

DYNAMIC SIMULATION OF
A PRESSURIZED WATER REACTOR

A Thesis

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ABSTRACT

The purpose of this thesis is to present to the Louisiana State University Nuclear Science Center the equipment and the procedure for the simulation of a pressurized-water-cooled nuclear reactor steam generation plant operation on an analog-digital hybrid computer.

Primary attention is focused on lumped-parameter dynamic equations (the so-called point-reactor and point-heat exchanger models). The spatially-dependent reactor and spatially-dependent heat exchanger models are not considered in this presentation. However, consideration of these models is found in the preliminary design of the simulator.

From the need expressed by the Nuclear Science Center for a simulator arose the study of building the nuclear reactor-power-systems simulator on an analog computer. The well-established field of reactor simulation offers many solutions to the problem.

The primary loop of the nuclear-reactor-power systems is found to be well documented. Restrictions imposed by the assumptions that the primary coolant flow rate is constant during all transient periods of operation and that the average steam temperature in the secondary loop is constant at all time are eliminated with the aid of a reactor kinetics network and the XDS Sigma 5 Digital Computer. The reactor kinetics network permits a reduction in the number of components used in the simulation of the reactor kinetics equation. The savings

realized in this are used to model the secondary loop. The XDS Sigma 5 Digital Computer is used in conjunction with the Electronic Associates, Inc., (EAI), 680 Analog Computer and the EAI 693 Data Conversion System to regulate the primary coolant flow rate.

The nuclear-reactor-power systems are modeled in real time. The xenon poisoning during start up and shut down is time scaled to permit a study of the problem in a reasonable amount of time. Therefore, the xenon start up and shut down problem is treated separately.

A self-contained step-by-step procedure which is used to operate the simulator is found in the presentation.

CHAPTER ONE

INTRODUCTION

The simulation of nuclear reactor power systems is valuable in a nuclear engineering curriculum, for reactor operator training, and for public demonstrations of reactor operation.

Classroom training in basic reactor control principles and reactor theory is more meaningful to the student if he is given practical exercise in the subject. The student should have a clearer understanding of control concepts if he simulates theoretical control processes taught in the classroom on a working reactor model that closely reproduces the behavior of a power reactor. Some changes in the parameters of the model may allow one the opportunity to observe the characteristics of several other types of nuclear reactors.

The reactor simulator package described in this work is such that someone with an introductory course in nuclear engineering should be capable of using the device. This simulator is documented with both general and step-by-step instructions for its use.

The three main types of control stimuli are augmented from real time parameters to scaled machine parameters so that adequate control data can be obtained in a reasonable amount of time. This is necessary because of the wide range of times of interest. Control rod effects are in the milli-second domain. Temperature effects are in the seconds-to-minutes domain. Fission product effects are in the hours-to-days domain. Both magnitude of the effect and time are scaled to allow control studies in each domain.

The effects of the above stimuli to various reactor outputs can be monitored. The reactor vessel average, inlet, and outlet temperatures of the coolant; the fuel temperature; and the normalized thermal neutron concentration are among the outputs capable of being monitored on this simulator. The average heat exchanger temperature and the secondary loop steam temperature are other outputs that can be indicated. The response of these reactor parameters to changes in power plant load can also be studied.

The linearized mathematical model of the reactor power systems is a valuable tool for developing insight into the dynamic behavior of the system. The coupled linearized differential equations can be translated into state and output equations, which are then used to develop the systems transfer functions. Future thesis topics in this area could include studies of systems stability for other models. The Nyquist, Bode, and Root Locus methods could be used to yield distinct and explicit relationships between manipulated and controlled variables and thereby determine the plant characteristics. Study of the plant characteristics leads directly to the conceptual development of the reactor control system. Well-known linear control design theory can then be applied to solve basic control problems.

Linear control design theory can also be applied to obtain near-optimal characteristics using time and frequency domain techniques. Nonlinearities and time variant effects can be evaluated in an orderly fashion by progressive modifications to the linearized model.

The simulator is a relatively inexpensive, flexible, efficient, safe, and speedy method of teaching basic reactor control principles in a nuclear engineering curriculum. Training with the simulator

offers the advantage of actual operating conditions without the disadvantage of an on-line reactor operation that has kilowatt hours as its primary objective. The simulator eliminates the use of valuable plant time and the possibility of costly mishaps by inexperienced trainees that could occur on a real reactor. The observation of reactions in real or scaled time for both normal and abnormal conditions is another major advantage that a student receives from using the proper model. Also, the response of the system to emergency conditions can be safely studied. Currently this is of great interest to the nuclear community because of the controversy concerning the adequacy of emergency core cooling systems that must function after a loss-of-coolant accident.

2.1. The hardware, software, and documentation in this investigation provides the Louisiana State University Nuclear Science Center with an extremely useful tool. Nuclear plant operations may be effectively studied by a large number of students at a minimal cost.

CHAPTER TWO

BASIC ANALOG AND HYBRID COMPUTATION IN MODELING THE REACTOR POWER SYSTEMS

This chapter introduces the basic concepts of analog computers. The physical system modeled is a Reactor-Power-Systems Simulator.

Along with the introduction to basic analog computations, the presentation of the particular simulator is made. The method used to accomplish the simulation along with the basic problems encountered during the design of the model is discussed.

2.1. Analog Computation¹

The starting point of most problems studied with a computer is a physical system that must be synthesized. The problem is to synthesize the nuclear reactor power systems so that the completed physical system meets the performance requirements specified. The purpose of this section is to familiarize the reader with the techniques used to solve the above problem by means of an analog computer.

To illustrate how the use of an analog computer can aid synthesis, the problem solving process is outlined. The first step in any synthesis is to write a set of equations governing the actions of the system. The occurrence of differential equations is the usual result of describing a system mathematically. Often, these equations are ordinary differential equations with time as the only independent variable.

Also some mathematical techniques can be used to separate a partial differential equation into several ordinary differential equations. The study of systems described by simultaneous differential equations is greatly simplified by the use of an analog computer.

The second step in the synthesis process is to predict the performance of the systems equations. The predictions made in the above process determined the accuracy of the systems. A method used to determine the accuracy of the equations is to construct the physical system by building a mathematical model.

The model must meet the following requirements:

1. It must accurately obey the given set of equations.
2. It must be easy to construct as well as flexible enough to apply to a large class of problems.
3. It must have input and output parameters that can be accurately measured.
4. It must be understandable to the user.

The analog computer meets these requirements for ordinary differential equations. One independent variable, time in the computer, is available, and as many dependent variables as required can be used by employing enough computing equipment.

The physical system so modeled is in the form of electrical circuitry. Physical quantities become voltage outputs and inputs. The information at the inputs, outputs and intermediate points in the computer circuit is in the form of a continuous physical quantity.

The output responses can represent the end point of an analysis of a physical system if the outputs show a desired behavior of the system. However, after the computer model has been set up, it is

quite easy to adjust the system parameters and observe the behavior of the model to determine optimum values of the parameters. This makes synthesis by a trial-and-correction-of-error procedure practical because each trial requires a small amount of time to determine the response of the model. In contrast to the digital computer, the analog computer will trace out the behavior of a system to a given input stimulus in about the same time interval for either large or small problems. The reason for the difference is that the digital computer has one central arithmetic unit that works on the various steps of a problem in sequence so that the larger problem with more steps will require more time. In the analog computer, the units are working simultaneously so that adding more units to increase the size of the problem does not require an increase in computational time.

There is one further advantage to using an analog computer to study a complex system. Within the model, much information is available to describe the behavior of parts of the system. This information is available simultaneously within the information of the overall system performance and is of great value in establishing the rating of individual parts of the system.

2.1.1 Analog Computer Study

Once the equations to be studied are available, the study with an analog computer follows a standard sequence of operations.

1. Develop an ideal block diagram of the system under study.
2. Adapt this block diagram to the peculiarities of the computing equipment.
3. Establish scale relationships between the analog computer voltage units and the physical variables.

4. Program the problem on the computer and make a check for reasonable operation of the computer.
5. Obtain the required solution plots.
6. Reformulate the original problem on the basis of the results obtained and generate more computed data.
7. If necessary, condense the data obtained from the computer.

Many excellent books on analog computation are written. Such a book is Introduction to Analog Computation by J. Robert Ashley.*

Of particular interest to the operator of the reactor simulator, however, are the methods used in time scaling and in magnitude scaling of particular physical systems to meet the range of voltage units provided by the analog computer.

2.1.1a Magnitude Scaling

It is most important to establish a known relationship between voltages in the computer and the variables in the problem. These relationships must include the proper units to insure dimensional consistency.

The relation between a problem variable and the computer voltage representing the variable is determined by the maximum output capacity of the device which generates the voltage in the computer and the absolute value of the maximum expected of this variable. The relation between such a voltage and a problem variable is of the form

$$[X] = \frac{C_{\max}}{|X_{\max}|} X$$

* Available from John Wiley and Sons, Inc., publisher, New York, 1967.

where X is a problem variable, $|X_{\max}|$ is the absolute value of the maximum expected of this variable for a given solution, C_{\max} is the maximum voltage that can be safely attained as the output of a computing device (e.g., an integrator), and $[X]$ is a voltage representing X in the computer.

The above equation is called a scale factor equation and

$$\frac{C_{\max}}{|X_{\max}|}$$

is called the scale factor. A scale factor equation is required for every dependent variable in the problem. It is not required to know the exact maximum value of the problem variable X . An estimate of the maximum value is sufficient.

For example, letting $|X_{\max}| = 1000$, and $C_{\max} = 10$ volts, would give a scale factor of $1/100$. Supposing that the value X is 500, then the value of $[X]$ measured on the analog computer is

$$[X] = \frac{C_{\max}}{X_{\max}} X,$$

$$[X] = 5 \text{ volts.}$$

The analog diagrams used in the solution of the reactor-power-systems simulator are labeled with outputs that have a direct bearing to the physical problem. The outputs are labeled with the problem variable being multiplied by the scale factor. The problem variable can be obtained by simply dividing the output variable by the scale factor. Magnitude scaling is considered in further detail in this chapter when one considers the reactor-power-systems simulator.

2.1.1b Time Scaling

It is also important to establish a known relationship between real time and analog time. Certain conditions require the use of a time scaling technique. Problems involving extremely long or extremely short time constants require time scaling to facilitate the synthesis of the physical system within the computing range of the analog computer.

If one considers the relation

$$\tau_a = \beta t$$

where β is a scale factor, τ_a is the new analog time variable, and t is the real time variable; substitutes τ_a/β for t into the ordinary differential equations describing the physical system; and multiplies every term in the equation by β ; the physical coefficients of the equation will change such that the time constant of the problem will increase or decrease depending upon the value of β . A value of β less than one will cause the solution of the problem to be obtained in a smaller period of time. A value of β greater than unity will cause the solution of the problem to be obtained in a longer period of time.

As an example, if one desires to make two hours of physical operation to be studied in one second on the analog computer, the value of β would be 1/7200. Time scaling is presented in further detail in Appendix C in connection with the xenon shut down problem.

2.2 Reactor-Power-Systems Simulator

The analog computer is used to model the equations that describe the Reactor-Power-Systems Simulator. In this section, the basic model will be described in detail. Along with this description, the determination of time constants for the various power systems,

the determination of the controller time constant and controller gain, the addition of a reactor kinetics network to simulate the six group delayed neutron approximation, the implementation of the secondary loop to simulate variable load conditions on the reactor core, the modeling of xenon poisoning, and the hybridization of the reactor simulator to accommodate a variable primary loop coolant flow are discussed.

2.2.1 Nuclear-Reactor-Power-Systems Simulator

The simulation of the reactor-power-systems simulator on the Electronic Associates, Inc. (EAI) 680 Analog Computer and the Sigma 5 Digital Computer provides a convenient, rapid and accurate method of analyzing the dynamic response of a reactor-power-systems to control stimuli. The performance of the reactor power plant and control system is evaluated from the recording of the systems variables, represented in the simulator by direct-current voltages. By this means, transient and stability studies are made. Systems parameters, initial values, and input functions are changed conveniently by simple adjustment of the simulator setup.

The simulation of the reactor, power plant, and control system is accurately defined in the power range associated with the top two decades of output power below the full power rating of the reactor. This condition is satisfied by using a normalized power level to describe the dynamic response of the reactor.

