MULTIPARAMETER DISPLAY
FOR
A NUCLEAR REACTOR SIMULATION

A Thesis

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DEDICATED TO

my parents

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ABSTRACT

The theory and design of a simulation for a Pressurized Water Nuclear Reactor on a hybrid computer are the concerns of this thesis. A hybrid computer system combines the speed of the analog computer in solving differential equations, with the efficient logical control, the memory, and the flexibility of the digital computer. To increase the usefulness of this simulator, an auxiliary display panel was constructed. It features a diagram of the plant coolant and control systems along with fourteen display meters and four manual controllers. These controls are included so that the steam throttle opening, the primary coolant flow rate, the reference temperature of the control system, and the normalized power demand signal can be continuously varied.

Both normal and accident responses may be studied for a variety of plant conditions. Selected simulator results, including normalized neutron concentration, reactivity, fuel, coolant, and steam temperatures as function of time, are presented and discussed. The extensive capabilities of digital-directed-analog hybrid system in process control are well illustrated by this simulation.

CHAPTER ONE

INTRODUCTION

The rapid expansion of nuclear energy applications, resulting from the current energy crisis, has increased the demand for highly qualified engineers and other technical personnel to operate and to maintain nuclear reactors. This demand has placed special burdens on universities and industrial training centers to provide realistic educational tools through which students develop an appreciation for actual operating plants. Training reactors have been used in the past, but they are generally unsatisfactory because of expense, record keeping, and restrictions on experimental demonstrations. Reactor simulators, such as those at American Electric Power Simulator Training Center in Charleston, West Virginia, and Westinghouse Nuclear Training Center at Zion, Illinois, have therefore become increasingly popular.(1)

Simulation is a relatively inexpensive, speedy, efficient, and safe method of teaching basic reactor control theory. It gives a visual demonstration of the solution derived from the reactor theory equation, and abnormal or emergency situation can be studied without risking actual nuclear hazards. It affords a unique opportunity to blend theoretical study with realistic concern for nuclear power plant problems.

The simulation of a nuclear power plant and its associated plant digital computer is logically suited to a hybrid computer system (a combination of interactive analog and digital computers) because a nuclear power plant can be easily simulated on the analog portion and the digital portion will actuate the control executions after high-speed calculations. The input-output (I/O) devices, such as high-speed printers, and monitor scopes controlled by the digital section, can be used to monitor variables continuously. This action is called "data-logging" or "trending" and is widely used in power plant operation.

In educational institutions, simulators can perform a valuable dual role of demonstrating basic reactor charateristics and responses under various conditions, and of providing research opportunities. Generally, a university system is a relatively small scale simulation compared with those found in industry.

The Louisiana State University Nuclear Science Center has a simulation of Pressurized Water Reactor (PWR) on the XDS Sigma 5 and EAI model 680 hybrid computer system.(2) The original simulation was oriented toward research rather than instruction because it required detailed knowledge of the hybrid system.(3) A linearized mathematical model with a constant average temperature control system is used to reproduce the dynamic behavior of the primary loop of the PWR system. The simulator can represent most of the operating conditions from start-up, through full power, to shutdown--with its appropriate xenon effect. Accident conditions, such as loss of coolant or control system failure, also may be studied. In order to run this simulator, the operator was required to have a thorough understanding of the basic procedures of the hybrid system, especially of the analog computer.

If a simulation is too complex, its use will be limited to a small fraction of graduate students and staff. A simplified operation is needed in order to allow a wider usage of this simulator in instruction, without reducing its capability. The primary objectives of this thesis problem are to develop a prototype hybrid computer package to minimize the operation procedures of the analog computer and, simultaneously, to display the key output variables of the PWR simualtor.

CHAPTER TWO

BASIC HYBRID COMPUTING SYSTEM

The hybrid computing system of Louisiana State University is a medium-scale, general-purpose computer suitable for engineering and scientific research and design purposes. The system consists of a XDS Sigma 5 digital computer, an EAI 693 hybrid interface unit, and an EAI 680 scientific analog computer, which are shown in Figure 2-1.

2.1 Hybrid System

For ease of discussion, the hybrid system may be considered as divided into three parts:

1. The control interface,
2. The logic interface, and
3. The high-speed data interface.

The control interface is the section of the interface which permits the digital computer to exercise "button-pushing" control over the analog computer. This control includes:

Mode control (analog and logic),
Time scale control,
Analog components selection,
Digital volt meter (DVM) readout at selected analog components,
Potentiometer value selection and setting,
Analog console status,
Fault word readout, and
Console selection.

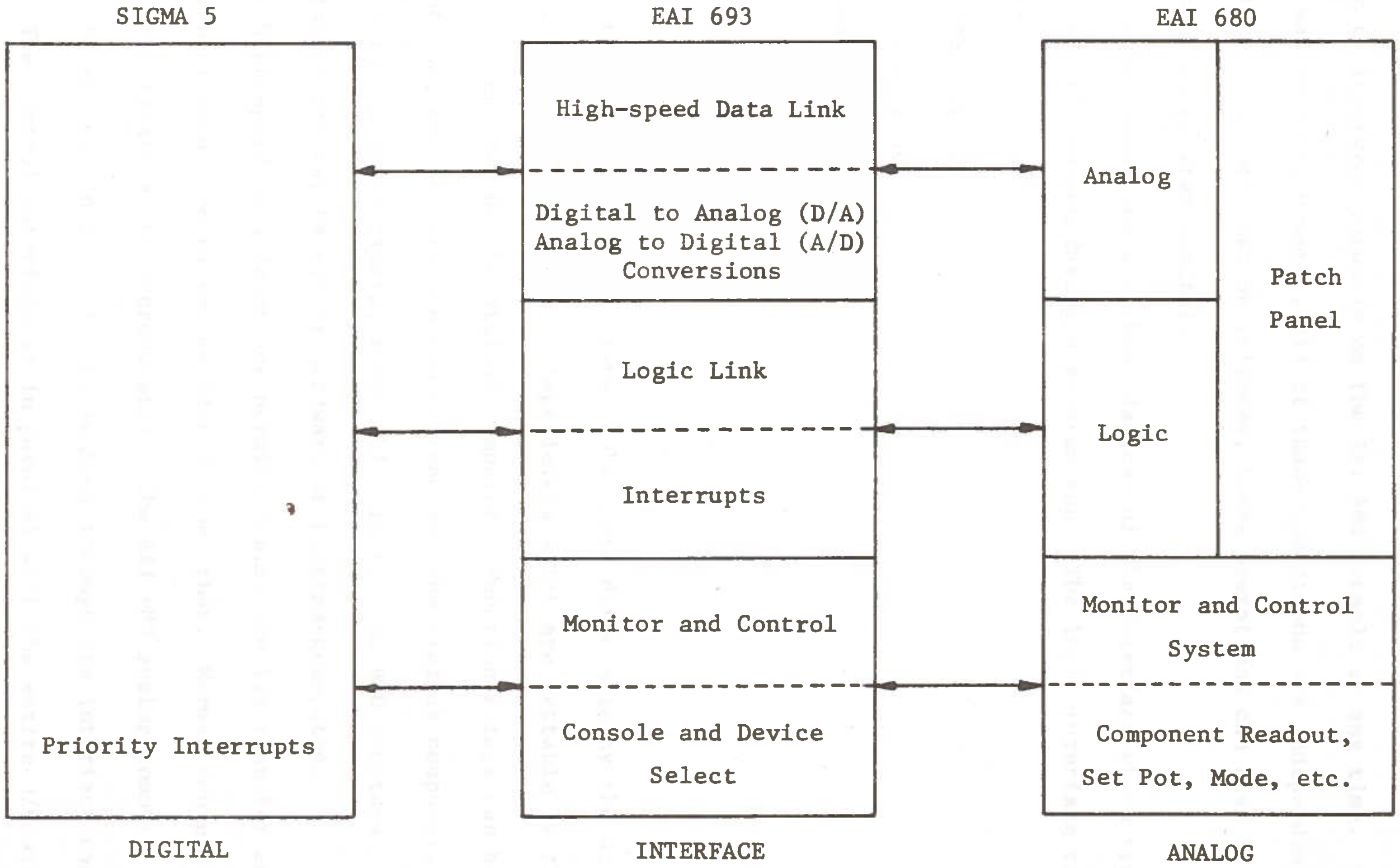


Figure 2-1. Block Diagram of the Hybrid System

These operations of linkage are in parallel with the manual(push-button) control on the console of the EAI 680, thus permitting the operator to intervene manually on the EAI 680 console at any time. Unlike manual control, however, all of these operations are independent, and no fixed sequence must be followed; these operations can also be under complete program control.

The logic interface are those devices of the interface which transmit logical information during a problem run. The logic interface consists of:

Control lines,
Function relays,
Sense lines,
Comparators,
Timers, and
Interrupts.

Control lines are voltage levels which are directable by the digital computer, and sense lines are voltage levels which are settable by the EAI 680 and detected by the digital computer. Function relays can be positioned by, and comparators can be read by, the digital computer. Timers include digital timers, monostable timers, and BCD counters. External interrupts may be either hardware or program-generated.

The high-speed data interface permits rapid, precise transfer and conversion of data from either machine to the other. Normal conversion time is approximately two microseconds. The EAI 680 analog computer is equipped to operate in a hybrid environment through its interface capability. The control interface is in parallel with the entire I/O system of the digital computer.

2.2 Advantages of Hybrid System

The different roles of digital and analog computers may be outlined to illustrate reasons for using a hybrid system rather than a digital or an analog system alone in simulation.

2.2.1 Analog Computers

Operational speed is an advantage of analog computers because all unites operate simultaneously and problem solutions appear in real-time. In many cases, time scaling can be introduced to expand or to compress time intervals.

Another feature of the analog computers is that the programing of time-varying differential equation is relatively easy. More complex problems require only additional components. However, once a problem has been satisfactorily set up on the computer, simulation described by the equations can be thoroughly and easily investigated for a wide range of conditions and parameter values.

The form of presentation of the solution is continuous, giving a clear insight into the behavior of the simulation. By applying proper scaling factors, output voltages of amplifiers can be readily converted into actual simulated values and displayed on the I/O devices, such as meters, recorders, or monitor scopes.

A disadvantage of analog computers is their limited accuracy, which is derived from the tolerance of electronic components; the performance of these elements may also change with time and environment.

Interference from electronic noise affects the measuring accuracy of the output voltage. It is not easy to obtain a solution with a voltage variation of less than 0.001% full scale. Also, analog systems lack a capability for long-term information storage.

2.2.2 Digital Computers

Digital computers are capable of greater precision than analog computers because the solution to a problem can be made as accurate as the machine and the mathematical model allow. For a 16 bits word, a last bit change is equivalent to a variation in the solution of one part of 100,000. Digital computers also have the advantage of a large memory with no limit on the storage time for information. Logic operations are much more efficiently carried and more rapidly performed.

Digital systems are good at solving algebraic equations with floating point arithmetic, and there is no scaling problem with data. The main disadvantage of small digital systems is the serial mode of operation. Since there is only one arithmetic unit for such a computer, it has to be shared by all the required operations. Also, integration cannot be performed continuously in the manner provided by analog computers.

2.2.3 Hybrid Computers

From the comparison of the advantages and disadvantages of the two types of computers, it becomes obvious that they complement each other for many applications. Hybrid computers provide solutions for complex simulation problems which require both high-speed, continuous solutions and large storage for arithmetic operations.

Digital-analog simulation is the most common hybrid computer application because of the ease of implementation. A general digital controlled analog computation is shown in Figure 2-2.

The digital computer acts as a supervisory control for the analog computation through sequencing operations. Variations in parameter values generated by the analog computer are evaluated and controlled by the digital computer through a predetermined program or integration of

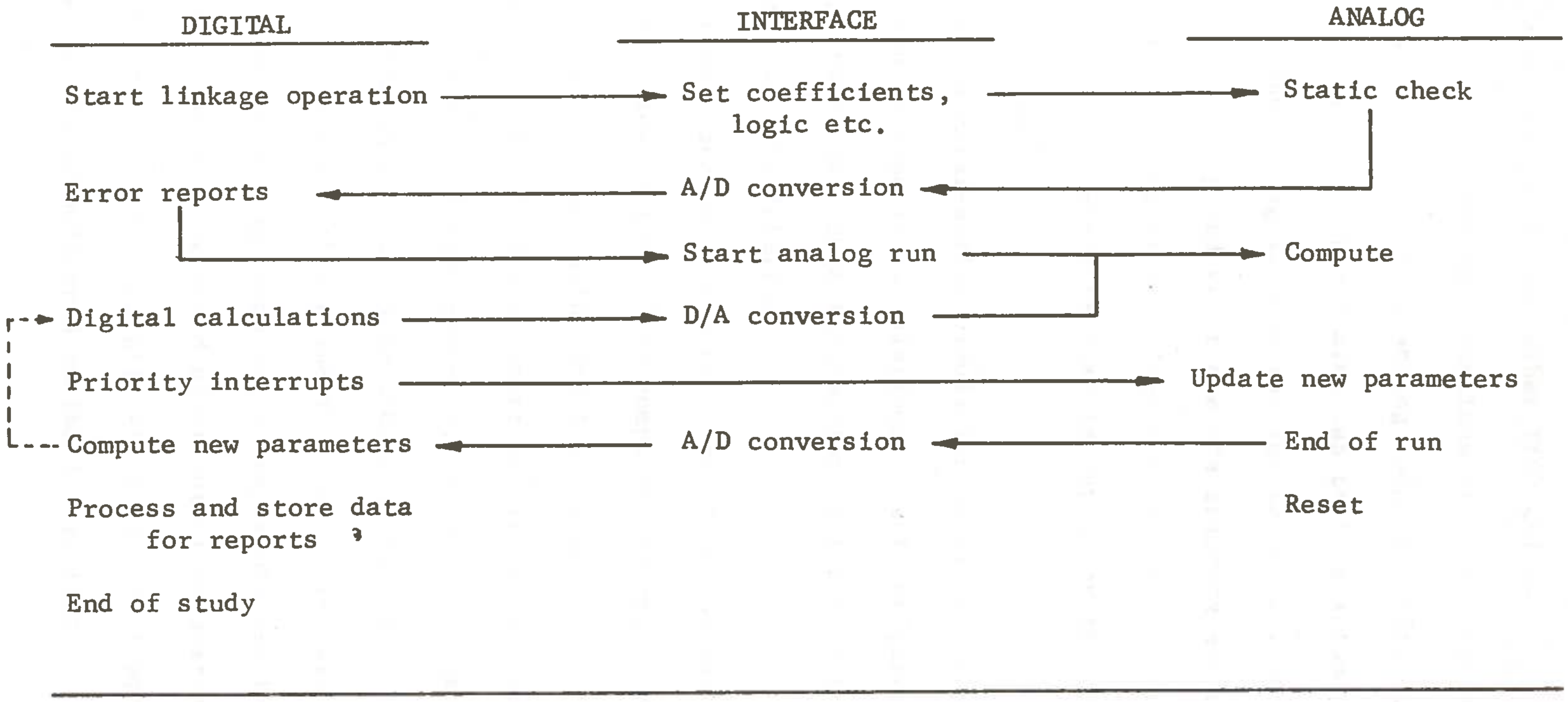


Figure 2-2. Digitally Controlled Analog Computation

past results. The outputs of an analog computer can be converted and printed as formatted reports on the digital high-speed printer, or displayed on a monitor scope and other I/O devices.

Digital "house-keeping" functions provide diagnoses for the analog computer, such as pinpointing analog computer malfunctions for the operator. The digital computer also can perform automatic "static checks" by measuring the propagation of the initial condition throughout the analog computer setup and can therefore indicate errors before the actual solutions of differential equations are carried out by the analog computer. As a result, enormous time is saved for the operator in checking the circuit design.

Combined digital-analog simulation provides for parallel differential equation-arithmetic calculations, functions generation, or coordinate transformations. Such information is transferred between the two machines through the interface.

The Pressurized Water Reactor simulation has taken advantage of all these capabilities of the hybrid computer system. The digital computer provides the preliminary setup and testing of the initial information by static checks, and provides a report before the simulator is actually started. As the simulation proceeds, the digital computer controls the progress of the analog-mode selection and other logic operations, and continuously calculates the primary coolant flow rate and transfers the value back to the analog computer as the inputs for heat-flow calculation. Steady state values of selected plant output parameters are tabulated and printed in the high-speed printer. Transient response of those output variables may be monitored on the X-Y plotter.

CHAPTER THREE

MATHEMATICAL MODEL OF REACTOR SIMULATION

The development of a workable mathematical model achieves a successful simulation. A linearized model permits total differential equations to be used rather than partial ones, because this simulation deals with the behavior of the primary loop for various disturbances, and not with equipment design. It also provides for the usage of average quantities for many terms in the simulation, and in reactor control system design.

The mathematical model consists of space- and time-dependent differential equations describing the neutron flux density and the primary coolant loop heat transfer. A hybrid computer may be used to simulate a PWR system accurately for the reasons covered in Chapter II. Because of the limited capability of the EAI 680 analog computer, it is necessary to reduce the multidimensioned neutron flux and heat flow equations to one dimensioned time dependence. These techniques enhance the effective capacity of the analog computer and allow a more detailed simulation of the entire reactor system.

The one-group reactor kinetics equation can be approximated by the Diffusion Theory as:

$$D\nabla^2\Phi(r,t) - \Sigma_a\Phi(r,t) + S = \frac{\partial n(r,t)}{\partial t} \qquad (3\text{-}1)$$

in which r is the radial distance from the origin in cm

t is the time in seconds

Φ is the neutron flux in n/cm^2-sec

D is the diffusion coefficient in cm

Σ_a is the macroscopic absorption cross section in cm^{-1}

S is the neutron source term in n/cm^3-sec

n is the neutron density in n/cm^3

If the reactor is assumed to be close to critical so that the effective multiplication factor (k) is near unity, the shape of the neutron flux will remain constant, even though it rises in amplitude with time; as a consequence, $\nabla^2\Phi$ is equal to $-B^2\Phi$, in which B^2 is the buckling in cm^{-2}. Equation 3-1 therefore becomes time-dependent only, and allows use of dn/dt in place of $\partial n/\partial t$.(4) This is also called the point reactor approximation. The transient neutronic equations are:

$$\frac{dn(t)}{dt} = \frac{\delta k-\beta}{\ell} n(t) + \sum_{11}^{m} \lambda_i C_i + S \qquad (3\text{-}2)$$

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\ell} n(t) - \lambda_i C_i \qquad (3\text{-}3)$$

in which δk is the reactivity which is equal to k-1 for k≃1

β_i is the delayed neutron yield

β is the total delayed neutron yield which is equal to $\Sigma\beta_i$

ℓ is the neutron lifetime

λ_i is the decay constant of the ith delayed neutron group

C_i is the concentration of the ith delayed neutron group

S is the neutron source term

The source term includes neutrons produced by cosmic rays and spontaneous fission, as well as the steady-state neutron sources used for a reactor. In practice, S may be assumed to be zero in Equation 3-2 because usually the reactor is operated at a power level at which the fission-produced neutrons overshadow the independent-source-produced neutrons. Six groups of delayed-neutron emitters are currently considered necessary and sufficient for detailed determination of the kinetic behavior of a system. However, for a training simulator, a one-group approximation is also provided to demonstrate the gross behavior of the reactor system.

Neutron behavior may be discussed from the macroscopic viewpoint by the "point reactor" approximation; however, this simplified approach cannot be used to determine heat flow in the core coolant channels. The additional complexity is imposed because consideration of fuel, cladding, coolant, and structural components, each of which has different thermal properties, is necessary. This simulation assumes a unit cell containing the fuel which consists of a cylindrical rod with concentric cylinders of cladding materials and coaxially moving coolant. Axial conduction of heat is considered to be negligible, so that the heat conduction equations become functions only of time and radius (measured from the center of the fuel rod). An important consequence is that the equations for radial heat flow are the same at any axial location. Thus, the heat transport equations are coupled in the direction of the coolant flow. If a small increment along the fuel rod axis is considered, the radial temperature distribution may be treated as invariant within any increment. The coolant temperature is thus assumed to vary linearly along the fuel rod axis. With the above analysis, equations of radial heat flow and coolant temperature may be simulated for only one small axial increment. It is also assumed that there is a linear temperature profile with respect to the axial distance. Temperature increase of the coolant through the core is the integral over the entire length of the fuel rod, and is represented by the mass flow rate of the coolant because the mass flow rate is the product of the axial length of the fuel rod, the cross sectional area of the coolant flow channel, and the density of the coolant. The preceding assumptions and simplifications lead to heat flow equations that are time dependent only.(5)

In this study, reactor control is based on the negative feedback control system, which is used to describe the behavior of an controlled system when the system responds to an error in such a manner as to counteract the error; i.e., an increase in reactivity results from the withdrawal of control rods. Actual power output is assumed to be proportional to neutron density. The power-demand is determined by a constant-average-coolant-temperature control system, which is made up of a comparator, the proportional-integral-controller, and a control rod drive unit.

Reactivity (δk) is the sum of the built-in reactivity, temperature-dependent reactivity, reactivity related to control rod position, and reactivity arising from xenon poisoning:

$$\delta k = \delta k_f + \delta k_t + \delta k_c + \delta k_p \qquad (3\text{-}4)$$

in which δk_f is the built-in reactivity of the fuel

δk_t is the temperature-dependent reactivity, which is equal to $\alpha(T_f - T_r)$

α is the temperature coefficient of reactivity in $°F^{-1}$

T_f is the fuel temperature in °F

T_r is the reactivity reference temperature (temperature contribution is zero) in F

δk_c is the reactivity related to control rod position

δk_p is the reactivity arising from poison

Built-in reactivity may be assumed to be constant for a short transient period, because its variation depends on fuel depletion with time. Reactivity arising from poison has little affect on over-all reactivity compared to the effect resulting from fuel temperature and control rod position during normal reactor operation. In this model, reactivity contributions from the fuel temperature and control rod position are negative; built-in reactivity has the only positive effect. The system is self-regulated; i.e., as the reactor heats up, the reactivity is reduced.

An error signal (ε) is generated through the comparator, which senses the difference of the average temperature and the reference temperature:

$$\varepsilon = T_{ref} - T_{ave} \tag{3-5}$$

in which T_{ref} is the reference temperature in °F

T_{ave} is the average temperature which is equal to $\frac{1}{2}(T_{oc} - T_{ox})$ in °F

T_{oc} is the coolant temperature at outlet of reactor vessel in °F

T_{ox} is the coolant temperature at outlet of heat exchanger in °F

This error signal is fed to the proportional-plus-integral-controller, which in turn positions the control rods to correct the difference by regulating the total number of neutrons produced by fission.

Proportional-plus-integral-control is expressed mathematically as:

$$n_0(t) = \tau_c K_c \varepsilon + K_c \int_0^t \varepsilon \, dt \tag{3-6}$$

in which n_0 is the demand power

τ_c is the controller time constant in second

K_c is the controller gain in $n/°F\text{-sec-cm}^2$

The control rod drive unit, which positions control rods, is defined by:

$$\frac{d^2\mu(t)}{dt^2} + \frac{1}{\tau_m}\frac{d\mu(t)}{dt} = \frac{K_m}{\tau_m}\left[\frac{n_0(t) - n(t)}{n(t)}\right] \tag{3-7}$$

in which μ is the departure of control rod reactivity from its initial value

τ_m is the control rod drive unit time constant in second

K_m is the modified gain constant in sec^{-1}

n is the neutron density in n/cm^3

In practice, reactivity related to control rod position and actual control rod position have nonlinear relationships, but for simplicity of simulation they are assumed to be proportional.

In considering the negative feedback system with the above control system design, it should be realized that it is the change in the output of the reactor which determines feedback effect. As mentioned in preceding paragraphs, reactivity contributions from fuel temperature and control rod position have the essential effect on over-all reactivity. Suppose that, as a result of a power demand, the reactivity is increased by moving a control rod, then the accompanying temperature change provides a negative reactivity feedback which tends to counteract the reactivity change from the power demand. Thus, the reactor eventually stabilizes at a new steady state with a higher temperature, which in turn provides more power output.

