by the calculation of the model eigenvalues, the response of TS1 is first-order. The response of TS1 is critically damped and varying  $K_I$  had no effect on its response. The response of TS2 and TS3 were damped second-order as predicted by the direct calculation

# ROOT LOCUS PLOT

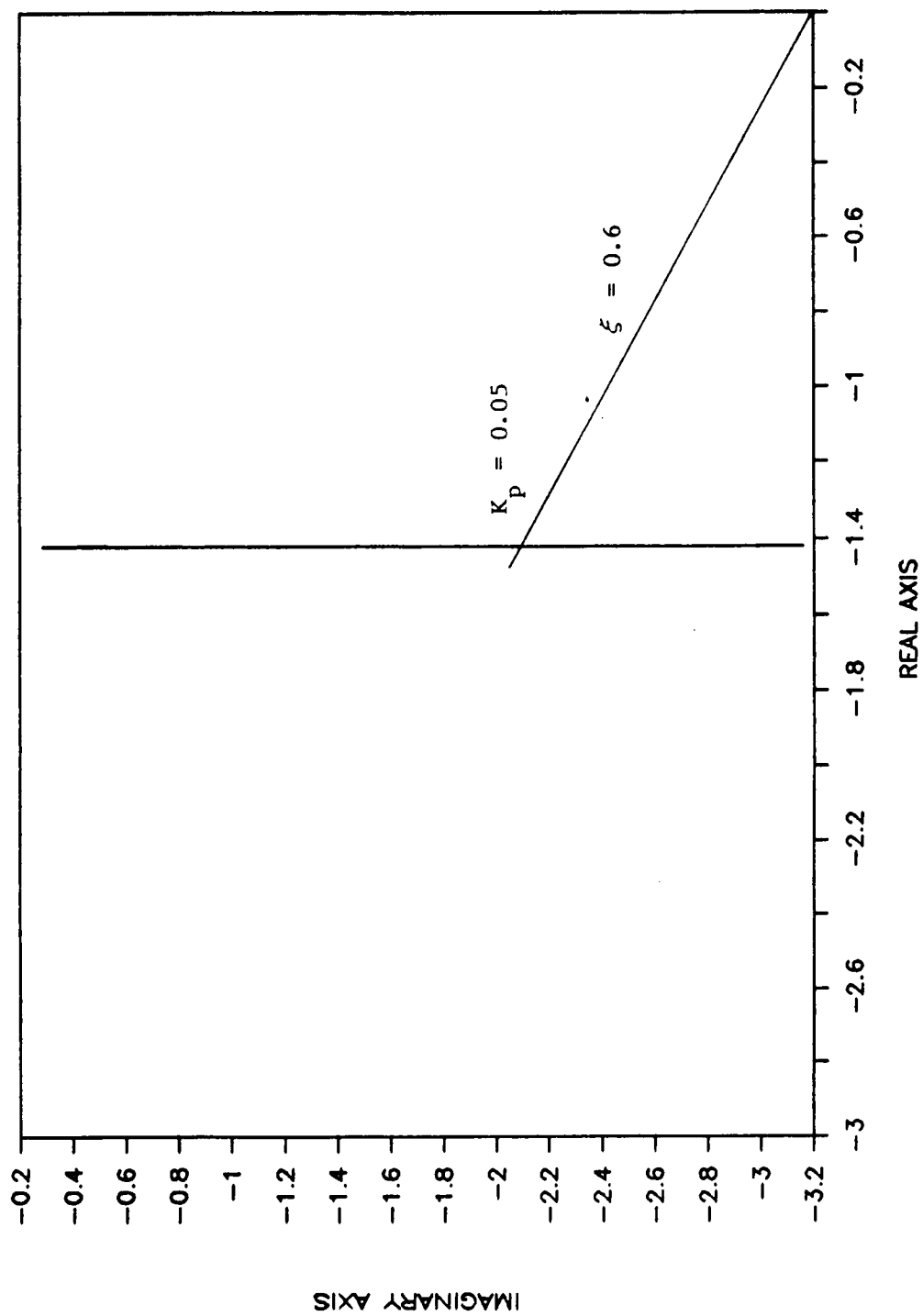


FIGURE VI.2 Selection of the Design Value for  $K_p$

# STEAM TEMPERATURE 1st SUPERHEATER

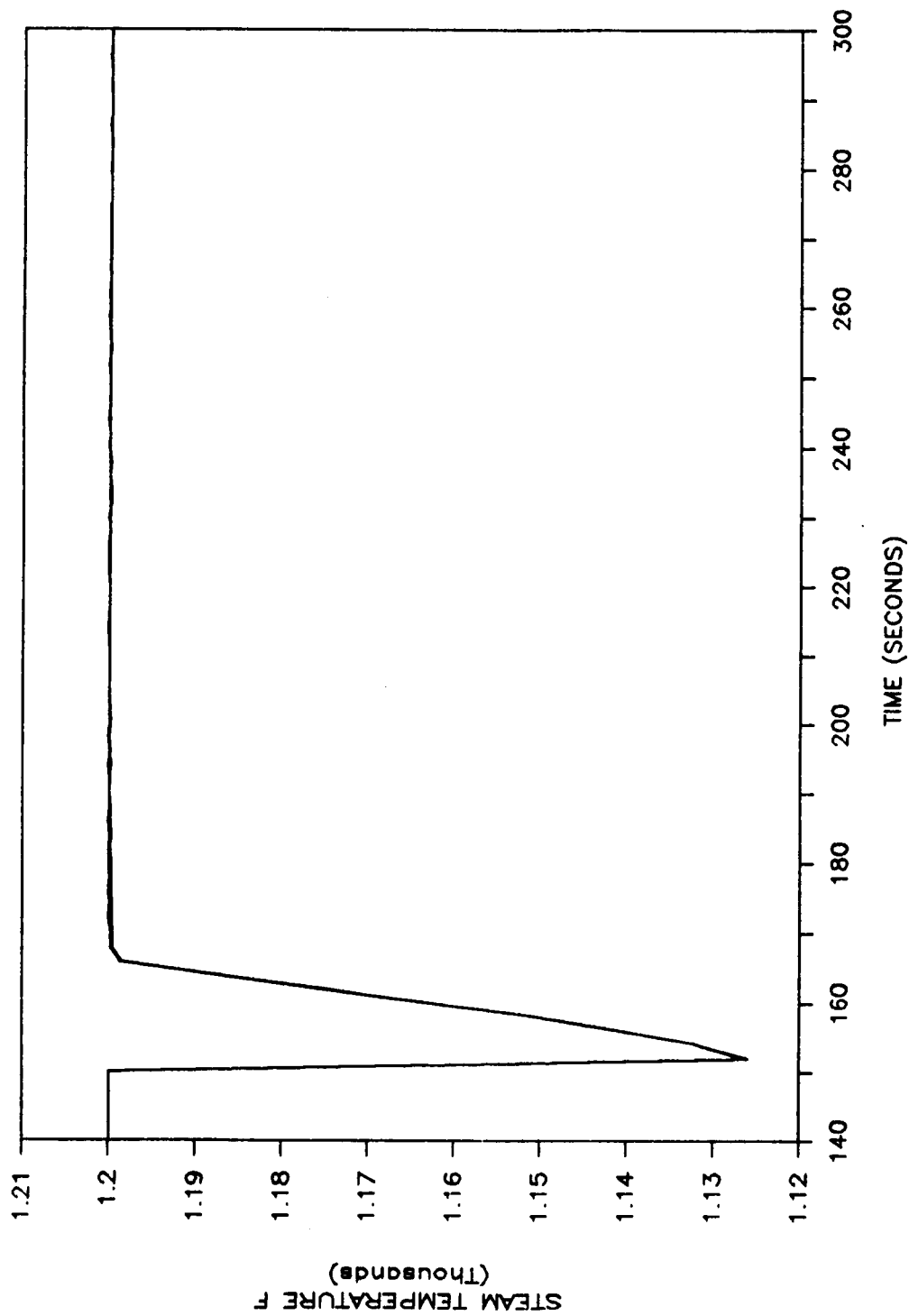


FIGURE VI.3 First Order Response of TS1

# STEAM TEMPERATURE 2nd SUPERHEATER

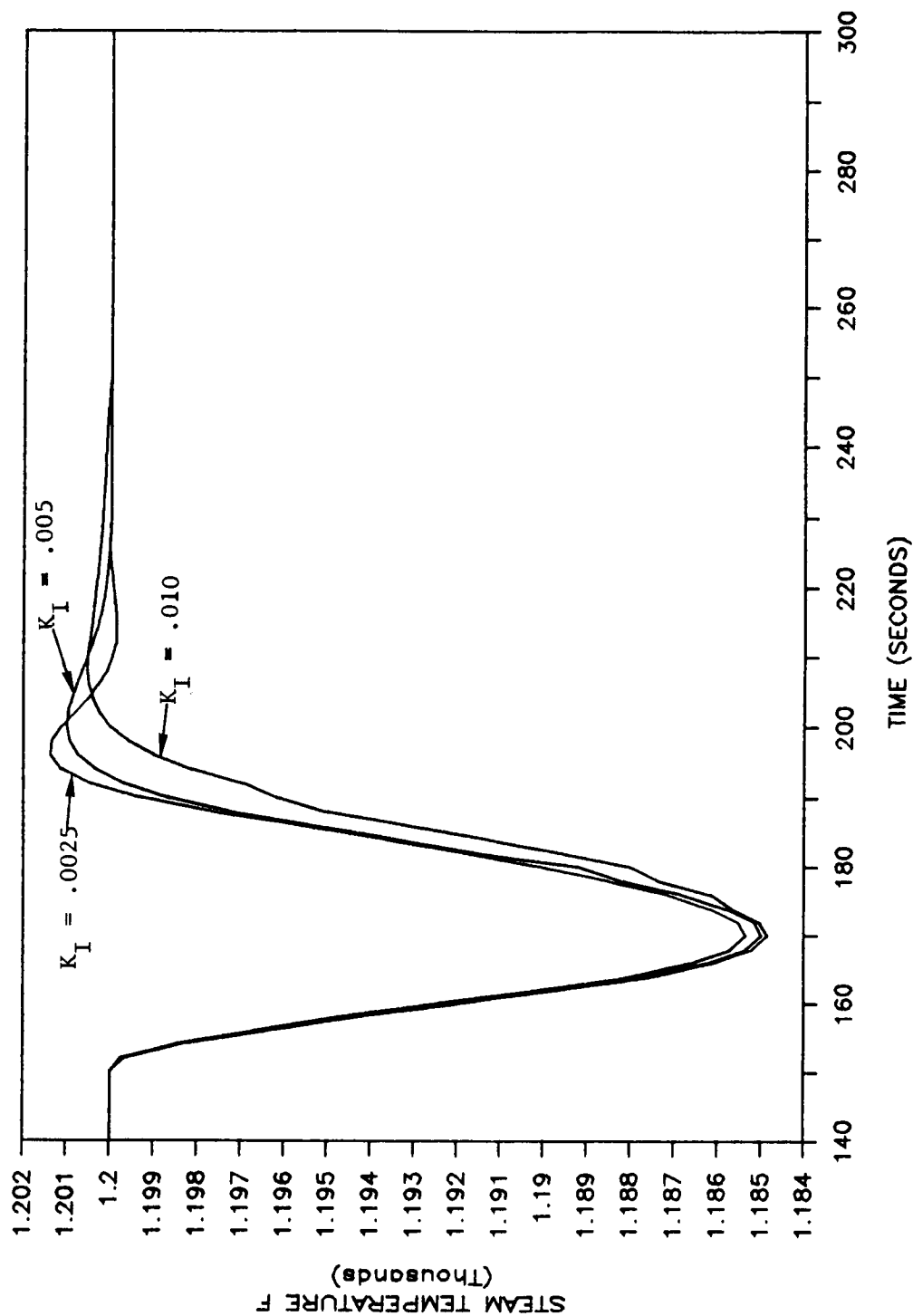


FIGURE VI.4 Selection of  $K_I$  for TS2

# STEAM TEMPERATURE 3rd SUPERHEATER

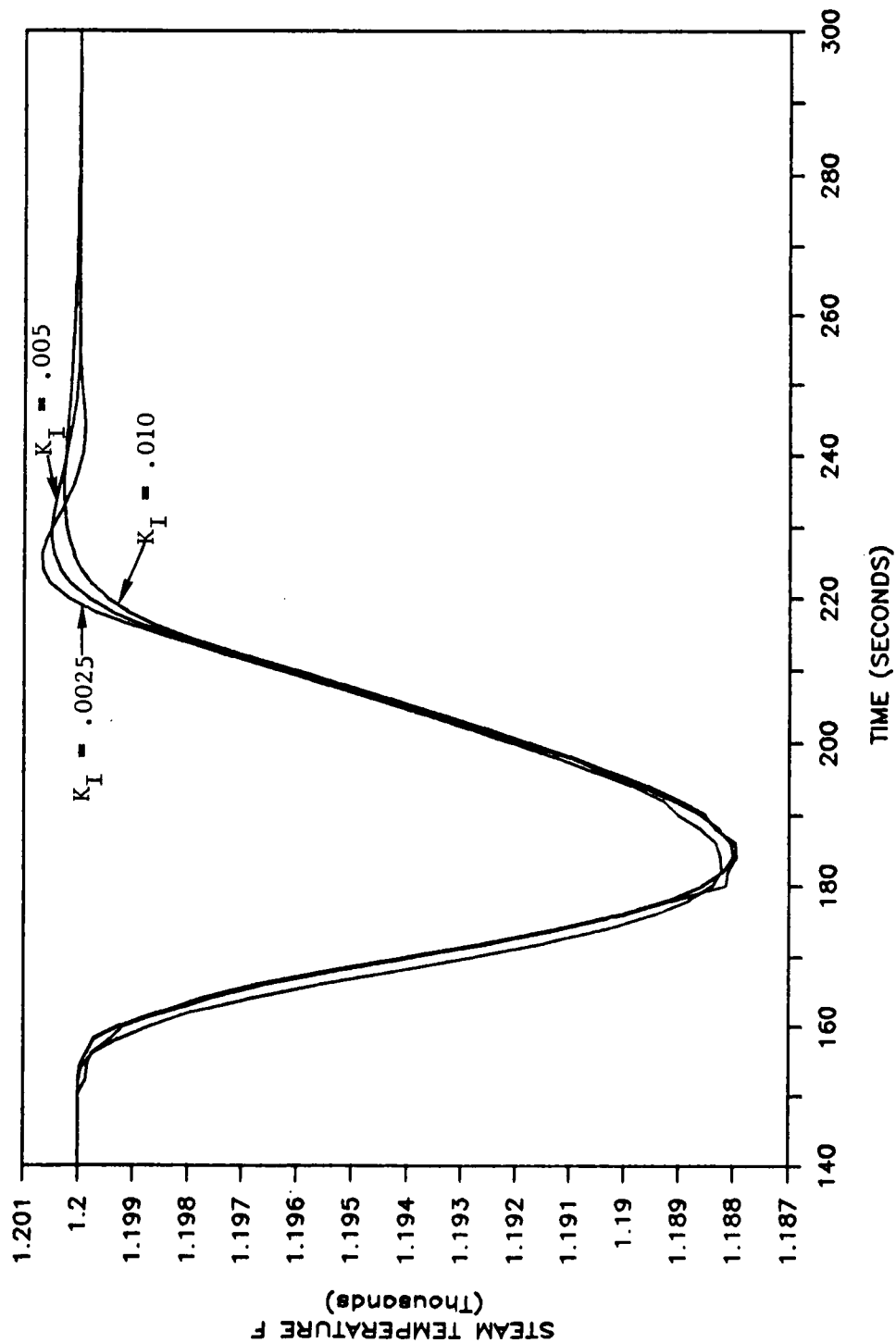


FIGURE VI.5 Selection of  $K_I$  for TS3

of the model eigenvalues. The responses of TS2 and TS3 were sensitive to varying  $K_I$ .

The value of  $K_I$  selected was 0.005 by virtue of its response having relatively less overshoot than  $K_I = 0.0025$  and quicker settling time than  $K_I = 0.010$ . The similarity of the response of TS2 and TS3 validates the earlier assumption that the superheater sections were equally represented by the root locus plot.

## CHAPTER VII

### CONCLUSIONS AND RECOMMENDATIONS

#### Conclusions

The only simplifying assumptions made in the model development were those regarding the boundary conditions for the model. The model produced a response which closely approximated the CFFF plant data in a transient condition.

The largest discrepancy between the model and the plant response was in the steam flow from TS1. There is a good possibility that this discrepancy was due to changes in the slagging coefficient (KSGS1) from the dramatic increase in flue gas temperature (TGE1).

After the model was constructed and validated, the controller gains for the superheater test-section steam flows were designed. The MMS model provided the optimum gains for the superheater test-section steam flows after only two runs of the model. For large models, the ability to specify control loop gains without trial and error runs is an important utility provided by MMS.

The response of TS2 and TS3 to a step-change in TGE1 was damped second-order, and the optimum gains for the PI

controllers for TS2 and TS3 were  $K_p = 0.05$  and  $K_I = 0.005$ . The response of TS1 was first-order, critically damped, and the values of  $K_p = 0.05$  and  $K_I = 0.005$  gave a good response for TS1 to a step-change in TGE1. For design of the PI controllers for steam flow into TS1, TS2, and TS3 this work suggests

$$K_p = 0.05 \quad \text{(VII.1)}$$

$$K_I = 0.005 \quad \text{for TS1, TS2, and TS3.} \quad \text{(VII.2)}$$

The completion of the superheater test-section model developed in this work required one man-month of engineering time and about \$800 in computer expenditures. The lion's share of time spent on this work was spent setting up MMS on the computer system at UTSI. This initial setup effort is not included in the one man-month engineering time allocated to the model development.

MMS forces the user to develop an executable FORTRAN code which is object-oriented (Modular Concept) and allows the user to avoid many of the repetitious programming errors associated with variable name duplication and improper subroutine nesting.

MMS has one major shortcoming which needs to be mentioned, that is; the program doesn't have the capability to

do a cold startup. This is a problem because the user has to specify initial conditions for some of the states. This means that the initial conditions chosen by the user must be reasonable for the steady state to which the process is being driven. For a complicated model the program may ask the user to specify initial conditions at many places in the model. The value selected for one or more of the initial conditions may result in program termination because of negative flows before steady state can be reached. In this situation, it may not be immediately apparent to the user which initial condition value caused the model termination. This results in an appreciable amount of debugging effort.

#### Recommendations

MMS could prove to be a valuable tool for ECP in its efforts to simulate a commercial MHD plant. There are several areas where this work could be continued.

To facilitate the operation of the CFFF and to continue to gain experience among ECP personnel about modeling power plant components using MMS, the following extensions of this work are recommended.

1. Complete modeling of the economizer sections specifying flows and control.
2. Add new superheater test-sections which were added subsequent to this work.

3. Add a turbine to simulate electricity production.
4. Construct a module for the MHD Topping Cycle.

Given the level of system programming expertise available to ECP, it should be possible for ECP to develop auxiliary code for MMS which would allow the program to calculate its own initial condition values and model a cold startup. This auxiliary programming has already been done by a group of entrepreneurs who were involved in the creation of MMS. The resulting product offered by this group is called PC-TRAX. PC-TRAX is very similar to MMS. The major differences are that PC-TRAX can simulate the cold startup and PC-TRAX is developed exclusively for use on personal computers.