The simulation shown in Figure 2.1 involves equations for the following processes:

1. Neutron generation described by the kinetics equations.

- | | |
|-------------------------------------|---------------------------------|
| 1. Reactor Core | 9. Comparator |
| 2. Reactor Vessel | 10. Averaging System |
| 3. Inlet Plenum | 11. Pump for Primary Loop |
| 4. Outlet Plenum | 12. Boiler Feed Water Pump |
| 5. Control Rods | 13. Throttle |
| 6. Control Rods Drive Unit | 14. Turbine |
| 7. Control System | 15. Load (Electrical Generator) |
| 8. Reactor Kinetics (Neutron Level) | 16. Condenser |

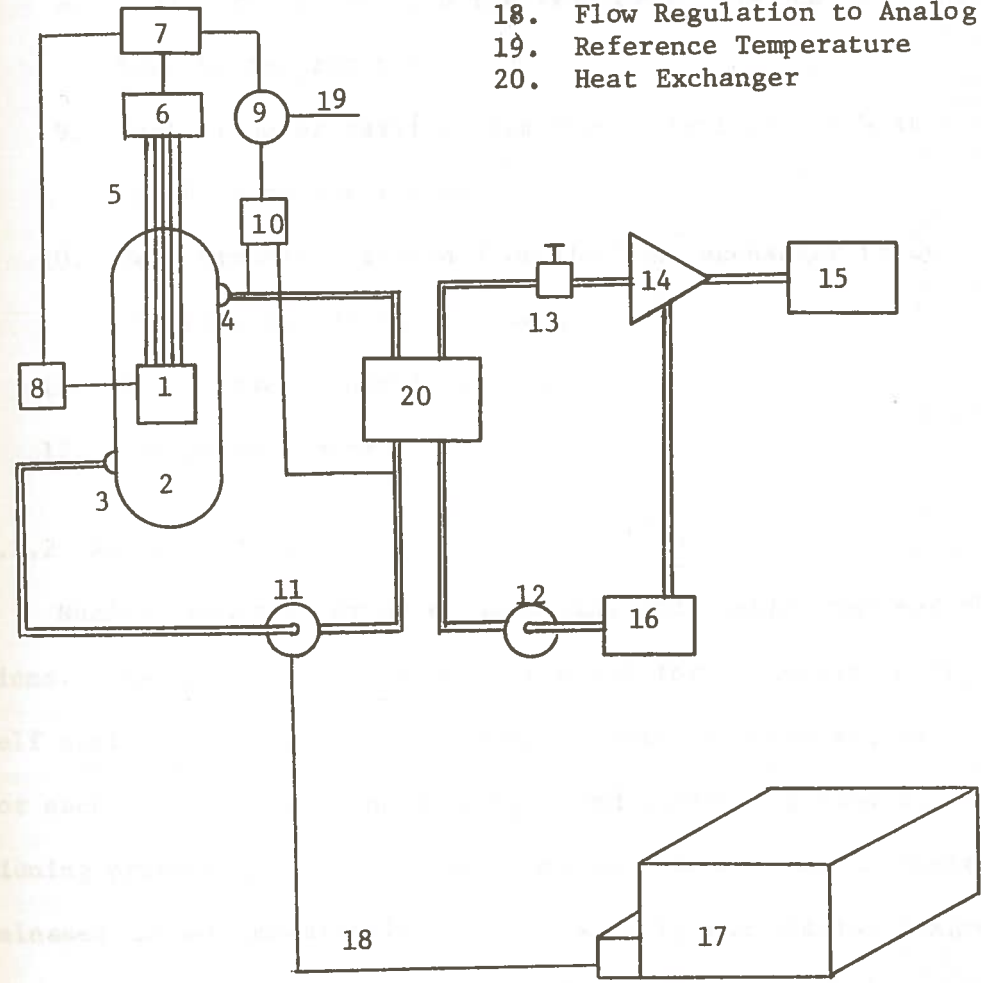


Figure 2.1
Block Diagram Of PWR Power Plant And Control System

2. Formation of poison described by xenon-iodine equations.
3. Reactivity due to temperature.
4. Reactivity due to control-rod position.
5. Fuel element heat transfer.
6. Heat transfer from fuel elements to the coolant.
7. Mixing in the reactor inlet and outlet chambers.
8. Transport delays from the reactor to the heat exchanger and back to the reactor.
9. Heat transfer carried from the coolant to the heat-exchanger and back to the reactor.
10. Heat transfer carried from the heat exchanger through the throttle by saturated steam.
11. Power-level control system.
12. Period indicator.

2.2.2 Nuclear Reactors

Nuclear reactors produce, maintain, and control nuclear chain reactions. The correct conditions must exist for the chain reaction to be self sustaining. At least one neutron must be produced, on the average, for each nucleus capturing a neutron and undergoing fission. The fissioning produces, in turn, more neutrons. Some of these neutrons are released almost immediately after fission by the fission fragments; others are emitted later by the fission fragments and their radioactive decay products. Still others may be produced by the action of the gamma rays that accompany the fission process.

All of the neutrons resulting from fission are usually classified under two headings, "prompt neutrons" and "delayed neutrons".

The "prompt neutrons" are those which are released almost immediately after fission. The "delayed neutrons" are those which are released later by various radioactive decay processes. Both classes of neutrons are capable of producing further fissions.

In the self-sustaining fission process taking place in a reactor the neutrons resulting from fission move about for a time inside the reactor, losing their initial kinetic energy in successive collisions with the nuclei of various materials in the reactor. Ultimately, every neutron suffers one of three possible fates; (1) it may leak out of the reactor; (2) it may be absorbed by a nucleus which does not fission; (3) it may be absorbed by a nucleus which does fission, and which, in turn, produces more neutrons. Assuming that there are no sources of neutrons in the reactor other than fission, the following holds true: if, of all the neutrons in the reactor, an average of one neutron produced per fission causes further fission, a constant fission rate results.

By changing the leakage and absorption of neutrons so as to vary the average number of neutrons per fission that causes further fission, one can control the fission rate. This condition is expressed in terms of a multiplication factor, defined as the ratio of the number of neutrons of any generation to the number of corresponding neutrons of the immediately preceding generation.

Reactor control, however, is generally described in terms of a quantity called "reactivity", which is a measure of the deviation of the multiplication factor (K) from unity. The relation of the multiplication factor to the reactivity of the reactor is expressed as

$$\delta K = (K - 1)/K. \quad (2.1)$$

If the multiplication factor is unity, then $\delta K = 0$ and the reactor is in a critical state. If the multiplication factor is greater than unity, then δK is positive, and the reactor is in a super-critical state. But if K is less than unity, then δK is negative, and the reactor is in a subcritical state.

The kinetic energy of fission degenerates immediately into heat that can be used to produce large quantities of useful power. The proper technique of heat removal is an important requirement in reactor design. The power output must be controlled to meet the power demand and stay within the over-all performance limits of the system, including those of safety. Since the power output is proportional to the neutron flux in the reactor, the output can be controlled through the flux, usually by movable control rods having a high absorption cross section (absorption-affinity) for neutrons. When the control rods are withdrawn, fewer neutrons are absorbed in the rods and the reactivity of the reactor increases. When the control rods are inserted, absorption increases and reactivity decreases. In the closed loop, automatic control system, the power demanded is compared with the power output to produce an error signal that positions the control rods so that the power output is equal to the demand.

2.2.2a Reactor Kinetics

The relation between the neutron population, n , and the reactivity, δK , of a stationary fuel reactor is well approximated by the following set of differential equations:

$$\frac{dn}{dt} = \delta K n / \ell - \beta K n / \ell + \sum_{i=1}^6 \lambda_i C_i + S, \quad (2.2)$$

$$dC_i/dt = -\lambda_i C_i + \beta_i nK/\ell, \quad (2.3)$$

where: n = neutron concentration (neutrons/cubic centimeter),

δK = reactivity,

ℓ = prompt (effective) neutron lifetime (sec.),

β_i = delayed neutron fraction associated with group "i",

β = total delayed neutron fraction,

K = multiplication factor,

λ_i = decay constant associated with group "i" (sec^{-1}),

C_i = delayed neutron precursor concentration associated with group "i" (atoms/cubic centimeter),

S = neutron source (neutrons/sec.).

The source term, S , includes the neutrons which are produced by the action of cosmic rays, the neutrons which result from spontaneous fission, and the neutrons which are produced by the radioactive neutron source that are initially inserted in the reactor to prime the fission process; S also includes the photo-neutrons that are produced at an essentially constant rate by the action of the gamma radiation emitted by the very-long-lived radioactive fission products.

Usually the reactor is operated at a level in which the fission-produced neutrons overshadow the independent-source-produced neutrons, and to a good approximation, S is negligible except when the reactor is being started up.

The above equations require at least seven integrator components on the EAI 680 Analog Computer System. The number of integrators can be reduced by using a plug-in resistor and capacitor (RC) network called the "reactor kinetics network". The RC network is dis-

malized neutron flux. The one group delayed neutron approximation used in the reactor kinetics equation determines the value of the reactor period. The RC network is not used in the determination of T . Using the one group delayed neutron approximation does not inhibit the accuracy of the problem significantly.

2.2.3 Nuclear Power Plant

The majority of nuclear reactors now in operation are of the heterogeneous type, in which the reactor core is made up of solid fuel elements whose shape and arrangement in the core permits the heat which is generated by fission in the fuel elements to be carried away by a primary gas or liquid coolant passing through the core.

The primary coolant passes through the core to pipes in which it is transported to the heat exchanger. In the heat exchanger, the heat is transferred through the walls of the tubing to the secondary loop feedwater which is converted to steam. The steam travels through the throttle and drives the turbine, condenses, and then returns to the heat exchanger as feedwater.

2.2.3a Reactor Thermal System

The fuel elements are generally composed of an inner fissionable material which is surrounded by a thin protective layer of non-fissionable material called "cladding". The process of heat transfer from the inner fissionable material, through the cladding, into the coolant, and out of the core is most accurately described by a set of partial differential equations in which time and spatial coordinates are independent variables. Linearizing the fuel element-to-coolant heat transfer results in the following approximate equations describing

cussed in detail in Chapter Three. Another method of reducing the number of equations is to use a one group approximation to model the six groups of delayed neutrons.

The task of solving the sixth degree equation can be avoided by assuming that the set of delayed neutron emitters is replaced by a single emitter. The transient response will be only qualitatively correct and applicable only to small changes in K . The solution is easy to obtain, however, and serves to display the distinction between behavior at short and long times after the disturbance in K is applied. The comparison of results between a six group delayed neutron approximation and a one group delayed neutron approximation is presented in Chapter Three.

2.2.2b Reactivity

The total reactivity is the sum of the built-in reactivity, reactivity due to xenon poisoning, reactivity due to temperature, and reactivity due to position of the control rods. The total reactivity is expressed as

$$\delta K = \delta K_f + \delta K_p + \delta K_T + \delta K_c, \quad (2.4)$$

where: δK_f = built in reactivity of the fuel,

δK_p = reactivity due to poison concentration,

δK_T = reactivity contribution due to the fuel temperature,

δK_c = reactivity contribution due to control rod position,

The reactivity caused by the concentration of the fuel, geometry of construction, etc., is called built-in reactivity. The built-in reactivity is altered by self-induced changes within the reactor core while the reactor is operating. As the reaction proceeds, the primary

fissionable nuclei become depleted, causing a change in reactivity. The change may take the form of an increase or decrease in reactivity depending on the degree of breeding* taking place within the reactor. The variation of reactivity with time caused by fuel depletion will be neglected in the simulation since it takes place slowly.

Another type of self-induced reactivity is caused by the formation of poisons. The poisons, materials with high-absorption cross sections for thermal neutrons, are formed in the fuel elements. The poison formation in this simulation is xenon-135. The concentration changes have a negligible effect of overall reactivity compared to the effect of fuel temperature and control rod movement. For this reason, δK_p is assumed to be constant in the simulation. It should be noted, however, that the effect of poisons is quite important during simulation of start up and shut down procedures. For this reason a separate section is included to simulate the xenon poisoning problem during start up and shut down. This section is separate from the reactor-power-systems simulation since difficulty is encountered when attempting to simulate the relatively long time constant found in the xenon poisoning problem in real time. The xenon poisoning problem is discussed in further detail in Chapter Six.

The temperature coefficient of reactivity is an important control system parameter. Reactors with negative temperature coefficients possess the desired inherent self-regulation, (i.e., as the reactor

* When the average number of fissile atoms produced in a reactor per fuel atom consumed either by fission or absorption is greater than one, the reactor is said to "breed".

heats up, its reactivity is reduced). The reactivity change is caused by a change in the temperature of the fuel and of the moderator. Assuming that the reactivity contribution due to the moderator temperature is small in comparison to the reactivity contribution caused by the fuel temperature, the temperature coefficient of reactivity becomes that which is caused by the temperature of the fuel (T_f) alone. This is represented by the equation

$$\delta K_T = \alpha(T_f - T_r), \quad (2.5)$$

where: T_r = temperature coefficient of reactivity reference temperature (e.g., temperature at which temperature contribution to reactivity is zero in °F),

α = temperature coefficient of reactivity in units of reactivity per degree of temperature change,

δK_T = reactivity contribution due to the fuel temperature.