CHAPTER FOUR

MULTIPARAMETER DISPLAY PANEL

The multiparameter display panel is a small replica of a power plant control board. It consists of a diagram of the basic plant, with key input and output variables highlighted. Fourteen meters display the dynamic output responses of plant parameters, and four adjustable input controllers may be used to set plant variables. A central control section provides for the operation and adjustment of the hybrid simulation system contained on this board.

The operator has the option of changing a wide variety of thermal and neutronic parameters, including the primary coolant flow rate, the secondary steam throttle control, the reference temperature controller, and the normalized power demand; in addition, either one-group or six-group delayed neutron approximations may be selected. Output variables which are affected by these input parameters include the normalized thermal neutron concentration, the average inlet and outlet coolant temperatures, the fuel temperature, the heat exchanger temperature, the steam temperature, the reactivity, the inverse reactor period, and the relative control rod position. These output variables are displayed simultaneously for steady-state operation, or may be displayed individually for transient conditions on a hybrid computer X-Y plotter.

Operation of the simulator utilizes real-time direct communication between the operator and the hybrid computer. In this system, the digital computer performs predetermined operations, which may be actuated from the control panel section by giving command signals to the digital section through pust-button controls.

The PWR multiparameter display panel is intended to provide students with visual display of the time dependent behavior of a reactor system. Dynamic behavior of a nuclear reactor involves the interaction of many physical phenomena. Thus, operational response characteristics are often not immediately obvious, and can be understood and anticipated only if the various physical phenomena involved are well understood. This is especially true of a full-scale nuclear power generation unit where the characteristics of energy removal and conversion system have a significant influence on the behavior of the nuclear power plant itself.

For ease of construction, the panel has four separable sections: the meter section, the control section, the adjustable controllers, and the plant diagram. Detailed functions of each section are described on the following paragraphs.

4.1 Meter section

Fourteen meters with their labels are arranged on this panel, and the meter layout is shown in Figure 4-1. Each meter displays the steady-state response of a parameter from the analog computer output. Meters 1 through 12 are protected by a group of relays from possible overloading caused by the analog computer malfunction during the simulator preliminary setup period. No signal will be transmitted to these meters before satisfactory checks, which are provided by the digital computer, are accepted by the operator. Each meter is also protected by a diode to avoid current reversing of some analog outputs. Meters 13 and 14 are directly connected to proper amplifier outputs, because their initial

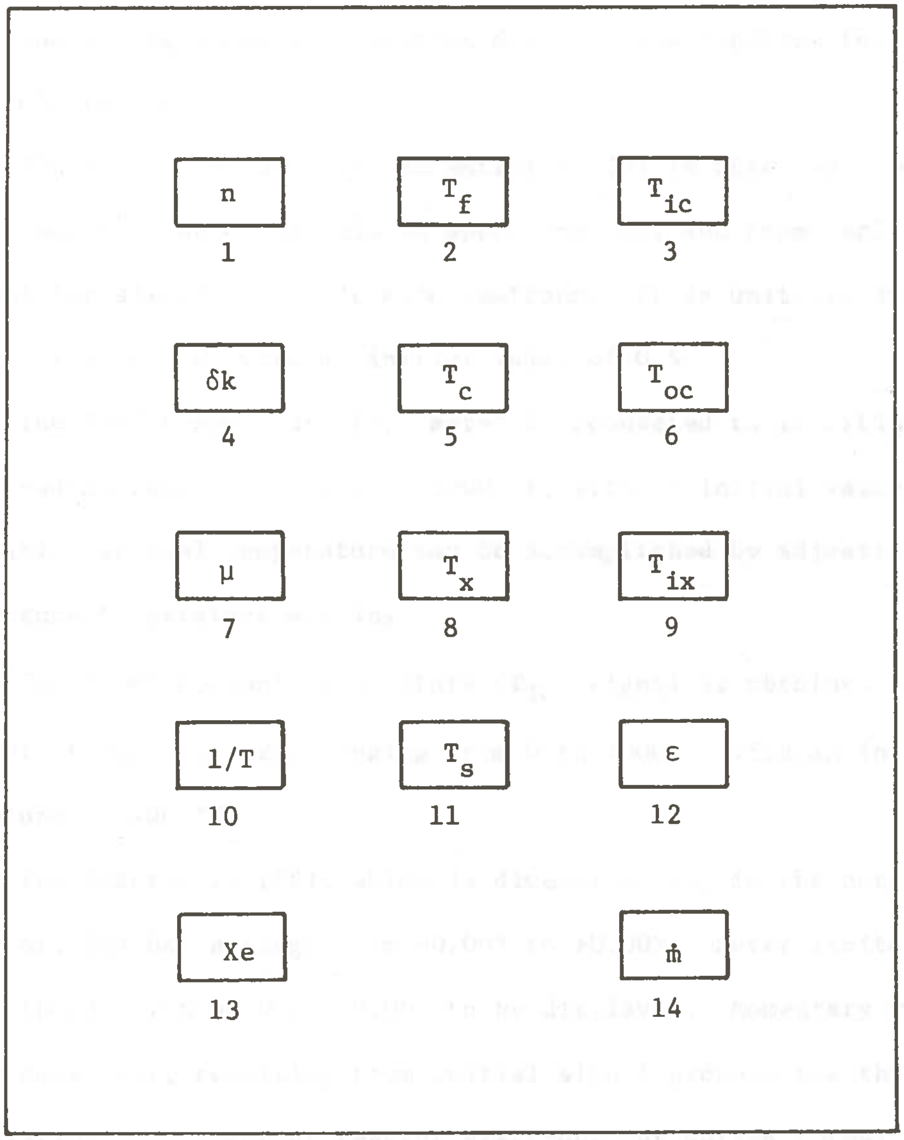


Figure 4-1. Display Meter Layout

values are zero and are controlled by the digital program. Every meter is in series with a 10K ohm current limit resistor, which is also used for meter calibration.

Succeeding paragraphs provide detailed descriptions for meter instrumentation:

The normalized neutron concentration (n) is obtained from amplifier 66 output for one group delayed approximation, and from amplifier 110 output for six groups of delayed neutrons. It is unitless and has a range of 0 to 1.0, with an initial value of 0.5.

The fuel temperature (T_f) meter is connected to amplifier 31 output. The reading range is from 0 to 2000 °F, with an initial value of 1000 °F. Variation of fuel temperature may be accomplished by adjusting the reference temperature setting.

The inlet coolant temperature (T_{ic}) signal is obtained from the output of amplifier 21, ranging from 0 to 1000 °F with an initial temperature of 400 °F.

The reactivity (δK), which is dimensionless, is the output of amplifier 61, and has a range from -0.005 to +0.005. Meter limitation allows only the portion of 0 to +0.005 to be displayed. Momentary overload of this amplifier, resulting from initial signal propagating through the simulation, may occur at reactor start-up; but during normal operation, the reactivity should be very nearly zero.

The average coolant temperature (T_c) is obtained from the output of amplifier 1 and ranges from 0 to 1000 °F. The initial value is 500 °F, which is the linear average of the inlet and outlet coolant temperatures.

The outlet coolant temperature (T_{oc}) is read from the amplifier 17 output. It has a range of 0 to 1000 °F, and an initial temperature of

600 °F.

The relative control rod position (μ) signal is taken from amplifier 45 output, ranging from -1.0 to +1.0 in dimensionless units. Under usual operating conditions with the normalized neutron level at 0.5 and fuel temperature at 1000°F, the relative control rod position is indicated as zero on the meter. Any disturbance, resulting from adjustment of the input parameters, causes the control rods to depart from their initial position, leading to a non-zero meter reading. Control-rod withdrawal causes the output of amplifier 45 to go negative, and insertion causes a positive output; however, the meter limitation allows for an apparent positive reading.

The heat exchanger temperature (T_x) signal is obtained from amplifier 102, scaled from 0 to 1000 °F. This temperature is the linear average of coolant temperatures at inlet and outlet of the heat exchanger, and is initialized to 500 °F.

The coolant temperature at inlet of the heat exchanger (T_{ix}) is derived from the output of amplifier 71. It ranges from 0 to 1000 °F, with an initial value of 600 °F. This temperature is the same as the coolant outlet temperature but because of a heat transport delay, a lag of 4 seconds is involved.

The secondary steam temperature (T_s) is provided by the output of 75. It ranges from 0 to 1000 °F, with an initial temperature of 350 °F. Steam temperature is allowed to vary with power output.

The inverse of the reactor period (1/T), obtained from the output of amplifier 7 and has a normalized range of -1.0 to +1.0. At steady state, the reactor period is close to infinity so the inverse period is essentially zero. For transient situations, however, reactivity changes result in finite periods and lead to meter readings, which are always displayed as positive because of meter limitations. In reality, reactor start-up or power-level increases are positive signals, and scram or power-level decrease are negative signals from the amplifier.

The error signal (ε) is provided by amplifier 9, with a range of -200 to +200 °F. The meter displays the variations from 0 to +200 °F when when the reference temperature is decreased. Conversely, if the reference temperature increases, the meter indicates only zero.

The flow rate ($\dot{m}$) is obtained from amplifier 82, which inverts the signal from D/A channel 11. The flow rate value which is stored in the digital computer memory, ranges from 0 to 125% of full flow, and is entered on the digital console by the operator.

The xenon poison (Xe) is provided by amplifier 91 output, with a range from 0 to 1.0. During normal operation, saturated xenon poison level is approximately 0.04; xenon built-up after shutdown may be considerably more and depends on the neutron flux level at the moment of shutdown as well as the time after shutdown. This meter shows xenon built-up after shutdown only if the xenon poison study subroutine is requested.

These various meters serve the purpose of providing a simultaneous display of the response of the simulator to various stimuli which result from adjusting the input parameters on the control section. Slowly varying transient phenomena as well as changes in steady state conditions may also be observed. Precise transient responses of meters 1 to 9 and meter 11 under various operating conditions can be studied on the X-Y plotter as explained in next section.

4.2 Control section

The control section of the panel, shown in Figure 4-2, consists of a group of switches and lights. Reactor operations, selected transient behavior studies of plant output parameters with either one- or six-group delayed neutron approximations, and investigation of simulated accidents are functions provided by this section.

Transient response switches (PW 1-10), located on the upper left-hand of the control panel, include ten interlocked-push-buttons. When it is pressed, each push-button (associated with a light indicator on the plant diagram, with the exception of reactivity) links the corresponding plant output parameter to X-Y plotter, and a permanent record of transient responses is obtained. The assignment of these push-buttons switches are given in Table B-1.

Digital control switches trigger the real-time interrupt services; that is, an action of pushing a switch by the operator results in a command to the digital computer. A particular subroutine, which performs a sequential logical control on the analog computer or up-dates the value stored in the digital computer memory, is executed. When the digital computer is executing that subroutine, a light associated with the subroutine is turned on to serve an indicator of computer status for the operator.

The start switch (S1) places the analog computer to "OP" mode which essentially starts the reactor simulation and X-Y plotter. An orange light (L1) directly above this switch is associated with this subroutine.

The reset switch (S2) repositions all relays and sets all logic signals to low state on the analog computer; it also brings the simulator from "OP" to "IC" mode, to be ready for next study. A green light (L3) directly above this switch will be on when the digital

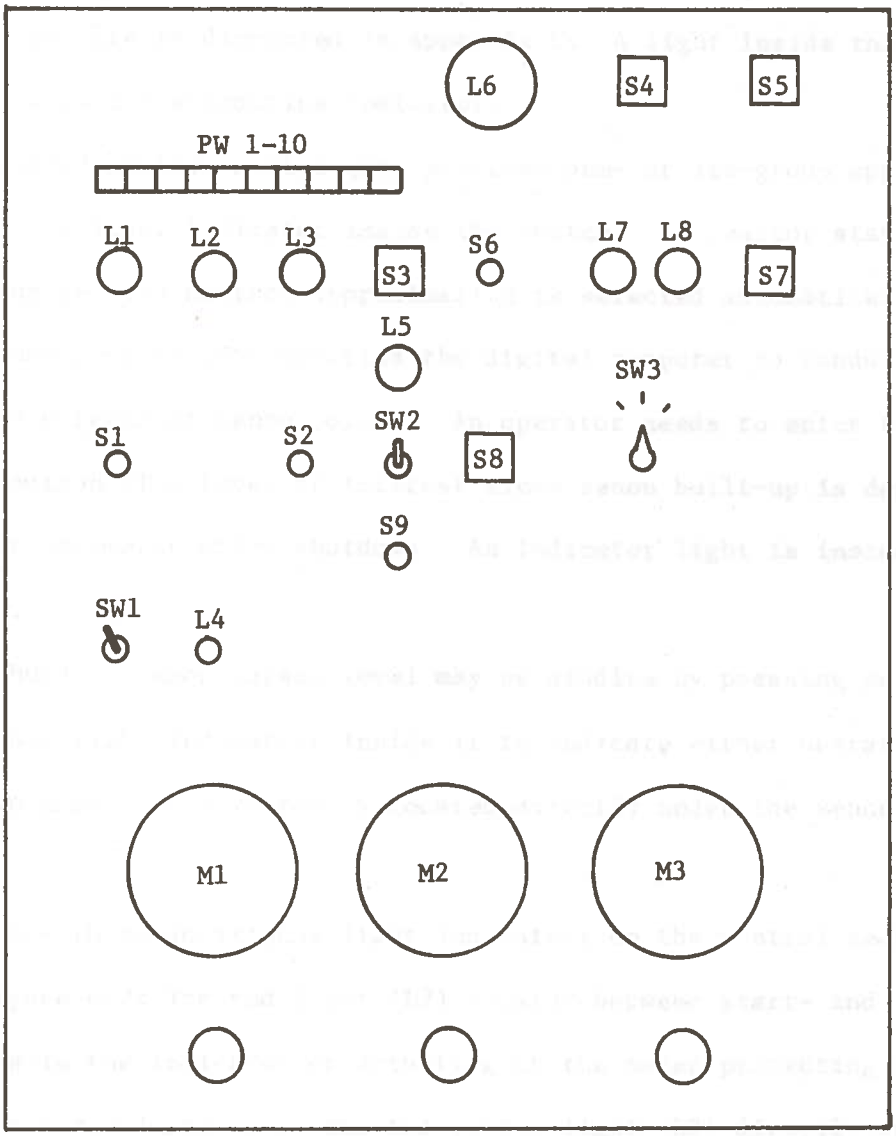


Figure 4-2. Control Layout

computer is serving this subroutine.

The flow rate switch (S3) allows the operator to change the primary coolant flow rate at any time on the digital console. The input format of flow rate is discussed in Appendix C. A light inside this switch serves as the subroutine indicator.

The delayed neutron switch (S4) provides one- or six-group approximations, with a light indicator inside the switch. At reactor start-up, the one-group delayed neutron approximation is selected automatically.

The xenon control (S5) notifies the digital computer to conduct a study of the effects of xenon poison. An operator needs to enter the operating neutron flux level of interest since xenon built-up is dependent on this parameter after shutdown. An indicator light is inside this switch.

Post-shutdown xenon poison level may be studies by pressing switch (S7) which has light indicators inside it to indicate either operation or shut-down mode. This switch is located directly under the xenon switch.

There are three additional light indicators on the control section shown in Figure 4-2: The red light (L2) located between start- and reset-lights is the indicator of actuating of the meter protecting relays; the dark-red light (L7), and the yellow light (L8) directly under the delayed neutron switch are the indicators for one-or six-group delayed neutron approximations respectively.

A switch (S9) controlling step changes in reactivity is located under the flow rate switch and a blue light (L5) indicates input of step change reactivity. Positive or negative 0.0025 step changes in reactivity are provided by positioning a toggle switch (SW2).

A scram condition is indicated by flashing light (L6) and an alarm. This condition may have resulted from the neutron level exceeding 0.95, or from pressing switch (S6). Actuation of this scram system causes immediate and complete insertion of all control rods. This action opens the feedback error signal relay to the control system, and reduces the primary coolant flow rate to its lowest level.

A simulated control system failure may be actuated by pressing switch (S8) which disables the control system by grounding the input to amplifier 45. Thus, control rods are frozen to a position where the control system fails. A light located inside switch (S8) indicates this condition.

The prompt neutron lifetime is selected on switch (SW3), which is located under the delayed neutron light indicators. One of three prompt neutron lifetimes (10^{-5}, 10^{-4}, or 10^{-3}) seconds may be chosen using six group approximation to treat the delayed neutron population.

A panel power switch (SW1) is located on the lower lefthand of control panel. It should be turned on before the hybrid system starts to function, and turned off to release the hybrid program from Sigma 5.

With the above controls, the operator is able to start and to reset the simulator, to investigate the responses of the reactor to abnormal conditions.

4.3 Controllers

Three controls with meter indicators located directly under the control section, are used to vary power demand, reference temperature and throttle opening. By adjusting these input variables with different flow rate, various operating conditions can be simulated, and the responses of the reactor can be studied.

The normalized power demand control (M1) has a range of 0 to 1.0 with an initial value of 0 which must be maintained in order to start the simulator. If amplifier 41 output is 0.1037 on the static check report, then the setting of the normalized power demand control is correct.

The reference temperature (M2) ranges from 0 to 1000 °F, and should be set at 500 °F during normal operation. Fuel temperature can be changed by adjusting the reference temperature after startup.

The steam throttle opening control (M3) regulates the amount of steam admitted to the turbine. Its range is from 0 completely closed, to 1.0 fully open position of the steam throttle valve. This throttle should be kept fully open during normal operation.

4.4 Plant diagram

A schematic diagram of the reactor system, shown in Figure 4-3, serves as a direct visual aid to the operator and to observers. When the transient response switch is pressed, a flashing light associated with its proper location on the diagram indicates that this parameter is being sent to the X-Y plotter. The three lights that constantly stay on indicate the flow rate, the reference temperature, and the secondary loop steam throttle opening.

4.5 Digital program

The tasks performed by the digital computer in the control section are directed by digital programs which are part of the hybrid package. Appendix D-1 presents the main digital program flow which controls the operations of the hybrid computer through appropriate digital and linkage operations:

1. It sets the servo-pot coefficients, the positions of the

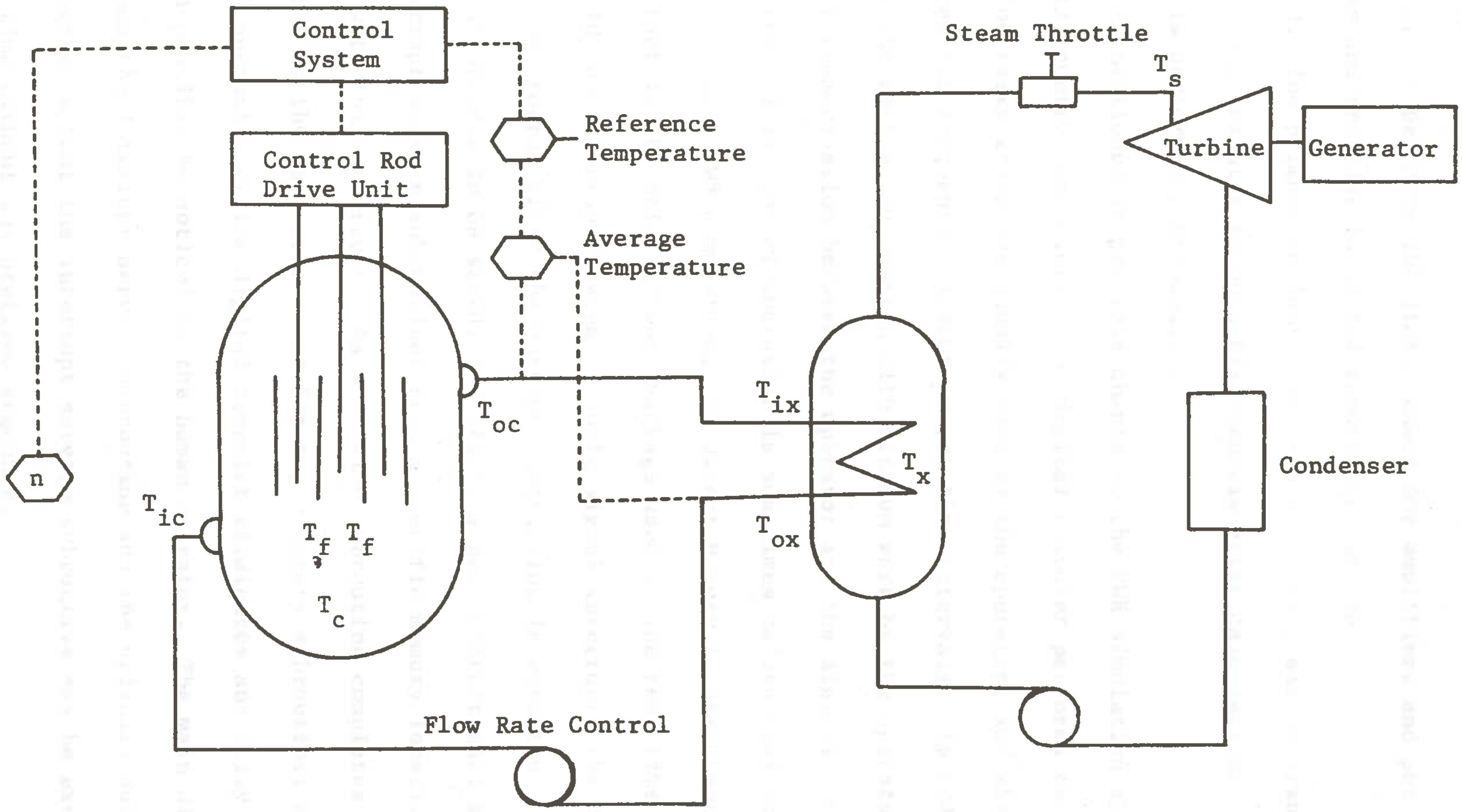


Figure 4-3. Reactor Plant Diagram

function relays and the logic states of each control line during preliminary setup.

2. It performs the static check for amplifiers and pot setting checks and provides tabulated reports for errors.

3. The primary coolant flow rate is stored, and is transmitted to the analog computer through D/A channels after calculations. This process is performed continuously.

As mentioned in previous chapters, the PWR simulation system is a digital-control structure. The digital computer performs certain routine tasks which are usually done by the operator, and which must be carried out frequently without preset time intervals. In order to achieve the partial automation with minimum work by the operator, a direct communication between the operator and the digital computer is required. This type of operation is sometimes called real-time operation. In this PWR simulation, the Direct Memory Access Channel (DMAC) interrupt is the main software package used in the real-time operation.

In an interrupt system, a logic signal interrupts the digital computer program after the current instruction is executed, causes the current program to be saved, and starts a new instructional sequence (interrupt service subroutine) from a specific memory location associated with that interrupt. As a service subroutine completes its job, it returns to the main program as for any ordinary subroutine; and the high-speed operation of the digital computer eliminates any delay which could possibly be noticed by the human operator. The main difference between the interrupt service subroutine and the ordinary subroutine in a program is that the interrupt service subroutine may be executed in real time without any prefixed sequence.

Interrupt operation would be simple if there were only one possible source of interrupts; but this is not true in practice. Digital computer usually has various levels of interrupts, which act as watchdogs for its operational status. Such details as power, digital clock, I/0 devices, etc., are internally generated as part of the digital computer hardware and software package. A digital computer usually also provides several groups of external and general purpose interrupts which can be controlled by programs. In order to execute these internal and external interrupts properly, a practical interrupt system, therefore, must have the following features:

1. The ability to "trap" the program in different memory locations corresponding to the specific interrupt, and
2. The ability to execute the interrupt service with priorities in case of simultaneous or successive demands for the services. In a priority interrupt system, a logic signal can cause an interrupt if, and only if, the interrupt is enabled by the digital computer and no higher priority interrupt is being served.[6]

In the XDS Sigma 5 digital computer, the first group of external interrupts, which has the highest priority among other groups of external interrupts, is incorporated with the EAI analog computer. Six external interrupts are provided, and five of these interrupts are connected to service subroutines for PWR simulation.