The cost of MMS or PC-TRAX to a private concern is between \$20,000 to \$30,000. In the case of MMS, the software can be acquired by a university for \$1250 to \$2250. It may be that the DOE has already paid the licensing fee for MMS. If not, ECP may be able to acquire MMS through its affiliation with UTSI.

## LIST OF REFERENCES

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## APPENDICES

APPENDIX A  
SUPERHEATER TEST-SECTIONS  
MODEL PARAMETERIZATION

PHYSICAL DATA REQUIRED FOR MODULE PARAMETERIZATION (SPRHTR)

| SYMBOL  | VALUES    |           |           | DESCRIPTION                                                                                 | SOURCE/COMMENT  |
|---------|-----------|-----------|-----------|---------------------------------------------------------------------------------------------|-----------------|
|         | <u>S1</u> | <u>S2</u> | <u>S3</u> |                                                                                             |                 |
| $d_o =$ | 1.25      | 1.25      | 1.25 (in) | Tube outer diameter                                                                         | Design Drawings |
| $d_i =$ | 1.12      | 1.12      | 1.12 (in) | Tube inner diameter                                                                         | Design Drawings |
| $N_R =$ | 4.00      | 2.00      | 2.00      | Number of rows in direction of gas flow.                                                    | Design Drawings |
| $N_w =$ | 8.00      | 8.00      | 8.00      | Number of tubes wide; number of tubes<br>over which gas passes in each row.                 | Design Drawings |
| 1 =     | 3.00      | 3.00      | 3.00 (in) | Tube space (center to center) perpendicular<br>to direction of gas flow.                    | Design Drawings |
| 1 =     | 3.00      | 3.00      | 3.00 (in) | Tube spacing (center to center) parallel to<br>direction if gas flow; spacing between rows. | Design Drawings |

PHYSICAL DATA REQUIRED FOR MODULE PARAMETERIZATION (SPRHTR)

| SYMBOL     | VALUES    |           |                   | DESCRIPTION                                                                                                                 | SOURCE/COMMENT                                                                               |
|------------|-----------|-----------|-------------------|-----------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------|
|            | <u>S1</u> | <u>S2</u> | <u>S3</u>         |                                                                                                                             |                                                                                              |
| $L_T =$    | 6.00      | 6.00      | 6.00 (ft)         | Tube length extending into gas path.                                                                                        | Design Drawings                                                                              |
| $L_w =$    | 6.00      | 6.00      | 6.00 (ft)         | Width of gas flow passage.                                                                                                  | Design Drawings                                                                              |
| $F_{sg} =$ | .15       | .15       | .15               | Slagging coefficient - $F_{sg}$ is the fractional reduction in heat transfer effectiveness due to slag and/or soot buildup. | $K_{sg} = 0.$ for clean systems with no design margin.<br>Maximum $K_{sg}$ approximately 0.3 |
| $M_f =$    | .05       | .05       | .05<br>(fraction) | Moisture fraction of flue gas.                                                                                              | Plant data                                                                                   |
| $P_{se} =$ | 110       | 110       | 110<br>(psia)     | Pressure of steam entering.                                                                                                 | Plant data                                                                                   |
| $P_{sl} =$ | 67        | 67        | 67                | Pressure of steam leaving.                                                                                                  | Plant data                                                                                   |

PHYSICAL DATA REQUIRED FOR MODULE PARAMETERIZATION (SPRHTR)

| SYMBOL     | VALUES    |             |           | DESCRIPTION                       | SOURCE/COMMENT |
|------------|-----------|-------------|-----------|-----------------------------------|----------------|
|            | <u>S1</u> | <u>S2</u>   | <u>S3</u> |                                   |                |
| $T_{ge} =$ | 2150      | 1450<br>(F) | 1209      | Temperature of flue gas entering. | Plant data     |
| $T_{gl} =$ | 2050      | 1409<br>(F) | 1168      | Temperature of flue gas leaving.  | Plant data     |
| $T_{se} =$ | 341       | 341<br>(F)  | 341       | Temperature of steam entering.    | Plant data     |
| $T_{sl} =$ | 800       | 820<br>(F)  | 850       | Temperature of steam leaving.     | Plant data     |