The amount of reactivity released by the control rods can be expressed as a function of the position of the rod. The position of these rods is continually adjusted to maintain the desired temperature and power output. The discussion of the control system used to position the rods will be described in this chapter.

2.2.2c Reactor Period

The period, T , of a reactor is defined as the amount of time that the reactor takes to change its power level by a factor of e ($e \approx 2.716$). It can be expressed as:

$$T = \frac{n}{dn/dt} \cdot \quad (2.6)$$

In the simulation of the reactor, the inverse period is obtained by dividing the derivative of the normalized neutron flux by the nor-

the heat transfer process in the core:

Fuel element heat transfer,

$$M_f C_f \frac{dT_f}{dt} = n \Delta H_f - UA(T_f - T_c); \quad (2.7)$$

Fuel element-to-coolant heat transfer,

$$M_c C_c \frac{dT_c}{dt} = UA(T_f - T_c) - W_c C_c (T_{oc} - T_{ic}), \quad (2.8)$$

where: T_c = average coolant temperature ($^{\circ}\text{F}$),

T_f = average fuel temperature ($^{\circ}\text{F}$),

ΔH_f = heat of fission (BTU-cc/sec.-neutron),

U = overall coefficient of heat transfer in the reactor core (BTU/sec.-ft.²- $^{\circ}\text{F}$),

A = heat transfer area in reactor (sq. ft.),

M_f = effective mass of fuel and moderator (lb.),

C_f = effective specific heat of moderator and fuel (BTU/lb.- $^{\circ}\text{F}$),

M_c = mass of coolant (lbs.),

C_c = specific heat of coolant (BTU/lb.- $^{\circ}\text{F}$),

W_c = mass flow rate of coolant (lb./sec.),

T_{ic} = temperature of coolant entering reactor ($^{\circ}\text{F}$),

T_{oc} = temperature of coolant leaving reactor ($^{\circ}\text{F}$).

A by-product of this linearization is that the inlet, average, and outlet temperatures of the coolant flowing in the core are related by the equation

$$T_c = \frac{T_{ic} + T_{oc}}{2}. \quad (2.9)$$

This approximation is obviously crude, but is nevertheless considered sufficiently accurate for approximate engineering studies of nuclear

plant dynamics. This equation may be combined with Equation 2.8 to obtain

$$M_c C_c \frac{dT_c}{dt} = UA(T_f - T_c) - W_c C_c (2T_c - 2T_{ic}). \quad (2.10)$$

Equation 2.7 states that the rate of increase of thermal energy in the fuel is equal to the rate of heat transfer from the fuel to the coolant plus the rate at which heat is generated in the fuel by fission. Here, the thermal resistance of the fuel, cladding, and coolant are lumped into one overall thermal resistance, equal to the reciprocal of the product of the heat transfer coefficient U and the area A . The heat generation is assumed proportional to n , which neglects the slowly varying heat generation due to the radioactive decay of long-lived fission products.

Equation 2.8 which describes the transfer of heat energy between the fuel elements and the flowing coolant can be given, verbally, as: The total heat energy accumulated by the coolant in the reactor equals the difference between the heat input by the fuel and the total heat removed by the coolant.

2.2.3b Heat Exchanger and Steam Generator

In the heat exchanger, the coolant flows through a tube bundle surrounded by the heat exchanger water, and then is returned to the reactor for reheating. The heat-exchanger water is converted to steam by heat transfer through the walls of the tubing. The steam travels through the throttle and drives the turbine, condenses, and then returns to the boiler as feedwater.

The equations governing the performance of the steam generator and of the heat exchanger are similar to the one governing the heat

transfer between the fuel and the coolant in the reactor core. That is, the total heat energy accumulated by the coolant in the heat exchanger equals the difference between the heat input and the total heat transferred to the secondary loop. On the steam (secondary) side of the heat exchanger, the rate of heat storage in the heat exchanger metal, the steam, and the water is equal to the difference between the rate at which heat is transferred across the exchanger tubes and the rate at which it is delivered to the turbine.

The equation governing the heat transfer in the heat exchanger is

$$M_x C_c \frac{dT_x}{dt} = W_c C_c (T_{ix} - T_{ox}) - U_x A_x (T_x - T_s), \quad (2.11)$$

where: M_x = mass of coolant in heat exchanger (lbs.),

U_x = overall coefficient of heat transfer in the heat exchanger (BTU/sec.-ft.²-°F),

T_x = average coolant temperature in heat exchanger (°F),

T_s = average temperature of steam in heat exchanger (°F),

T_{ix} = temperature of coolant entering the heat exchanger (°F),

T_{ox} = temperature of coolant leaving the heat exchanger (°F),

A_x = heat transfer area in heat exchanger (sq. ft.).

This equation is linearized as is Equation 2.8. Therefore the relationship

$$T_x = \frac{T_{ox} + T_{ix}}{2} \quad (2.12)$$

is valid for describing the operation of the heat exchanger.

Thus a more convenient form of Equation 2.11 is

$$M_x C_c \frac{dT_x}{dt} = 2W_c C_c T_{ix} - (U_x A_x + 2W_c C_c) T_x + U_x A_x T_s. \quad (2.13)$$

The equation governing the heat transfer process on the steam side

of the heat exchanger is²

$$(M_m C_m + M_s C_s) \frac{dT_s}{dt} = U A (T_x - T_s) - K_a A p(T_s), \quad (2.14)$$

where: M_s = mass of steam and water in heat exchanger tube metal
(lbs.),

M_m = mass of heat exchanger tube metal (lbs.),

C_m = specific heat of heat exchanger tube metal (BTU/lb.-°F),

C_s = average specific heat of steam and water in heat
exchanger (BTU/lb.-°F),

K_a = throttle constant (BTU/psia-sec.),

A = relative throttle opening (full open, $A = 1$),

$p(T_s)$ = pressure as a function of steam temperature

($p(T_s) = N T_s$ psia),

N = one psia/°F.

Several simplifying assumptions are made in obtaining Equation 2.13 and 2.14. The first of these assumptions is that the heat transfer between the primary coolant side and the steam side of the heat exchanger is represented by means of a single area and a single heat-transfer coefficient. The second of these assumptions is that the thermal capacity of the heat exchanger metal is lumped with that of the steam and water. Actually, there is a time delay associated with a transfer of heat between metal and steam. Neglecting this time delay will change the shape of the initial transient of output power encountered with thermal changes, but this approximation has little or no effect on the basic kinetics of the over-all loop. The third assumption is that the power output has been taken to be proportional only to the flow of steam through the throttle, assuming

that the enthalpy of the saturated steam is constant. The further assumption is made that the time spent by the coolant in passing through the heat exchanger is negligible in comparison with the time spent in the pipes and that the heat exchange in the heat exchanger is integrated and treated as though it occurred at one point.³

These assumptions limit the accuracy of the descriptive equations. However, the errors involved in these assumptions are usually less than the amount of uncertainty in the engineering values of the coefficients used.⁴

2.2.3c Simulation of Mixing Effects

There are generally a number of so-called "mixing chambers" in the reactor coolant loop where the coolant entering the chamber mixes with the coolant already in the chamber before making its exit. The inlet and outlet plenums of a reactor, for example, are usually regarded as mixing chambers. The effect of mixing on the circulation of temperature transients in a reactor coolant loop can be illustrated in terms of a idealized mixing chamber in which the entering coolant is instantaneously mixed with coolant in the chamber. The chambers are treated as stirred tanks. The heat balance equation for this chamber is the rate at which thermal energy is accumulated in the mixing chamber equals the rate at which the thermal energy is carried in minus the rate at which thermal energy is carried out. The equations governing this process for the inlet plenum and for the outlet plenum are

$$C_c M_i \frac{dT_{ic}}{dt} = W_c C_c (T_i - T_{ic}), \quad (2.15)$$

$$C_c M_o \frac{dT_o}{dt} = W_c C_c (T_{oc} - T_o), \quad (2.16)$$

where: T_o = coolant temperature at the outlet of the reactor
 outlet plenum chamber ($^{\circ}\text{F}$),
 M_o = mass of coolant in outlet plenum chamber (lbs.),
 T_i = coolant temperature at the input to the reactor inlet
 plenum chamber ($^{\circ}\text{F}$),
 M_i = mass of coolant in the inlet plenum chamber (lbs.).

2.2.3d Transport Delay Simulation

The propagation of temperature transients from one point to another in the reactor coolant loop is delayed by the time required for the coolant to traverse the distance between the two points. In the pipe lines joining the reactor and the heat exchanger, the coolant tends to move in a uniform manner, with essentially the same flow velocity over its flow cross section, and therefore tends to preserve the temperature-vs.-distance profile in the direction of flow. That is, the coolant acts like a continuous temperature recording medium which preserves the temperature variation introduced at one end of a pipe line. For constant flow, the temperature of the coolant at the inlet of the heat exchanger is approximated by

$$T_{ix} = T_o(t - \tau_o), \quad (2.17)$$

where: τ_o = time delay necessary for the coolant to flow from the
 outlet plenum chamber of the reactor core to the inlet
 of the heat exchanger,

= four seconds for the model considered.

The temperature of the coolant at the inlet plenum chamber is approximated by

$$T_i = T_{ox}(t - \tau_i), \quad (2.18)$$

where: τ_i = time delay necessary for the coolant to flow from the outlet of the heat exchanger to the inlet plenum chamber.
 = four seconds for the model considered.

The delay phenomenon just described, logically called the "transport delay", is the result of the transport of coolant from one point to another. The transport delays inherent in the reactor coolant loop are of major concern to the designer of plant controls who must tailor the response characteristics of the controls to satisfy the timing restrictions imposed by transport delay.

Transport delay effects are approximated by the use of standard computing elements found in the analog computer. Transport delay is simulated by the transfer function $e^{-\tau s}$ where s is the Laplacian operator and τ is the time delay. The simulation of this transfer function can be described by the second order Pade' approximation:⁵

$$e^{-\tau s} = \frac{1 - \tau s/2 + \tau^2 s^2/12}{1 + \tau s/2 + \tau^2 s^2/12} \quad (2.19)$$

2.2.4 Simulation of Controls

Basically, the control system must regulate the power reactor so that power is delivered to meet the demand. The reactor and power plant must be sufficiently stable and must have good transient performance. Also, the range of system variables must be compatible with the limitations of the equipment and materials, and controls must be provided to shut down the reactor quickly in case of a major system failure.

2.2.4a Steady-State Programming

The pattern that the temperatures, pressures, and flows

throughout the plant assumes as a function of power output is called the program. One type of desirable program for a nuclear power plant is the program whereby the average temperature of the primary coolant is constant regardless of the power output. For metal-alloy-fueled reactors having a negative temperature coefficient this is the natural program of the reactor and the one that requires the least amount of external control. A disadvantage of the constant average-temperature program is that the steam pressure in the secondary systems varies over a large range.

Another type of program is the constant steam-pressure program. Under this, the steady-state steam pressure is constant as a function of power level, and the coolant steady-state temperature is permitted to change. The constant-average-temperature program is the one preferred by the reactor, and the constant steam-pressure program is the one preferred by the secondary steam system. The type of control program used is the constant average-temperature program.

2.2.4b Power-Level Control

In large power-distribution systems, the load dispatcher controls the primary power level by ordering an output delivered to the bus bars by the power plant to meet the load requirements of the distribution system. The power plant is controlled manually or automatically to produce the desired power-level output. Automatic control of the power level is achieved by adjustment of the control rods in accordance with an error signal representing the difference between the power-demand signal and the power output. The power output is determined by measurement of the neutron flux, and the power-demand signal is

determined by computing a signal in accordance with the control program. The type of control program depends on the inherent stability and the required performance of the reactor and power-plant system. For a constant average-temperature program, a method to generate the power demand signal, n_o , is⁶

$$n_o = \tau_c K_c \epsilon + K_c \int_0^t \epsilon dt, \quad (2.20)$$

where: τ_c = controller time constant (sec.),

K_c = controller gain (neutrons/ $^{\circ}$ F-sec.-cm.³),

ϵ = $(T_{Ref} - T_{ave})$ in $^{\circ}$ F,

T_{ave} = $(T_{ox} + T_{oc})/2$ in $^{\circ}$ F,

T_{Ref} = reference temperature ($^{\circ}$ F).