Interrupts as well as other logic commands respond to logic signals which are basically step inputs of 5 volts DC. When a logic signal is high, it stays at 5 volts, triggering the interrupt of other logic components; and when the logic signal is low, it has a zero voltage.

The digital computer reads status of these logic signals through the interface to perform programmable commands.

Subroutine "START", which essentially sets the analog computer to operate with a series of logical controls, is outlined in Appendix D-2. Because this simulation is designed to demonstrate reactor system responses to various disturbances to the steady state, calculations of pot coefficients and outputs of amplifiers of the analog computer are based on the steady-state condition. In order to start this PWR simulation with reasonably balanced amplifiers, the control system is not implemented when the analog computer is placed in "OP" mode. A 10-second delay is required before the error feedback signal are admitted to the proportional-plus-integral-controller; then, after an additional 20-second delay, the control system is enabled. Relays 9 and 64, which admit the error signal and control system signal, respectively, are excited by monostable timers. When the analog computer is placed in "OP" mode, the X-Y plotter is also started. Since the simulator reaches an operable state after 30 seconds delay, the plotter pen is placed down just before relay 64 is closed to provide a transient study at reactor start-up. The above actions are executed by hybrid subroutines with setting or resetting control lines, and a logic diagram as shown in Figure 4-4. This interrupt service has highest priority level of X'61'.

The service subroutine "RESET" places the PWR simulation in its initial state by setting the analog computer in the "IC" mode and resetting all logic components, including monostable timers, functional relays, and the plotter. This service is required for terminating transient studies at start-up and during any simulated accident, such as

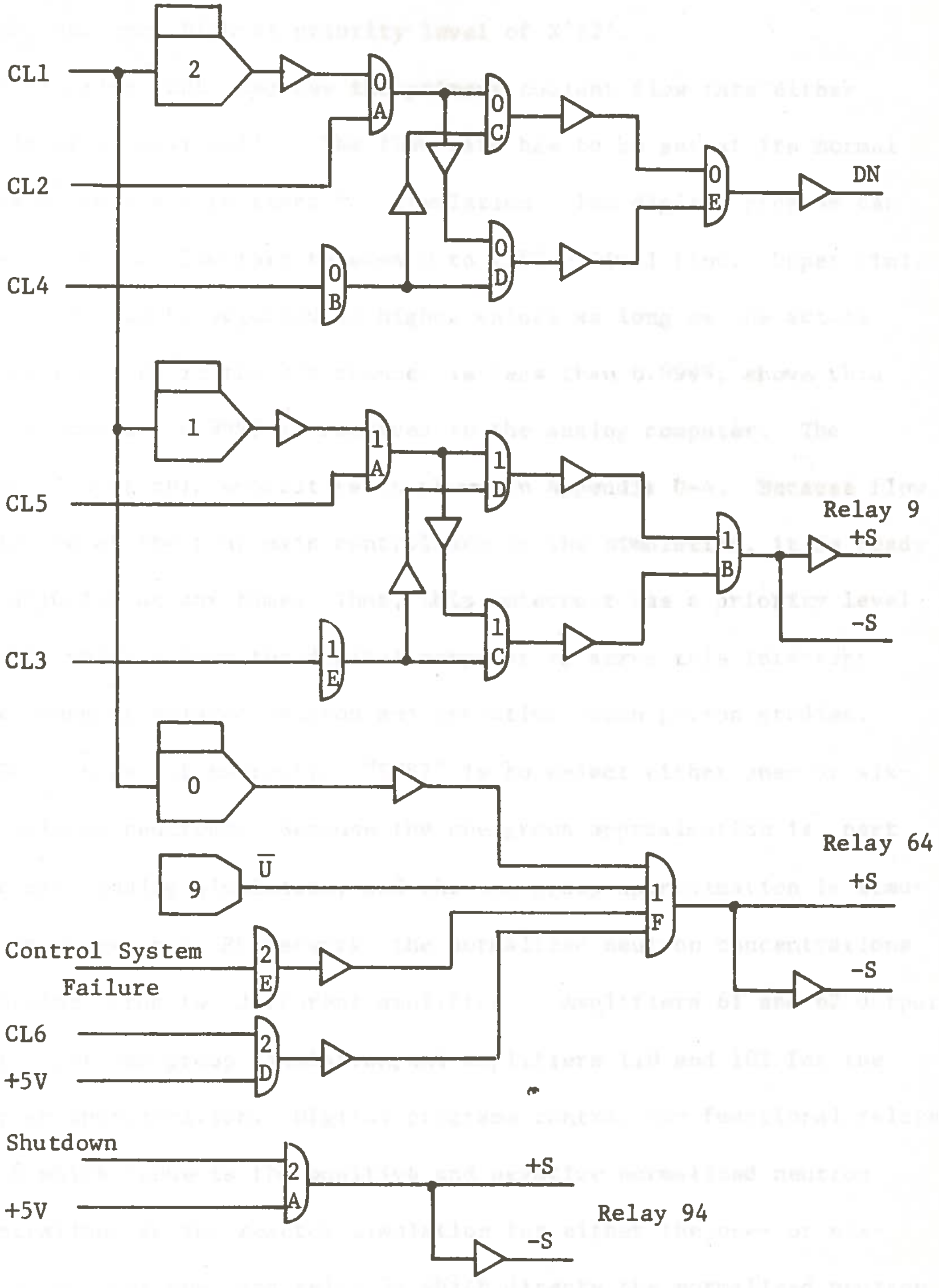


Figure 4-4. Logic Diagram

loss of primary coolant flow, to allow overloaded amplifiers to reset. A program flow of this subroutine is shown in Appendix D-3. This interrupt has the next highest priority level of X'62'.

Subroutine "SUB" updates the primary coolant flow rate either manually or automatically. The flow rate has to be set at its normal full valve in order to start the simulation. The digital program can be used to set a flow rate between 0 to 125% of full flow. Upper limit of flow rate can be adjusted to higher values as long as the actual value transmitted in the D/A channel is less than 0.9999; above this limit, a constant 0.9999 is received in the analog computer. The program flow of this subroutine is shown in Appendix D-4. Because flow rate is one of the four main controllers in the simulation, it is ready to be adjusted at any time. Thus, this interrupt has a priority level of X'63', which allows the digital computer to serve this interrupt before changing delayed neutron and executing xenon poison studies.

The purpose of subroutine "SUB2" is to select either one- or six-group delayed neutrons. Because the one-group approximation is part of the main analog simulation, and the six-group approximation is simulated on an external RC network, the normalized neutron concentrations are obtained from two different amplifier. Amplifiers 61 and 62 outputs are used for one-group simulation, and amplifiers 110 and 102 for the six-group approximation. Digital programs control two functional relays: relay 4 which connects the positive and negative normalized neutron concentrations to the reactor simulation for either the one- or six-group approximations, and relay 34 which directs the normalized neutron concentration to the plotter and amplifier 68 output to RC network if the six-groups are used. This program flow is shown in Appendix D-5.

This interrupt has a priority level of X'64'.

Xenon poison studies are performed by subroutine "Xenon." This algorithm provides different levels of neutron flux for the build-up of Xe-135 after shutdown. Various flux levels are simulated by setting pots 60, 91 and 93 through the digital computer controlled program. Because xenon poison has a different time scale factor than normal operations, the simulation is separated from the main reactor circuit, and the xenon poison signal is directed to the plotter automatically through a relay which is controlled by the digital program after the neutron flux is selected. The digital program also places the plotter pen down without time delay because the initial values are all zero for these amplifiers. The program flow is shown in Appendix D-6. This interrupt has the lowest priority of X'65'.

In addition to the above five real-time interrupt services, a data-logging subroutine "SSVP" (which is not part of interrupt system) is provided. The operator can obtain a formatted report of key plant parameters at any time during reactor operation. This feature may be further expanded to display these parameters on a monitor scope with incorporation of a real-time interrupt in any given time interval (e.g, every second). Currently, triggering this subroutine is done through a sense line (shown in Appendix D-7).

Interrupt services perform the necessary digital and data manipulations required to achieve a set of control tasks on the analog computer. Each interrupt service with its associate digital program can be further expanded to accomplish more control tasks which may improve the performance of the simulation.

4.6 Description of general operation

In steady state, responses of PWR simulation under various simulated conditions are achieved by adjusting four controllers: the primary coolant flow rate, the secondary steam throttle opening, the reference temperature, and the normalized power demand signal. All controllers are manually operated, with the exception of flow rate, which has an additional automatic mode.

The primary coolant flow rate is set at 100% of full flow during simulation preliminary set up, and is automatically reduced to 50% of full flow when the reactor scrams. In manual control, the interrupt service is triggered and the desired flow rate is entered by the operator through the digital console. This type of control system is "base-loaded," which means that the generated power of the reactor is constant unless the flow rate is changed while holding other input parameters constant. Power extracted from the reactor core depends on heat removed by the coolant to the heat exchanger. At a constant flow rate, the power is inversely proportional to the coolant temperature at the reactor vessel inlet. An increase of flow rate causes a rise in inlet coolant temperature and a drop in outlet coolant temperature. Consequently, the total power output increases because the higher flow rate provides an increase of heat extracted from the reactor core. The purpose of rate control, which is one of the PWR simulation response studies, is to set the optimum relation between the flow rate, temperature difference between outlet and inlet of the reactor vessel, and the net power output. Obviously, it is not economical or desirable to maintain a given low power demand with high flow rate which increases the inplant loss. Conversely, a low flow rate at high power demand cannot provide enough heat to the steam generators, and the control system would eventually shut down the reactor.

This PWR simulation utilizes the constant-average-coolant-temperature control programs in the primary loop. At steady state, secondary steam temperature and pressure are allowed to vary without automatic co control because of the limited number of analog components which are available. The secondary steam throttle regulates the amount of steam flow, temperature, and pressure. Performance of the turbine depends on the available enthalpy in the steam, and the output power of generator is directly proportional to the torque input, provided by the turbine, under a constant speed which is required to maintain a constant frequency.[7] If the steam throttle is gradually closed down, steam flow decreases and less steam is admitted to the turbine, resulting in a reduction of turbine output torque delivered to the generator. Then the slow steam flow also causes the average temperature of the heat exchanger to increase, and the constant-average-coolant temperature control system responds to the large temperature difference by inserting control rods into the core. The ultimate effect is to reduce the neutron population (which is also directly related to the power output). Since the control system limits the neutron population at lower settings of the steam throttle opening, the reactor cannot be started with a closed steam throttle. Hence, the recommended throttle setting is full open for reactor start-up.

Power produced by the reactor is directly proportional to the average temperature in this control system, as stated above. The reference temperature controller sets the operating temperature for the reactor through the control system. That is, higher reference temperatures are associated with higher fuel temperatures. Consequently, more heat can be extracted from fuel by the coolant and carried to the heat exchanger to generate steam. Closing the steam throttle results in a decrease in neutron population. This increased reference temperature causes neutron population to settle at a higher level. With the present control system design, it is not advisable to operate the simulator at high reference temperatures during start-up because neutron multiplication increases too rapidly. Conversely, the control system prevents the neutron level from increasing at very low reference temperatures. Reference temperature settings between 450 °F to 550°F are recommended for start-up transient studies. When the simulator reaches its steady state, this reference temperature may be set higher as long as the neutron level is below the maximum allowable value of 95% of full scale.

The normalized power demand signal controller acts as a manual power "booster"; that is, an increase in this controller results in a sudden rise of neutron population, fuel temperature, and a withdrawal of control rods. However, the control system eventually brings the simulator back to its original state. Conversely, this controller also causes a drastic reduction in neutron population for a short period during reactor operation. This controller may be used with other controllers to prevent the simulation from reaching scram conditions by injecting a function counteracting neutron multiplication during transients. After the simulator reaches steady state, this controller may be raised by steps to any desirable value as long as the normalized neutron level remains less than 95% of full scale. It is recommended that this controller be set at 0.5 during steady state operation.

Simulated reactor accident studies may include total loss of the primary coolant flow and control system failure. These studies should conducted at steady state levels rather than during reactor start-up periods.

A loss of coolant accident is initiated by the operator triggering the flow rate interrupt service by entering zero on the digital console. Consequently, the neutron population gradually decreases to its minimum value as the control system responds by inserting control rods. Coolant temperature at the outlet of the reactor rises to very high levels and the inlet coolant temperature decreases to very low value. These actions result from the linearized mathematical model used with this particular control system. The simulation must then be reset because of a number of amplifiers will be overloaded.

The control system failure demonstrates the events due to a malfunctioning of the control rod drive unit. When this simulated accident occurs, the control rods remain in a fixed position, and the neutron level also remains at a fixed value. The system must be reset since the large accumulated error signal causes overloading of amplifiers.

The scram or reactor protection system is actuated either automatically or manually. This system monitors the neutron concentration and if the normalized neutron concentration is above 0.95, a scram condition is reached and the control system is disabled with a large negative reactivity feedback. After a manual scram, the primary coolant flow is reduced to 10% of its normal value, and an audible alarm and a flashing red light on the panel will be actuated. Sometimes a scram condition cannot be cleared instantly by resetting the simulator. The operator must allow the system to recover from amplifiers overloading for approximately 5 minutes before it can be reset.

CHAPTER FIVE

TYPICAL SIMULATION RESULTS

Typical responses of this PWR simulator for various disturbances and inputs, either at steady state or at start-up, are shown in the curves in this chapter. These curves are plotted while one input parameter is varying and the others are set to designed steady-state values. That is, if the reference temperature is changed, the flow rate is set at 100% of full flow, the steam throttle opening is 1.0, and the normalized power demand signal is zero. If the steam throttle is gradually opened, the reference temperature is set at 500 °F, the flow rate is set at 100% of full flow, and the power demand signal is zero. The curves indicate the system responses using six groups of delayed neutrons unless otherwise stated. The actual values of these curves, in different computer runs, have slight off-set which result from the accumulated error of the analog computer components such as setting of servo pots, of the input parameters, and electronic noise. Thus, all curves have been normalized to their calculated steady-state values in order to be consistent. Carefully investigating the error reports, provided by the digital printer, of static check with necessary adjustments may reduce these off-set.

The first set of curves, illustrated in Figures 5-1 through 5-5, show the behavior of the system for various start-up conditions. Since this simulation was designed to demonstrate the system responses for various disturbances in steady-state operation, these curves are relative, not absolute, representations of possible system behavior at start-up for

Normalized Neutron Concentration for Various Reference Temperatures
at Start-up (One Group)

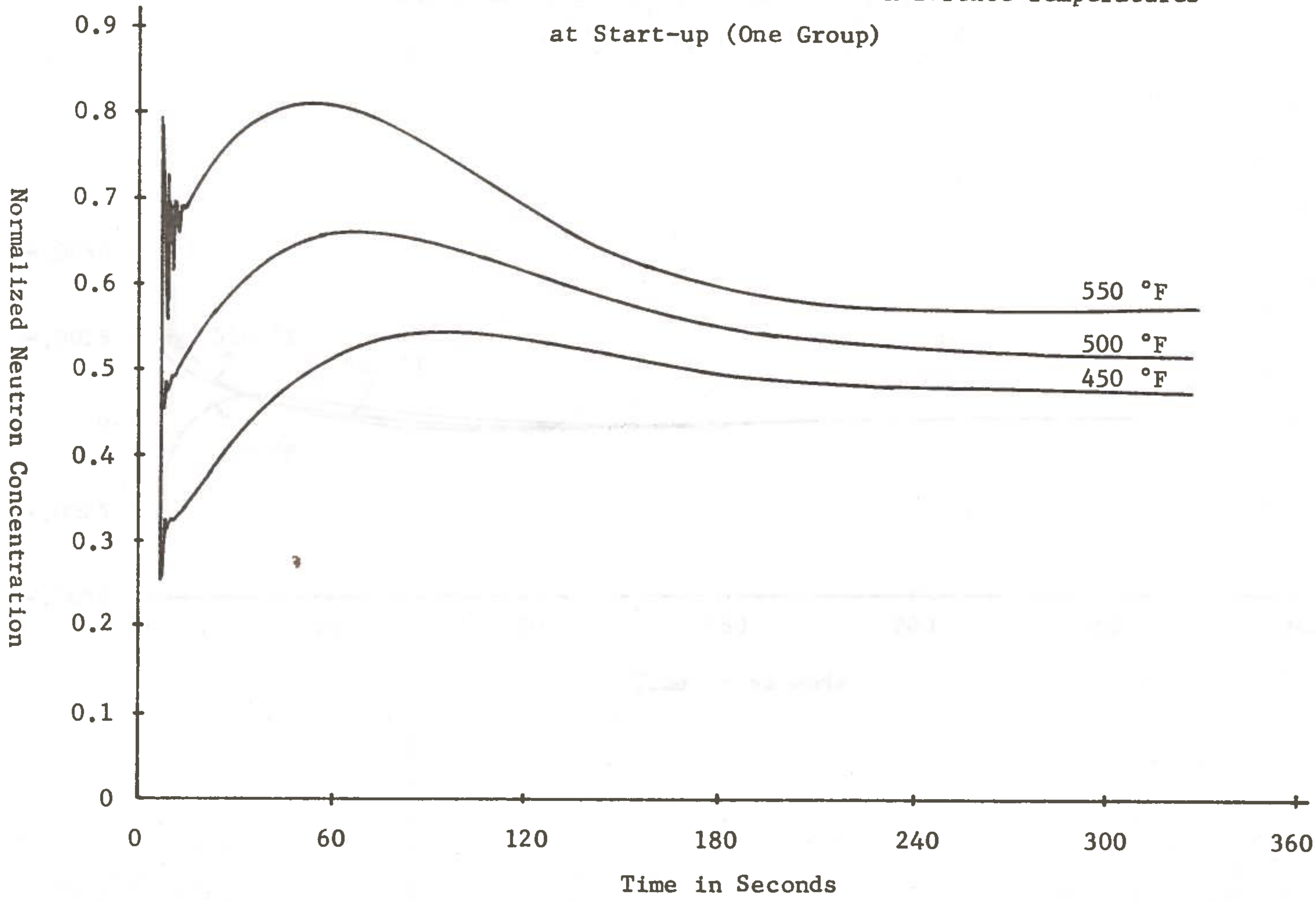


Figure 5-1.

Reactivity for Various Reference Temperatures
at Start-up (One Group)

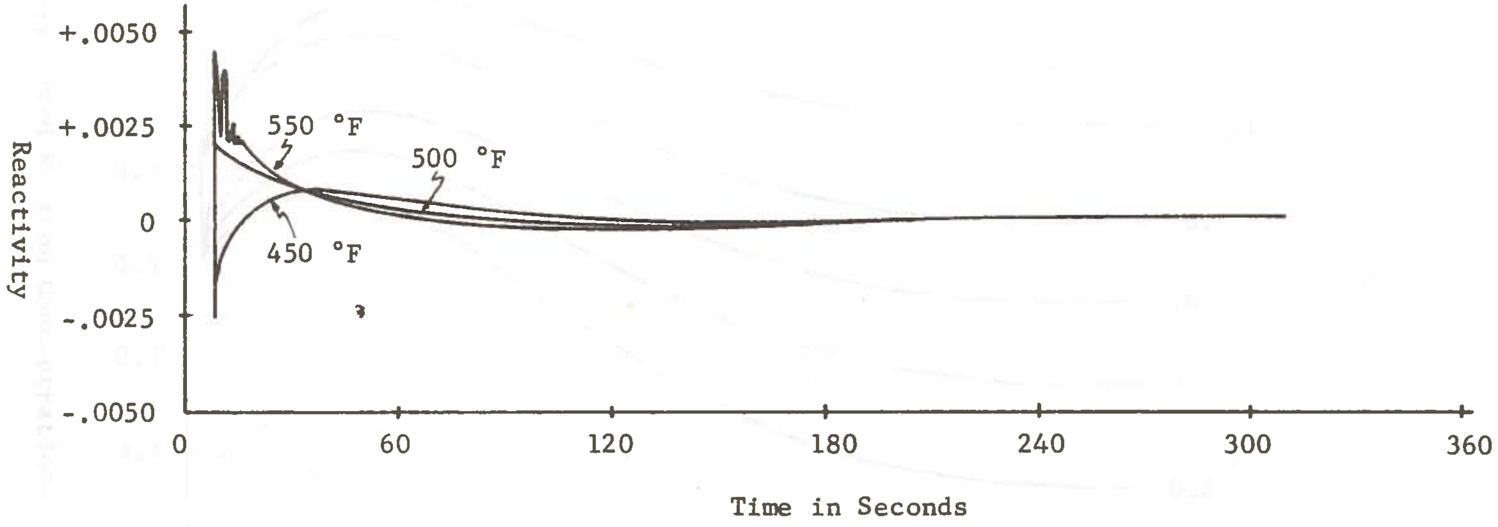


Figure 5-2.

Normalized Neutron Concentration for Various Throttle Openings
at Start-up (One Group)

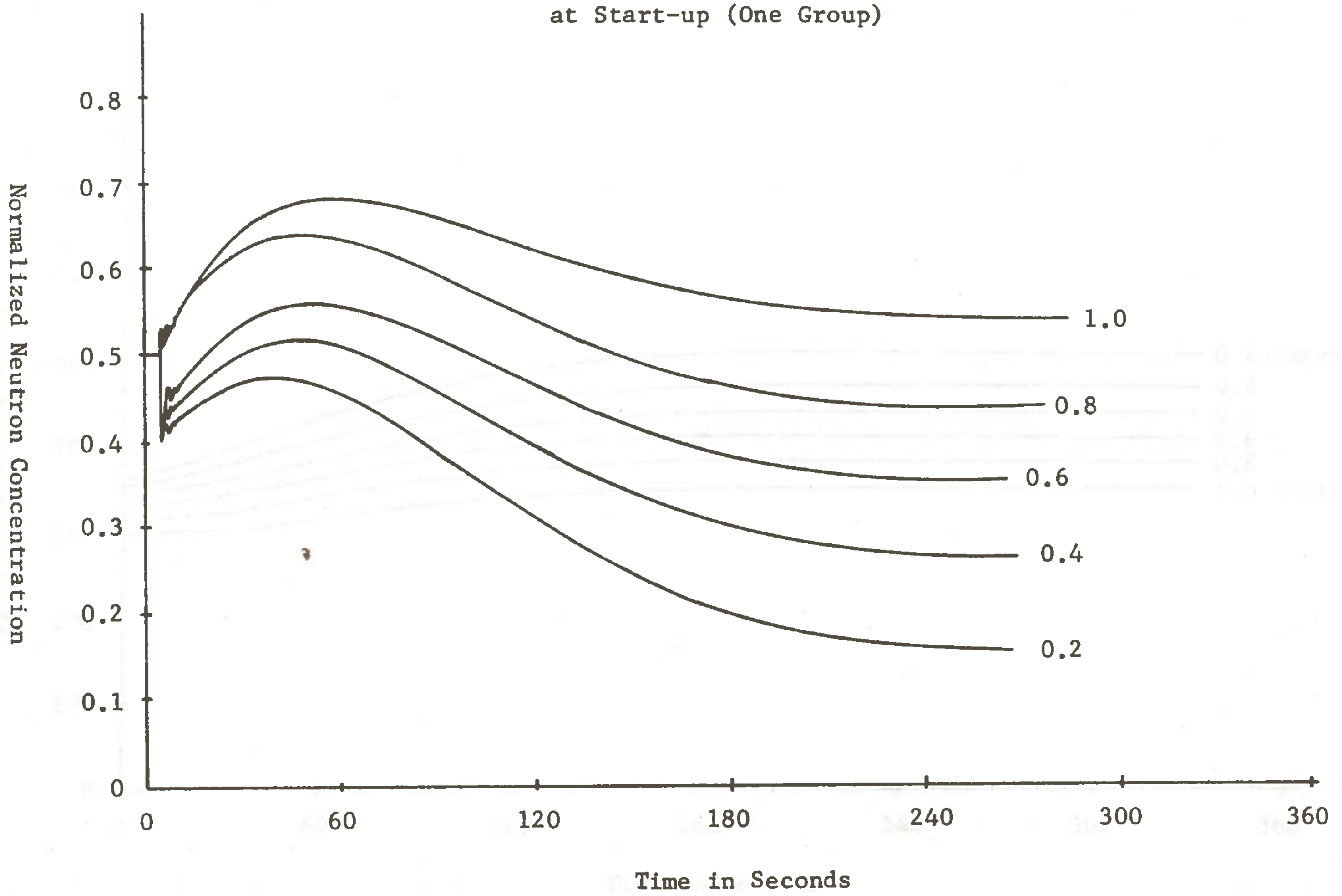


Figure 5-3.