PHYSICAL DATA REQUIRED FOR MODULE PARAMETERIZATION (SPRHTR)

| SYMBOL      | VALUES    |           |            | DESCRIPTION                                | SOURCE/COMMENT            |
|-------------|-----------|-----------|------------|--------------------------------------------|---------------------------|
|             | <u>S1</u> | <u>S2</u> | <u>S3</u>  |                                            |                           |
| $X_t =$     | .47       | .47       | .47        | Valve pressure ratio at choked conditions. | Valve manufacturers spec. |
|             |           |           | (fraction) |                                            |                           |
| $P_{se}$    | 120       | 120       | 120        | Entering pressure                          | Plant data                |
|             |           |           | (psia)     |                                            |                           |
| $P_{sl}$    | 110       | 110       | 100        | Leaving pressure                           | Plant data                |
|             |           |           | (psia)     |                                            |                           |
| $w_{se}$    | 10,000    | 2,500     | 2,500      | Flowrate                                   | Valve manufacturers spec. |
|             |           |           | (lbm/hr)   |                                            | Max rated flow            |
| $\rho_{se}$ | .267      | .267      | .267       | Density of steam entering.                 | Plant data                |
| $w_{ge}$    | 45,000    | 45,000    | 45,000     | Flowrate of flue gas.                      | Plant data                |
|             |           |           | (lbm/hr)   |                                            |                           |

## SPRHTR - Superheater

### A. Calculated Parameters

KCF Flow Conductance

$$KCF = \frac{W_{se}}{\sqrt{P_{se} (P_{se} - P_{s1})}}$$

KKT Heat Exchanger Arrangement Parameter (Integer)

KKT = 1 : Counterflow

KKT = 2 : Parallel Flow

KMF: Moisture Fraction of Flue Gas

$$KMF = M_f$$

KMM Mass of Metal

$$KMM = M_m = L_T \cdot N_R \cdot N_W [\pi/4 (d_o^2 - d_i^2)/144]$$

KSG Slagging Factor

$$KSG = F_{sg}$$

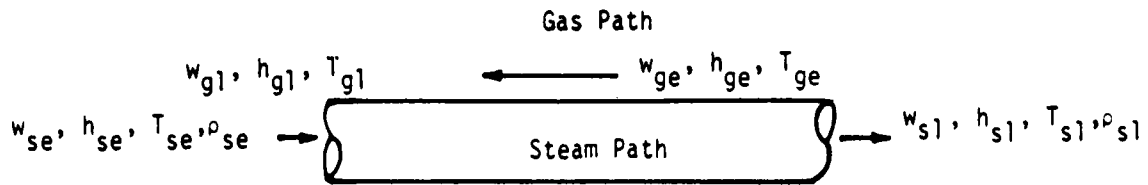
KUC Flue Gas Convective H-T Parameter

KUR Flue Gas Radiant H-T Parameter

KUS Steam Heat Transfer Parameter

} User Manual, Appendix A SPRHTR - 3,11

The superheater is represented schematically below:



- $h_{ge}$  - enthalpy of flue gas entering
- $h_{gl}$  - enthalpy of flue gas leaving
- $h_{se}$  - enthalpy of steam entering
- $h_{sl}$  - enthalpy of steam leaving
- $T_{ge}$  - temperature of flue gas entering
- $T_{gl}$  - temperature of flue gas leaving
- $T_{se}$  - temperature of steam entering
- $T_{sl}$  - temperature of steam leaving
- $w_{ge}$  - flow rate of flue gas entering
- $w_{gl}$  - flow rate of flue gas leaving
- $w_{se}$  - flow rate of steam entering
- $w_{sl}$  - flow rate of steam leaving
- $\rho_{se}$  - density of steam entering
- $\rho_{sl}$  - density of steam leaving

The general plan of the solution for Superheater is to define the flue gas enthalpy and the steam density and specific internal energy as states. Algebraic relations are used to calculate fluid properties, flowrates, and heat transfer rates as a function of these states. Conservation of energy and mass are used to define the differential equations describing the state dynamics.

The thermodynamic relations for the tube-side are based on representing the fluid mass as a single well stirred mass node as discussed in Part II of this Manual.

That manual presents the relation for Conservation of Mass:

$$\frac{dp_1}{dt} = \frac{(w_e - w_l - \rho_e A_e V_{se} + \rho_l A_l V_{sl})}{V}$$

For fixed boundaries, and with unit conversions:

$$\frac{d\rho_s}{dt} = (w_{se} - w_{s1}) / (3600 V_s) \quad (1)$$

$V_s$  - Volume of superheater steam

On the gas-side, flue gas pressure-flow dynamics are not addressed; the speed of these reactions is such that they may be treated as quasi-steady-state:

$$w_{g1} = w_{ge} \quad (2)$$

Part II of this manual provides for Conservation of Energy:

$$\frac{du_1}{dt} = \frac{1}{(\rho V)} \cdot \left\{ w_e h_e - w_1 h_1 + \frac{1}{778} g_c [g(w_e z_e - w_1 z_1) + \frac{(w_e V_e^2 - w_1 V_1^2)}{2} \right. \\ \left. + e_1 \rho_1 A_1 V_{s1} - e_e \rho_e A_e V_{se} + q - V_u \frac{dp}{dt} \right\}$$

For fixed boundaries and a stirred tank the rate of change of the steam specific internal energy,  $u_{s1}$ , is:

$$\frac{du_{s1}}{dt} = \frac{(w_{se} h_{se} - w_{s1} h_{s1} + q_T - V_s u_{s1} d\rho_{s1}/dt)}{\rho_{s1} V_s}$$

$q_T$  - Heat transfer rate

However, in the superheater, energy may be stored not only in the fluid but in the tubing and piping,  $M_m$ .

If the tube and piping temperature closely follows the steam temperature, the following approximation may be made:

$$\frac{d}{dt} (M_m c_{pm} T_m) = \frac{d}{dt} (M_m c_{pm} T_{s1}) = \frac{d}{dt} [M_m (c_{pm}/c_{ps}) u_{s1}]$$

And, with unit conversions:

$$\frac{du_{s1}}{dt} = \frac{(w_{se}h_{se} - w_{s1}h_{s1} + q_T - 3600 V_s d\rho_{s1}/dt)}{3600 (\rho_{s1}V_s + 0.25 M_m)} \quad (3)$$

On the flue-gas side:

$$\frac{du_{g1}}{dt} = \frac{[w_{ge} (h_{ge} - h_{g1}) - q_T - 3600 \cdot V_g d\rho_{g1}/dt]}{(3600 \cdot \rho_{g1} V_g)}$$

$V_g$  - Flue gas volume

$u_{g1}$  - Specific internal energy of flue gas

$\rho_{g1}$  - Density of flue gas

With the assumptions that flue gas flow is uniform and that it may be treated as an ideal gas at atmospheric pressure:

$$\frac{dh_{g1}}{dt} = K \frac{du_{g1}}{dt}$$

$$\rho_{g1} = \frac{P}{RT_{g1}}$$

$$\frac{dh_{g1}}{dt} = 9.8 \times 10^{-6} [w_{g1} (h_{ge} - h_{g1}) - q_T] \cdot (T_{g1} + 460)/V_g \quad (4)$$

The effects of steam and gas momentum are negligible.

This module represents heat transfer for a typical flue gas to steam superheater. Calculations provide for steam on the tube-side of what is normally a multiple pass arrangement where the basic flow pattern may be either counterflow or parallel flow.

|                 |                                                   |                        |
|-----------------|---------------------------------------------------|------------------------|
| C <sub>f</sub>  | Flow conductance                                  |                        |
| c <sub>v</sub>  | Specific heat of steam at constant volume         | (Btu/lbm F)            |
| c <sub>pm</sub> | Specific heat of steel                            | (Btu/lbm F)            |
| h <sub>ge</sub> | Enthalpy of gas entering                          | (Btu/lbm)              |
| h <sub>gl</sub> | Enthalpy of gas leaving                           | (Btu/lbm)              |
| h <sub>se</sub> | Enthalpy of steam entering                        | (Btu/lbm)              |
| h <sub>sl</sub> | Enthalpy of steam leaving                         | (Btu/lbm)              |
| M <sub>f</sub>  | Moisture fraction                                 |                        |
| M <sub>m</sub>  | Mass of metal                                     | (lbm)                  |
| P <sub>se</sub> | Pressure of steam entering                        | (psia)                 |
| P <sub>sl</sub> | Pressure of steam leaving                         | (psia)                 |
| Q <sub>T</sub>  | Heat transfer                                     | (Btu/hr)               |
| T <sub>ge</sub> | Temperature of gas entering                       | (F)                    |
| T <sub>gl</sub> | Temperature of gas leaving                        | (F)                    |
| T <sub>se</sub> | Temperature of steam entering                     | (F)                    |
| T <sub>sl</sub> | Temperature of steam leaving                      | (F)                    |
| U <sub>c</sub>  | Gas to metal convective heat transfer coefficient | (Btu/hr-F)             |
| U <sub>s</sub>  | Metal to steam heat transfer coefficient          | (Btu/hr-F)             |
| U <sub>r</sub>  | Gas to metal radiant heat transfer coefficient    | (Btu/hr-F)             |
| u <sub>sl</sub> | Internal energy of steam leaving                  | (Btu/lbm)              |
| V <sub>g</sub>  | Gas volume                                        | (ft <sup>3</sup> )     |
| V <sub>s</sub>  | Steam volume                                      | (ft <sup>3</sup> )     |
| w <sub>ge</sub> | Flowrate of flue gas entering section             | (lbm/hr)               |
| w <sub>gl</sub> | Flowrate of flue gas leaving section              | (lbm/hr)               |
| w <sub>se</sub> | Flowrate of steam entering                        | (lbm/hr)               |
| w <sub>sl</sub> | Flowrate of steam leaving                         | (lbm/hr)               |
| ρ <sub>se</sub> | Density of steam entering                         | (lbm/ft <sup>3</sup> ) |
| ρ <sub>sl</sub> | Density of steam leaving                          | (lbm/ft <sup>3</sup> ) |

Model execution is stopped by SPRHTR if a reverse flowrate is encountered:

$$w_{se} < 0.$$

$U_{rg}$  Gas Side Radiant Coefficient

$$U_{rg} = \frac{U_o U_{c2}}{U_{c2} - U_o} - U_{cc}$$

$$KUR = \frac{A_{hx} U_{rg} \Delta T_{LM}}{\left( \frac{T_{ge} + T_{gL}}{2} + 460 \right)^4 - \left( \frac{T_{se} + T_{SL}}{2} + 460 \right)^4}$$

KVG Volume of Flue Gas

$$KVG = V_g = L_T L_W N_R \cdot 12 \cdot L_u$$

KVS Volume of Steam

$$KVS = V_s = L_T N_R N_w \frac{\pi}{4} \left( \frac{d_o}{12} \right)^2$$

## B. Initial Conditions

IHGL Enthalpy of Flue Gas Leaving

$$IHGL = h_{g1}$$

IRSL Density of Steam Leaving

$$IRSL = \rho_{s1}$$

IUSL Specific Internal Energy of Steam Leaving

$$IUSL = u_{s1}$$

APPENDIX B  
COMPLETED USER WORKSHEETS FOR SUPERHEATER  
TEST-SECTIONS MODEL

USER WORKSHEET: PIPEWR (Water)

or

PIPESR (Steam)