The reactor power demand signal, n_o , is generated by a proportional-plus-integral controller which operates on a so-called "average temperature signal*", equal to one half the sum of the reactor outlet temperature, T_{oc} , and the heat exchanger outlet temperature, T_{ox} . The purpose of this controller as mentioned above is to regulate the reactor power, through n_o , so as to maintain a constant average temperature, equal to T_{Ref} , under steady state conditions,

* Two idealizations have been made to simplify the analog representation: (a) The time lags of the thermometers have been neglected. (b) The thermometers have been placed at the outlets of the heat transfer regions of the reactor and heat exchanger, rather than in the outlet pipes of the vessels (as is the usual practice).

and to prevent undesirable excursions in average temperature during variations in the steam flow.

2.2.4c Comparator

Along with the power level control scheme there is an $(n_o - n)/n$ comparator whose purpose is to generate an error signal to operate the reactor control rods. The comparator compares the neutron-level and the power-demand signals. The division by n compensates for the fact that the effective gain of the reactor as an element in the neutron density feedback loop is strictly proportional to n . This compensation results in a loop gain that is independent of neutron density or power level, which is desirable from the point of view of control system stability.⁷

2.2.4d Control-Rod Drive System

The control rod drive unit, which positions the control rods, can be defined by the transfer function

$$X = \frac{K'}{s(1 + \tau_m s)} \frac{(n_o - n)}{n}, \quad (2.21)$$

where: K' = control rod drive unit gain,

τ_m = control rod drive unit time constant (sec.),

X = control rod position.

In practice, the reactivity contribution of the control rod position is a non-linear function. In the interest of simplicity, it is assumed to be proportional to the control rod position. Therefore Equation 2.21 becomes

$$\delta K_c = \frac{K_m}{s(1 + \tau_m s)} \frac{(n_o - n)}{n}, \quad (2.22)$$

where K_m is a modified gain constant. If, however, one defines the variable

$$\mu = \delta K_c - \delta K_c(0), \quad (2.23)$$

and combines Equation 2.23 with 2.22, and converts the transfer function to a differential equation, the governing differential equation for the control rod drive unit becomes

$$\frac{d^2\mu}{dt^2} + \frac{1}{\tau_m} \frac{d\mu}{dt} = \frac{K_m}{\tau_m} \frac{(n_o - n)}{n}. \quad (2.24)$$

2.2.4e Scram Control

A "scram" is defined as a rapid insertion of the control rods to cut down the neutron level as quickly as possible. The term "scram" dates from the earliest days of reactor technology. It has been replaced with the term "trip". These terms are used interchangeably in this investigation. Scramming systems are used only in case of a major failure that would result in an excessively high neutron level. The most common type of scramming system is the over-power-lever scram. In this, a trip mechanism is activated and the rods are forced into the reactor when the power level exceeds a preset value. However, if the power level is changing at a fast rate when it reaches the trip level, the power level will overshoot to an excessive value before a corrective action takes place. For this reason, period scram systems are preferred. If the positive period gets too low, the reactor is scrammed. Because of the complications involved in simulating the period of the reactor while using the RC network, the period scram is omitted from the simulation. Scramming by a manual signal is also provided.

For the present simulator, a scram condition exists if the neutron level gets too high or if the manual scram button is pushed. The scram system must release the rods from the normal operating control and drive the rods into the core rapidly. If the normalized neutron level exceeds its set point (.95), a voltage energizes a function relay on the analog computer, and a large negative reactivity is inserted into the reactor core. Also, the reactor control rod drive system is removed from the control scheme.

2.3 Analog And Digital Program

The mathematical model for the entire system, which is schematically shown in Figure 2.1, is developed in Section 2.2 of this chapter. The analog and digital program used to represent this model is given in the following subsections. The quantities C^* , n_o^* , n_m , K_c^* , and n^* which appear in the remainder of this section are the result of redefining the neutron density as

$$n^* = \frac{n}{n_m}, \quad (2.25)$$

where n^* is the normalized neutron density and n_m is the maximum practical neutron density. Neutron density is normalized to avoid scaling difficulties which would be encountered in mechanizing the mathematical model. This also aids in presenting the results of the simulation in more general terms.

2.3.1 Summary of Variables

<u>Variable</u>	<u>Initial Value</u>	<u>Maximum Value</u>	<u>Scale Factor</u>	<u>Scaled Variable</u>
T_f	1000°F	2000°F	1/200	$[T_f/200]$
T_c	500°F	1000°F	1/100	$[T_c/100]$
T_{oc}	600°F	1000°F	1/100	$[T_{oc}/100]$
T_{ic}	400°F	1000°F	1/100	$[T_{ic}/100]$
T_{ix}	600°F	1000°F	1/100	$[T_{ix}/100]$
T_x	500°F	1000°F	1/100	$[T_x/100]$
T_{ox}	400°F	1000°F	1/100	$[T_{ox}/100]$
T_o	400°F	1000°F	1/100	$[T_o/100]$
T_s	350°F	1000°F	1/100	$[T_s/100]$
T_i	400°F	1000°F	1/100	$[T_i/100]$
n^*	.5	1.0	10	$[10n^*]$
n_o^*	.02	1.0	10	$[10n_o^*]$
ϵ	-100°F	200°F	1/100	$[\epsilon/100]$
δK	0.0	.005	2000	$[2000\delta K]$
μ	0.0	.005	2000	$[2000\mu]$

2.3.2 Scaled Equations

The scaled variable equations are given in Appendix A. The scaled equations used in the six group delayed neutron approximation by use of the RC network, follow in Appendix B. The scaled equations used in the one group approximation are found in Appendix A. The Scaled equations used in the xenon problem are found in Appendix C.

The scaled equations given in Appendix A are obtained directly from

the mathematical description of the reactor power systems described in this chapter.

2.3.3 Analog Computer Diagram⁸

The schematic representation of the scaled mathematical equations is found in Appendix A. The diagrams represent the analog computer components used to solve the problem. The diagrams representing the reactor kinetics equations are those of the one group delayed neutron approximation. A six group delayed neutron approximation using the RC network can be studied by modifying the above diagrams to include the RC network. The wiring of this modification is discussed in Chapter Eight. A schematic representation of the RC network hook up is given in Appendix B. A schematic representation of the xenon poisoning problem is presented in Appendix C.

2.3.4 Digital Computer Program

The XDS Sigma 5 Digital Computer is used in the dynamic simulation to modify the primary coolant mass flow rate, W_c . The program is presented in Appendix D.

very large periods of time after a disturbance to the system. The error in the intermediate range may be quite large.⁹

For small and intermediate positive reactivities, the one group n has one rising exponential **and one rapidly decaying exponential** term. The absence of the intermediate branches of the reactor kinetics dynamic response results in underestimates of the **elapse** time after a reactivity step before the asymptotic term is dominant. This can be misleading when observing measurements of period-reactivity data by means of observing asymptotic responses to small reactivity steps.¹⁰

For large negative reactivities, the one-group model is useless. Here all terms in n are decaying exponentials, and the term having the smallest decay constant will eventually dominate. The one group model predicts an asymptotic decay that is much too rapid.¹¹

The above discussion is observed by comparing Figure 3.6 with Figure 3.12 during the insertion of a large negative reactivity in the form of a "scram" rod into the reactor core. If one observes the qualitative shape of the curve for a period of forty seconds after the scram signal is initiated, the difference between the one group and six group approximation to the reactor kinetics equation is observed in the value of n^* over this period.

Small reactivity changes give no noticeable difference in the two methods used to simulate the reactor kinetics equation. This condition is shown by comparing Figures 3.1 through 3.5 with Figures 3.7 through 3.11, respectively. It is noted that the above figures are obtained by assuming a constant steam temperature in the secondary loop. This condition is discussed further in Chapter Seven.

CHAPTER THREE

REACTOR KINETICS SIMULATION

Six distinct groups of delayed-neutron emitters are generally used for reactor dynamic studies. There are grounds, both experimental and theoretical, for recognizing the presence of others, but existing neutron-emission data are satisfactorily interpreted by assuming six decay constants. It is observed that six exponential periods are necessary and sufficient for optimum least-squares fit to data.

There is significant variation among the sets of six half-lives and abundances obtained for different isotopes and incident neutron energies. For this reason separate data is used for each fissile species and each neutron spectrum. The data used in the creation of the RC network is summarized in Section 3.1 of this chapter.

As observed in Chapter Two, the reactor kinetics equation requires the use of at least seven integrator circuits for the simulation of the six groups of delayed neutrons. In this chapter, the discussion of methods used to solve this problem is discussed. One such method is by using an approximation to the six groups of delayed neutrons. This approximation is a one group delayed neutron reactor kinetics equation. The results obtained by this approximation are discussed and compared to a six group delayed neutron approximation.

Another method used to solve the above mentioned problem is by using an RC network to simulate the six groups of delayed neutrons. This method is compared to the six group delayed neutron simulation

which was patched on the analog computer by using seven expensive integrator components found behind the analog patch panel.

The six group delayed neutron simulation which was patched on the analog computer by using seven integrators is removed from the patch panel so that the above mentioned integrators could be used for other areas of study. The patch panel now contains only the one group delayed neutron approximation which requires only two integrators. Also found on the patch panel is a method for simulating the six groups of delayed neutrons by use of the RC network. An integrator component is used as a high gain amplifier for the RC network. As one compares the six group delayed neutron simulation by using seven integrators to the six group delayed neutron simulation by using the RC network and only one integrator which is used as a high gain amplifier, one realizes the savings involved in computing equipment.

3.1 One Group Delayed Neutron Approximation

The task of solving the sixth degree reactor kinetics equation can be avoided by assuming that the set of delayed neutron emitters are replaced by a single emitter. The transient response will be only qualitatively correct and applicable only to small changes in K . The solution is easy to obtain, however, and serves to display the dynamic behavior of reactor kinetics at short and long time periods after a disturbance is applied to the reactor system.

Supposing that the equivalent single emitter has a mean life $\bar{\tau} = 1/\lambda$, given by

$$\bar{\tau} = \frac{\sum_{i=1}^6 \beta_i \tau_i}{\beta} = \frac{1}{\lambda}, \quad (3.1)$$

$$\text{where: } \beta = \sum_{i=1}^6 \beta_i;$$

τ_i = half-life of the delayed neutron precursor associated with group i (sec.);

$$\begin{aligned} \lambda &= \text{mean decay constant (sec.}^{-1}\text{)}, \\ &= .0766 \text{ sec.}^{-1} \text{ for } {}^{235}\text{U}; \end{aligned}$$

β_i = delayed neutron fraction of the precursor associated with group i .

Also the modified precursor concentration is simply C . From the above, it is shown that the equations shown below:

$$\frac{dn}{dt} = \delta K n / \ell - \beta K n / \ell + \sum_{i=1}^6 \lambda_i C_i + S, \quad (3.2)$$

and

$$\frac{dC_i}{dt} = -\lambda_i C_i + \beta_i n K / \ell \quad (3.3)$$

can be replaced by

$$\frac{dn}{dt} = n \delta K / \ell - \beta K n / \ell + \lambda C, \quad (3.4)$$

and

$$\frac{dC}{dt} = -\lambda C + \beta K n / \ell. \quad (3.5)$$

These simultaneous differential equations are solved by conventional methods. It is found that the general solution for n takes the form

$$n = a_1 e^{\lambda_1 t} + a_2 e^{\lambda_2 t}.$$

Since λ_2 is generally large and negative, the exponential term $e^{\lambda_2 t}$ decreases rapidly with time and is important only at time near zero. The dominant term is $e^{\lambda_1 t}$ corresponding to λ_1 being small and positive for small and positive reactivities.