Steam Temperature for Various Throttle Openings
at Start-up (One Group)

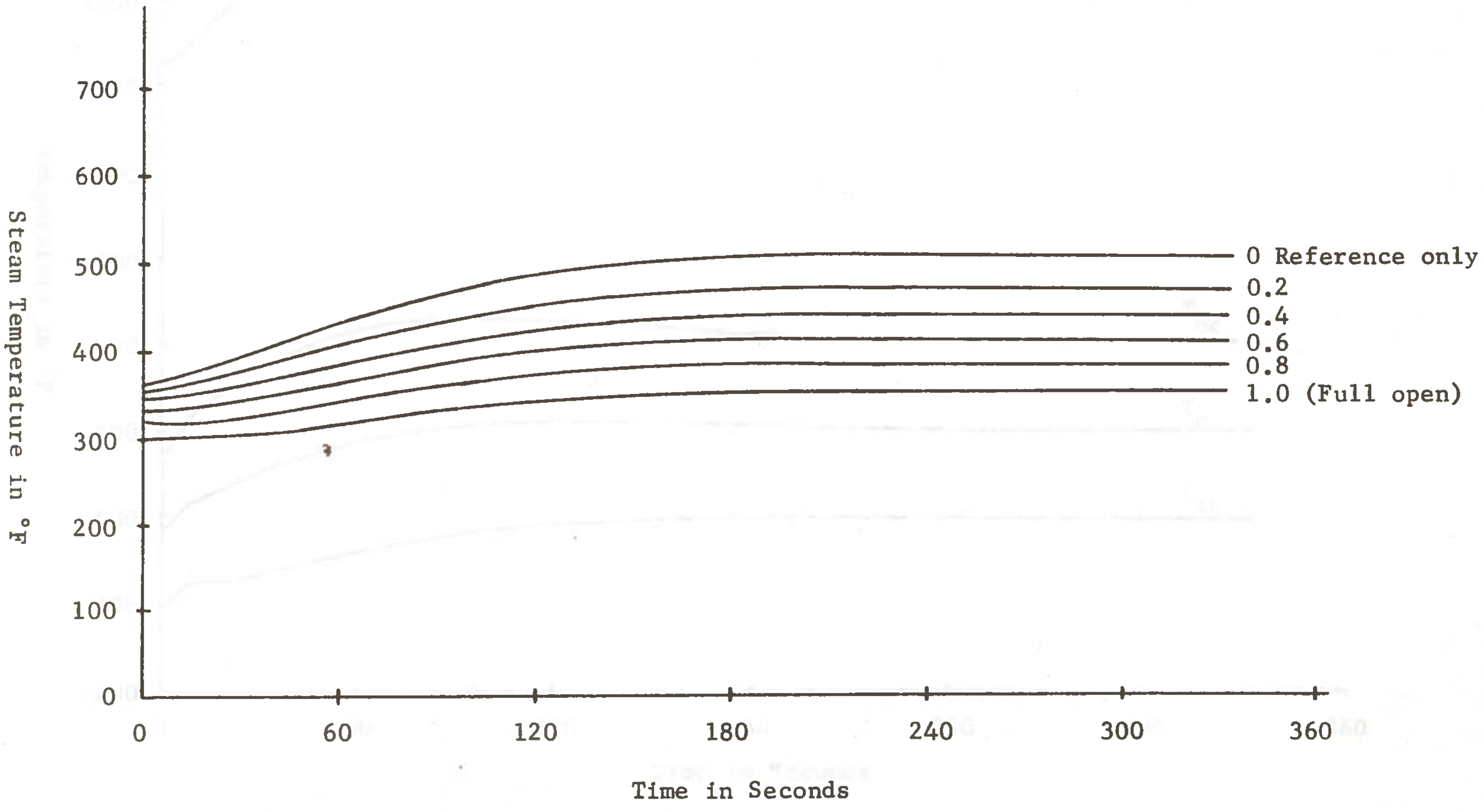


Figure 5-4.

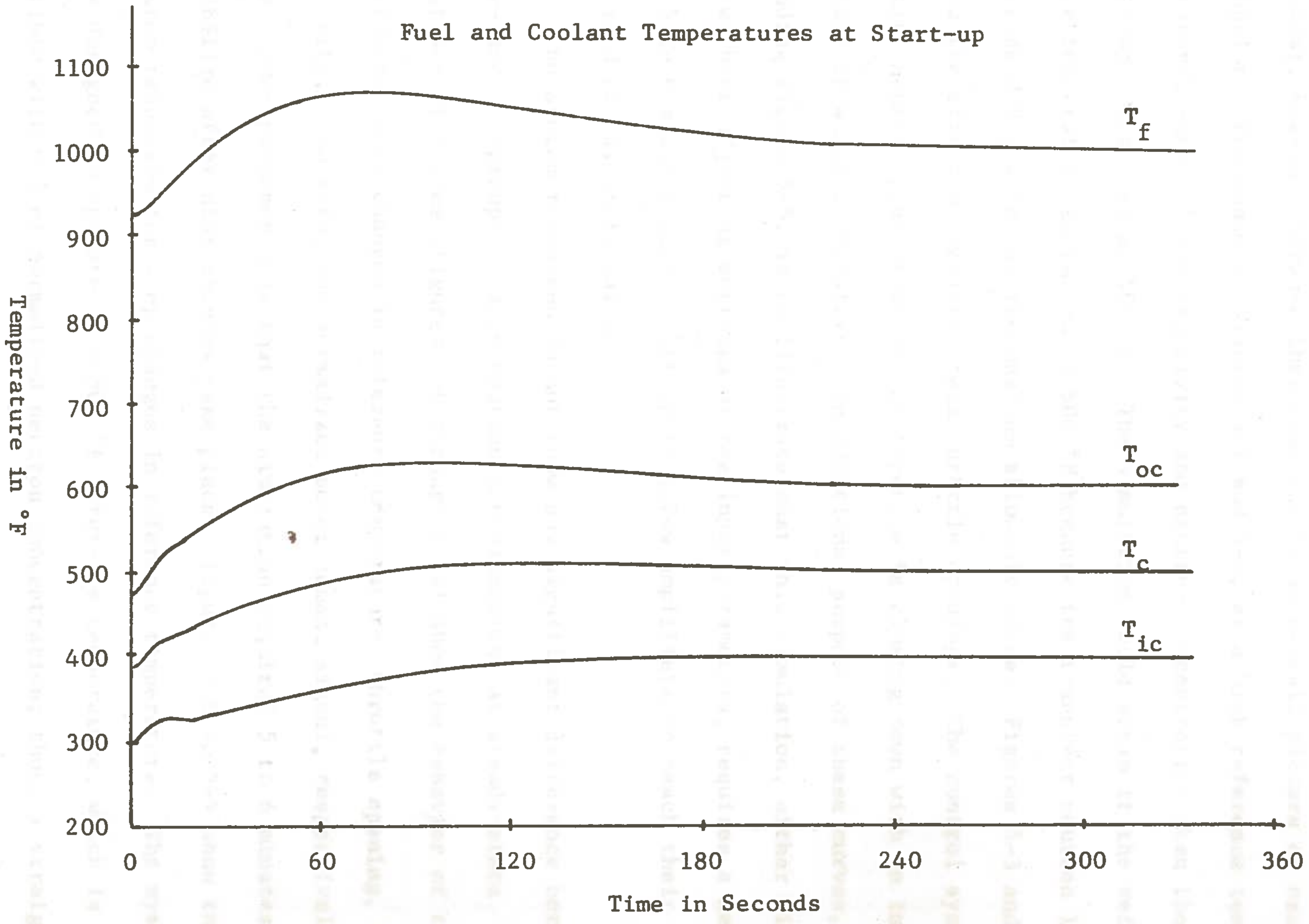

Fuel and Coolant Temperatures at Start-up
T_f
T_{oc}
T_c
T_{ic}
Temperature in °F
1100
1000
900
800
700
600
500
400
300
200
0
60
120
180
240
300
360
Time in Seconds

Figure 5-5.

a particular implementation of the control system discussed in Chapter Four. If the timing of implementing the control system is changed, different curves will be obtained. The general shape of these curves are similar, however, because they demonstrate an overall picture of neutron behavior. For example, Figures 5-1 and 5-2, at a high reference temperature, show a large reactivity and neutron concentration than those corresponding ones at 500 °F. The simulation would scram if the reference temperature is raised to 600 °F because the transient neutron level exceeds 0.95, which is the maximum allowable value. Figures 5-3 and 5-4 show the effect of various steam throttle openings. The control system limits neutron generation as the throttle is closing down with an increase in steam temperature. An additional purpose of these curves, including Figure 5-5, is to illustrate that this simulation, either with or without adjusting settings of the input parameters, requires a delay of 5 to 6 minutes after start-up to allow amplifiers to reach their calculated steady-state values.

The system responses do not show any significant difference between one- and six-groups delayed neutron approximations at steady-state. The next set of curves (Figures 5-6 through 5-14) show the behavior of the system for step changes in reference temperature, throttle opening, reactivity, flow rate, and normalized power demand signal, respectively. One common phenomenon is that the simulation required 5 to 6 minutes to stabilize after disturbances take place. Figures 5-6 to 5-9 show the system responses for step changes in reference temperature. The system was designed to operate at a 500 °F reference temperature, which is compatible with 0.5 of normalized neutron concentration; thus, a straight line was drawn at 0.5, as it is shown in Figure 5-6. It is observed that

Normalized Neutron Concentration for Step Changes
in Reference Temperature at Steady-State

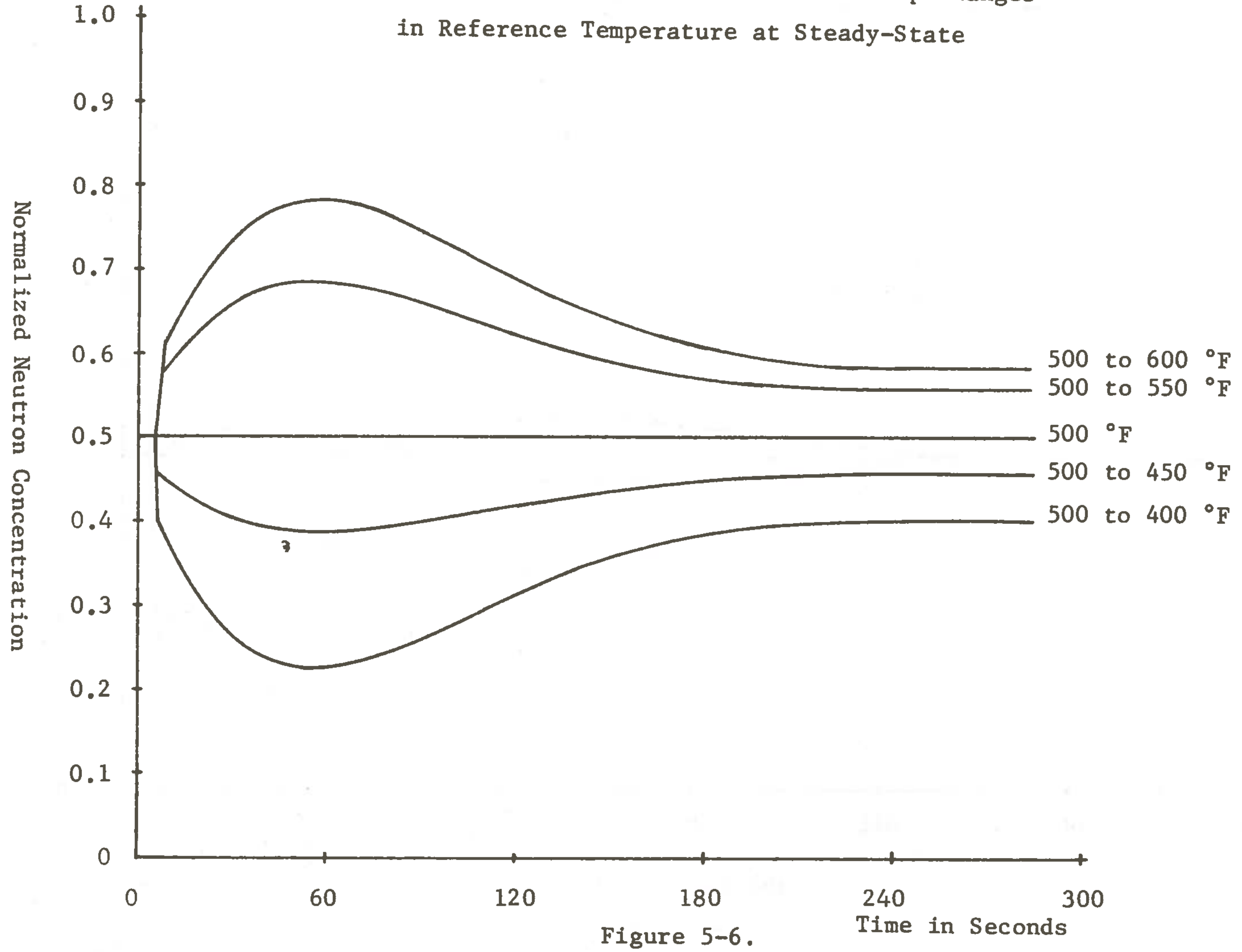


Figure 5-6.

Reactivity for Step Changes in Reference Temperature at Steady-State

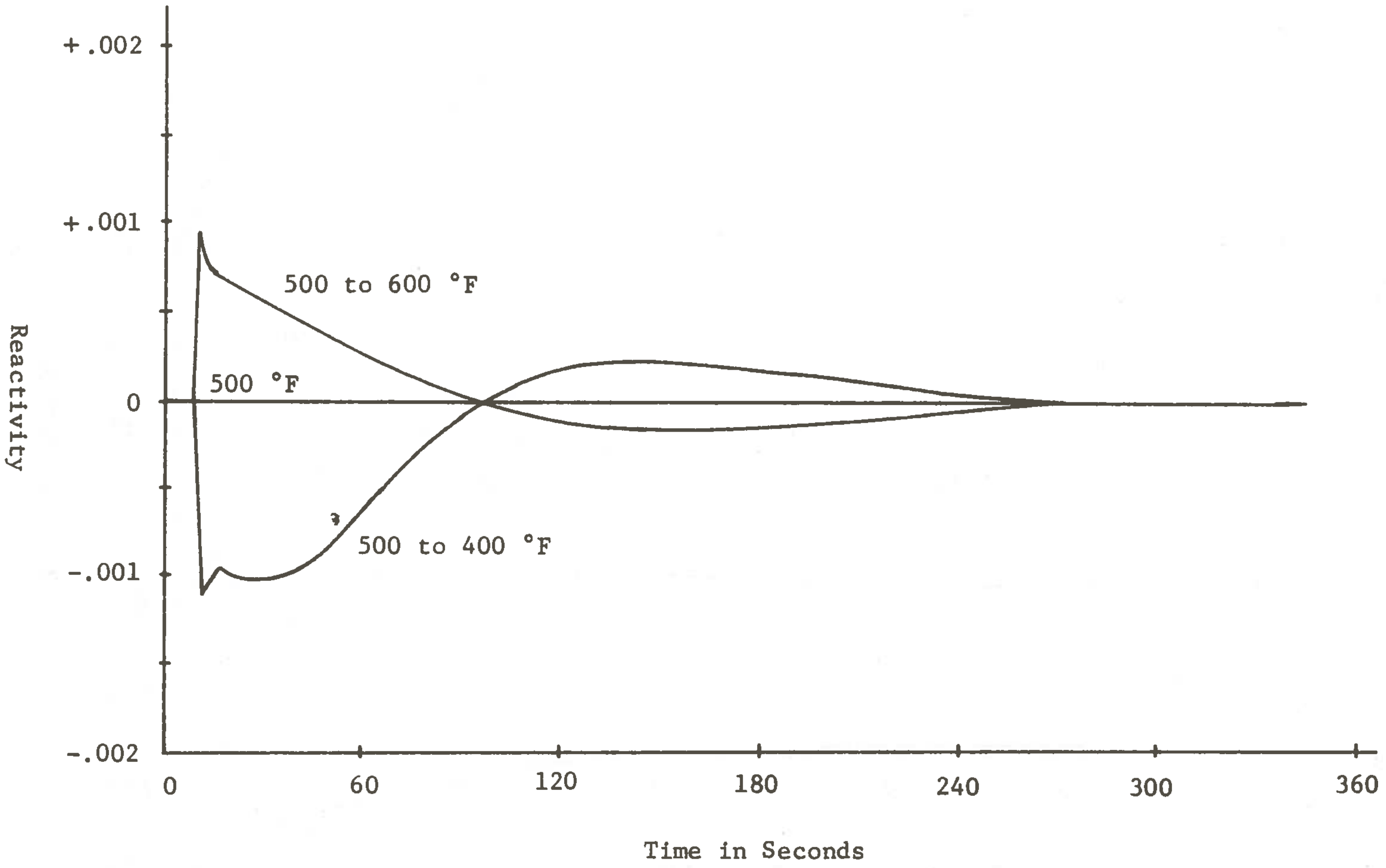


Figure 5-7.

Responses for Step Increases in Reference Temperature
from 500 to 600 °F at Steady-State

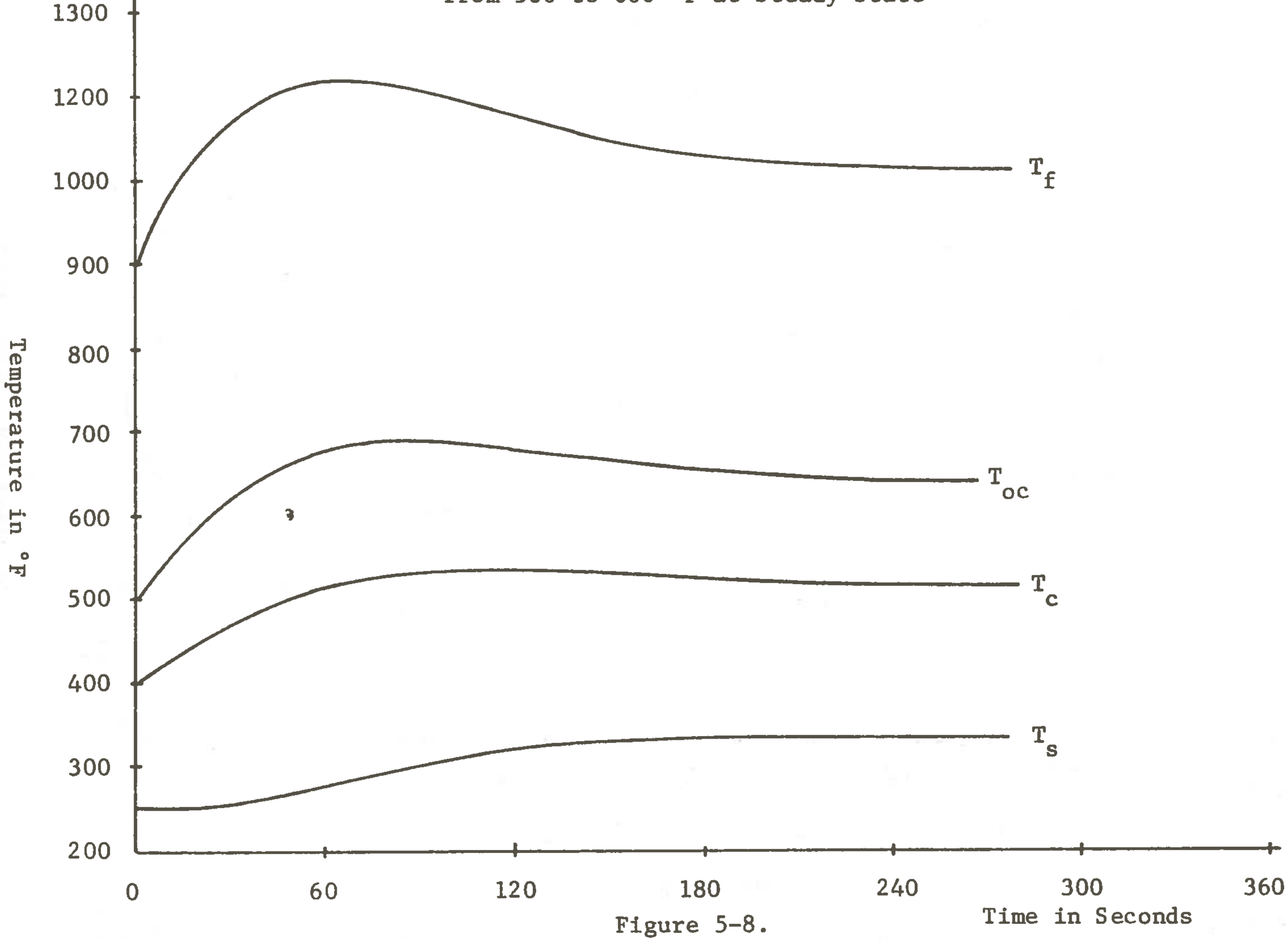
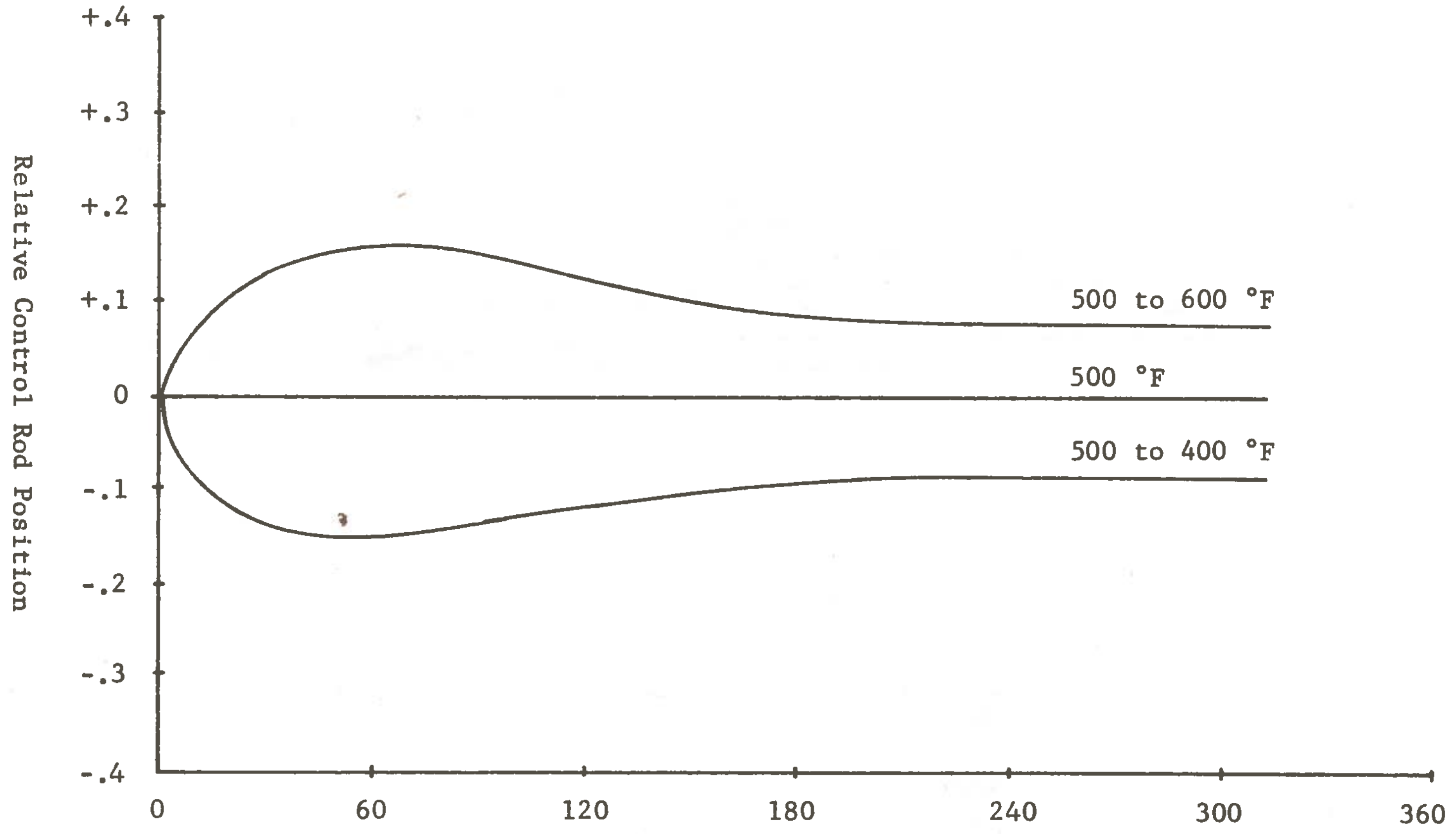