MACRO INVOCATION:

|        |    |       |    |        |       |        |
|--------|----|-------|----|--------|-------|--------|
| PIPEWR |    |       |    |        |       |        |
| or     | (  | 'E1A' | ,  | 'STM1' | ,     | 'LE1A' |
| PIPESR | ID | WE    | WL | INERT  | THERM | DELAY  |

INERT: 1 - Inertia effects represented  
0 - No inertia effects

THERM: N - N thermal storage nodes, heat loss to ambient represented  
DELAY: 0 - No thermal storage or heat loss

DELAY: 1 - Transport delay  
0 - No transport delay

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

ALL PIPES

Logical Check Valve Switch (.TRUE. or .FALSE.) : KCKE1A = 0

Pipe Conductance : KCFE1A = 2100

Elevation difference between entering and  
leaving port ( $Z_e - Z_L$ ) (ft): KDHE1A = 0

USER WORKSHEET: CONNC

MACRO INVOCATION:

CONNC ('N1', 'LE1A', 'LN1')  
          ID      WE      WL

INITIAL CONDITIONS:

Leaving Pressure   P   WL       (psia): IPLN1 = 120

VARIABLES:

|   |                          |                        |
|---|--------------------------|------------------------|
| H | WE - Enthalpy Entering   | (Btu/lbm)              |
| H | WL - Enthalpy Leaving    | (Btu/lbm)              |
| P | WE - Pressure Entering   | (psia)                 |
| P | WL - Pressure Leaving    | (psia)                 |
| R | WL - Density Leaving     | (lbm/ft <sup>3</sup> ) |
| W | WE - Flowrate Entering   | (lbm/hr)               |
| W | WL - Flowrate Leaving    | (lbm/hr)               |
| T | WL - Temperature Leaving | (F)                    |

## USER WORKSHEET: VALVEC

### MACRO INVOCATION:

VALVEC ('C1', 'LN1', 'LC1')  
          ID      SE      SL

NOTE: Valve and Actuator must have same ID.

### CONSTANT PARAMETERS: (All Parameters are Appended by ID)

Logical Check Valve Switch (.TRUE. or .FALSE.) : KCKC1 = .F.

Maximum Valve Conductance (pph/ pcf.psi): KVC1 = 4070

Logical Valve Characteristic Parameter (Integer): KVAC1 = 2

- 1 - Equal Percentage
- 2 - Linear
- 3 - Quick Open

Valve Choking Pressure Ratio (fraction): KXTC1 = .47

### VARIABLES:

|   |                        |                        |
|---|------------------------|------------------------|
| H | SE - Enthalpy Entering | (Btu/lbm)              |
| H | SL - Enthalpy Leaving  | (Btu/lbm)              |
| P | SE - Pressure Entering | (psia)                 |
| P | SL - Pressure Leaving  | (psia)                 |
| R | SE - Density Leaving   | (lbm/ft <sup>3</sup> ) |
| W | SE - Flowrate Entering | (lbm/hr)               |
| W | SL - Flowrate Leaving  | (lbm/hr)               |
| T | ID - Valve Position    | (fraction)             |

USER WORKSHEET: CONNC

MACRO INVOCATION:

CONNC ('N2', 'LC1', 'LN2')  
          ID      WE      WL

INITIAL CONDITIONS:

Leaving Pressure   P   WL       (psia): IPN2 = 115

VARIABLES:

|   |                          |                        |
|---|--------------------------|------------------------|
| H | WE - Enthalpy Entering   | (Btu/lbm)              |
| H | WL - Enthalpy Leaving    | (Btu/lbm)              |
| P | WE - Pressure Entering   | (psia)                 |
| P | WL - Pressure Leaving    | (psia)                 |
| R | WL - Density Leaving     | (lbm/ft <sup>3</sup> ) |
| W | WE - Flowrate Entering   | (lbm/hr)               |
| W | WL - Flowrate Leaving    | (lbm/hr)               |
| T | WL - Temperature Leaving | (F)                    |

USER WORKSHEET: SPRHTR

MACRO INVOCATION:

SPRHTR ('S1', 'GE1', 'LN2', 'GL1', 'SL1')  
ID GE SE GL SL

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

Flow Conductance (pph/ pcf.psi): KCFS1 = 2828

Heat Exchanger Arrangement Parameter (Integer): KTTS1 = 1  
(1: Counterflow, 2: Parallel Flow)

Moisture Fraction of Flue Gas : KMFS1 = .05

Mass of Metal (lbm): KMMS1 = .32

Slagging Factor (Fractional Reduction in HX Effectiveness) : KSGS1 = .15

Gas Convective H-T Parameter : KUCS1 = .70

Steam H-T Parameter : KUSS1 = 30

Volume of Gas (ft<sup>3</sup>): KVGs1 = 5184

Volume of Steam (ft<sup>3</sup>): KVSS1 = 1.64

USER WORKSHEET: ECON

MACRO INVOCATION:

ECON ('CO1', 'GLS1', 'CWI1', 'GLC1', 'CW01')  
ID GE WE GL WL

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

Flow Conductance (pph/ pcf.psi): KCFC01 = 3000  
Heat Exchanger Arrangement Parameter (Integer): KKTC01 = 1  
(1: Counterflow, 2: Parallel Flow)  
Moisture Fraction of Flue Gas : KMFC01 = .05  
Mass of Metal (lbm): KMMC01 = .5  
Slagging Factor (Fractional Reduction in HX Effectiveness) : KSGC01 = 0.1  
Gas Convective H-T Parameter : KUCC01 = 1  
Volume of Flue Gas (ft<sup>3</sup>): KVG01 = 5184  
Volume of Water (ft<sup>3</sup>): KVSC01 = 1.64

USER WORKSHEET: ECON

MACRO INVOCATION:

ECON ('CO2', 'GLS2', 'CWI2', 'GLC2', 'CW02')  
          ID      GE      WE      GL      WL

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

Flow Conductance (pph/ pcf.psi): KCFC02 = 3000  
Heat Exchanger Arrangement Parameter (Integer): KKTC02 = 1  
(1: Counterflow, 2: Parallel Flow)  
Moisture Fraction of Flue Gas : KMFC02 = .05  
Mass of Metal (lbm): KMMC02 = .5  
Slagging Factor (Fractional Reduction in HX Effectiveness) : KSGC02 = 0.1  
Gas Convective H-T Parameter : KUCC02 = 1  
Volume of Flue Gas (ft<sup>3</sup>): KVG02 = 5184  
Volume of Water (ft<sup>3</sup>): KVSC02 = 1.64

USER WORKSHEET: PIPEWR (Water)

or

PIPESR (Steam)

MACRO INVOCATION:

|        |    |       |    |       |       |        |
|--------|----|-------|----|-------|-------|--------|
| PIPEWR |    |       |    |       |       |        |
| or     | (  | 'EX1' | ,  | 'SL1' | ,     | 'LEX1' |
|        |    |       |    | 0     | ,     | 0      |
| PIPESR | ID | WE    | WL | INERT | THERM | DELAY  |

INERT: 1 - Inertia effects represented  
0 - No inertia effects

THERM: N - N thermal storage nodes, heat loss to ambient represented  
DELAY: 0 - No thermal storage or heat loss

DELAY: 1 - Transport delay  
0 - No transport delay

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

ALL PIPES

Logical Check Valve Switch (.TRUE. or .FALSE.) : KCKEX1 = .F.

Pipe Conductance : KCFEX1 = 2100

Elevation difference between entering and  
leaving port ( $Z_e - Z_L$ ) (ft): KDHEX1 = 0

USER WORKSHEET: PICON

MACRO INVOCATION:

PICON ('CC1', DEMAN1, SUPPL1, YC1 , 1 )  
ID CSP PVAR OUTVAR ACTION

CSP Complete Name of Controller Setpoint

PVAR Complete Name of Process Variable Being Controlled

OUTVAR Complete Name of Process Parameter Being Changed  
by Controller

ACTION Direct Acting = 1

Reverse Acting = 2

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

Proportional Gain : CPGCC1 = .052

Integral Gain : CIGCC1 = .0026

Low Limit of Controller Output : KLLCC1 = 0

High Limit of Controller Output : KHLCC1 = 1

INITIAL CONDITIONS:

Initial Controller Output Z01 ID : ZICCC1 = .5

USER WORKSHEET: PIPEWR (Water)

or

PIPESR (Steam)

MACRO INVOCATION:

|        |                                  |    |    |       |       |       |
|--------|----------------------------------|----|----|-------|-------|-------|
| PIPEWR |                                  |    |    |       |       |       |
| or     | ('E2A', 'STM2', 'LE2A', 0, 0, 0) |    |    |       |       |       |
| PIPESR | ID                               | WE | WL | INERT | THERM | DELAY |

INERT: 1 - Inertia effects represented  
0 - No inertia effects

THERM: N - N thermal storage nodes, heat loss to ambient represented

DELAY: 0 - No thermal storage or heat loss

DELAY: 1 - Transport delay  
0 - No transport delay

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

ALL PIPES

Logical Check Valve Switch (.TRUE. or .FALSE.) : KCKE2A = 0

Pipe Conductance : KCFE2A = 550

Elevation difference between entering and  
leaving port ( $Z_e - Z_L$ ) (ft): KDHE2A = 0

USER WORKSHEET: CONNC

MACRO INVOCATION:

CONNC ('N3', 'LE2A', 'LN3')  
          ID      WE      WL

INITIAL CONDITIONS:

Leaving Pressure   P   WL       (psia): IPLN = 120

VARIABLES:

|   |                          |                        |
|---|--------------------------|------------------------|
| H | WE - Enthalpy Entering   | (Btu/lbm)              |
| H | WL - Enthalpy Leaving    | (Btu/lbm)              |
| P | WE - Pressure Entering   | (psia)                 |
| P | WL - Pressure Leaving    | (psia)                 |
| R | WL - Density Leaving     | (lbm/ft <sup>3</sup> ) |
| W | WE - Flowrate Entering   | (lbm/hr)               |
| W | WL - Flowrate Leaving    | (lbm/hr)               |
| T | WL - Temperature Leaving | (F)                    |

## USER WORKSHEET: VALVEC

### MACRO INVOCATION:

VALVEC ('C2', 'LN2', 'LC2')  
          ID      SE      SL

NOTE: Valve and Actuator must have same ID.

### CONSTANT PARAMETERS: (All Parameters are Appended by ID)

Logical Check Valve Switch (.TRUE. or .FALSE.) : KCKC2 = .F.