The above derivation indicates that the one group and six group dynamics should approximate each other closely during very small and

Figure 3.1. n^* Versus Time for Various Reference Temperatures (T_{Ref})
Step Inputs Using One Group Delayed Neutrons

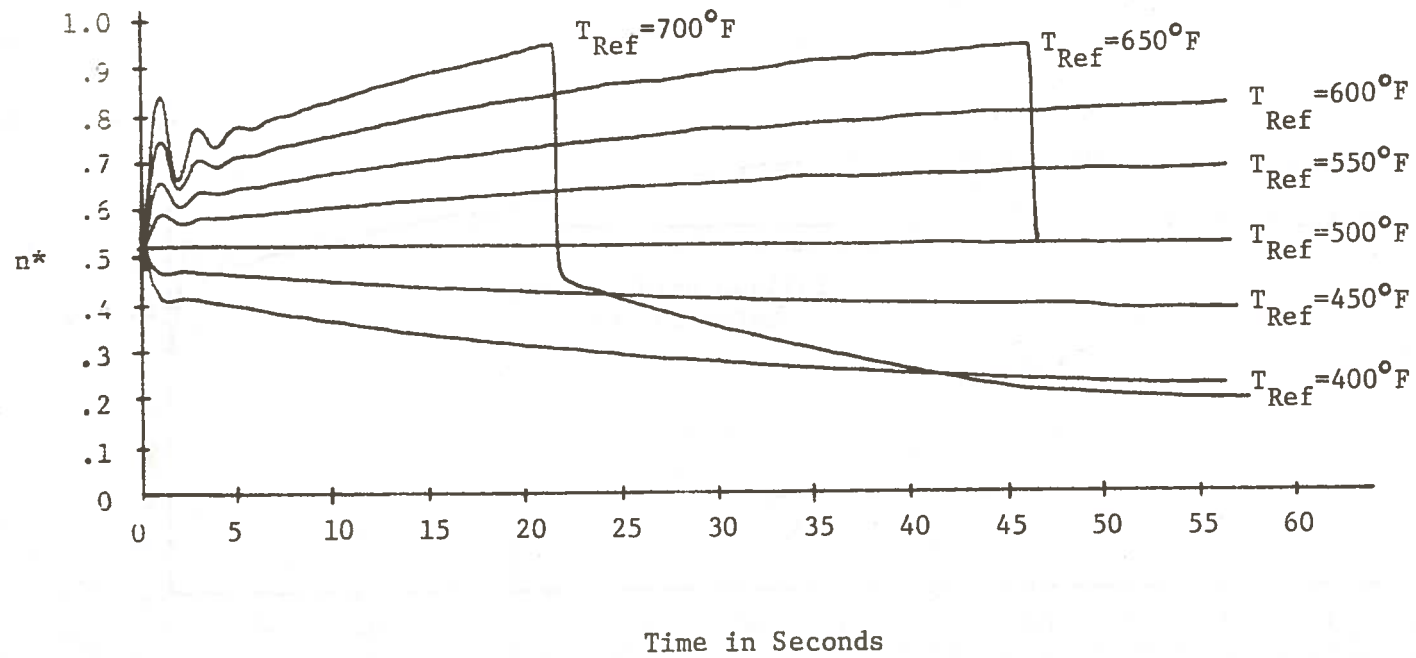
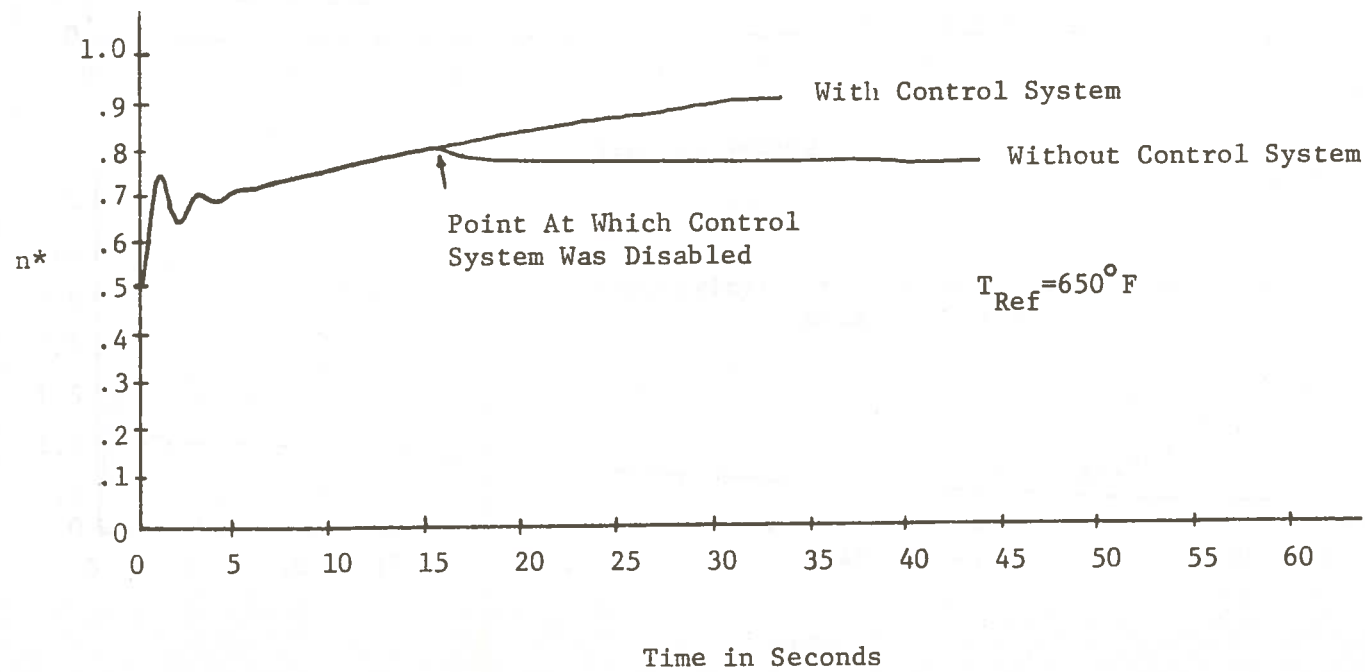


Figure 3.2. n^* Versus Time Showing the Effect of Control Rod Failure With One Group Delayed Neutrons



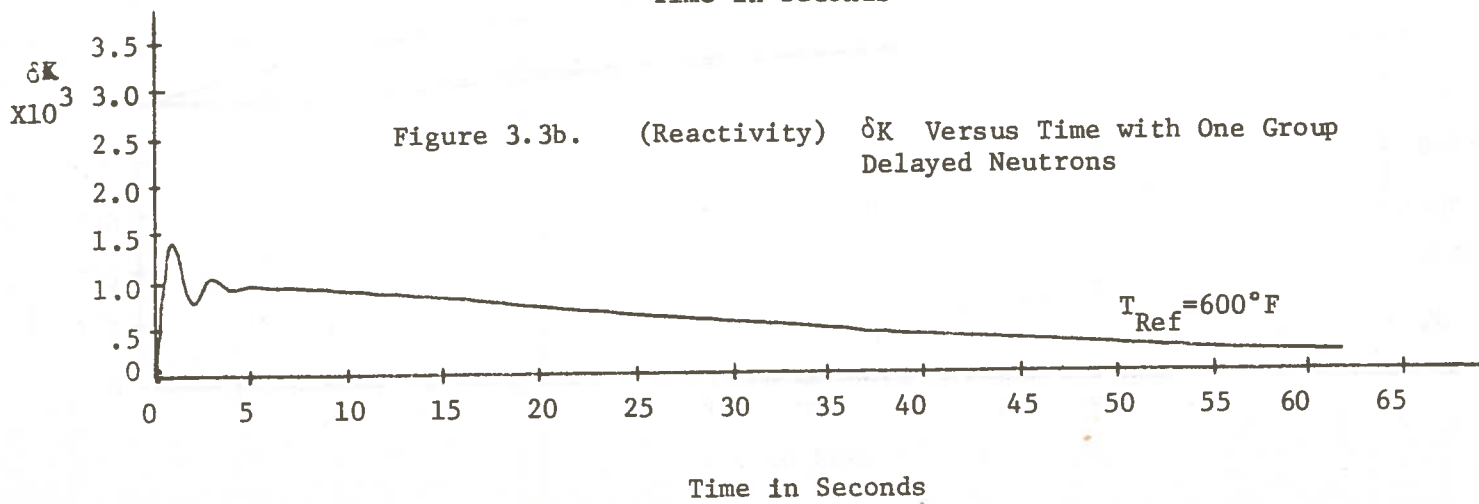
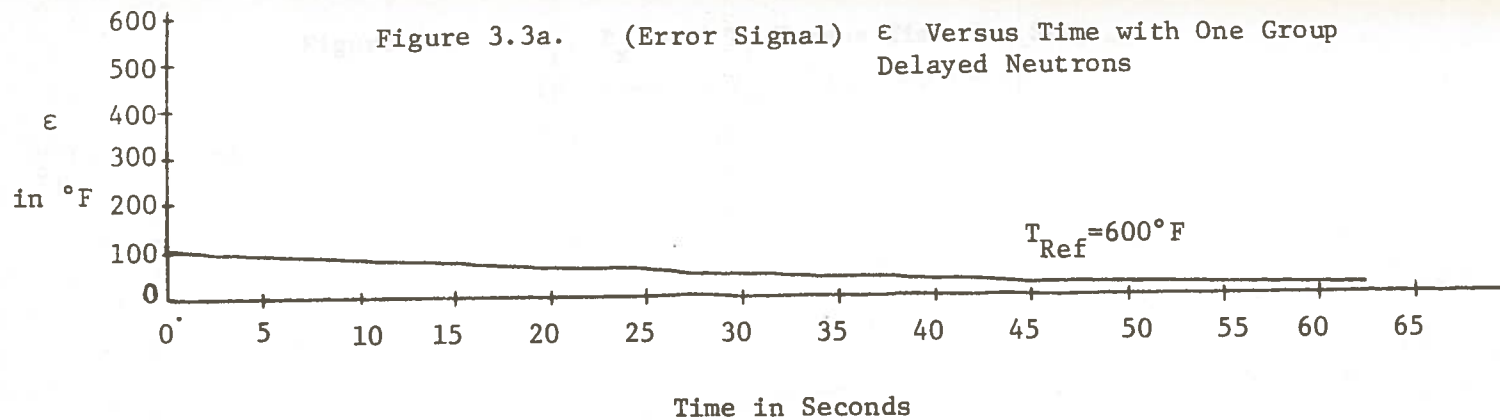


Figure 3.4. T_c , T_x , and T_f Versus Time for Step Increase in T_{Ref} With One Group Delayed Neutrons

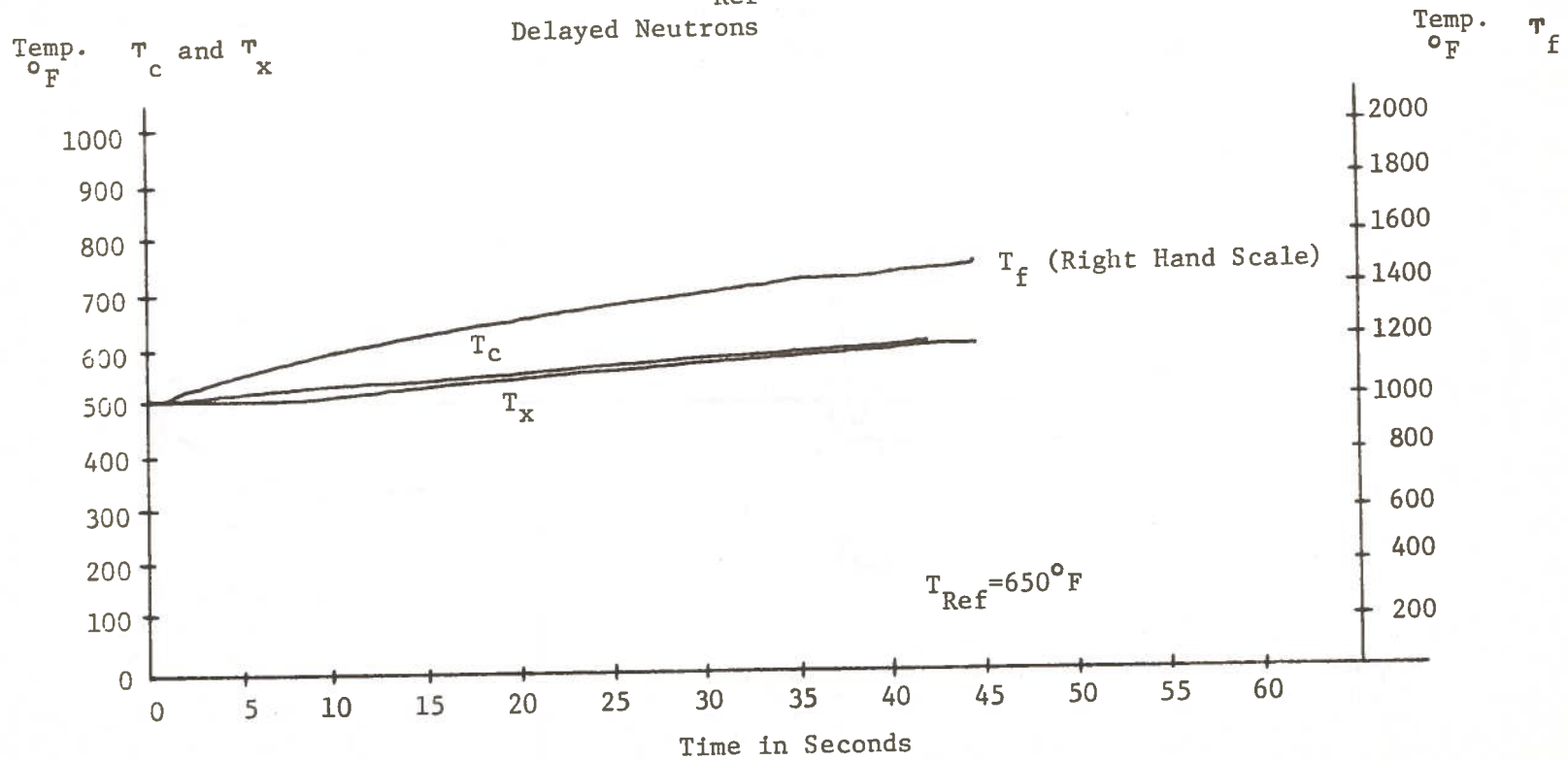


Figure 3.5. n^* Versus Time for Step Input in Reactivity With One Group Delayed Neutrons