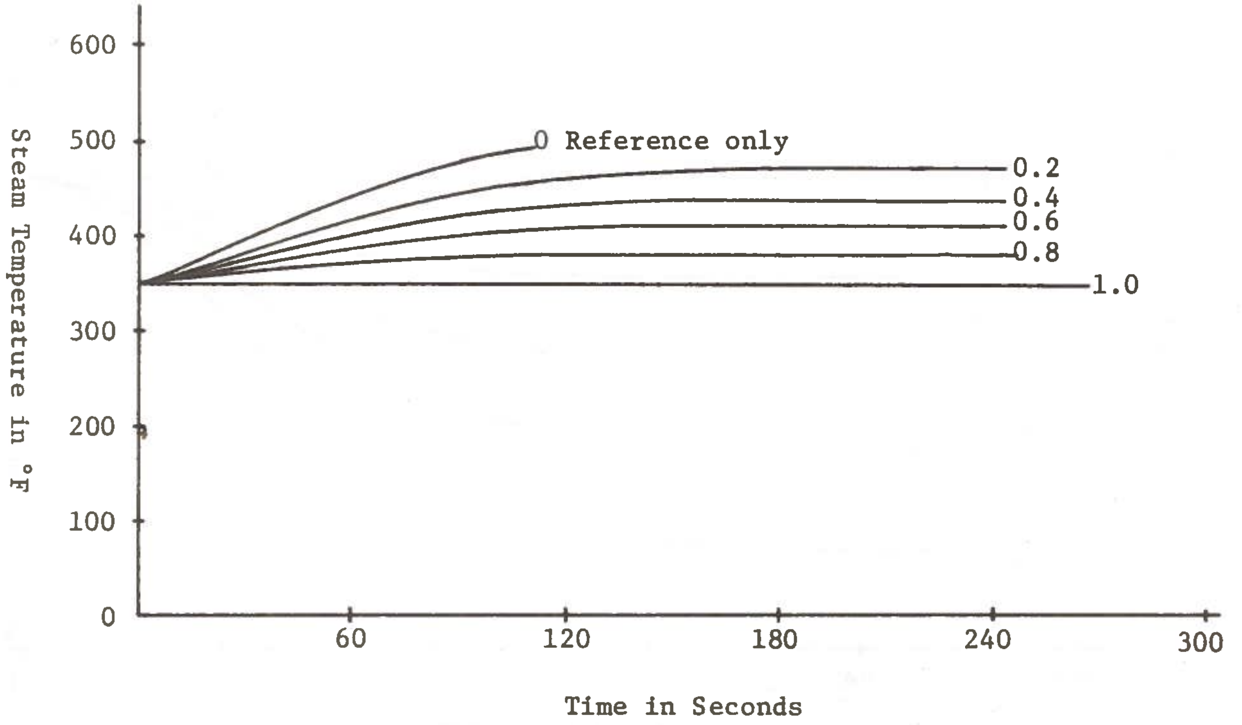
Figure 5-8.

Relative Control Rod Position for Step Changes
in Reference Temperature at Steady-State



Time in Seconds

Figure 5-9.



Steam Temperature for Various Throttle Openings at Steady-State

Figure 5-10.

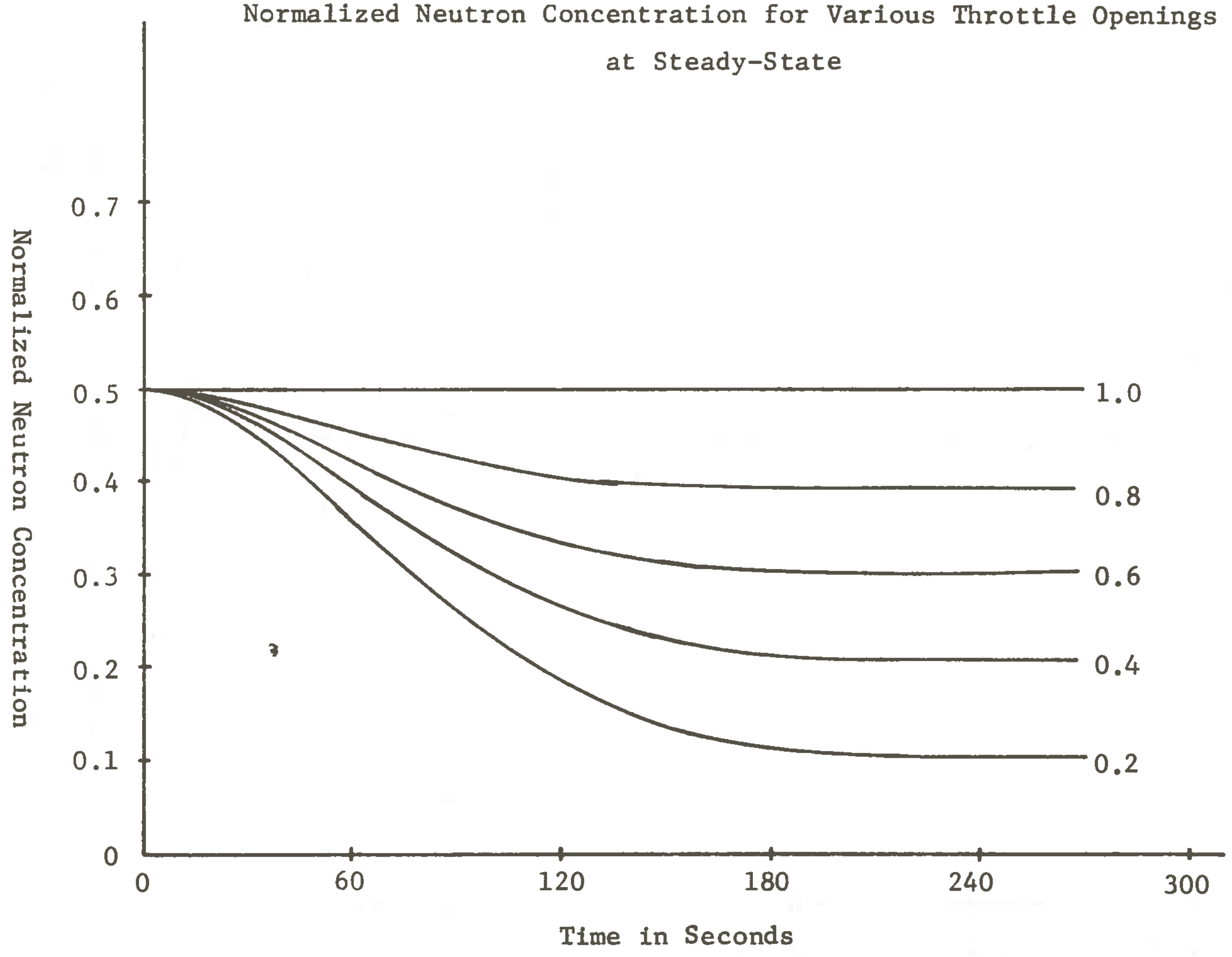
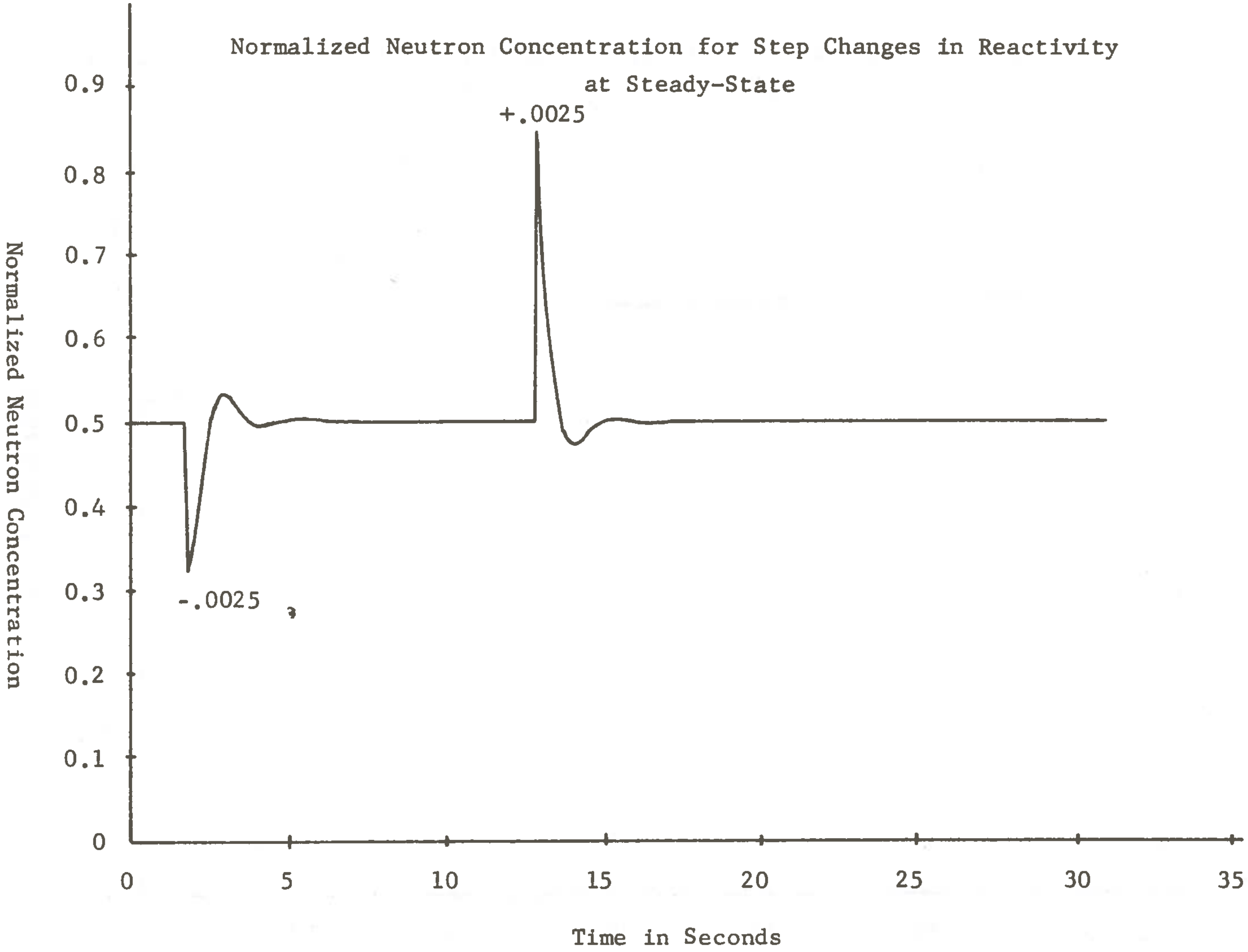
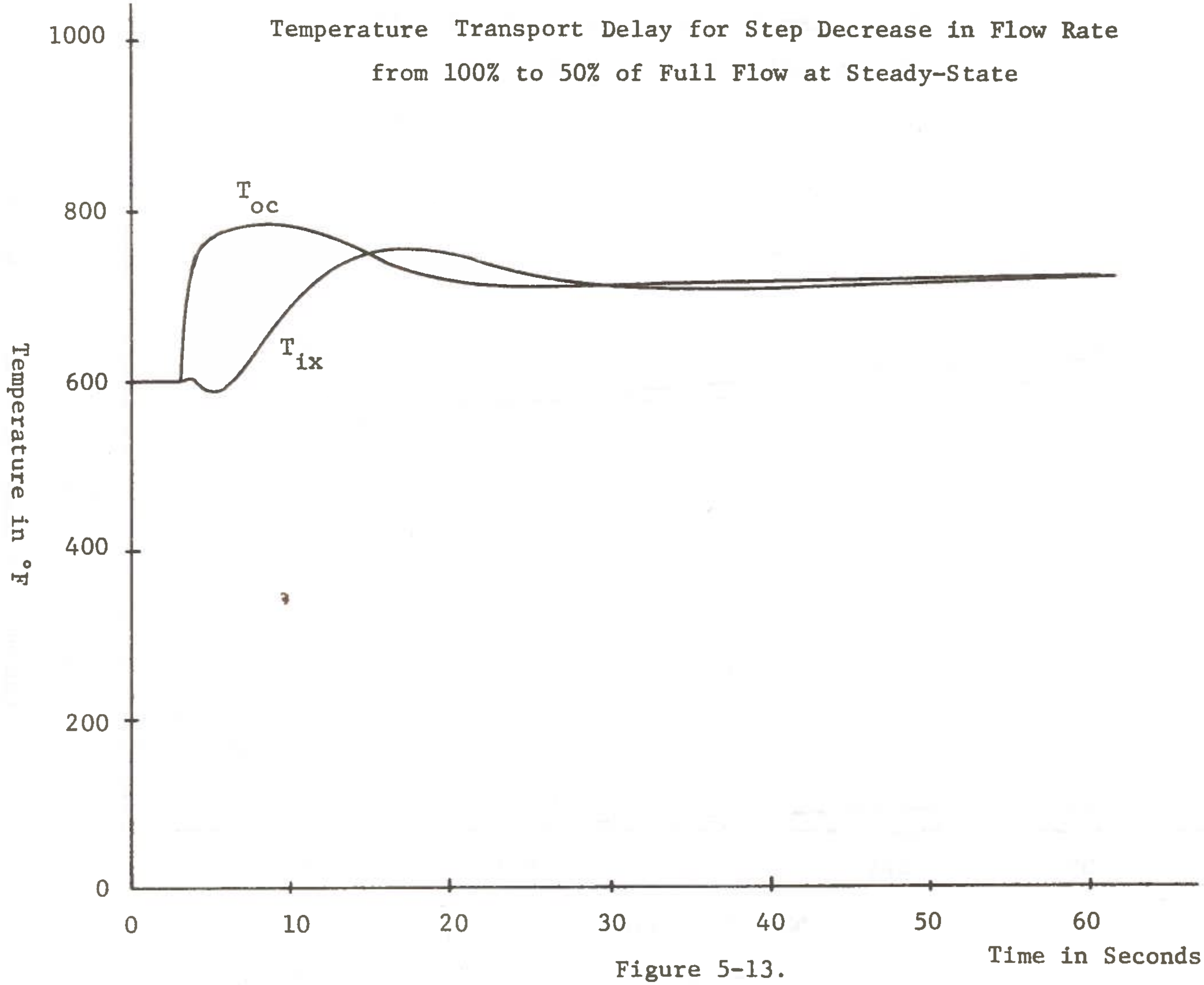

Normalized Neutron Concentration for Various Throttle Openings at Steady-State

Figure 5-11.



Normalized Neutron Concentration for Step Changes in Reactivity at Steady-State

Figure 5-12.



Temperature Transport Delay for Step Decrease in Flow Rate from 100% to 50% of Full Flow at Steady-State

Figure 5-13.

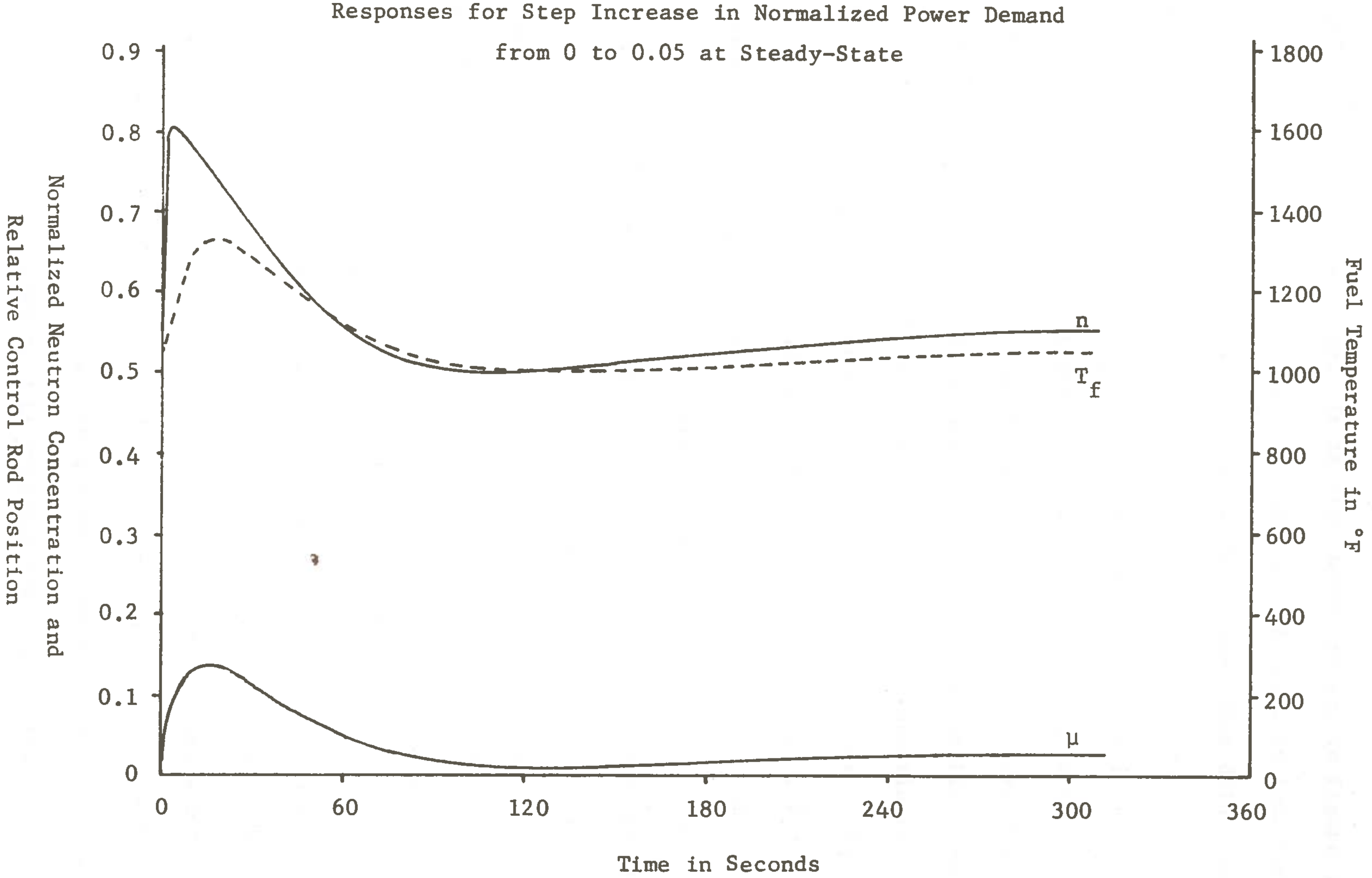

Responses for Step Increase in Normalized Power Demand
from 0 to 0.05 at Steady-State
Normalized Neutron Concentration and
Relative Control Rod Position
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Fuel Temperature in °F
1800
1600
1400
1200
1000
800
600
400
200
0
n
T_f
μ
0
60
120
180
240
300
360
Time in Seconds

Figure 5-14.

the normalized neutron concentration reaches its highest or lowest value within approximately 50 seconds, but a much longer time is required for restabilization at a new state. It is also demonstrated, in Figure 5-8, that changes in neutron level cause an immediate increase in fuel temperature. The coolant temperature rises with a slight time delay due to the effect of the heat transfer process, which has a built-in transport delay in simulation, between T_{oc} and T_{ix} as shown in Figure 5-13; the figure also illustrates the temperature increase resulting from decreasing coolant flow rate. The steam temperature and neutron level show the same effect (see Figures 5-10 and 5-11) for the various throttle openings as those for Figures 5-3 and 5-4, namely that while the throttle is closing down, steam temperature rises and neutron level decreases. Figure 5-12 shows the system reaching its stable state within 5 seconds after a step change in reactivity. A positive step increase in the reactivity has a large effect on overall neutron concentration at the instant that the reactivity is inserted. The relative control rod position, shown in Figure 5-9, demonstrates the relation between the normalized neutron concentrations and the control rod positions. Figure 5-14 shows the effect of a change in normalized power demand signal which "boosts" the neutron level by withdrawing control rods, after which the automatic control system restabilizes the simulation to its original state.