Maximum Valve Conductance (pph/ pcf.psi): KCVC2 = 1018

Logical Valve Characteristic Parameter (Integer): KVAC2 = 2

- 1 - Equal Percentage
- 2 - Linear
- 3 - Quick Open

Valve Choking Pressure Ratio (fraction): KXTC2 = .47

### VARIABLES:

|   |                        |                        |
|---|------------------------|------------------------|
| H | SE - Enthalpy Entering | (Btu/lbm)              |
| H | SL - Enthalpy Leaving  | (Btu/lbm)              |
| P | SE - Pressure Entering | (psia)                 |
| P | SL - Pressure Leaving  | (psia)                 |
| R | SE - Density Leaving   | (lbm/ft <sup>3</sup> ) |
| W | SE - Flowrate Entering | (lbm/hr)               |
| W | SL - Flowrate Leaving  | (lbm/hr)               |
| T | ID - Valve Position    | (fraction)             |

USER WORKSHEET: CONNC

MACRO INVOCATION:

CONNC ('N4', 'LC2', 'LN4')  
          ID      WE      WL

INITIAL CONDITIONS:

Leaving Pressure   P   WL       (psia): IPN4 = 115

VARIABLES:

|   |                          |                        |
|---|--------------------------|------------------------|
| H | WE - Enthalpy Entering   | (Btu/lbm)              |
| H | WL - Enthalpy Leaving    | (Btu/lbm)              |
| P | WE - Pressure Entering   | (psia)                 |
| P | WL - Pressure Leaving    | (psia)                 |
| R | WL - Density Leaving     | (lbm/ft <sup>3</sup> ) |
| W | WE - Flowrate Entering   | (lbm/hr)               |
| W | WL - Flowrate Leaving    | (lbm/hr)               |
| T | WL - Temperature Leaving | (F)                    |

USER WORKSHEET: SPRHTR

MACRO INVOCATION:

SPRHTR ('S2', 'GE2', 'LN4', 'GL2', 'SL2')  
ID GE SE GL SL

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

Flow Conductance (pph/ pcf.psi): KCFS2 = 707  
Heat Exchanger Arrangement Parameter (Integer): KKTS2 = 1  
(1: Counterflow, 2: Parallel Flow)  
Moisture Fraction of Flue Gas : KMFS2 = .05  
Mass of Metal (lbm): KMMS2 = .16  
Slagging Factor (Fractional Reduction in HX Effectiveness) : KSGS2 = .15  
Gas Convective H-T Parameter : KUCS2 = .31  
Steam H-T Parameter : KUSS2 = 15  
Volume of Gas (ft<sup>3</sup>): KVGS2 = 2592  
Volume of Steam (ft<sup>3</sup>): KVSS2 = .82

USER WORKSHEET: ECON

MACRO INVOCATION:

ECON ('CO3', 'GLS3', 'CWI3', 'GLC3', 'CW03')  
ID GE WE GL WL

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

Flow Conductance (pph/ pcf.psi): KCFC03 = 3000  
Heat Exchanger Arrangement Parameter (Integer): KKTC03 = 1  
(1: Counterflow, 2: Parallel Flow)  
Moisture Fraction of Flue Gas : KMFC03 = .05  
Mass of Metal (lbm): KMMC03 = .5  
Slagging Factor (Fractional Reduction in HX Effectiveness) : KSGC03 = 0.1  
Gas Convective H-T Parameter : KUCC03 = 1  
Volume of Flue Gas (ft<sup>3</sup>): KVG03 = 5184  
Volume of Water (ft<sup>3</sup>): KVSC03 = 1.64

USER WORKSHEET: PIPEWR (Water)

or

PIPESR (Steam)

MACRO INVOCATION:

|        |    |       |    |       |       |        |
|--------|----|-------|----|-------|-------|--------|
| PIPEWR |    |       |    |       |       |        |
| or     | (  | 'EX2' | ,  | 'SL2' | ,     | 'LEX2' |
| PIPESR | ID | WE    | WL | INERT | THERM | DELAY  |

INERT: 1 - Inertia effects represented  
0 - No inertia effects

THERM: N - N thermal storage nodes, heat loss to ambient represented  
DELAY: 0 - No thermal storage or heat loss

DELAY: 1 - Transport delay  
0 - No transport delay

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

ALL PIPES

Logical Check Valve Switch (.TRUE. or .FALSE.) : KCKEX2 = .F.

Pipe Conductance : KCFEX2 = 1750

Elevation difference between entering and  
leaving port ( $Z_e - Z_L$ ) (ft): KDHEX2 = 0

USER WORKSHEET: PICON

MACRO INVOCATION:

PICON ('CC2', DEMAN2, SUPPL2, YC2 , 1 )  
ID CSP PVAR OUTVAR ACTION

CSP Complete Name of Controller Setpoint

PVAR Complete Name of Process Variable Being Controlled

OUTVAR Complete Name of Process Parameter Being Changed  
by Controller

ACTION Direct Acting = 1

Reverse Acting = 2

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

Proportional Gain : CPGCC2 = .052

Integral Gain : CIGCC2 = .0026

Low Limit of Controller Output : KLLCC2 = 0

High Limit of Controller Output : KHLCC2 = 1

INITIAL CONDITIONS:

Initial Controller Output Z01 ID : ZICCC2 = .5

USER WORKSHEET: PIPEWR (Water)

or

PIPESR (Steam)

MACRO INVOCATION:

|        |    |       |    |        |       |        |
|--------|----|-------|----|--------|-------|--------|
| PIPEWR |    |       |    |        |       |        |
| or     | (  | 'E3A' | ,  | 'STM3' | ,     | 'LE3A' |
| PIPESR | ID | WE    | WL | INERT  | THERM | DELAY  |

INERT: 1 - Inertia effects represented  
0 - No inertia effects

THERM: N - N thermal storage nodes, heat loss to ambient represented  
DELAY: 0 - No thermal storage or heat loss

DELAY: 1 - Transport delay  
0 - No transport delay

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

ALL PIPES

Logical Check Valve Switch (.TRUE. or .FALSE.) : KCKE3A = 0

Pipe Conductance : KCFE3A = 550

Elevation difference between entering and  
leaving port ( $Z_e - Z_L$ ) (ft): KDHE3A = 0

USER WORKSHEET: CONNC

MACRO INVOCATION:

CONNC ('N5', 'LE3A', 'LN5')  
          ID      WE      WL

INITIAL CONDITIONS:

Leaving Pressure   P   WL       (psia): 1PLN = 120

VARIABLES:

|   |                          |                        |
|---|--------------------------|------------------------|
| H | WE - Enthalpy Entering   | (Btu/lbm)              |
| H | WL - Enthalpy Leaving    | (Btu/lbm)              |
| P | WE - Pressure Entering   | (psia)                 |
| P | WL - Pressure Leaving    | (psia)                 |
| R | WL - Density Leaving     | (lbm/ft <sup>3</sup> ) |
| W | WE - Flowrate Entering   | (lbm/hr)               |
| W | WL - Flowrate Leaving    | (lbm/hr)               |
| T | WL - Temperature Leaving | (F)                    |

## USER WORKSHEET: VALVEC

### MACRO INVOCATION:

VALVEC ('C3', 'LN3', 'LC3')  
          ID      SE      SL

NOTE: Valve and Actuator must have same ID.

### CONSTANT PARAMETERS: (All Parameters are Appended by ID)

Logical Check Valve Switch (.TRUE. or .FALSE.) : KCKC3 = .F.

Maximum Valve Conductance (pph/ pcf.psi): KCVC3 = 1018

Logical Valve Characteristic Parameter (Integer): KVAC3 = 2

- 1 - Equal Percentage
- 2 - Linear
- 3 - Quick Open

Valve Choking Pressure Ratio (fraction): KXTC3 = .47

### VARIABLES:

|   |                        |                        |
|---|------------------------|------------------------|
| H | SE - Enthalpy Entering | (Btu/lbm)              |
| H | SL - Enthalpy Leaving  | (Btu/lbm)              |
| P | SE - Pressure Entering | (psia)                 |
| P | SL - Pressure Leaving  | (psia)                 |
| R | SE - Density Leaving   | (lbm/ft <sup>3</sup> ) |
| W | SE - Flowrate Entering | (lbm/hr)               |
| W | SL - Flowrate Leaving  | (lbm/hr)               |
| T | ID - Valve Position    | (fraction)             |

USER WORKSHEET: CONNC

MACRO INVOCATION:

CONNC ('N3', 'LE2A', 'LN3')  
          ID      WE      WL

INITIAL CONDITIONS:

Leaving Pressure   P   WL       (psia): IPLN = 120

VARIABLES:

|   |                          |                        |
|---|--------------------------|------------------------|
| H | WE - Enthalpy Entering   | (Btu/lbm)              |
| H | WL - Enthalpy Leaving    | (Btu/lbm)              |
| P | WE - Pressure Entering   | (psia)                 |
| P | WL - Pressure Leaving    | (psia)                 |
| R | WL - Density Leaving     | (lbm/ft <sup>3</sup> ) |
| W | WE - Flowrate Entering   | (lbm/hr)               |
| W | WL - Flowrate Leaving    | (lbm/hr)               |
| T | WL - Temperature Leaving | (F)                    |

USER WORKSHEET: SPRHTR

MACRO INVOCATION:

SPRHTR ('S3', 'GE3', 'LN6', 'GL3', 'SL3')  
          ID      GE      SE      GL      SL

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

Flow Conductance (pph/ pcf.psi): KCFS3 = 707  
Heat Exchanger Arrangement Parameter (Integer): KKTS3 = 1  
          (1: Counterflow, 2: Parallel Flow)  
Moisture Fraction of Flue Gas : KMFS3 = .05  
Mass of Metal (lbm): KMMS3 = .16  
Slagging Factor (Fractional Reduction in HX Effectiveness) : KSGS3 = .15  
Gas Convective H-T Parameter : KUCS3 = .31  
Steam H-T Parameter : KUSS3 = 15  
Volume of Gas (ft<sup>3</sup>): KVG33 = 2592  
Volume of Steam (ft<sup>3</sup>): KVSS3 = .82

USER WORKSHEET: PIPEWR (Water)

or

PIPESR (Steam)

MACRO INVOCATION:

|        |    |       |        |          |       |           |
|--------|----|-------|--------|----------|-------|-----------|
| PIPEWR |    |       |        |          |       |           |
| or     | (  | 'EX3' | , SL3' | , 'LEX3' | , 0   | , 0 , 0 ) |
| PIPESR | ID | WE    | WL     | INERT    | THERM | DELAY     |

INERT: 1 - Inertia effects represented  
0 - No inertia effects

THERM: N - N thermal storage nodes, heat loss to ambient represented  
DELAY: 0 - No thermal storage or heat loss

DELAY: 1 - Transport delay  
0 - No transport delay

CONSTANT PARAMETERS: (All Parameters are Appended by ID)

ALL PIPES

Logical Check Valve Switch (.TRUE. or .FALSE.) : KCKEX3 = .F.

Pipe Conductance : KCFEX3 = 1850

Elevation difference between entering and  
leaving port ( $Z_e - Z_L$ ) (ft): KDHEX3 = 0

APPENDIX C  
SUPERHEATER TEST-SECTIONS MODEL  
COMPUTER CODE

PROGRAM SUPERHEATER TEST-SECTION MODEL

DYNAMIC

TGE1=GAUSS (MTGE1,STDVT)

HGE1=GAUSS (MHGE1,STDVH)

TERMT (T.GE.TSTOP)

CONSTANT TSTOP=1000.,IALG=2,OMASK=.FALSE.

CINTERVAL CINT=.02

DERIVATIVE

" FRONT PIPE SECTION # 1 "

PIPESR("E1A","STM1","LE1A",0,0,0)

CONSTANT KCFE1A=3500.,KDHE1A=0.

CONSTANT KCKE1A=0.

CONSTANT TSTM1=341.26,PSTM1=120.,HSTM1=1160

CONSTANT RSTM1=.267

" CONECTION # 1 "

CONNC("N1","LE1A","LN1")

CONSTANT IPLN1=120.

" CONTROL VALVE # 1 "

VALVEC("C1","LN1","LC1")

CONSTANT KXTC1=.52,KVAC1=5,KCKC1=.FALSE.

CONSTANT KCV1=4080.

" CONECTION # 2 "

CONNC("N2","LC1","LN2")

CONSTANT IPLN2=115.