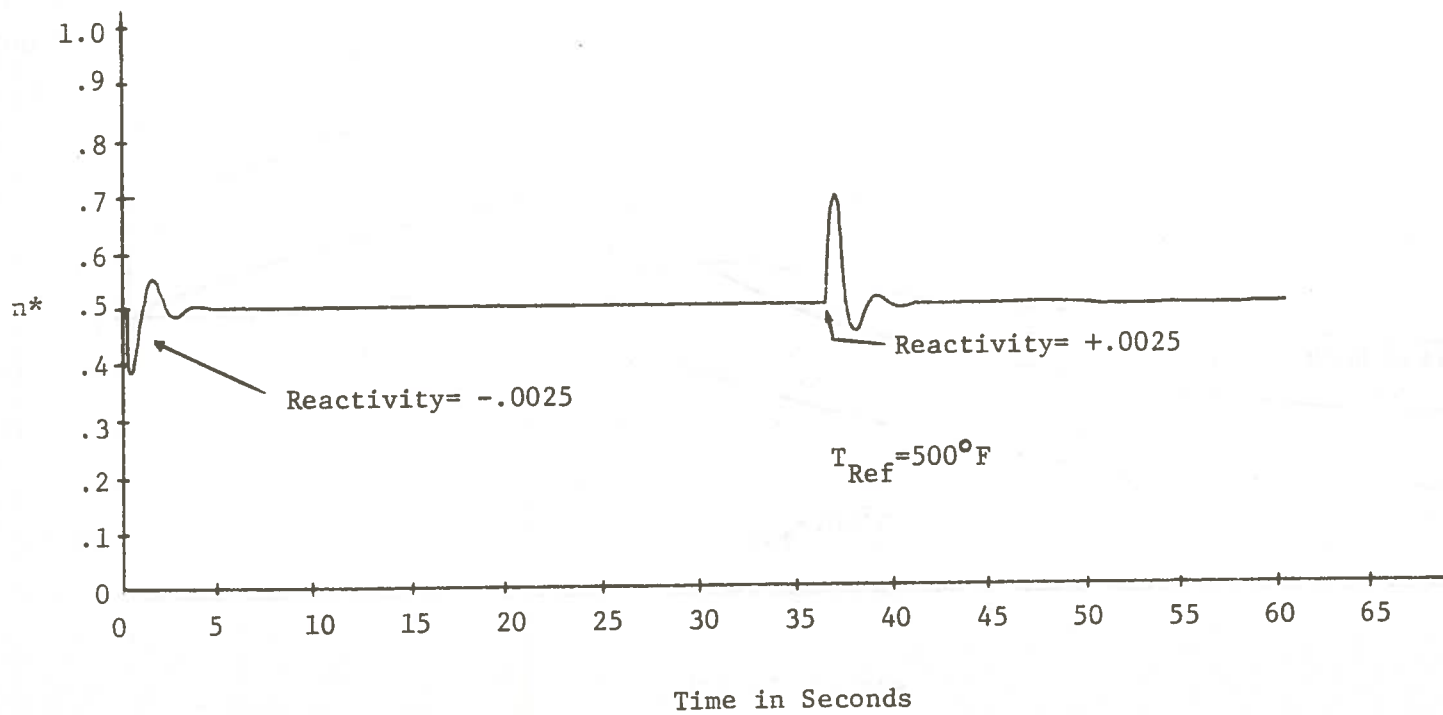


Figure 3.6. Effect of "Scramming" on n^* , T_f , and T_x Versus Time Using One Group Delayed Neutrons

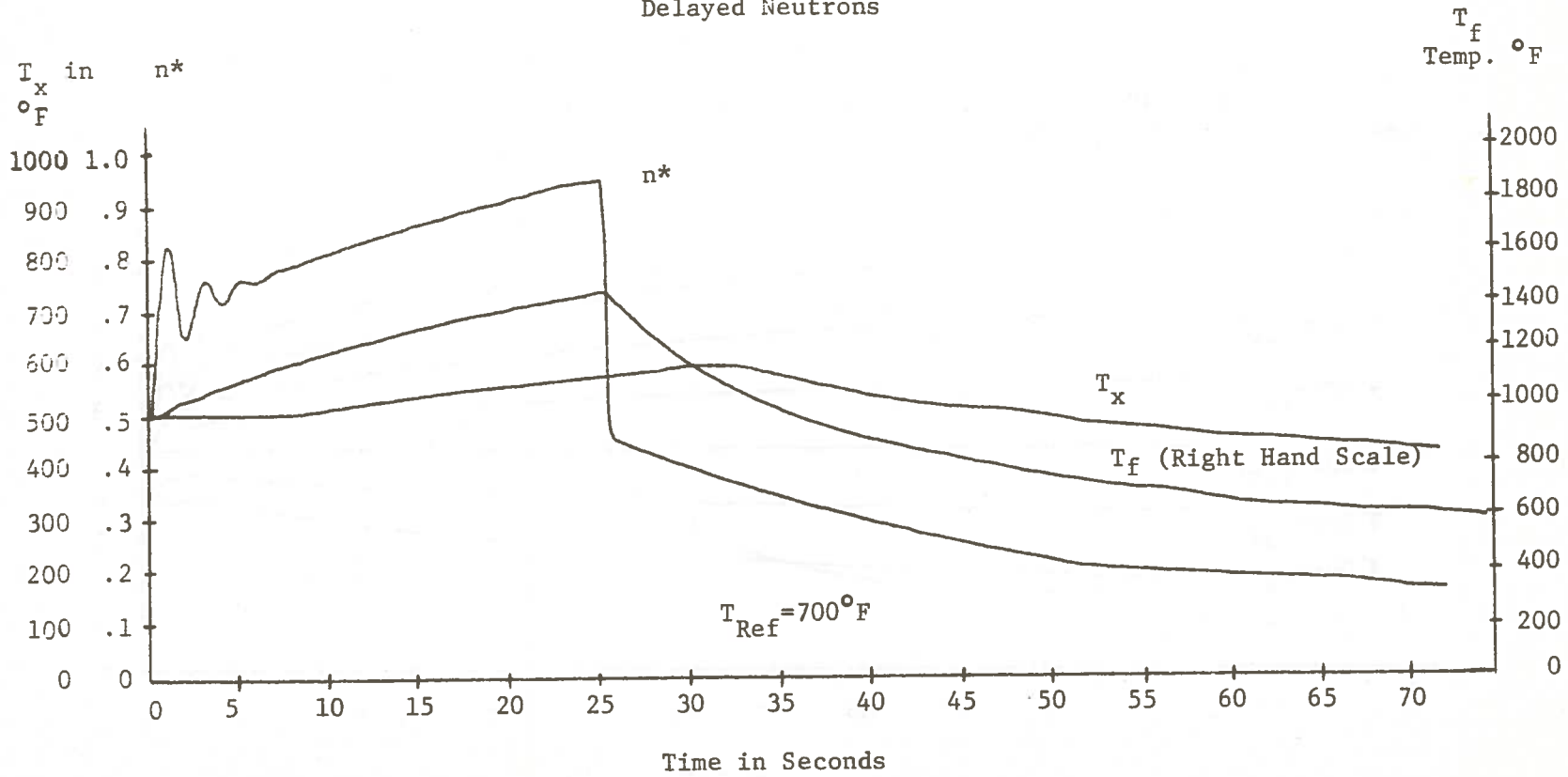


Figure 3.7. n^* Versus Time for Various Reference Temperatures (T_{Ref}) Step Inputs Using Six Group Delayed Neutrons

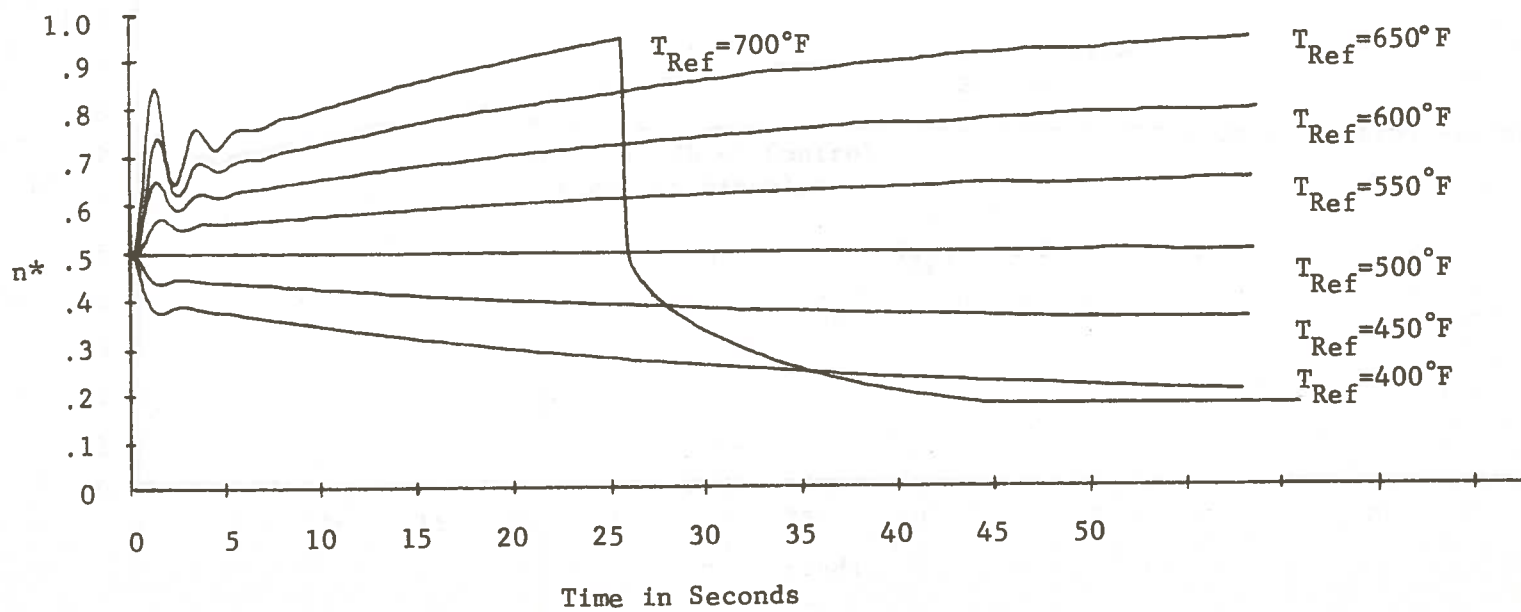
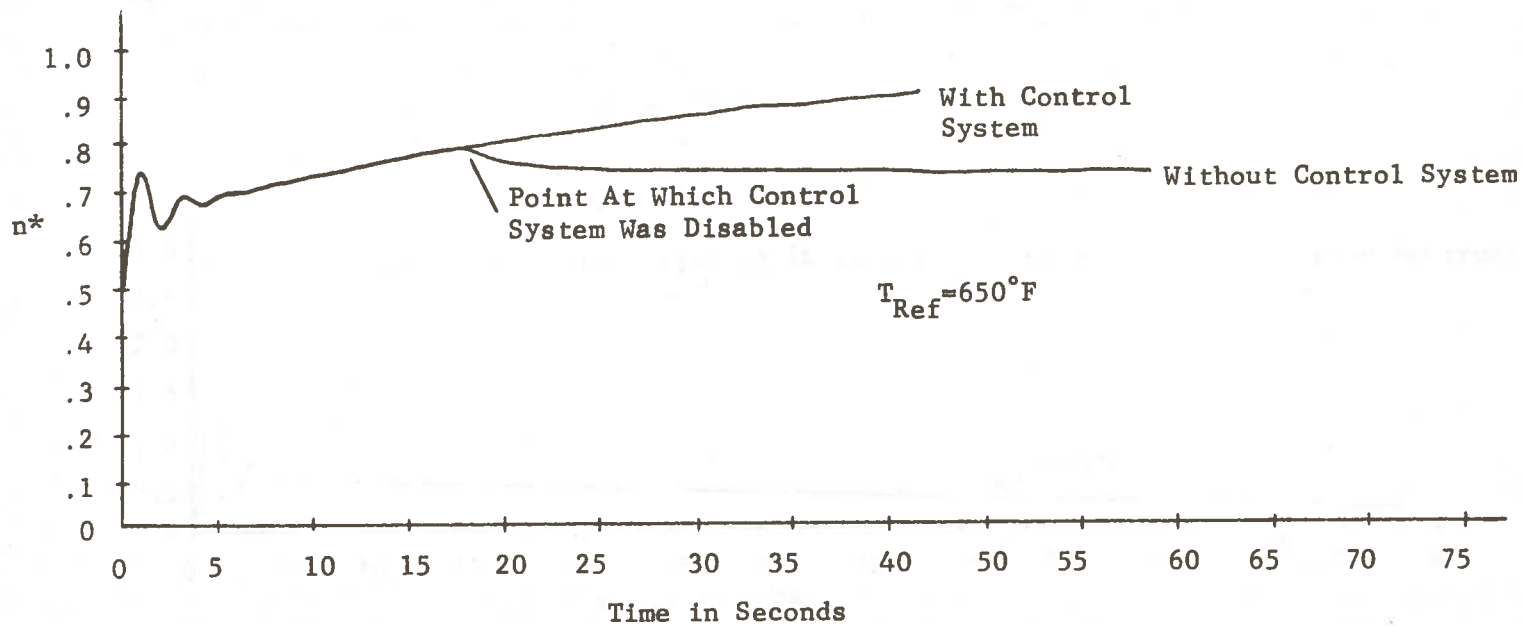