The third set of data show system responses during simulated accidents. The response that results from the loss of primary coolant flow is shown in Figure 5-15; the neutron level decreases to zero within approximately 180 seconds. It should also be noted that the neutron level drops very rapidly at first and then gradually decreases to zero. Control system failure is simulated by pressing the control switch, and the

Normalized Neutron Concentration for Loss of Primary Coolant
at Steady-State

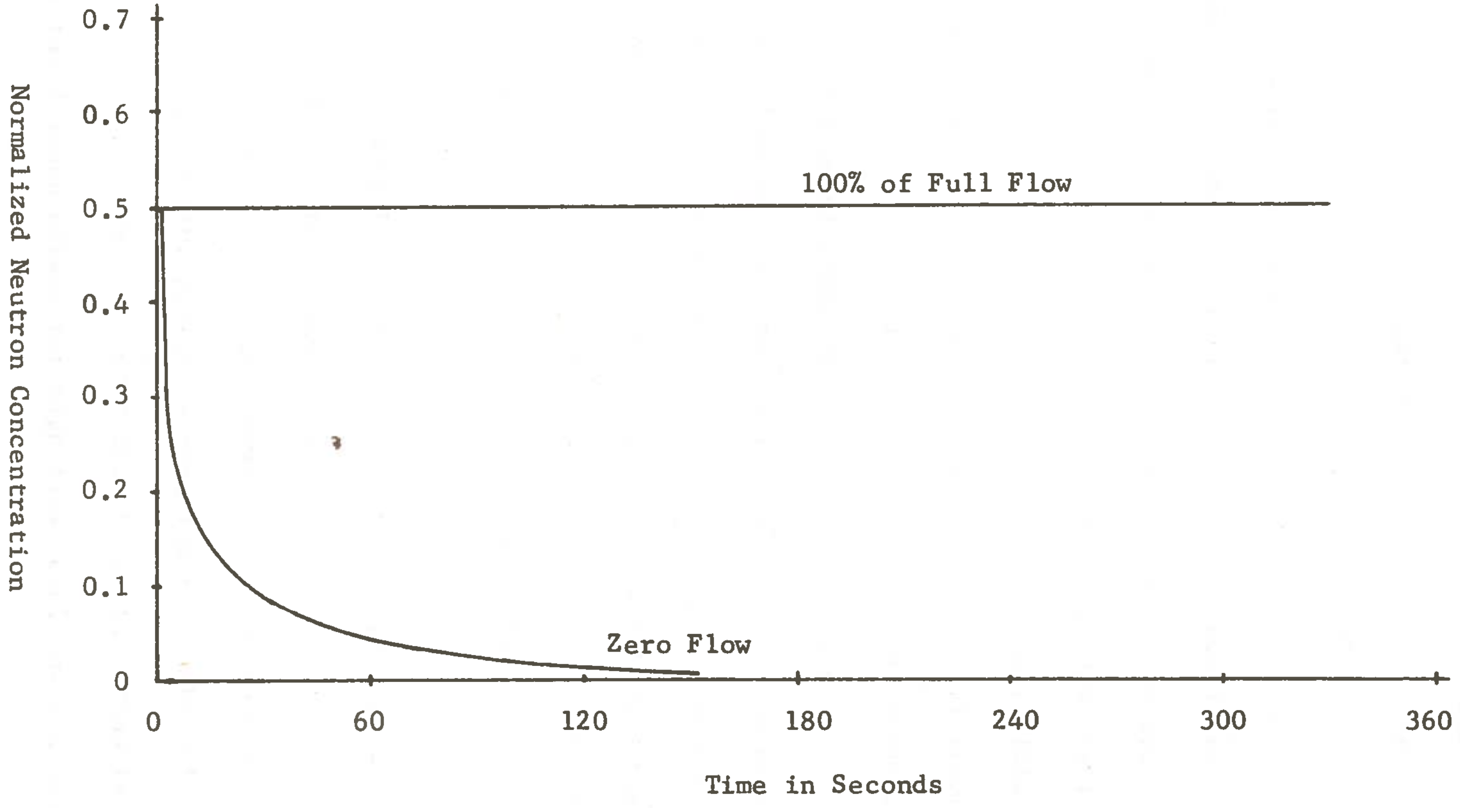
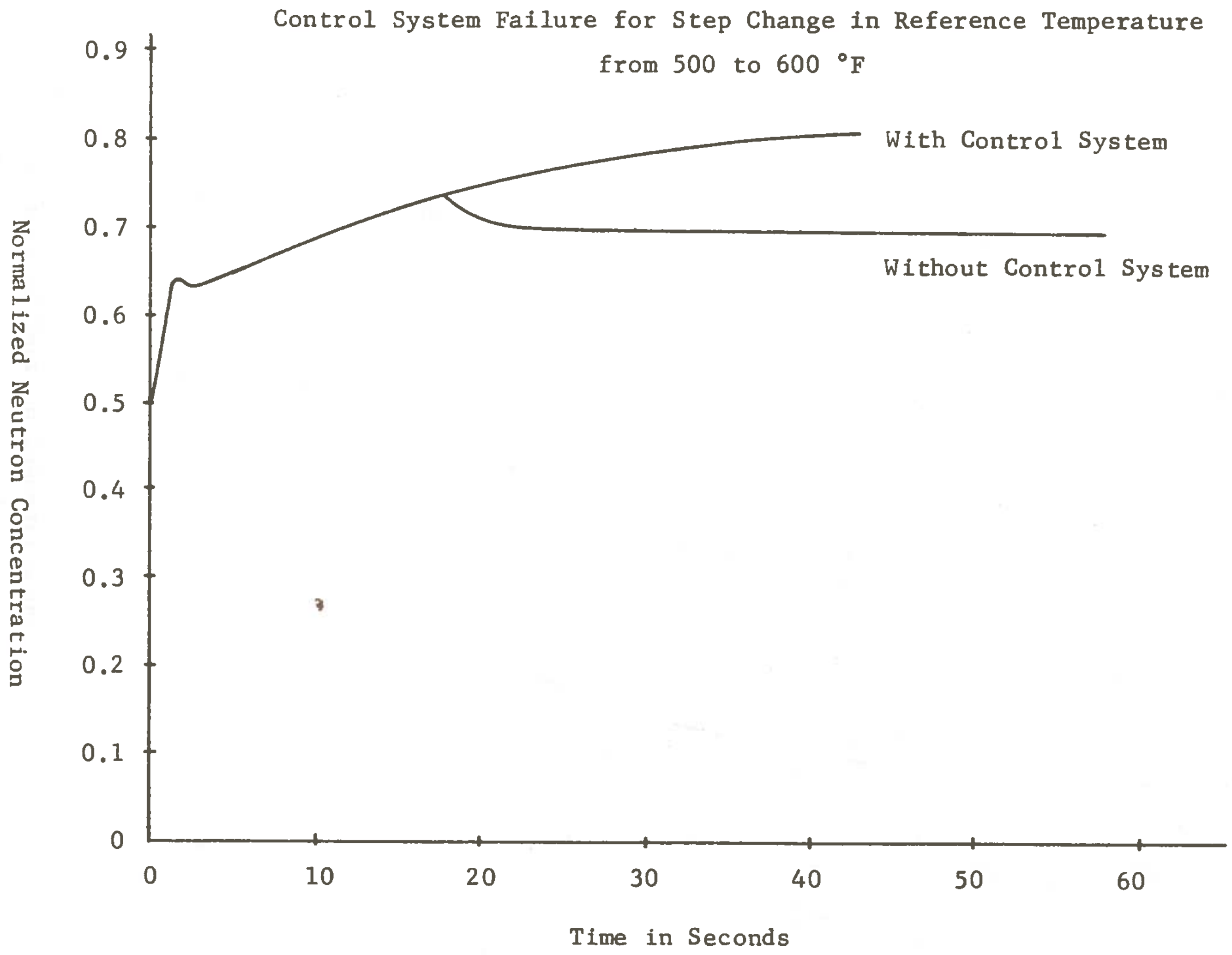


Figure 5-15.

control rods are frozen at a given position. Note that the neutron level remains at a constant value of 0.7 after the control system failure, as shown in Figure 5-16. A scram, illustrated in Figure 5-17, is simulated by increasing the reference temperature to 700°F at steady-state. The normalized neutron level reachs its maximum value of 1.0 and the scram mechanism, which removes the control system from the simulation circuit and feeds a large negative reactivity to amplifier 61, is actuated. The neutron level responds as expected by dropping quickly toward zero, first rapidly then more slowly as the delayed neutron precursors decay.

The build-up of the isotope Xe-135 after a rapid shutdown is illustrated by Figure 5-18. The neutron absorption due to this radioisotope may govern how long a reactor must be shut down as a result of xenon build-up. Because the half-lives of I-135 and Xe-135 are so short and the absorption cross section of xenon is so large, the concentrations of these isotopes quickly rise to their saturation values. At the moment of reactor shutdown, production of xenon is ceased, but xenon continues to be produced as the result of decay of the I-135, which initially has a greater decay rate than xenon, present in the system. The xenon concentration therefore initially increases, after shutdown, then eventually disappears by its own decay.

If the poison level must be 0.1 or less to attain criticality, the reactor dead-time will be 35 and 45 hours for operating neutron fluxes of 10^{14} and 2.5×10^{14} n/cm^2-sec respectively. However, if the neutron flux is 2.5×10^{13} n/cm^2-sec, no waiting period is required since the poison level never reaches 0.1. It should be noted that there is virtually no difference in saturated xenon poison for high flux levels during reactor operation.(8)



Control System Failure for Step Change in Reference Temperature from 500 to 600 °F

Figure 5-16.

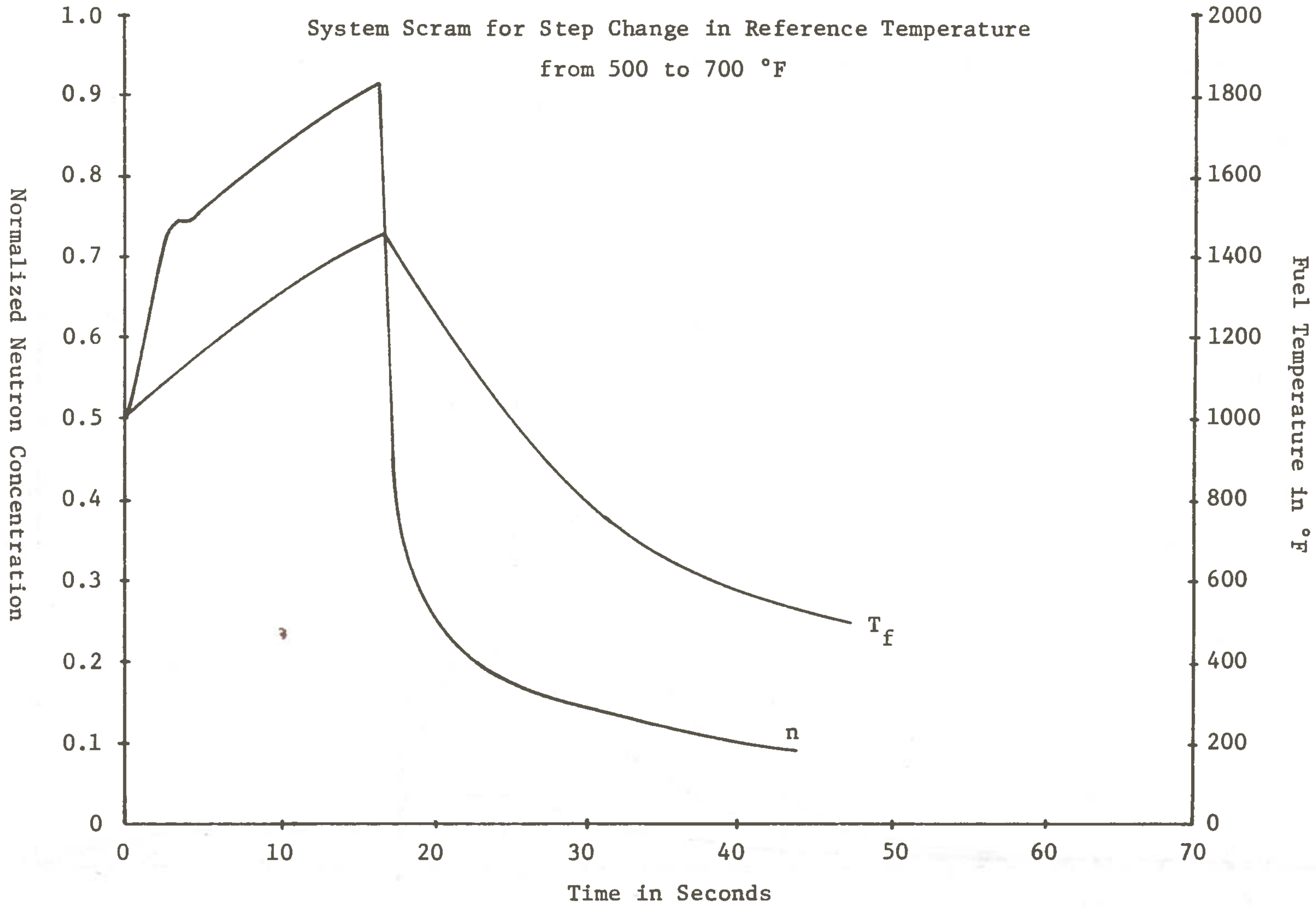

System Scram for Step Change in Reference Temperature
from 500 to 700 °F
Normalized Neutron Concentration
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Fuel Temperature in °F
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Time in Seconds
0
10
20
30
40
50
60
70
T_f
n

Figure 5-17.

Xenon Poison for Various Neutron Flux Levels at Steady-State and after Shutdown

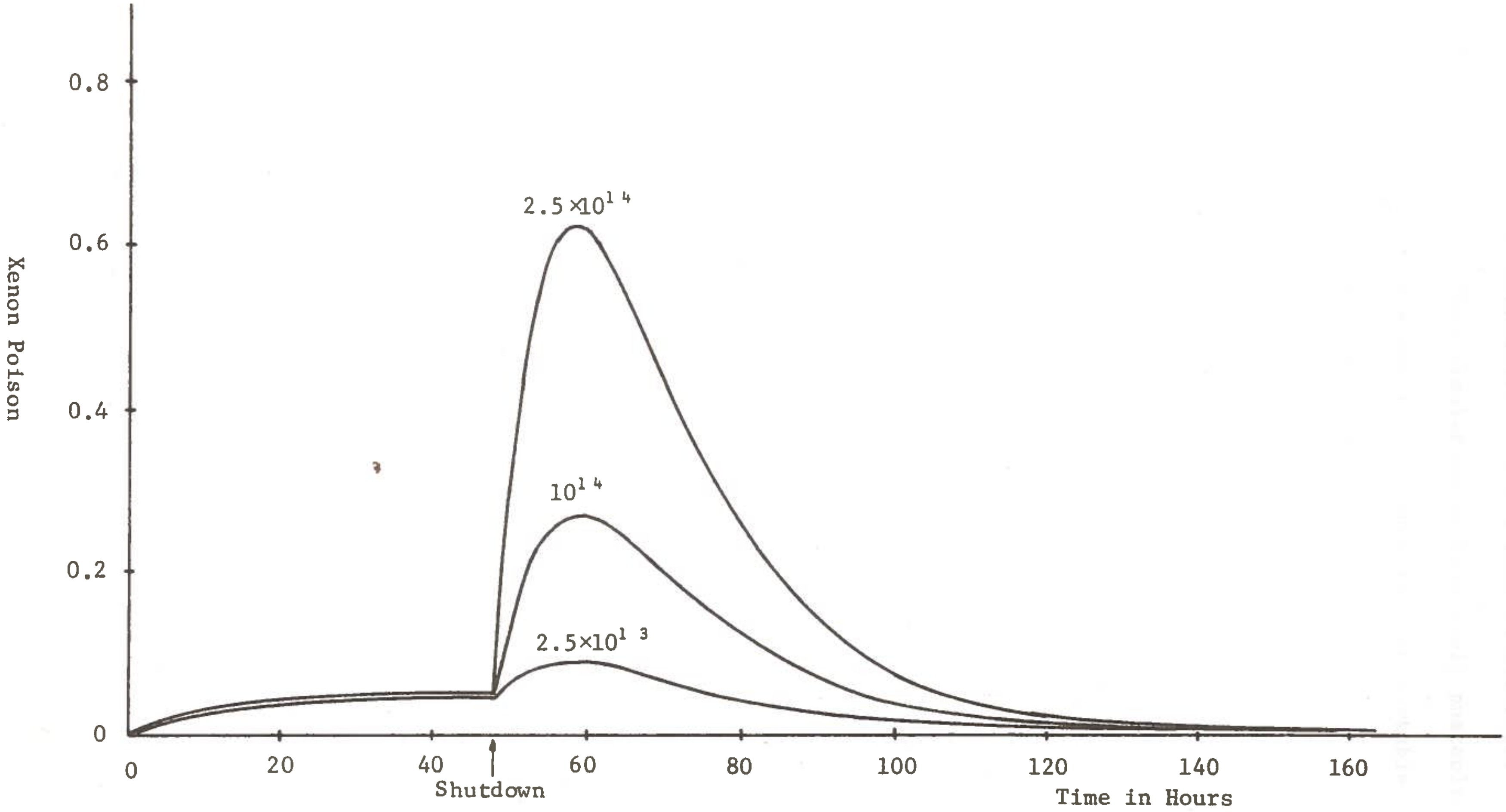


Figure 5-18.

All results are well representative of the system behavior for various operating conditions. This simulation is relatively unstable at start-up, but at steady-state, the control system maintains a stable operation within its designed limit.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

In nuclear engineering education, the simulation of a nuclear reactor provides an extremely useful laboratory tool for investigating behavior and responses under various conditions. The multiparameter display panel was designed following a detailed study of the capability of the existing PWR simulation and the availability of equipment which could be obtained within an allowable budget. The display panel was required to meet the criteria of the ability to demonstrate steady-state responses and to record the transient behavior of the important plant parameters, and also to be operated by a person who does not have an extensive background of hybrid computer operation.

Instantaneous readout for plant parameters on the display meters, permanent records of the transient responses on the X-Y plotter, and the unlimited ability of the hybrid system in process control are demonstrated by the entire system of the PWR simulation. The PWR system--which includes the digital computer program, the analog simulation, and the display panel-- is now operating successfully, and all components function as they were designed. The only existing problem is unexpected triggering of interrupts in the hybrid system.

Further expansion can be made in the digital computer programs to provide more detailed study for the PWR simulation. A more sophisticated control system, which should include the secondary loop, would be very helpful to increase the stability of the present simulation. For example, a constant steam temperature control system, in which the digital computer would actuate the necessary controls from calculating the steam temperature, would allow for optimizing the heat transfer cycle for a maximum turbine power output.(9) At the present time, all controllers are manually adjusted. It would be desirable to incorporate the option for either manual or automatic mode in the control system.

A linearized model is easily simulated, but in some case it does not reflect the actual system response. For example, the average coolant temperature currently is the linear average of the inlet and outlet temperatures, and it is not realistic that an increase in outlet coolant temperature will result a decrease in inlet coolant temperature.

Another area that needs expansion is in the simulation of abnormal situations. Ideally, the instructor should have the ability to introduce non-normal conditions so that the students can take the necessary steps to achieve the desired reactor condition, and the digital computer could be used to examine those actions which the students should take.

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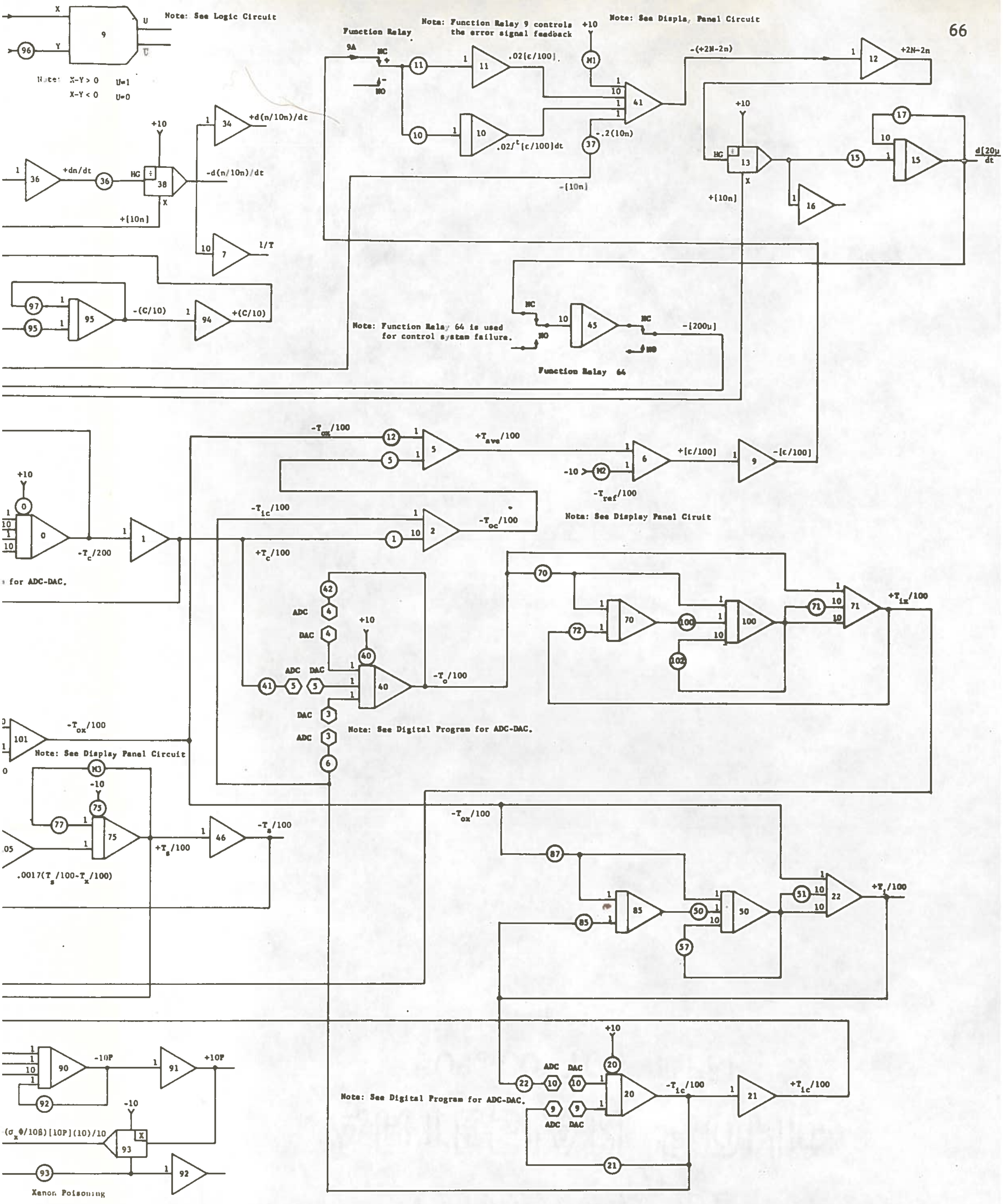

Note: See Logic Circuit

Note: X-Y > 0 U=1
X-Y < 0 U=0

Note: Function Relay 9 controls the error signal feedback

Note: See Displa, Panel Circuit

Note: Function Relay 64 is used for control system failure.

Note: See Display Panel Ciruit

Note: See Digital Program for ADC-DAC.

Note: See Display Panel Circuit

Note: See Digital Program for ADC-DAC.