" SUPERHEATER # 1 "

SPRHTR("S1","GE1","LN2","GL1","SL1")

" CALCULATED PARAMETERS FOR SUPERHEATER # 1 "

CONSTANT KCFS1=2828.,KKTS1=1,KMFS1=.05,KMMS1=.324

CONSTANT KVGS1=5184,KUSS1=2.55,KURS1=1.84E-9

CONSTANT KUCS1=.71,KVSS1=1.64,KSGS1=.1

" BOUNDARY CONDITIONS FOR SUPERHEATER # 1 "

CONSTANT WGE1=45000.,TGE1=2100,HGE1=580

" INITIAL CONDITIONS FOR SUPERHEATER # 1 "

CONSTANT IUSL1=497., IRSL1=.158, IHGL1=675.  
CONSTANT IPSL1=110

ECON ("COA", "GL1", "CWIA", "GLCA", "CWOA")

CONSTANT KCFCOA=3000, KKTCOA=1, KMFCOA=.05, KMMCOA=.341  
CONSTANT KSGCOA=.1, KUCCOA=1, KURCOA=1, KVGCOA=5184  
CONSTANT KVWCOA=1.64, IHGLCA=450, IHCWOA=300  
CONSTANT HCWIA=200, PCWIA=60, RCWIA=1, TCWIA=40  
CONSTANT PCWOA=40

ECON ("CO1", "GLCA", "CWI1", "GLC1", "CWO1")

CONSTANT KCFCO1=3000, KKTCO1=1, KMFCO1=.05, KMMCO1=.341  
CONSTANT KSGCO1=.1, KUCCO1=1, KURCO1=1, KVGCO1=5184  
CONSTANT KVWCO1=1.64, IHGLC1=450, IHCWO1=300  
CONSTANT HCWI1=200, PCWI1=60, RCWI1=1, TCWI1=40  
CONSTANT PCWO1=40

ECON ("CO2", "GLC1", "CWI2", "GLC2", "CWO2")

CONSTANT KCFCO2=3000, KKTCO2=1, KMFCO2=.05, KMMCO2=.341  
CONSTANT KSGCO2=.1, KUCCO2=1, KURCO2=1, KVGCO2=5184  
CONSTANT KVWCO2=1.64, IHGLC2=450, IHCWO2=300  
CONSTANT HCWI2=200, PCWI2=60, RCWI2=1, TCWI2=40  
CONSTANT PCWO2=40

" BACK PIPE SECTION # 1 "

PIPESR("EX1", "SL1", "LEX1", 0, 0, 0)

CONSTANT KCFEX1=3500., KDHEX1=0.  
CONSTANT PLEX1=110., KCKEX1=0.

" PI CONTROLLER #1 "

CONSTANT DEMAN1=906  
SUPPL1=TSLL  
PICONT("CC1", DEMAN1, SUPPL1, YC1, 2)

CONSTANT CPGCC1=-.005, CIGCC1=0.001, KLLCC1=0.0, KHLCC1=1.  
CONSTANT ZOICC1=1., ZICCC1=1.

" FRONT PIPE SECTION #2"

PIPESR("E2A","STM2","LE2A",0,0,0)

CONSTANT KCFE2A=3500.,KDHE2A=0.  
CONSTANT KCKE2A=0.

CONSTANT TSTM2=341.26,PSTM2=120.,HSTM2=1160  
CONSTANT RSTM2=.267

" CONECTION # 3 "

CONNC("N3","LE2A","LN3")  
CONSTANT IPLN3=120

" CONTROL VALVE # 2 "

VALVEC("C2","LN3","LC2")

CONSTANT KXTC2=.52,KVAC2=2,KCKC2=.FALSE.  
CONSTANT KCVC2=115.

" CONECTION # 4 "

CONNC("N4","LC2","LN4")  
CONSTANT IPLN4=115

" SUPERHEATER # 2 "

SPRHTR("S2","GLC2","LN4","GL2","SL2")

" CALCULATED PARAMETERS FOR SUPERHEATER # 2 "

CONSTANT KCFS2=707.,KKTS2=1,KMFS2=.05,KMMS2=.162  
CONSTANT KVGs2=2592.,KUSS2=1.28,KURS2=9.0E-10  
CONSTANT KUCS2=.355,KVSS2=.82,KSGS2=.1

" BOUNDARY CONDITIONS FOR SUPERHEATER # 2 "

"CONSTANT WGE1=45000.,TGE1=2134."  
"CONSTANT HGE1=675."

" INITIAL CONDITIONS FOR SUPERHEATER # 2 "

CONSTANT IUSL2=491.,IRSL2=.042,IHGL2=668.  
CONSTANT IPSL2=110

ECON ("CO3","GL2","CWI3","GLC3","CWO3")

CONSTANT KCFCO3=5000,KKTCO3=1,KMFCO3=.05,KMCO3=.341  
CONSTANT KSGCO3=.1,KUCCO3=1,KURCO3=1,KVGCO3=5184  
CONSTANT KVCWO3=1.64,IHGLC3=450,IHCWO3=300  
CONSTANT HCWI3=200,PCWI3=60,RCWI3=1,TCWI3=40  
CONSTANT PCWO3=40

" BACK PIPE SECTION #2"

PIPESR("EX2","SL2","LEX2",0,0,0)

CONSTANT KCFEX2=3500.,KDHEX2=0.  
CONSTANT PLEX2=110,KCKEX2=0.

" PI CONTROLLER # 2 "

CONSTANT DEMAN2=1282  
SUPPL2=TS12  
PICON2("CC2",DEMAN2,SUPPL2,YC2,2)

CONSTANT CPGCC2=-.00,CIGCC2=0.00,KLLCC2=0.0,KHLCC2=1.  
CONSTANT ZOICC2=1.,ZICCC2=1.

" FRONT PIPE SECTION #3"

PIPESR("E3A","STM3","LE3A",0,0,0)

CONSTANT KCFE3A=3500.,KDHE3A=0.  
CONSTANT KCKE3A=0.

CONSTANT TSTM3=341.26,PSTM3=120.,HSTM3=1160  
CONSTANT RSTM3=.267

" CONECTION # 5 "

CONNC("N5","LE3A","LN5")  
CONSTANT IPLN5=120

" CONTROL VALVE # 3 "

VALVEC("C3","LN5","LC3")

CONSTANT KXTC3=.52,KVAC3=2,KCKC3=.FALSE.  
CONSTANT KVC3=1020.

" CONECTION # 6 "

CONNC("N6","LC3","LN6")  
CONSTANT IPLN6=115

" SUPERHEATER # 3 "

SPRHTR("S3","GLC3","LN6","GL3","SL3")

" CALCULATED PARAMETERS FOR SUPERHEATER # 3 "

CONSTANT KCFS3=707.,KKTS3=1,KMFS3=.05,KMMS3=.162  
CONSTANT KVG3=2592.,KUSS3=1.27,KURS3=9.E-10  
CONSTANT KUCS3=.355,KVSS3=.82,KSGS3=.1  
CONSTANT ZUOS3=500

```
"      BOUNDARY CONDITIONS FOR SUPERHEATER  # 3  "
"CONSTANT WGE1=45000.,TGE1=2134."
"CONSTANT HGE1=380."
```

```
"      INITIAL CONDITIONS FOR SUPERHEATER  # 3  "
CONSTANT IUSL3=487.,IRSL3=.042,IHGL3=662.
CONSTANT IPSL3=110
```

```
"      PIPE SECTION #3"
```

```
PIPESR("EX3","SL3","LEX3",0,0,0)
```

```
CONSTANT KCFEX3=3500.,KDHEX3=0.
```

```
CONSTANT PLEX3=110,KCKEX3=0.
```

```
"      PI CONTROLLER  # 3  "
```

```
CONSTANT DEMAN3=927
```

```
SUPPL3=TSL3
```

```
PICONT("CC3",DEMAN3,SUPPL3,YC3,2)
```

```
CONSTANT CPGCC3=-.005,CIGCC3=0.001,KLLCC3=0.0,KHLCC3=1.
```

```
CONSTANT ZOICC3=1.,ZICCC3=1.
```

```
INTEGER COUNT,KOUNT
```

```
PROCEDURAL (COUNT=)
```

```
CONSTANT COUNT=0.,KOUNT=1000
```

```
COUNT=COUNT+1
```

```
TERMT (COUNT.GE.KOUNT)
```

```
END
```

```
END
```

```
END
```

```
END
```

APPENDIX D  
RUNTIME COMMAND FILE FOR  
MODEL VALIDATION

```

SET ZUOC01=2100,ZUOCA=2100
SET KCFC01=500,KFC02=1000,KFC03=1000

PREPAR T,TSL1,TSL2,TSL3
SET PLT=4,NXPPL=50,NGXPPL=10,PRNPLT=.T.,CALPLT=.F.

SET ZZIERR=.F.,TJNITG=.9,KXX1=100,KXX2=100,KXX3=100
SET DEMAN1=800,DEMAN2=820,DEMAN3=853
SET OMASK=.T.

SET MTGE1=2153,MHGE1=586

SET CPGCC1=0.05,CPGCC2=0.05,CPGCC3=0.05,CIGCC1=.000010,...
CIGCC2=0.000010,CIGCC3=0.000010

SET KCFE1A=2100,KCFE2A=550,KCFE3A=550,KCFEX1=2100
SET KCFEX2=1750,KCFEX3=1850
SET KCVC2=1750,KVC3=1850

SET ZOICC1=.295,ZOICC2=.15,ZOICC3=.13,...
ZICCC1=.295,ZICCC2=.15,ZICCC3=.13

SET NDBUG=1,TSTOP=3000,CINT=10,NSTP=10000

SPARE$START$SPARE

REINIT
ANALYZ 'freeze'=zoicc1,zoicc2,zoicc3,'FRACDL'=.2,...
'NITRMX'=20,'LIST'=.T.,'TRIM'
SAVE 'IC'
REINIT
ANALYZ 'FREEZE'=ZOICC1,ZOICC2,ZOICC3, 'FRACDL'=.9,...
'LIST'=.T.,'TRIM'

SAVE 'IC'
REINIT
SET MTGE1=2149,MHGE1=585.5
SET DEMAN1=800,DEMAN2=820,DEMAN3=853
SET TSTOP=60,CINT=3

SET CPGCC1=0.05,CPGCC2=0.05,CPGCC3=0.05,CIGCC1=0.00,...
CIGCC2=0.000,CIGCC3=0.000

SET ZZTICG=0
SPARE$START$SPARE

```

REINIT  
SET MTGE1=2147,MHGE1=585.5  
SET TSTOP=120,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2148,MHGE1=585.5  
SET TSTOP=180,CINT=3

SET DEMAN1=798,DEMAN2=820,DEMAN3=855

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2149,MHGE1=585.5  
SET TSTOP=240,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2153,MHGE1=587  
SET TSTOP=300,CINT=3  
SET DEMAN1=800,DEMAN2=820,DEMAN3=853  
SPARE\$START\$SPARE

REINIT  
SET MTGE1=2154,MHGE1=587  
SET TSTOP=360,CINT=3

SET DEMAN1=800,DEMAN2=819,DEMAN3=852

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2158,MHGE1=587  
SET TSTOP=420,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2148,MHGE1=585  
SET TSTOP=480,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2155,MHGE1=587

SET TSTOP=540,CINT=3

SET DEMAN1=799,DEMAN2=821,DEMAN3=851

SPARE\$START\$SPARE

REINIT

SET MTGE1=2159,MHGE1=589

SET DEMAN1=800,DEMAN2=820,DEMAN3=853

SET TSTOP=600,CINT=3

SPARE\$START\$SPARE

SAVE 'IC'

REINIT

SET MTGE1=2160,MHGE1=589

SET TSTOP=660,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2161,MHGE1=589

SET TSTOP=720,CINT=3

SET DEMAN1=804,DEMAN2=824,DEMAN3=854

SPARE\$START\$SPARE

REINIT

SET MTGE1=2160,MHGE1=589

SET TSTOP=780,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2160,MHGE1=589

SET TSTOP=840,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2160,MHGE1=589