Figure 3.8a (Error Signal) ρ Versus Time with Six Group Delayed Neutrons

Figure 3.8. n^* Versus Time Showing the Effect of Control Rod Failure With Six Group Delayed Neutrons



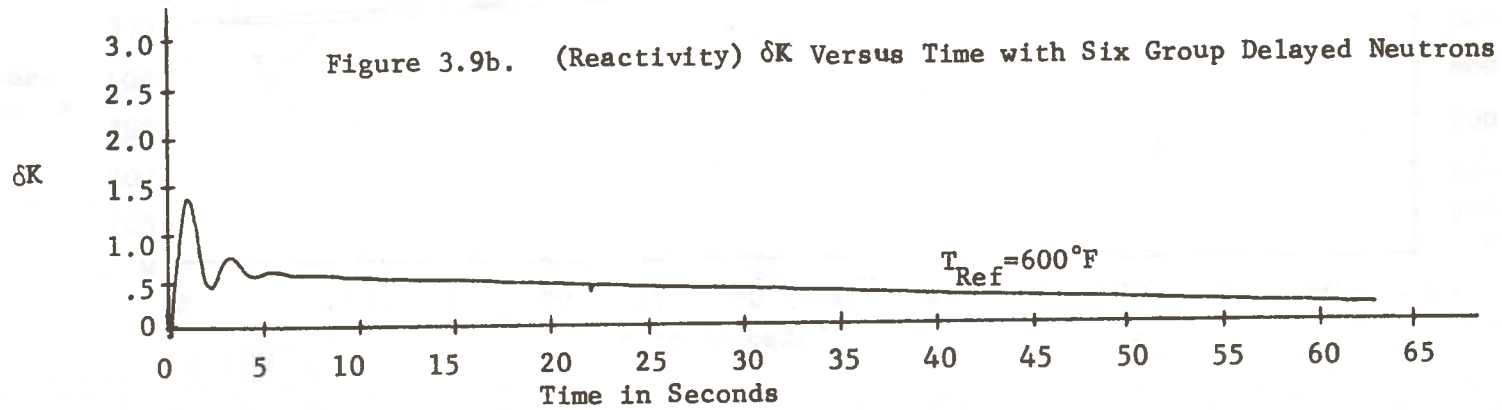
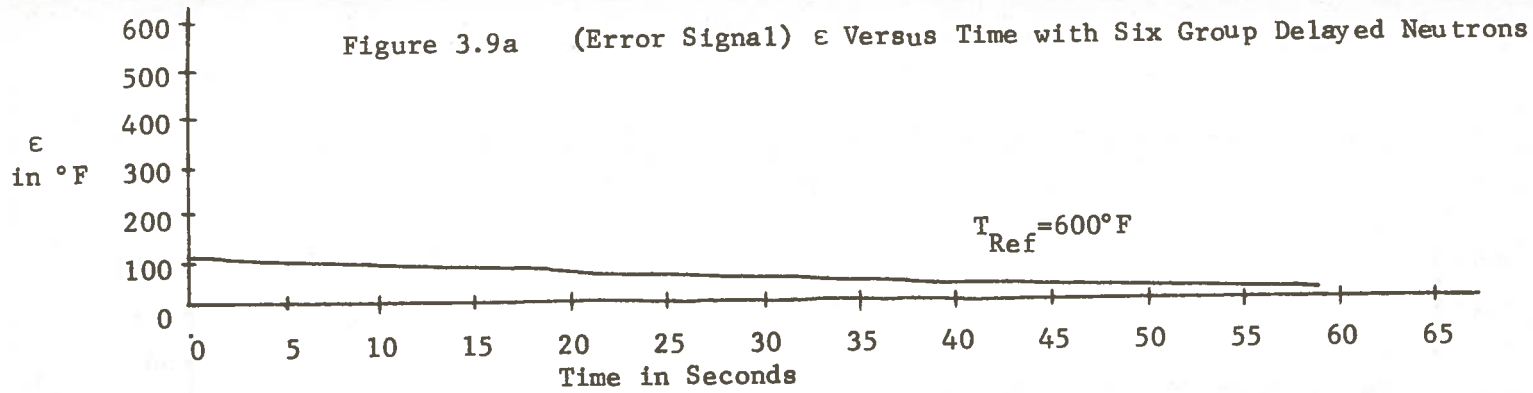


Figure 3.10. T_c , T_x , and T_f Versus Time for Step Increases in T_{Ref}
With Six Group Delayed Neutrons

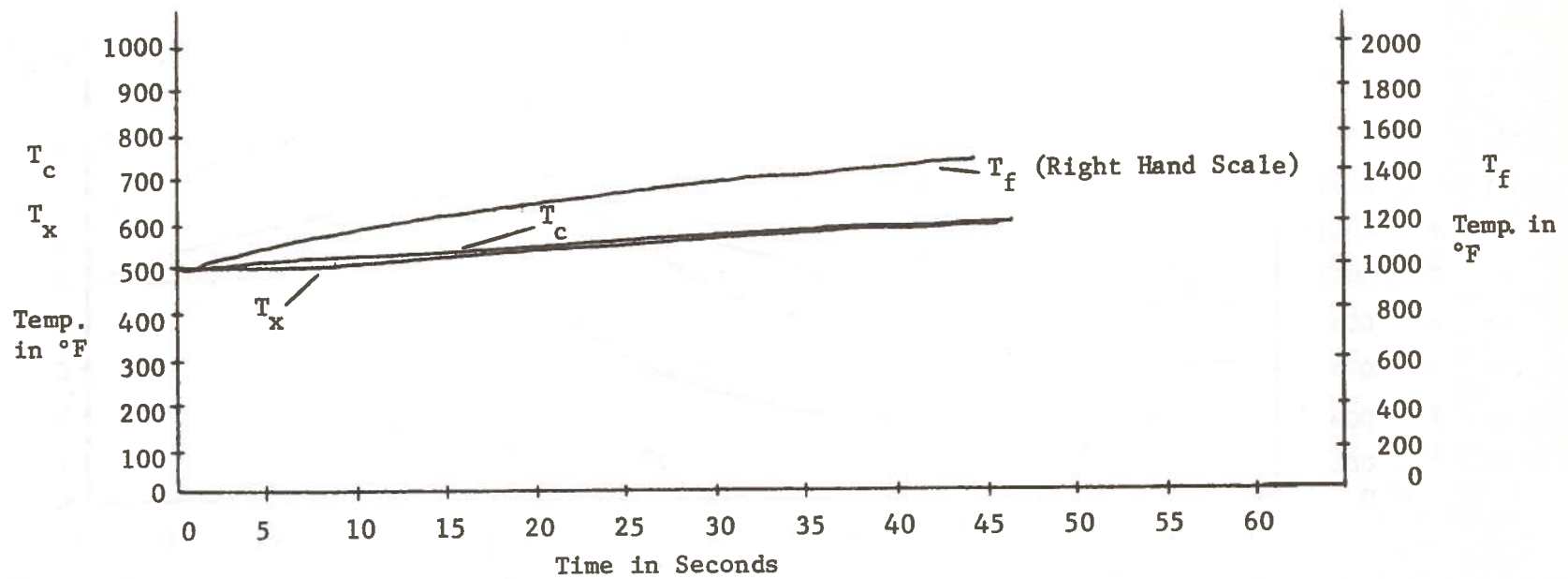
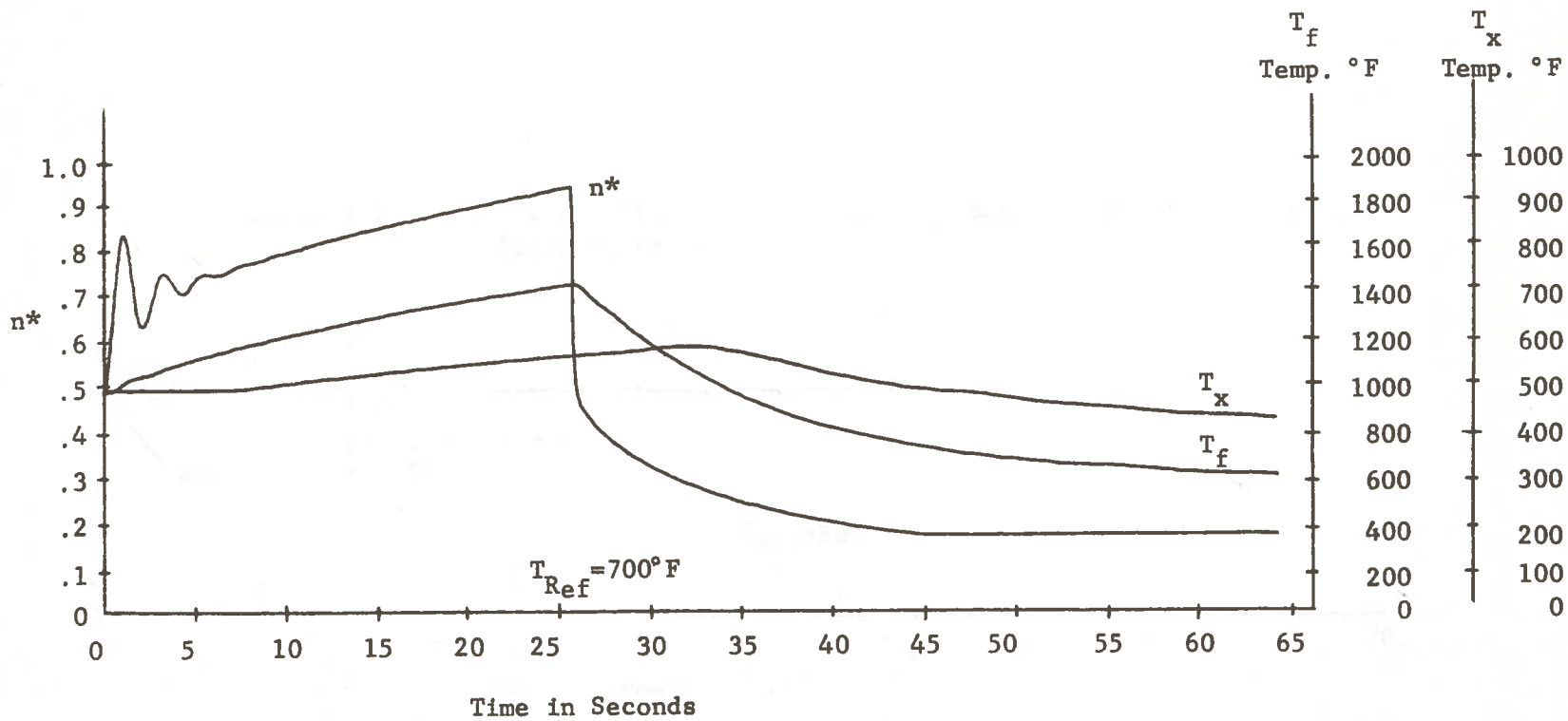
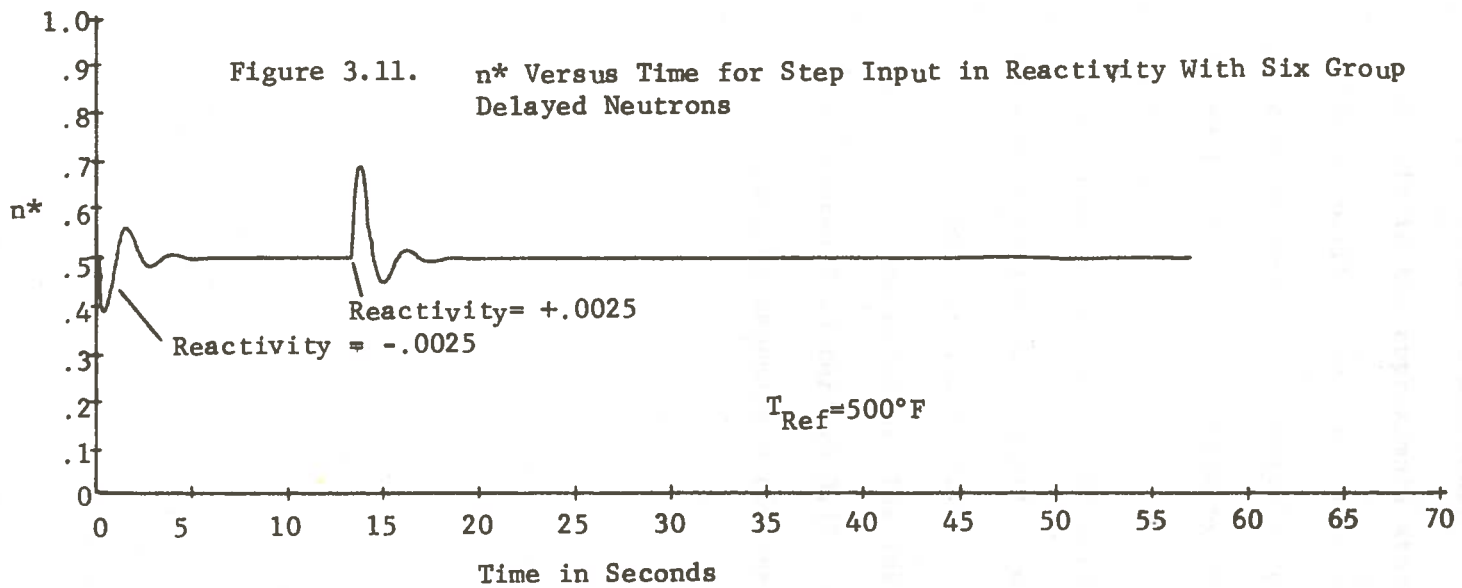