TABLE A-1

POTENTIOMETER ASSIGNMENT SHEET

Pot	Parameter Expression	Check Setting	Run Setting
0	0.500	0.500	0.500
1	0.200	0.200	0.200
2	UA/M_cC_c	0.500	0.500
3	$2W_cC_c/10M_cC_c$	0.250	0.250
5	0.500	0.500	0.500
6	W_c/M_o	0.500	0.500
7	$2W_cC_c/M_cC_c$	0.250	0.250
10	$2000K_c$*	0.020	0.020
11	$20\tau_cK_c$*	0.020	0.020
12	0.500	0.500	0.500
15	$10K_m/\tau_m$	0.800	0.800
17	$1/10\tau_m$	0.400	0.400
20	0.400	0.400	0.400
21	W_c/M_i	0.500	0.500
22	W_c/M_i	0.500	0.500
25	$2W_cC_c/M_xC_c$	0.600	0.600

TABLE A-1. (continued)

POTENTIOMETER ASSIGNMENT SHEET

Pot	Parameter Expression	Check Setting	Run Setting
27	$2W_cC_c/M_xC_c$	0.600	0.600
30	0.500	0.500	0.500
31	$n_m\Delta H/2000M_fC_f$	0.100	0.100
32	$UA/2M_fC_f$	0.100	0.100
33	UA/M_fC_f	0.200	0.200
35	10λ	0.766	0.766
36	0.100	0.100	0.100
37	0.200	0.200	0.200
40	0.400	0.400	0.400
41	$2W_c/M_o$	1.000	0.999
42	W_c/M_o	0.500	0.500
45	0.400	0.400	0.400
50	$1/\tau$	0.250	0.250
51	0.200	0.200	0.200
52	U_xA_x/M_xC_x	0.400	0.400
57	$3/5\tau$	0.150	0.150

TABLE A-1. (continued)

POTENTIOMETER ASSIGNMENT SHEET

Pot	Parameter Expression	Check Setting	Run Setting
60	$3\gamma_I\sigma_x\Phi\Sigma_f/\Sigma_{af}\beta 10$		
61	$2000\delta k/10$	0.500	0.500
62	λ_I/β	0.209	0.209
63	$\|4\times10^4\alpha\|$	0.800	0.800
65	0.500	0.500	0.500
66	$\beta K/10\ell$	0.650	0.650
67	$1/2000\ell$	0.500	0.500
70	$1/\tau$	0.250	0.250
71	0.200	0.200	0.200
72	$1/\tau$	0.250	0.250
75	0.350	0.350	0.350
77	$K_a/M_mC_m + M_sC_s$	0.005	0.005
80	0.200	0.200	0.200
82	$U_xA_x/10M_xC_c$	0.040	0.040
85	$1/\tau$	0.250	0.250
87	$1/\tau$	0.250	0.250

TABLE A-1. (continued)

POTENTIOMETER ASSIGNMENT SHEET

Pot	Parameter Expression	Check Setting	Run Setting
90	$10\lambda_I/3\beta$	0.696	0.696
91	$\sigma_x\gamma_x\Phi\Sigma_f/\Sigma_{af}\beta$		
92	λ_x/β	0.151	0.151
93	$\Phi\sigma_x/10\beta$		
95	$\beta/100\ell$	0.065	0.065
96	0.950	0.950	0.950
97	λ	0.076	0.076
100	$1/\tau$	0.250	0.250
101	0.200	0.200	0.200
102	$3/5\tau$	0.150	0.150
105	$U_xA_x/M_mC_m + M_sC_s$	0.012	0.012
107	$U_xA_x/M_mC_m + M_sC_s$	0.012	0.012
110	0.500	0.500	0.500
115	0.001	0.001	0.001

TABLE A-2

AMPLIFIER ASSIGNMENT SHEET AND STATIC CHECK

Amp	Use	Output Parameter	Calculated Value	Measured Value
0	$\int$	$-T_c/100$	-5.00	-5.00
1	-	$+T_c/100$	+5.00	+5.00
2	Σ	$-T_{oc}/100$	-6.00	-5.99
5	Σ	$+T_{ave}/100$	+6.00	+5.99
6	Σ	$+\varepsilon/100$	0.00	0.00
7	-	$+dn/dt/n$	-6.50	-6.49
9	-	$-\varepsilon/100$	0.00	0.00
10	$\int$	$+.02\int[\varepsilon/100]dt$	-1.00	-0.99
11	-	$+.02\varepsilon/100$	-0.02	-0.02
12	-	$+2N-2n$	-1.04	-1.04
13	M÷	$+(2N-2n)/n$	+2.07	+2.07
15	$\int$	$+d20\mu/dt$	10.00	10.00
16	-	$-(2N-2n)/n$	-2.07	-2.07
20	$\int$	$-T_{ic}/100$	-4.00	-3.99
21	-	$+T_{ic}/100$	+4.00	+3.99
22	Σ	$+T_i/100$	+4.00	+4.01

TABLE A-2. (continued)

AMPLIFIER ASSIGNMENT SHEET AND STATIC CHECK

Amp	Use	Output Parameter	Calculated Value	Measured Value
30	∫	$-T_f/200$	-5.00	-5.00
31	-	$+T_f/200$	+5.00	+5.00
34	-	+dn/dt/10n	-0.65	-0.64
35	Σ	-dn/dt	+3.25	+3.24
36	-	+dn/dt	-3.25	-3.24
38	M÷	-dn/dt/10n	+0.65	+0.64
40	∫	$-T_o/100$	-6.00	-6.00
41	Σ	-(2N-2n)	+1.04	+0.98
45	∫	-200μ	10.00	10.00
46	-	$-T_s/100$	-3.50	-3.49
50	∫	Pade' Network	10.00	10.00
60	∫	+3I'	10.00	10.00
61	Σ	+2000δk	0.00	+0.04
62	-	-2000δk	0.00	-0.04
63	M×	-2000δkn	0.00	-0.02
64	-	+.5(2000δkn)	0.00	+0.01

TABLE A-2. (continued)

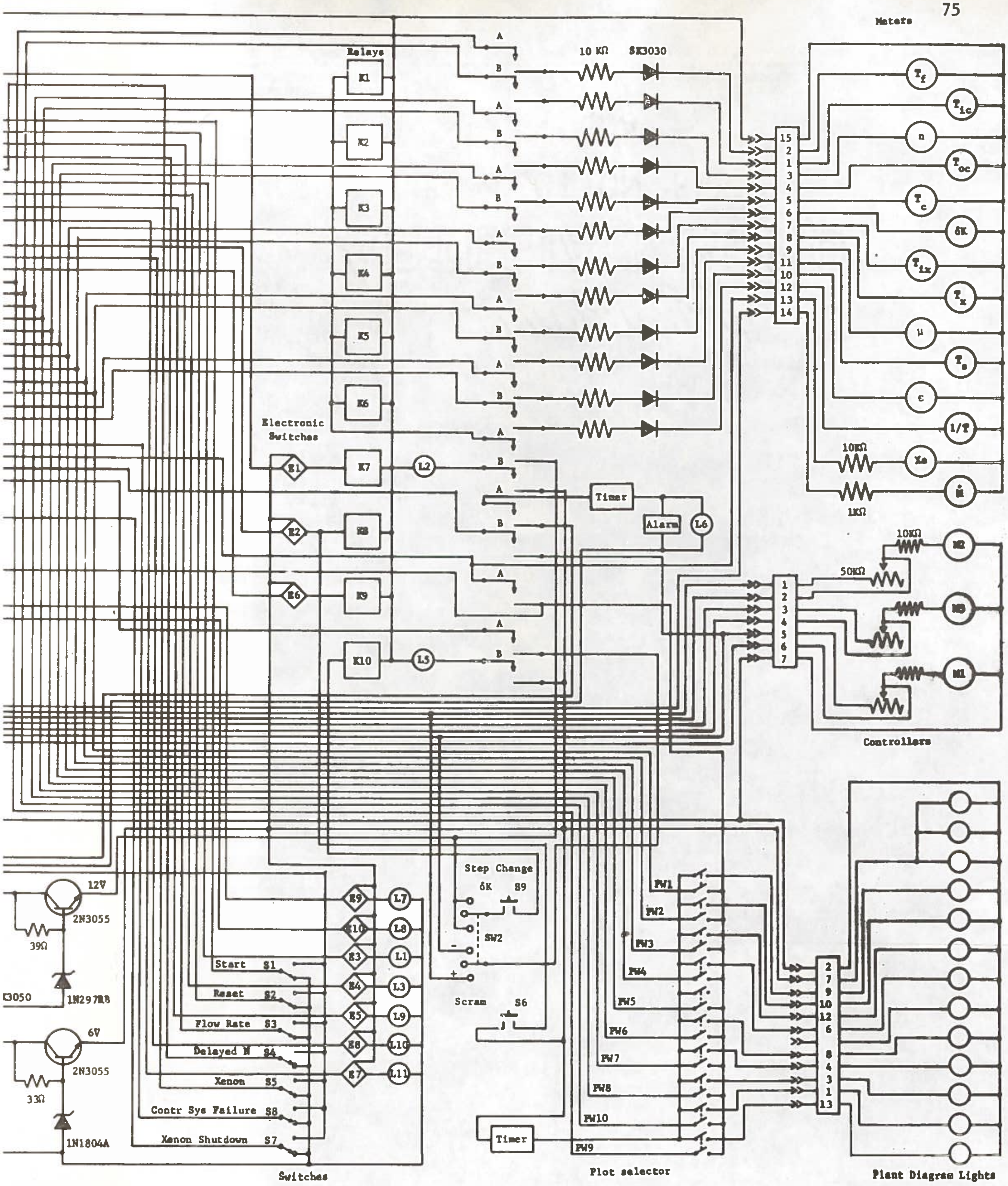
AMPLIFIER ASSIGNMENT SHEET AND STATIC CHECK

Amp	Use	Output Parameter	Calculated Value	Measured Value
65	$\int$	$-10n$	-5.00	-4.99
66	-	$+10n$	+5.00	+4.99
70	$\int$	Pade' Network	10.00	10.00
71	Σ	$+T_{ix}/100$	+6.00	+6.03
72	-	$-T_{ix}/100$	-6.00	-6.03
75	$\int$	$+T_s/100$	+3.50	+3.50
80	$\int$	$-T_x/100$	-5.00	-4.99
82	-	Flow Rate	-1.00	-1.00
85	$\int$	Pade' Network	10.00	10.00
90	$\int$	$-10P$	10.00	10.00
91	-	$+10P$	10.00	10.00
93	M×	$-(\sigma_x\Phi/10\beta)[10P]$		
94	-	$+C/10$	10.00	10.00
95	$\int$	$-C/10$	10.00	10.00
100	$\int$	Pade' Network	10.00	10.00
101	Σ	$-T_{ox}/100$	-4.00	-3.99

TABLE A-2. (continued)

AMPLIFIER ASSIGNMENT SHEET AND STATIC CHECK

Amp	Use	Output Parameter	Calculated Value	Measured Value
102	-	$+T_x/100$	+5.00	+4.99
105	Σ	$+.0117(T_s/100-T_x/100)$	-0.02	-0.01
110	HG	+10n (RC Network)	+5.00	+5.00
112	-	-10n (RC Network)	-5.00	-5.00
115	∫	Plotter Time Scale	10.00	10.00


Meters
Relays
K1
K2
K3
K4
K5
K6
A
B
10 KΩ
SK3030
15
2
1
3
4
5
6
7
8
9
11
10
12
13
14
T_f
T_{ic}
n
T_{oc}
T_c
δK
T_{ix}
T_x
μ
T_s
ε
1/T
10KΩ
Xe
$\dot{m}$
1KΩ
Electronic Switches
E1
K7
L2
Timer
Alarm
L6
E2
K8
E6
K9
K10
L5
10KΩ
M2
50KΩ
M3
M1
1
2
3
4
5
6
7
Controllers
12V
2N3055
39Ω
K3050
1N2970B
6V
2N3055
33Ω
1N1804A
Step Change
δK
S9
SW2
-
+
Scram
S6
Start S1
Reset S2
Flow Rate S3
Delayed N S4
Xenon S5
Contr Sys Failure S8
Xenon Shutdown S7
E9
L7
E10
L8
E3
L1
E4
L3
E5
L9
E8
L10
E7
L11
Switches
PW1
PW2
PW3
PW4
PW5
PW6
PW7
PW8
PW10
PW9
Timer
Plot selector
2
7
9
10
12
6
8
4
3
1
13
Plant Diagram Lights

RAM

TABLE B-1

TRANSIENT RESPONSE SELECTING SWITCHES ASSIGNMENT (FROM LEFT TO RIGHT)

SWITCH	SYMBOL	PARAMETER DISPLAYED
PW 1	T_s	Steam Temperature
PW 2	μ	Relative Control Rod Position
PW 3	T_x	Heat Exchanger Temperature
PW 4	T_{ix}	Coolant Temperature at Inlet of Heat Exchanger
PW 5	δk	Reactivity
PW 6	T_c	Average Coolant Temperature
PW 7	T_{oc}	Outlet Coolant Temperature
PW 8	n	Normalized Neutron Concentration
PW 9	T_f	Fuel Temperature
PW 10	T_{ic}	Inlet Coolant Temperature

APPENDIX C

SIMULATOR OPERATION INSTRUCTION

Preoperation Procedures

The following procedures should be followed prior to making the reactor dynamic study:

1. Turn on analog computer.
2. Engage patch panel and make sure that patch panel engage light is on.
3. Set manual pot-setting control to "KEY".
4. Set monostable timers 0, 1, and 2 to 30, 10, and 25 respectively.
5. Set digital clock rate to 10^6.
6. Set limiter of amplifier 61 to ± 10 volts.
7. All push-buttons should be in low state.
8. Plug multiconductor to display panel from analog computer.
9. Turn on display panel power.
10. Set reference temperature to 500 °F.
11. Set normalized power demand to zero.
12. Set secondary throttle to full open.
13. Turn on X-Y plotter switches which should be pushed down.
14. Set X-axis scale to 0.1 volts/inch and Y-axis scale to 10 volts/inch (the time scale will be 300 sec/11cm).
15. Place paper on X-Y plotter and select zero reference.
16. Read digital program in cardreader.
17. Check error messages of pot settings and amplifiers static check.
18. Check integrators as indicated on digital console with -10 volts

patched into "IC" input of each integrator.

19. If all checks are satisfactory, the operator enters "1" in the digital console and presses the new-line key. Thus, the simulator is in ready state with 100% of full flow rate and one group delayed neutrons. If some of the errors are crucial, the operator has to correct them by manually setting pots and entering "2" in the digital console, and new error report is provided.

Display Panel Operation

The following steps are required to operate the PWR simulator in its normal mode. Adjustments can be made to simulate reactor operations under other than normal (e.g., accident) conditions.

1. Start the reactor is done by pressing the "START" button, and 5 minutes should be allowed before the reactor reaches steady-state.
2. Reset the reactor is done by pressing the "RESET" button which will set the simulator to its initial state. If scram is triggered, sometimes the operator needs to allow the system to be stabilized for few more minutes.
3. Change flow rate is triggered by pressing "FLOW RATE" button. The operator enters the flow rate with a format of F4.2 in the digital console and presses new-line key. For example, if the desired flow rate is 50% of full flow, the operator enters 0.5, and the new flow rate will be observed on the flow rate meter and the console.
4. Select delayed neutrons is done by pressing "DELAYED NEUTRON" button. Then the operator needs to enter code of "1" or "6" for one- or six-groups delayed neutrons respectively, and presses new-line key.
5. Xenon poison study is triggered by pressing the "XENON" button. The

operator enters codes of "1", "2" or "3", which represnet neutron flux levels of 2.5 x 10^{14}, 10^{14} or 2.5 x 10^{13} n/cm^2-sec respectively, and presses the new-line key. No other parameter is directed to the plotter; that is, no transient responses selecting switches are pushed in. Reactor shutdown is simulated by pressing the switch directly under the "XENON" button.

6. Manual scram can be triggered by pressing the red scram button.
7. Manual control system failure is done by pressing the control switch, and a light will indicate this condition.
8. Step change in reactivity is inserted by first selecting either positive or negative 0.0025 step through the toggle switch, and then pressing the red button.
9. Prompt neutron lifetime is selected as are indicated on the panel.
10. "Data logging" can be obtained by setting and resetting push-button No. 5, and then high-speed printer provides a tabulated report for key plant parameters.
11. Reset x-y plotter time scale may be done by placing a positive voltage (through a pot) to amplifier 115 input manually until the plotter arm returns to its original position.

Shutdown

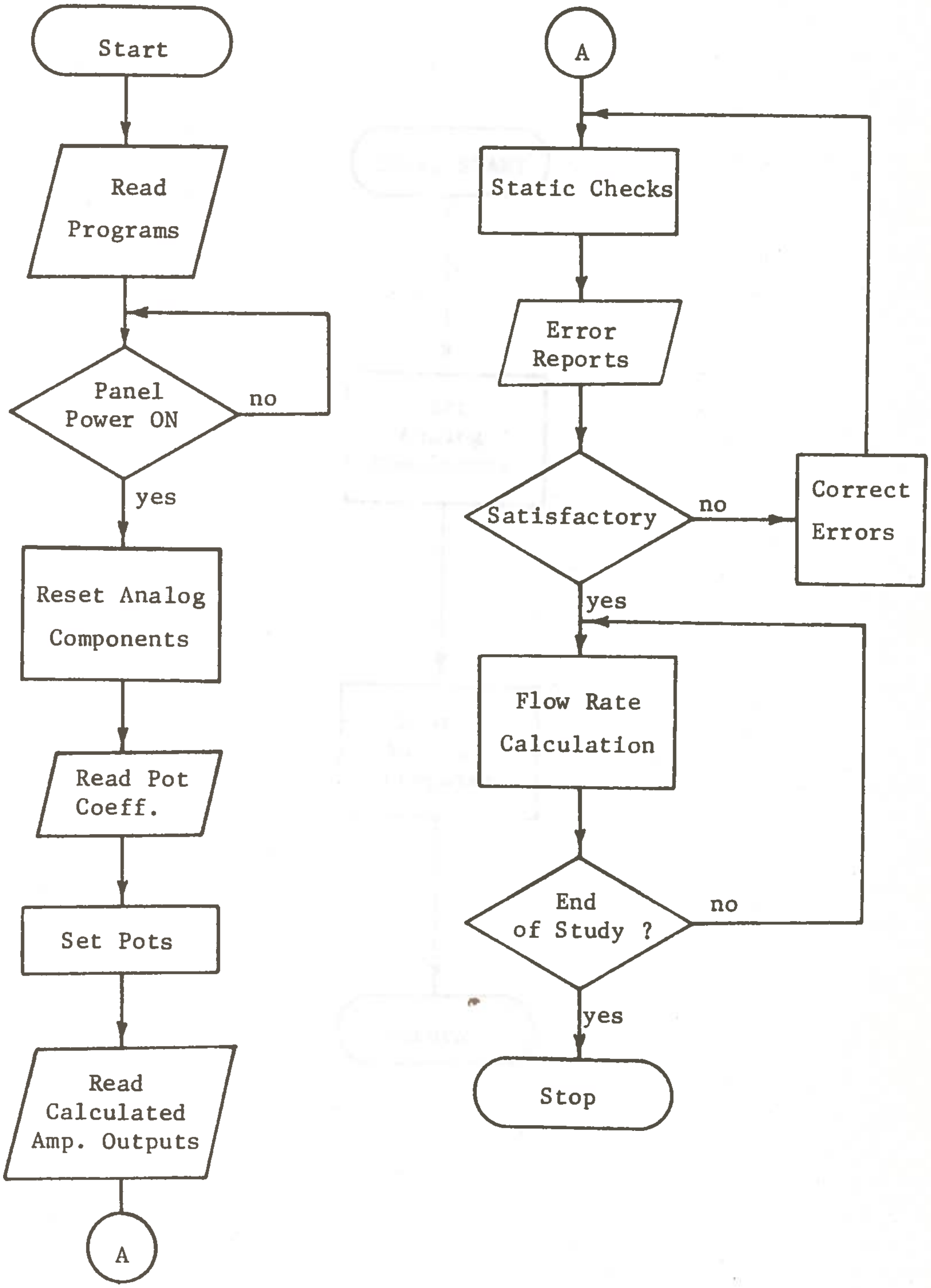
1. Unplug the multiconductor, which will release the digital program from the Sigma 5 computer.
2. Turn off the panel power.
3. Disconnect the power core to the display panel.
4. Disengage the analog patch panel.
5. Turn off the analog computer.

Trouble Shooting

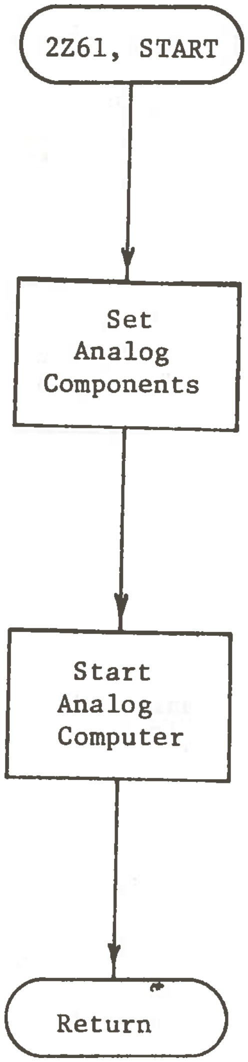
There are few malfunctionings of the hybrid system which may occur at preliminary set-up of the simulator with exception of the unexpected triggering interrupts. In order to operate the simulator, all errors have to be cleared.

1. The unexpected triggering interrupt services are caused by any small voltage flunctuation in the power supply circuit which feeds the computer system. It is a direct result from the improper grounding of the interrupt system hardwares. The operator has to respond to the requests which are indicated on the digital console.
2. A console message of "WATCHDOG TIMER RAN OUT" is caused by tripping a -6 volt circuit breaker in the interface cabinet. The operator needs to set the analog computer to "PC" mode and the digital timer to "C". Then the operator should reboot the digital monitor, and should return the circuit breaker to its original position. Sometimes it requires several tries.
3. Amplifier 85 sometimes is overloaded after "START" button is pressed. The operator needs to reset the simulator; otherwise the simulator will scram. Pressing those wires connected to this amplifier firmly into their position should eliminate this problem.
4. Large error in servo potsetting is caused by tripping a -14 volt circuit breaker under the analog console. Flipping it up to the original position will eliminate this error.