SET TSTOP=900,CINT=3

SET DEMAN1=800,DEMAN2=820,DEMAN3=853

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2158,MHGE1=589  
SET TSTOP=960,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2160,MHGE1=589  
SET TSTOP=1020,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2156,MHGE1=589  
SET TSTOP=1080,CINT=3

SET DEMAN1=799,DEMAN2=820,DEMAN3=859

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2158,MHGE1=589  
SET TSTOP=1140,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2158,MHGE1=589  
SET TSTOP=1200,CINT=3

SET DEMAN1=797,DEMAN2=819,DEMAN3=857

SPARE\$START\$SPARE

SAVE 'IC'  
REINIT  
SET MTGE1=2158,MHGE1=589  
SET TSTOP=1260,CINT=3

SET DEMAN1=800,DEMAN2=820,DEMAN3=859

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2157,MHGE1=588  
SET TSTOP=1320,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2154,MHGE1=587  
SET TSTOP=1380,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2154,MHGE1=587  
SET TSTOP=1440,CINT=3

SET DEMAN1=800,DEMAN2=820,DEMAN3=858

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2153,MHGE1=587  
SET TSTOP=1500,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2143,MHGE1=584  
SET TSTOP=1560,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2141,MHGE1=583  
SET TSTOP=1620,CINT=3

SET DEMAN1=800,DEMAN2=820,DEMAN3=854

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2149,MHGE1=585.5  
SET TSTOP=1680,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2150,MHGE1=585.5,  
SET TSTOP=1740,CINT=3

SET KURCO1=.00000017,KURCOA=.00000017

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2152,MHGE1=586  
SET TSTOP=1800,CINT=3

SET DEMAN1=800.5,DEMAN2=817,DEMAN3=842

SET DEMAN1=800,DEMAN2=817,DEMAN3=840

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2149,MHGE1=585.5  
SET TSTOP=1860,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2123,MHGE1=577  
SET TSTOP=1920,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2170,MHGE1=592  
SET TSTOP=1980,CINT=3

SET DEMAN1=805,DEMAN2=817,DEMAN3=824

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2209,MHGE1=604  
SET TSTOP=2040,CINT=3

SET KURCO1=.00000011,KURCOA=.00000011

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2209,MHGE1=604  
SET TSTOP=2100,CINT=3  
SPARE\$START\$SPARE

REINIT  
SET MTGE1=2298,MHGE1=632  
SET TSTOP=2160,CINT=3

SET DEMAN1=786,DEMAN2=812,DEMAN3=831

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2309,MHGE1=636  
SET TSTOP=2220,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2316,MHGE1=638

SET TSTOP=2280,CINT=3

"SET CPGCC3=0.,CIGCC3=0.,ZOICC3=.88,ZICCC3=.88"

SPARE\$START\$SPARE

REINIT

SET MTGE1=2320,MHGE1=639

SET TSTOP=2340,CINT=3

SET DEMAN1=800,DEMAN2=807,DEMAN3=852

SPARE\$START\$SPARE

REINIT

SET MTGE1=2322,MHGE1=640

SET TSTOP=2400,CINT=3

SET DEMAN1=809,DEMAN2=809,DEMAN3=882

SPARE\$START\$SPARE

REINIT

SET MTGE1=2328,MHGE1=642

SET TSTOP=2460,CINT=3

SET cigcc3=0.,CPGCC3=0.,ZOICC3=.86,ZICCC3=.86

SPARE\$START\$SPARE

REINIT

SET MTGE1=2329,MHGE1=642

SET TSTOP=2520,CINT=3

set ksgsl=0

SET DEMAN1=807,DEMAN2=806,DEMAN3=851

SPARE\$START\$SPARE

REINIT

SET MTGE1=2334,MHGE1=643

SET TSTOP=2580,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2340,MHGE1=646

SET TSTOP=2640,CINT=3

SET DEMAN1=804,DEMAN2=803,DEMAN3=785

SPARE\$START\$SPARE

REINIT

SET MTGE1=2313,MHGE1=637

SET TSTOP=2700,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2309,MHGE1=636

SET TSTOP=2760,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2322,MHGE1=640

SET TSTOP=2820,CINT=3

SET DEMAN1=804,DEMAN2=803,DEMAN3=754

SPARE\$START\$SPARE

REINIT

SET MTGE1=2323,MHGE1=640

SET TSTOP=2880,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2328,MHGE1=642

SET TSTOP=2940,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2324,MHGE1=641

SET TSTOP=3000,CINT=3

SET DEMAN1=802,DEMAN2=803,DEMAN3=743

SPARE\$START\$SPARE

REINIT

SET MTGE1=2324,MHGE1=641

SET TSTOP=3060,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2324,MHGE1=641

SET TSTOP=3120,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2311,MHGE1=637

SET TSTOP=3180,CINT=3

SET DEMAN1=797,DEMAN2=797,DEMAN3=745

SPARE\$START\$SPARE

REINIT

SET MTGE1=2309,MHGE1=636

SET TSTOP=3240,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2306,MHGE1=635

SET TSTOP=3300,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2284,MHGE1=628

SET TSTOP=3360,CINT=3

SET DEMAN1=810,DEMAN2=805,DEMAN3=745

SPARE\$START\$SPARE

REINIT

SET MTGE1=2265,MHGE1=622

SET TSTOP=3420,CINT=30

SPARE\$START\$SPARE

REINIT

SET MTGE1=2256,MHGE1=619

SET TSTOP=3480,CINT=30

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2261,MHGE1=620  
SET TSTOP=3540,CINT=30

SET DEMAN1=808,DEMAN2=808,DEMAN3=740

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2268,MHGE1=623  
SET TSTOP=3600,CINT=30

SET DEMAN1=807,DEMAN2=809,DEMAN3=741

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2310,MHGE1=636  
SET TSTOP=3660,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2342,MHGE1=646  
SET TSTOP=3720,CINT=3

SET DEMAN1=794,DEMAN2=805,DEMAN3=744

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2353,MHGE1=650  
SET TSTOP=3780,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2355,MHGE1=650  
SET TSTOP=3840,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2337,MHGE1=645  
SET TSTOP=3900,CINT=3

SET DEMAN1=784,DEMAN2=801,DEMAN3=747

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2343,MHGE1=647  
SET TSTOP=3960,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2356,MHGE1=651  
SET TSTOP=4020,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2354,MHGE1=650  
SET TSTOP=4080,CINT=3

SET DEMAN1=783,DEMAN2=800,DEMAN3=755

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2361,MHGE1=652  
SET TSTOP=4140,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2365,MHGE1=654  
SET TSTOP=4200,CINT=3

SET DEMAN1=782,DEMAN2=800,DEMAN3=754

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2367,MHGE1=654  
SET TSTOP=4260,CINT=3

SET DEMAN1=783,DEMAN2=797,DEMAN3=757

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2363,MHGE1=653  
SET TSTOP=4320,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2365,MHGE1=654  
SET TSTOP=4380,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2362,MHGE1=653  
SET TSTOP=4440,CINT=3

SET DEMAN1=778,DEMAN2=797,DEMAN3=757

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2338,MHGE1=645  
SET TSTOP=4500,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2352,MHGE1=650  
SET TSTOP=4560,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2339,MHGE1=645  
SET TSTOP=4620,CINT=3

SET DEMAN1=771,DEMAN2=791,DEMAN3=751

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2331,MHGE1=643  
SET TSTOP=4680,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2333,MHGE1=643  
SET TSTOP=4740,CINT=3

SET KURCO1=.00000019,KURCOA=.00000019

SET DEMAN1=783,DEMAN2=801,DEMAN3=738

SPARE\$START\$SPARE

REINIT

SET MTGE1=2344,MHGE1=647

SET TSTOP=4800,CINT=3

SET DEMAN1=781,DEMAN2=800,DEMAN3=734

SPARE\$START\$SPARE

REINIT

SET MTGE1=2350,MHGE1=649

SET TSTOP=4860,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2356,MHGE1=651

SET TSTOP=4920,CINT=3

SET DEMAN1=775,DEMAN2=802,DEMAN3=709

set kurs2=.00000006,zoicc2=.2,ziccc2=.2  
cpgcc2=0.,cigcc2=0.

SPARE\$START\$SPARE

REINIT

SET MTGE1=2338,MHGE1=645

SET TSTOP=4980,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2293,MHGE1=630

SET TSTOP=5040,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2254,MHGE1=618

SET TSTOP=5100,CINT=3

SET DEMAN1=785,DEMAN2=797,DEMAN3=688

SPARE\$START\$SPARE

REINIT

SET MTGE1=2241,MHGE1=614

SET TSTOP=5160,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2215,MHGE1=606

SET TSTOP=5220,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2185,MHGE1=597

SET TSTOP=5280,CINT=3

SET DEMAN1=790,DEMAN2=795,DEMAN3=675

SPARE\$START\$SPARE

REINIT

SET MTGE1=2166,MHGE1=591

SET TSTOP=5340,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2156,MHGE1=688

SET TSTOP=5400,CINT=3

SET DEMAN1=794,DEMAN2=794,DEMAN3=668

SPARE\$START\$SPARE

REINIT

SET MTGE1=2153,MHGE1=587

SET TSTOP=5460,CINT=3

SET KURS2=.00000003,KURS3=.00000002

SET DEMAN1=795,DEMAN2=791,DEMAN3=662

SPARE\$START\$SPARE

REINIT

SET MTGE1=2143,MHGE1=584

SET TSTOP=5520,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2148,MHGE1=584

SET TSTOP=5580,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2141,MHGE1=583  
SET TSTOP=5640,CINT=3

SET DEMAN1=795,DEMAN2=776,DEMAN3=637

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2136,MHGE1=581  
SET TSTOP=5700,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2134,MHGE1=581  
SET TSTOP=5760,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2131,MHGE1=580  
SET TSTOP=5820,CINT=3

SET DEMAN1=797,DEMAN2=780,DEMAN3=644

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2139,MHGE1=582  
SET TSTOP=5880,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2126,MHGE1=578  
SET TSTOP=5940,CINT=3

SPARE\$START\$SPARE

REINIT  
SET MTGE1=2129,MHGE1=579  
  
SET DEMAN1=799,DEMAN2=781,DEMAN3=642  
SET TSTOP=6000,CINT=3

SET DEMAN1=798,DEMAN2=780,DEMAN3=642

SPARE\$START\$SPARE

REINIT

SET MTGE1=2127,MHGE1=578

SET TSTOP=6060,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2120,MHGE1=576

SET TSTOP=6120,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2125,MHGE1=578

SET TSTOP=6180,CINT=3

SET CPGCC3=.05

SET DEMAN1=794,DEMAN2=776,DEMAN3=637

SPARE\$START\$SPARE

REINIT

SET MTGE1=2119,MHGE1=576

SET TSTOP=6240,CINT=3

SET CPGCC3=.05

SPARE\$START\$SPARE

REINIT

SET MTGE1=2121,MHGE1=577

SET TSTOP=6300,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2080,MHGE1=564

SET TSTOP=6360,CINT=3

SET DEMAN1=797,DEMAN2=777,DEMAN3=668

SPARE\$START\$SPARE

REINIT

SET MTGE1=2078,MHGE1=563

SET TSTOP=6420,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2089,MHGE1=567

SET TSTOP=6480,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2105,MHGE1=572

SET TSTOP=6540,CINT=3

SET DEMAN1=799,DEMAN2=768,DEMAN3=690

SPARE\$START\$SPARE

REINIT

SET MTGE1=2102,MHGE1=570

SET TSTOP=6600,CINT=3

SET DEMAN1=797,DEMAN2=766,DEMAN3=695

SPARE\$START\$SPARE

REINIT

SET MTGE1=2094,MHGE1=568

SET TSTOP=6660,CINT=3

kurs3=.000000005

SPARE\$START\$SPARE

REINIT

SET MTGE1=2099,MHGE1=567

SET TSTOP=6720,CINT=3

SET DEMAN1=802,DEMAN2=765,DEMAN3=700

SPARE\$START\$SPARE

REINIT

SET MTGE1=2107,MHGE1=573

SET TSTOP=6780,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2110,MHGE1=573

SET TSTOP=6840,CINT=3

SPARE\$START\$SPARE

REINIT

SET MTGE1=2097,MHGE1=567

SET TSTOP=6900,CINT=30

SET DEMAN1=799,DEMAN2=771,DEMAN3=715

SPARE\$START\$SPARE

REINIT

SET MTGE1=2109,MHGE1=573

SET TSTOP=6960,CINT=30

SPARE\$START\$SPARE

REINIT

SET MTGE1=2098,MHGE1=569

SET TSTOP=7020,CINT=30

SPARE\$START\$SPARE

REINIT

SET MTGE1=2104,MHGE1=572

SET TSTOP=7080,CINT=30

SET DEMAN1=800,DEMAN2=774,DEMAN3=729

SPARE\$START\$SPARE

REINIT

SET MTGE1=2106,MHGE1=572

SET TSTOP=7140,CINT=30

SPARE\$START\$SPARE

REINIT

SET MTGE1=2104,MHGE1=572

SET TSTOP=7200,CINT=30

APPENDIX E  
RUNTIME COMMAND FILE FOR  
ROOT LOCUS PLOT

```

set cigcc1=.0001,cigcc2=.0001,cigcc3=.0001

PREPAR T,TSL1,TSL2,TSL3
SET PLT=4,NXPPL=50,NGXPPL=10,PRNPLT=.T.,CALPLT=.F.
SET STDVT=.0,STDVH=0

SET ZZIERR=.F.,TJNITG=.9,KKKX1=100,KKKX2=100,KKKX3=100
SET DEMAN1=900,DEMAN2=900,DEMAN3=900
SET OMASK=.T.

SET MTGE1=2153,MHGE1=586

SET CPGCC1=0.05,CPGCC2=0.05,CPGCC3=0.05,CIGCC1=.000010,...
CIGCC2=0.000010,CIGCC3=0.000010

SET KCFE1A=2100,KCFE2A=550,KCFE3A=550,KCFEX1=2100
SET KCFEX2=1750,KCFEX3=1850
SET KVC2=1750,KVC3=1850

SET ZOICC1=.295,ZOICC2=.15,ZOICC3=.13,...
ZICCC1=.295,ZICCC2=.15,ZICCC3=.13

SET NDBUG=1,TSTOP=3000,CINT=10,NSTP=10000

SPARE$START$SPARE

REINIT
ANALYZ 'freeze'=zoicc1,zoicc2,zoicc3,'FRACDL'=.2,...
'NITRMX'=20,'LIST'=.T.,'TRIM'
SAVE 'IC'
REINIT
ANALYZ 'FREEZE'=ZOICC1,ZOICC2,ZOICC3,'FRACDL'=.9,...
'LIST'=.T.,'TRIM'

SET CPGCC1=.00,CPGCC2=.00,CPGCC3=.00
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,PLN6,pln5,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3,'JACOB','EIGVEC'=.T.,'EIGEN'

SET CPGCC1=.01000,CPGCC2=.01000,CPGCC3=.01000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,PLN6,pln5,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3,'JACOB','EIGVEC'=.T.,'EIGEN'

SET CPGCC1=.02000,CPGCC2=.02000,CPGCC3=.02000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,PLN6,pln5,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3,'JACOB','EIGVEC'=.T.,'EIGEN'

```

SET CPGCC1=.03000,CPGCC2=.03000,CPGCC3=.03000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,PLN6,pln5,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T.,'EIGEN'

SET CPGCC1=.04000,CPGCC2=.04000,CPGCC3=.04000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,PLN6,pln5,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T.,'EIGEN'

SET CPGCC1=.05000,CPGCC2=.05000,CPGCC3=.05000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,PLN6,pln5,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T.,'EIGEN'

SET CPGCC1=.06000,CPGCC2=.06000,CPGCC3=.06000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,PLN6,pln5,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T.,'EIGEN'

SET CPGCC1=.07000,CPGCC2=.07000,CPGCC3=.07000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,PLN6,pln5,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T.,'EIGEN'

SET CPGCC1=.08000,CPGCC2=.08000,CPGCC3=.08000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,PLN6,pln5,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T.,'EIGEN'

SET CPGCC1=.09000,CPGCC2=.09000,CPGCC3=.09000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,PLN6,pln5,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T.,'EIGEN'

SET CPGCC1=.10000,CPGCC2=.1000,CPGCC3=.1000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,PLN6,pln5,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T.,'EIGEN'

SET CPGCC1=.011000,CPGCC2=.011000,CPGCC3=.011000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T.,'EIGEN'

SET CPGCC1=.012000,CPGCC2=.012000,CPGCC3=.012000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T.,'EIGEN'

SET CPGCC1=.013000,CPGCC2=.013000,CPGCC3=.013000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T.,'EIGEN'

```

SET CPGCC1=.014000,CPGCC2=.014000,CPGCC3=.014000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.015000,CPGCC2=.015000,CPGCC3=.015000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.016000,CPGCC2=.016000,CPGCC3=.016000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.017000,CPGCC2=.017000,CPGCC3=.017000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.018000,CPGCC2=.018000,CPGCC3=.018000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.019000,CPGCC2=.019000,CPGCC3=.019000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.02000,CPGCC2=.02000,CPGCC3=.02000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.021000,CPGCC2=.021000,CPGCC3=.021000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.022000,CPGCC2=.022000,CPGCC3=.022000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.023000,CPGCC2=.023000,CPGCC3=.023000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.02000,CPGCC2=.024000,CPGCC3=.024000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

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SET CPGCC1=.025000,CPGCC2=.025000,CPGCC3=.025000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.026000,CPGCC2=.026000,CPGCC3=.026000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.027000,CPGCC2=.027000,CPGCC3=.027000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.028000,CPGCC2=.028000,CPGCC3=.028000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.029000,CPGCC2=.029000,CPGCC3=.029000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.03000,CPGCC2=.03000,CPGCC3=.03000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.031000,CPGCC2=.031000,CPGCC3=.031000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.032000,CPGCC2=.032000,CPGCC3=.032000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.033000,CPGCC2=.033000,CPGCC3=.033000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.034000,CPGCC2=.034000,CPGCC3=.034000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.035000,CPGCC2=.035000,CPGCC3=.035000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

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```

SET CPGCC1=.036000,CPGCC2=.036000,CPGCC3=.036000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.037000,CPGCC2=.037000,CPGCC3=.037000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.038000,CPGCC2=.038000,CPGCC3=.038000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.039000,CPGCC2=.039000,CPGCC3=.039000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.04000,CPGCC2=.04000,CPGCC3=.04000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.041000,CPGCC2=.041000,CPGCC3=.041000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.042000,CPGCC2=.042000,CPGCC3=.042000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.043000,CPGCC2=.043000,CPGCC3=.043000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.044000,CPGCC2=.044000,CPGCC3=.044000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.045000,CPGCC2=.045000,CPGCC3=.045000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.046000,CPGCC2=.046000,CPGCC3=.046000
REINIT
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

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SET CPGCC1=.047000,CPGCC2=.047000,CPGCC3=.047000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.048000,CPGCC2=.048000,CPGCC3=.048000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.049000,CPGCC2=.049000,CPGCC3=.049000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.050000,CPGCC2=.050000,CPGCC3=.050000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.051000,CPGCC2=.051000,CPGCC3=.051000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.052000,CPGCC2=.052000,CPGCC3=.052000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.053000,CPGCC2=.053000,CPGCC3=.053000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.054000,CPGCC2=.054000,CPGCC3=.054000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.055000,CPGCC2=.055000,CPGCC3=.055000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.056000,CPGCC2=.056000,CPGCC3=.056000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.057000,CPGCC2=.057000,CPGCC3=.057000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

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SET CPGCC1=.058000,CPGCC2=.058000,CPGCC3=.058000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.059000,CPGCC2=.059000,CPGCC3=.059000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.06000,CPGCC2=.06000,CPGCC3=.06000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.061000,CPGCC2=.061000,CPGCC3=.061000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.062000,CPGCC2=.062000,CPGCC3=.062000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.063000,CPGCC2=.063000,CPGCC3=.063000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.064000,CPGCC2=.064000,CPGCC3=.064000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.065000,CPGCC2=.065000,CPGCC3=.065000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.066000,CPGCC2=.066000,CPGCC3=.066000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.067000,CPGCC2=.067000,CPGCC3=.067000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.068000,CPGCC2=.068000,CPGCC3=.068000
REINIT
ANALYZ 'FREEZE'=HCW01,HCW02,HCW03,HGLC1,HGLC2,HGLC3,...
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

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SET CPGCC1=.069000,CPGCC2=.069000,CPGCC3=.069000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.07000,CPGCC2=.07000,CPGCC3=.07000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.071000,CPGCC2=.071000,CPGCC3=.071000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.072000,CPGCC2=.072000,CPGCC3=.072000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.073000,CPGCC2=.073000,CPGCC3=.073000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.074000,CPGCC2=.074000,CPGCC3=.074000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.075000,CPGCC2=.075000,CPGCC3=.075000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.076000,CPGCC2=.076000,CPGCC3=.076000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.077000,CPGCC2=.077000,CPGCC3=.077000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.078000,CPGCC2=.078000,CPGCC3=.078000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.079000,CPGCC2=.079000,CPGCC3=.079000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.08000,CPGCC2=.08000,CPGCC3=.08000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.081000,CPGCC2=.081000,CPGCC3=.081000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.082000,CPGCC2=.082000,CPGCC3=.082000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.083000,CPGCC2=.083000,CPGCC3=.083000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.083000,CPGCC2=.083000,CPGCC3=.083000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.084000,CPGCC2=.084000,CPGCC3=.084000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.085000,CPGCC2=.085000,CPGCC3=.085000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.086000,CPGCC2=.086000,CPGCC3=.086000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.087000,CPGCC2=.087000,CPGCC3=.087000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.088000,CPGCC2=.088000,CPGCC3=.088000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

SET CPGCC1=.089000,CPGCC2=.089000,CPGCC3=.089000  
REINIT  
ANALYZ 'FREEZE'=HCWO1,HCWO2,HCWO3,HGLC1,HGLC2,HGLC3,...  
ZOICC1,ZOICC2,ZOICC3,RSL1,RSL2,RSL3, 'JACOB','EIGVEC'=.T., 'EIGEN'

## VITA

Roger D. Painter was born in Shelbyville, Tennessee on July 26, 1955. After leaving high school, he worked as a printer until September 1980 at which time he returned to school to pursue a Bachelor of Science degree in Chemical Engineering. In June of 1983, he was awarded a Bachelor of Science degree in Chemical Engineering from The University of Tennessee in Knoxville.

In June of 1983, Mr. Painter began full time employment as a Field Sales Engineer at Texas Instruments in Johnson City, Tennessee and Boston, Massachusetts.

In September of 1986, Mr. Painter returned to school to pursue a Master of Science degree in Chemical Engineering at The University of Tennessee Space Institute in Tullahoma, Tennessee. Mr. Painter finished his coursework in May of 1988. He then began full time employment as a Chemical Sales Engineer.

Mr. Painter is now pursuing a PhD in Chemical Engineering at Tennessee Technological University in Cookeville, Tennessee.

Mr. Painter is married to the former Valerie Pierce of Manchester, Tennessee and has two children, Joshua and Lindsey.