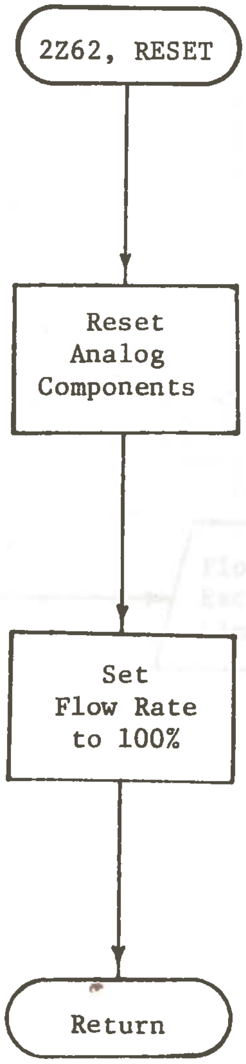
APPENDIX D-1. MAIN PROGRAM



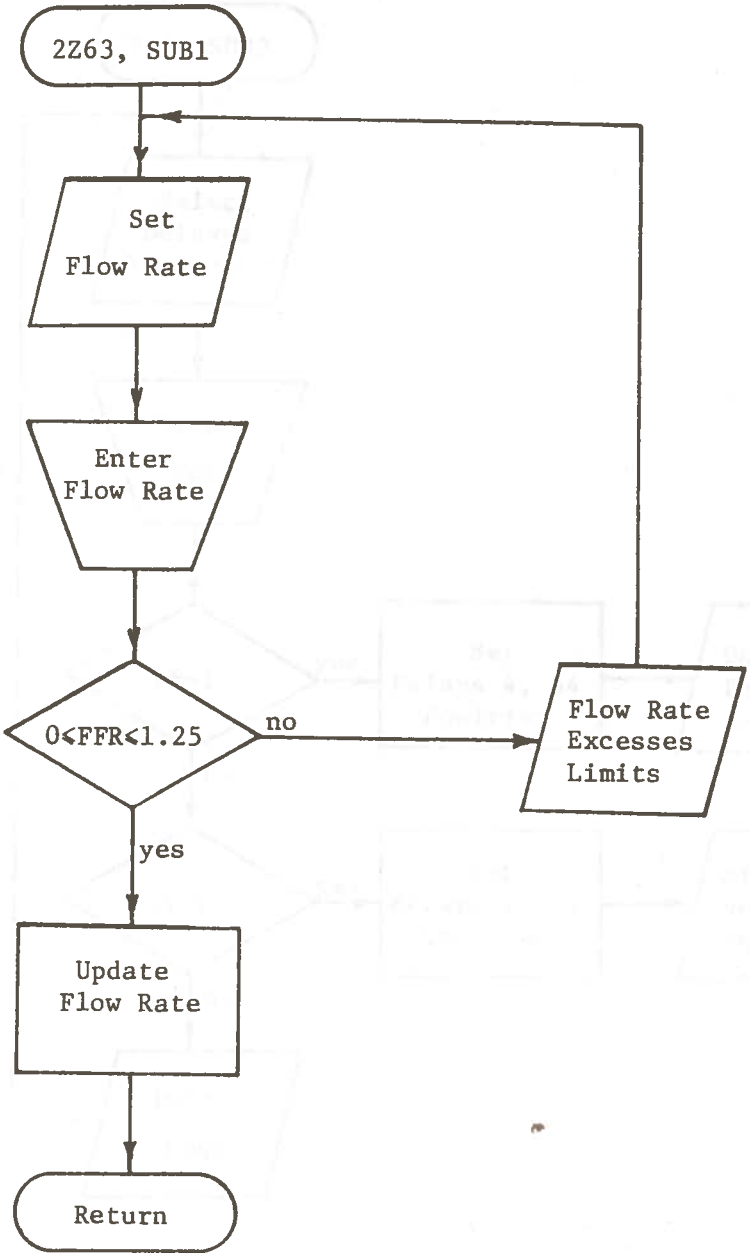
APPENDIX D-2. SUBROUTINE START



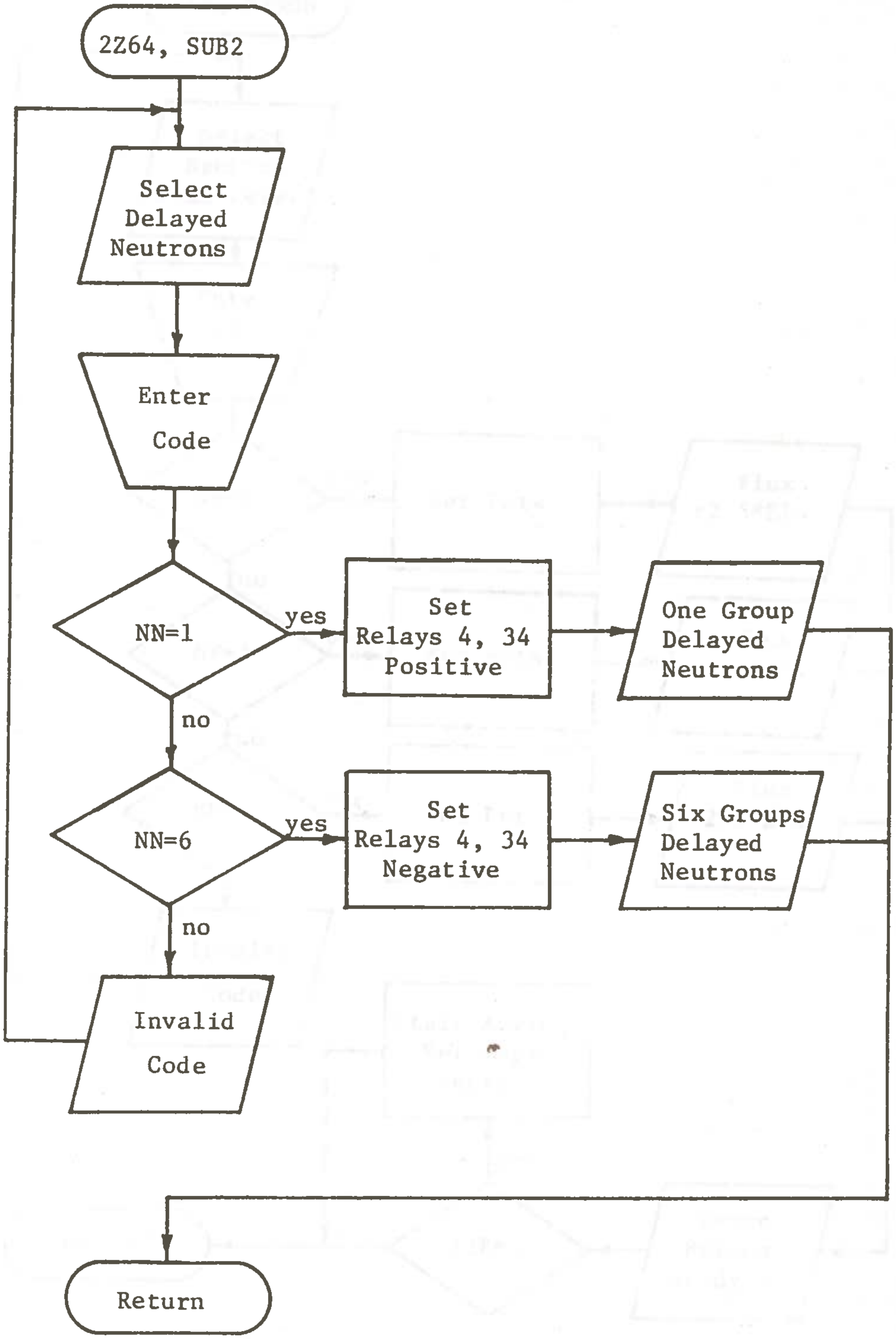
APPENDIX D-3. SUBROUTINE RESET



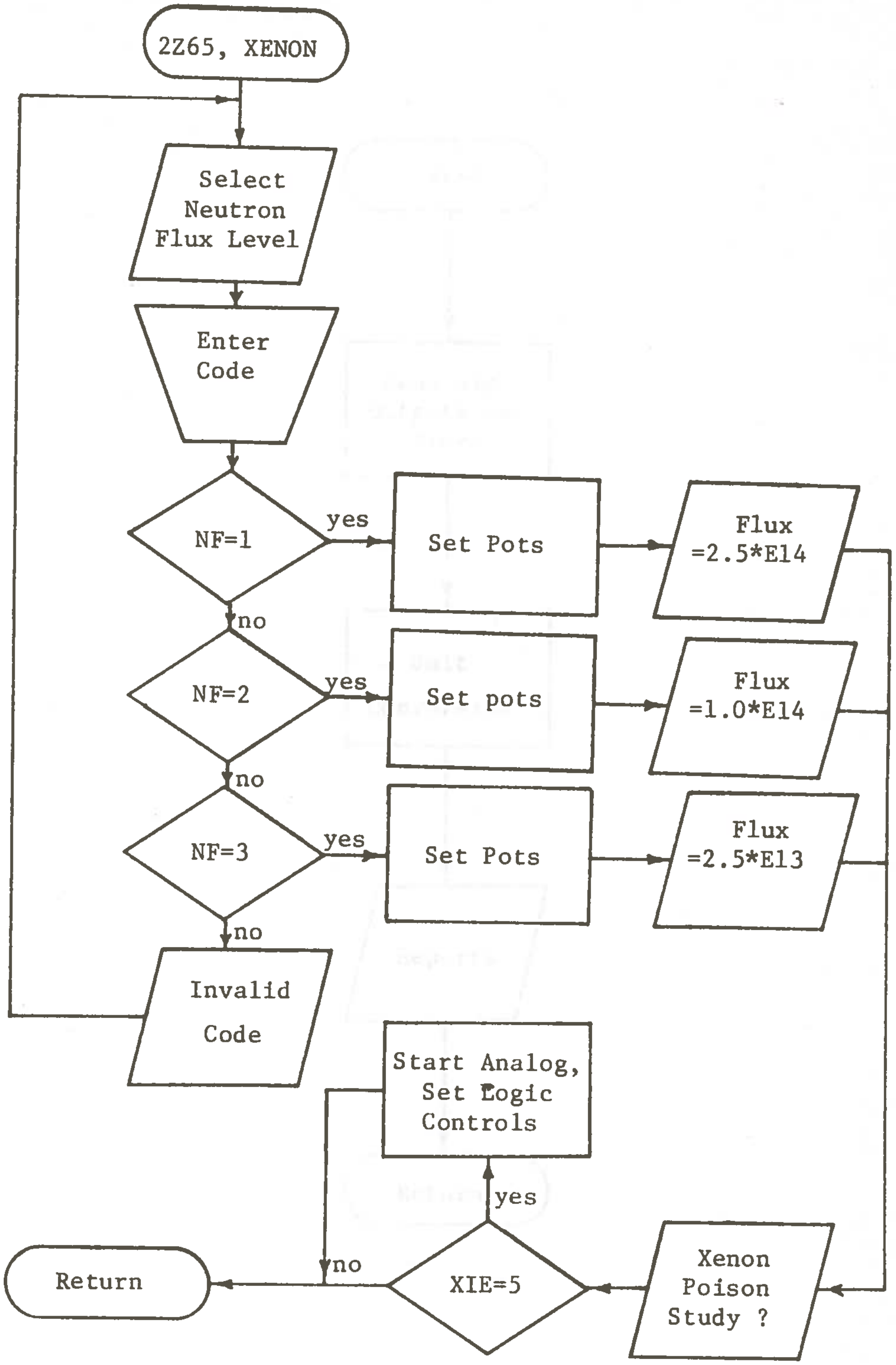
APPENDIX D-4. SUBROUTINE SUB1



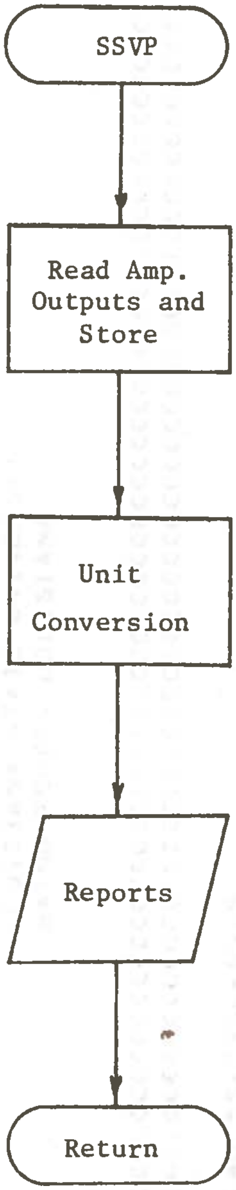
APPENDIX D-5. SUBROUTINE SUB2



APPENDIX D-6. SUBROUTINE XENON



APPENDIX D-7. SUBROUTINE SSVP



APPENDIX E

```
 JCB
 FCRTRANH GO,RT.S
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC                                                                             CC
CC                                                                             CC
CC       PRCGRAMER      EDMOND CHEN                                            CC
CC        MACHINES      XEROX SIGMA 5 AND EAI 680 HYBRID SYSTEM                CC
CC       LANCUAGE       FORTRAN IV-H                                           CC
CC       CATE           MAY, 1974                                              CC
CC       PURPCSE        DIGITAL PROCESS CONTROL FOR PWR SIMULATOR              CC
CC                      NUCLEAR SCIENCE CENTER                                 CC
CC                      LOUISIANA STATE UNIVERSITY                             CC
CC                      BATON ROUGE, LOUISIANA                                 CC
CC                                                                             CC
CC                                                                             CC
CCCCCCCCCCCCCCCCCCCCCCCCCCC&CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      LOGICAL SS,TRSL,RSCS
      CCMMCN FR
      CIMENSION IPOT(65),COEF(65),NA(65),SVLT(65)
      CONNECT (2Z61,START)
      CONNECT (2Z62,RESET)
      CONNECT (2Z63,SUB1)
      CONNECT (2Z64,SUB2)
      CONNECT (2Z65,XENON)
C
C     THIS SECTION CHECKS STATUS CF PANEL POWER
C
```

```
 4005 CONTINUE
      SS=TRSL(1)
      IF(.NOT.TRSL(1)) GO TO 4000
      GO TO 4100
 4000 WRITE(7,4001)
 4001 FORMAT(1X,'TURN ON THE PANEL POWER, STUPID---SOD')
      GO TO 4005
 4100 CONTINUE
C
C     THIS SECTION ESTABLISHES THE MODE OF THE ANALOG COMPUTER
C
      CALL STCO ('NS')
      CALL SLMO ('C')
      CALL RSCL (1)
      CALL RSCL (2)
      CALL RSCL (3)
      CALL RSCL (4)
      CALL RSCL (5)
      CALL RSCL (6)
      CALL RSCL (7)
      CALL RSCL (8)
      CALL RSCL (9)
      CALL RSCL (10)
      CALL RSCL (11)
      CALL RSCL (12)
      CALL RSCL (13)
      CALL RSCL (14)
      CALL RSCL (15)
C
C     THIS SECTION SETS SERVO POTS
```

```
      CALL SACO ('P',IFOT(M))
      CALL DVMR (PSV)
      ERRCR = FSV-COEF(M)
   15 WRITE(6,20) IPCT(M),PSV,COEF(M),ERROR
   20 FCRMAT(1X,'POT ',I3,'  SET-VALUE = ',F6.4,'  CALCULATED VALUE = '
     1,F6.4,'   ERROR =',F7.4)
C
C     AMPLIFIERS STATIC CHECKS
C
      CALL SLMC ('R')
      CALL SAMO ('ST')
      CALL SSRP (4)
      CALL RSCL (2)
      CALL SSCL (3)
      WRITE(6,30)
   30 FORMAT(////1X,' AMPLIFIER STATIC CHECK '//)
      KK = K-1
      CO 70 L=1,KK
      CALL SACO ('A',NA(L))
      CALL CVMR (VLT)
      ERC = VLT - SVLT(L)
      WRITE(6,101) NA(L),VLT,SVLT(L),ERO
  101 FORMAT (1X,'AMP ',I3,' OUTPLT V=',F7.4,'  CALCULATED V = ',F8.4,
     1 '   ERRCR=',F7.4)
   70 CCNTINUE
      WRITE (6,110)
  110 FORMAT(///1X,'IF CHECKS ARE NOT SATISFACTORY. SET POT MANUALLY
     * ANC ENTE2 1 ON CONSOLE',
     * //'PLOTTER X-SCALE 0.5V/INCH = 5.35 SEC/CM')
      WRITE (6,120)
```

```
C
      I=0
 9    CONTINUE
      CALL SACO ('P',IPOT(I))
      I=I+1
      READ(5,10) IPOT(I),COEF(I)
10    FORMAT(6X,I4,F10.5)
      CALL SFCT (IPOT(I),COEF(I))
      IF(IPOT(I).EQ.116) GO TO11
      GO TO 9
   11 CONTINUE
C
C     READ AMPLIFIERS CALCULATED OUTPUTS
C
      K = 0
   40 CONTINUE
      K = K + 1
      READ (5,50) NA(K),SVLT(K)
   50 FORMAT (I5,F10.4)
      IF (NA(K).EQ.116) GO TO 45
      GO TO 40
   45 CONTINUE
C
C     CHECK POT SETTING
C
      WRITE (6,1)
    1 FORMAT (////' POT SETTING CHECK'//)
      CALL SAMC ('PC')
      II = I-1
      DO 15 M=1,II
```

```
 120 FORMAT(1H1)
 198 WRITE (7,199)
 199 FORMAT (' HAVE YOU CHECKED AMP 10,45,50,95,100 WITH IC')
     READ (7,200) ICMAND
 200 FORMAT( I1)
     IF(ICMAND.EQ.1) GO TO 250
     IF(ICMAND.EQ.2) GO TO 45
 999 WRITE (7,201)
 201 FORMAT(' INVALID CODE')
     CALL SAMO ('PC')
     GO TO 198
 250 WRITE (7,202)
 202 FORMAT(' PWR IS READY ')
     CALL SAMO ('PC')
     CALL RSCL (1)
     CALL RSCL (2)
     CALL RSCL (3)
     CALL RSCL (4)
     CALL RSCL (5)
     CALL SSCL (9)
     CALL SAMO ('IC')
 300 CONTINUE
C
C    THIS SECTION ESTABLISHES THE CONDITION TO RUN HYBRID
C
     FR=1.0
     FRR = FR*100.0
     WRITE(7,520)FRR
 520 FORMAT(' FLOW RATE = ',F5.1,' PERCENT FULL')
 555 CALL SSRF (4)
```

```
      CALL SSRP (34)
      CALL SSCL (7)
  580 WRITE(7,581)
  581 FORMAT(1X,'ONE FROUP DELAYEC NEUTRON')
  590 CONTINUE
      SS=TRSL(1)
      IF (.NCT.TRSL(1))  GO TO 1000
      SS = TRSL(3)
      IF (TRSL(3)) CALL SSVP
      CALL RSCS (9)
      CALL RSCS (94)
      IF (RSCS (9)) GC TO 2500
      IF (FSCS(94)) GC TO 2500
      GO TO 2000
 2500 FR=0.5
      CALL RSCL (5)
      CALL SSCL (6)
 2000 CONTINUE
C
C     FLOW RATE CALCULATION
C
      CO 2001 I=1,10
      CALL CRAC(I,X)
      X = FR*X
      CALL LTDA(I,X)
      E = 0.1*FR
      CALL LTCA (11,E)
 2001 CONTINUE
      GC TO 590
C
```

```
C      THIS SECTION RELEASES THE DIGITAL COMPUTER
C
 1000 CALL SAMO('PC')
      CALL RSCL (9)
      CALL SLMO ('C')
      CALL RELECE
      STOP
      END
      SUBROUTINE START
      CALL SSCL(11)
      CALL SLMO ('R')
      CALL RSCL (1)
      CALL RSCL (2)
      CALL RSCL (3)
      CALL RSCL (4)
      CALL RSCL (5)
      CALL RSCL (6)
      CALL SAMO ('OP')
      CALL SSCL (1)
      CALL SSCL (2)
      CALL SSCL (5)
      CALL RSCL (1)
      CALL RSCL (11)
      RETURN
      END
      SUBROUTINE RESET
      COMMON FR
      CALL SSCL(12)
      CALL RSCL (1)
      CALL RSCL (2)
```

```
      CALL RSCL (3)
      CALL RSCL (4)
      CALL RSCL (5)
      CALL RSCL (6)
      CALL RSCL (10)
      FR= 1.0
      CALL SAMO ('IC')
      CALL RSCL (12)
      RETURN
      END
      SUBROUTINE SUB1
      COMMON FR
      CALL SSCL(13)
  400 WRITE(7,401)
  401 FORMAT(' SET THE FLOW RATE ')
      READ(7,410)  FFR
  410 FORMAT(F4.2)
      FFRR = FFR*100.0
      IF(FFR.LT. 0.0) GO TO 412
      IF(FFR.GT.1.25)  GO TO 412
      FR= FFR
      WRITE(7,420) FFRR
  420 FORMAT(' FLOW RATE = ',F5.1,' PERCENT FULL')
      GO TO 450
  412 WRITE(7,413)
  413 FORMAT(' FLOW RATE EXCESS THE LIMIT')
      GO TO 400
  450 CONTINUE
      CALL RSCL (13)
      RETURN
```

```
      END
      SUBROUTINE SUB2
      CALL SSCL(14)
      WRITE(7,640)
  640 FCRMAT (' SELECT 1 OR 6 GROUP DELAYED NEUTRONS')
  650 REAC (7,651) NN
  651 FORMAT(I1)
      IF (NN.EG.1)GO TO 655
      IF (NN.EQ.6)GO TC 660
      GO TO 670
  655 CALL SSRP (4)
      CALL SSCL (7)
      CALL RSCL (8)
      CALL SSRP (34)
      N=NN
      GO TC 680
  660 CALL SSRM (4)
      CALL RSCL (7)
      CALL SSCL (8)
      CALL SSRM (34)
      N=NN
      GO TO 680
  670 WRITE(7,675)
  675 FORMAT(' INVALID CODE')
      GC TO 650
  680 WRITE(7,681)  NN
  681 FORMAT(1X,I1,' GROUP NEUTRON')
      CONTINUE
      CALL RSCL (14)
      RETURN
```

```
      END
      SUBROUTINE XENON
      CALL SSCL(15)
  800 WRITE (7,801)
  801 FCRMAT (' SELECT NEUTRON FLLX LEVEL')
      CALL SLMO ('C')
      CALL SAMO ('PC')
      REAC (7,805) NF
  805 FCRMAT (I1)
      IF (NF.EQ.1) GO TO 840
      IF (NF.EC.2) GO TO 850
      IF (NF.EC.3) GC TO 860
      WRITE (7,810)
  810 FORMAT (' INVALID NEUTRON FLUX')
      GO TC 800
  840 CALL SFOT (60,C.C900)
      CALL SPOT (91,0.0160)
      CALL SFCT (93,0.6290)
      WRITE (7,845)
  845 FORMAT (' NEUTRON FLUX = 2.5*E14')
      GC TC 870
  850 CALL SPOT (60,C.0360)
      CALL SPOT (91,0.C064)
      CALL SFCT (93,0.2520)
      WRITE (7,855)
  855 FORMAT (' NEUTRON FLUX = 1.C*E14')
      GO TO 870
  860 CALL SFOT (60,C.C090)
      CALL SFOT (91,0.0016)
      CALL SFCT (93,0.0629)
```

```
      WRITE (7,865)
  865 FORMAT(' NEUTRON FLUX = 2.5*E13')
  870 CALL SAMO ('IC')
      WRITE (7,875)
  875 FCRMAT (' XENON FOISONING STUDY')
      REAC (7,880)IXE
  880 FORMAT (I1)
      IF (IXE. EQ.5) GC TO 890
      GC TO 891
  890 CALL RSCL (1)
      CALL RSCL (2)
      CALL RSCL (3)
      CALL SSCL (4)
      CALL RSCL (5)
      CALL SSCL (10)
      CALL SAMC ('IC')
      CALL SLMO ('R')
      CALL SAMO ('OP')
  891 CONTINUE
      CALL RSCL (15)
      RETURN
      END
      SUBROUTINE SSVP
      CIMENSION NV(10),VL(10),VVL(10)
      NV(1) = 96
      NV(2) = 61
      NV(3) = 31
      NV(4) = 1
      NV(5) = 21
      NV(6) =102
```

```
      NV(7) = 75
      NV(8) = 45
      NV(9) = 7
      CO 3000 I = 1,9
      CALL SACO ('A',NV(I))
      CALL DVMR (VL(I))
      IF (NV(I).EQ.61) GO TO 3300
      GC TC 3310
 3300 VVL(I)=VL(I)/2C00.0
      GO TO 3000
 3310 IF (NV(I).EQ.31) GO TO 3320
      GO TC 3330
 3320 VVL(I)=VL(I)*2C0C.0
      GO TO 3000
 3330 IF (NV(I).EQ.96) GO TO 3340
      GO TC 3350
 3340 VVL(I)=-VL(I)
      GO TO 3C00
 3350 IF (NV(I).EG.1 ) GO TO 3500
      IF (NV(I).EQ.21)GO TO 3500
      IF (NV(I).EQ.102) GO TO 350C
      IF (NV(I).EG.75 ) GO TO 3500
      VVL(I)=VL(I)
      GO TC 3000
 3500 VVL(I)=VL(I)*1C00.
 3000 CONTINUE
      WRITE (6,3100)(VVL(I),I=1,9)
 3100 FCRMAT (10X,'STEADY STATE VALUES'///,
     11X,'NEUTRCN LEVEL',5X,'=',F7.4/,
     21X,'REACTIVITY',8X,'=',E11.4/,
```

```
     31X,'FUEL TEMP.'8X,'=',F7.1,' F'/,
     41X,'COOLANT TEMP.'5X,'=',F7.1,' F'/,
     51X,'INLET CLT TEMP.'3X,'=',F7.1,' F'/,
     61X,'HEAT EXCH TEMP.',3X,'=',F7.1,' F'/,
     71X,'STEAM TEMP.'7X,'=',F7.1,' F'/,
     81X,'CONTROL RODS'6X,'=',F7.4/,
     91X,'INVERSE PERIOD',4X,'=',F7.4////)
      RETURN
      END
 CLOAD (GO),(UDCB,3),(LIB,USER,SYSTEM),(FORE,1600.).(TEMP,900)
0ASSIGN (F05,SI)
0ASSIGN (F06,LC)
0ASSIGN (F07,OC),VFC
 RCV
P         0      .5000
P         1      .2000
P         2      .5000
F         3      .2500
P         5      .5000
P         6      .5000
P         7      .2500
P        10      .0200
P        11      .0200
P        12      .5000
P        15      .8000
F        17      .4000
F        20      .4000
P        21      .5000
P        22      .5000
F        25      .6000
```

```
P          27      .6000
P          30      .5000
P          31      .100
P          32      .1000
P          33      .2000
P          35       .766
P          36      .1000
P          37      .2000
P          40      .6000
P          41      .9999
P          42      .5000
P          45      .4000
P          47      .9500
P          50      .2500
P          51      .2000
P          52      .4000
P          57      .1500
F          61      .5000
F          63      .8000
P          65      .5000
P          66      .6500
F          67      .5000
P          70      .2500
P          71      .2000
P          72      .2500
P          75      .3500
F          77      .0050
P          80      .5000
P          82      .0400
F          85      .2500
```

```
P      87   .2500
F      95   .0650
F      96   .9500
P      97   .0766
P     100   .2500
F     101   .2000
F     102   .1500
P     105   .0120
P     107   .0120
F     110   .5C00
P     115   .0010
P      62   .2088
P      90   .6960
P      92   .1512
P     116
    0   -.5000
    1    .5000
    2   -.6000
    5    .5000
    6    .0000
    7   -.6500
    9    .0000
   10   1.0000
   11    .0000
   12   -.1030
   13    .2070
   15   1.0000
   16   -.2070
   20   -.4000
   21    .4000
```

```
 22       .4000
 30      -.5000
 31       .5000
 34      -.0650
 35       .3250
 36      -.3250
 38       .0650
 40      -.6000
 41       .1037
 45      1.0000
 46      -.3500
 50      1.0000
 61       .0000
 62       .0000
 63       .0000
 64       .0000
 65      -.5000
 66       .5000
 70      1.0000
 71       .6000
 72      -.6000
 75       .3500
 80      -.5000
 85      1.0000
 94      1.0000
 95     -1.0000
100      1.0000
101      -.4000
102       .5000
105      -.0017
```

```
 110      .5000
 112     -.5000
 116
FIN
```

VITA

Edmond Chen was born in Peking, China, 13 January, 1946. His secondary education was obtained in Peking 25th School from which he graduated in 1963. In September, 1968 he entered Louisiana State University at Baton Rouge, where he received a Bachelor of Science in Electrical Engineering in May, 1972.

In September, 1972 he enrolled in the Graduate School of Louisiana State University. At present, he is a candidate for a degree of Master of Science in the Department of Nuclear Engineering.