Figure 3.12. Effect of "Scramming" on n^* , T_f , and T_x Versus Time Using Six Group Delayed Neutrons





3.2 Accuracy of RC Network to Simulate Six Group Delayed Neutrons

As shown in Appendix B, the accuracy of the electronic components used in the RC network in comparison to the desired reactor kinetics coefficients is limited to approximately 5 per cent. The accuracy of the components, however, are within the approximate statistical accuracies used to determine these coefficients. For this reason, the results obtained by using the RC network are comparable to the results obtained by modeling the reactor kinetics equation by using the seven integrator components mentioned earlier.

Comparing the results obtained by using the RC network with the six group delayed neutron approximation modeled with the seven integrator components, one observes that the qualitative difference between the two modeling techniques are not detectable. The results using the RC network are shown in Figures 3.13 through 3.18. As mentioned earlier, the results were obtained by assuming a constant steam temperature in the secondary loop.

Figure 3.13. n^* Versus Time for Various Reference Temperatures (T_{Ref})
Step Inputs Using R.C. Network

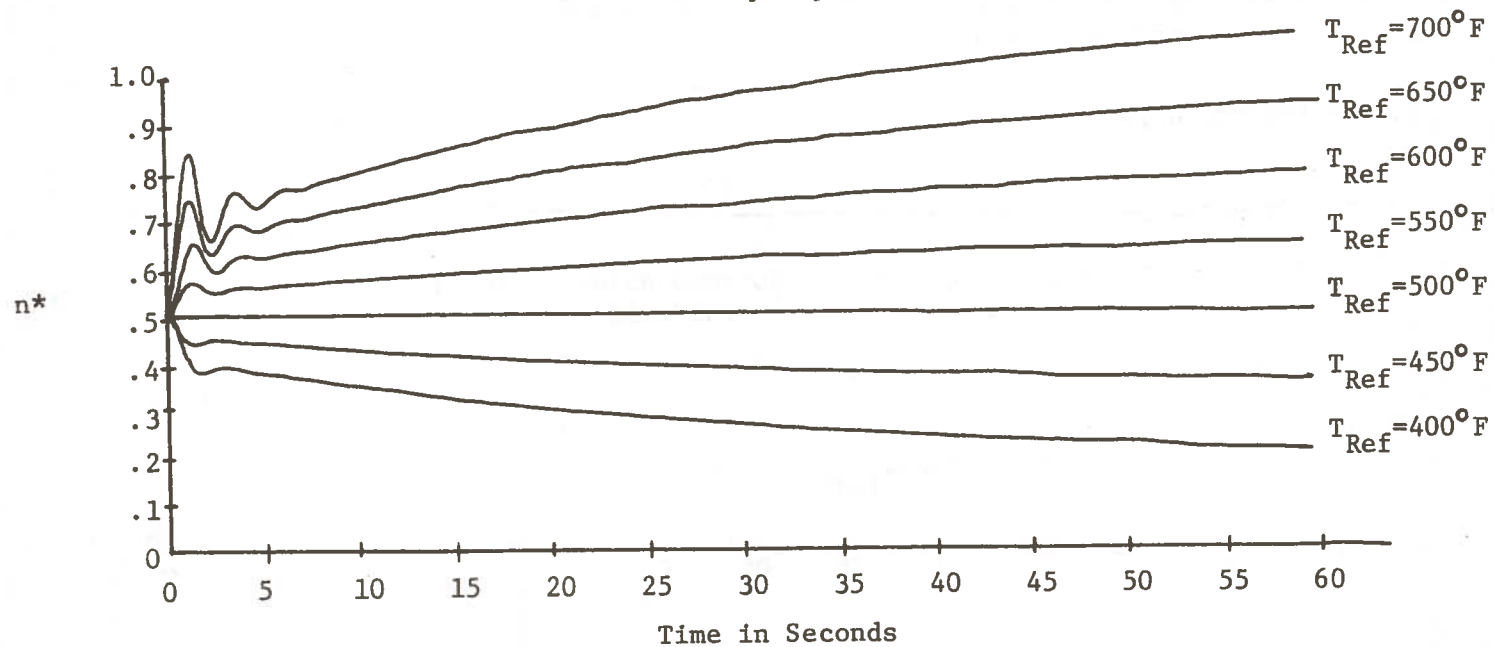
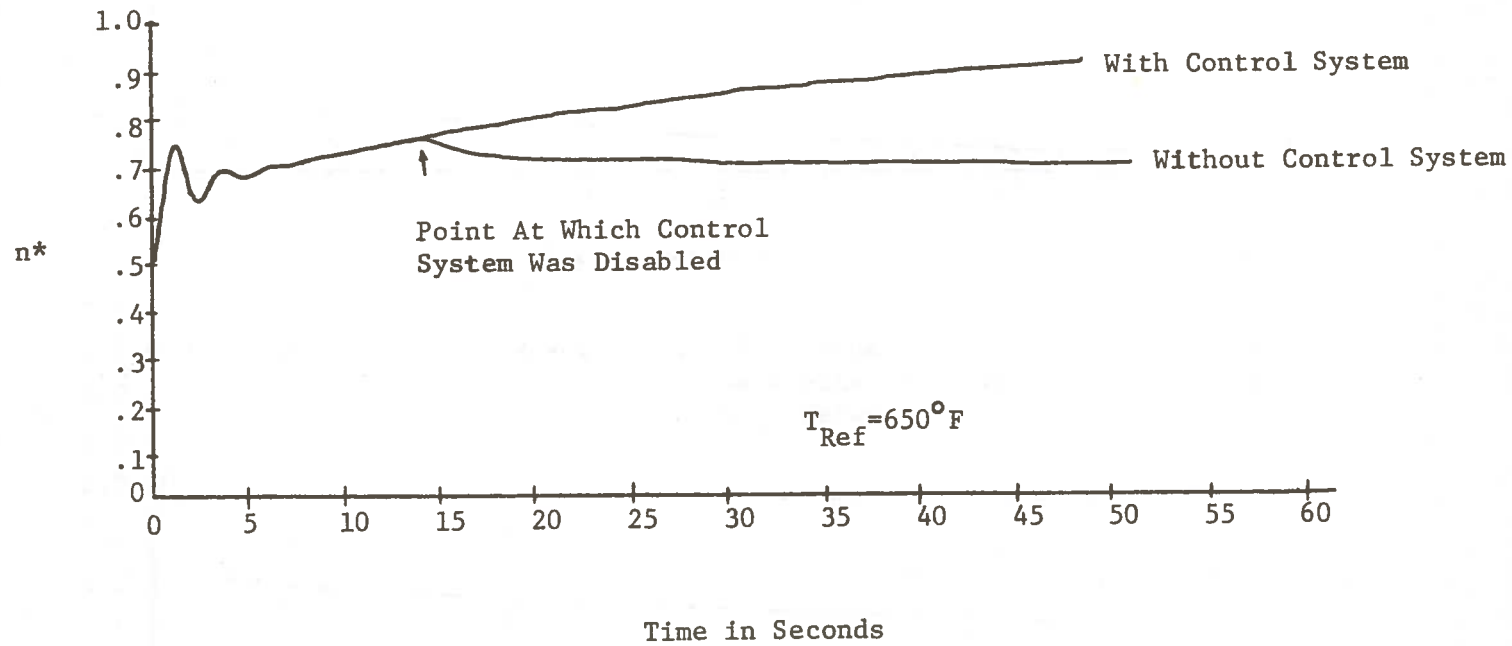


Figure 3.14. n^* Versus Time Showing the Effect of Control Rod Failure With R.C. Network



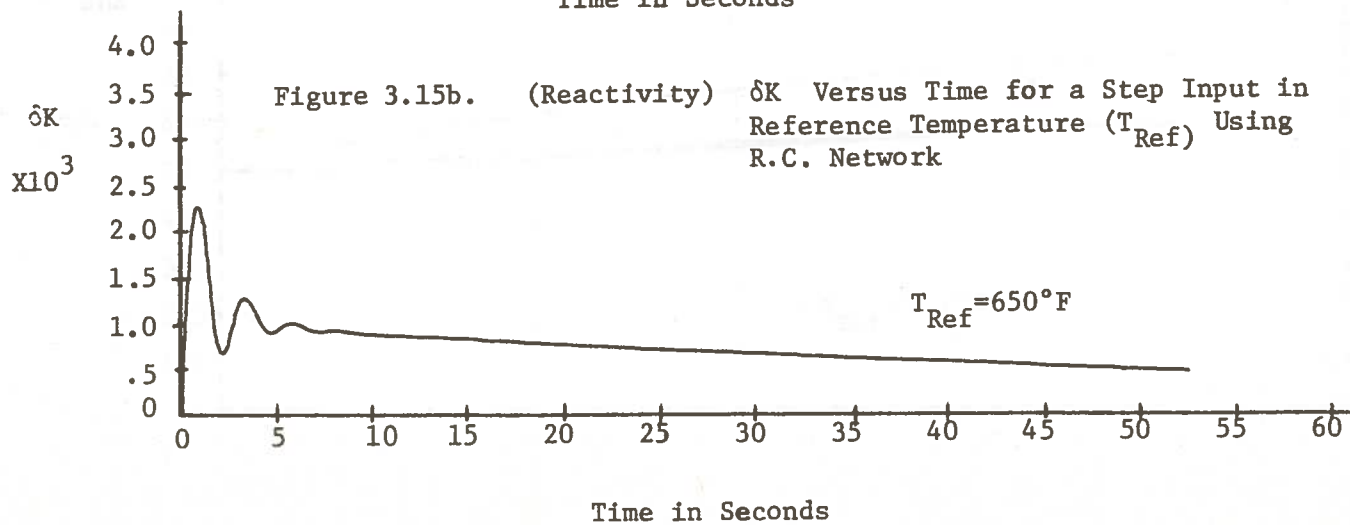
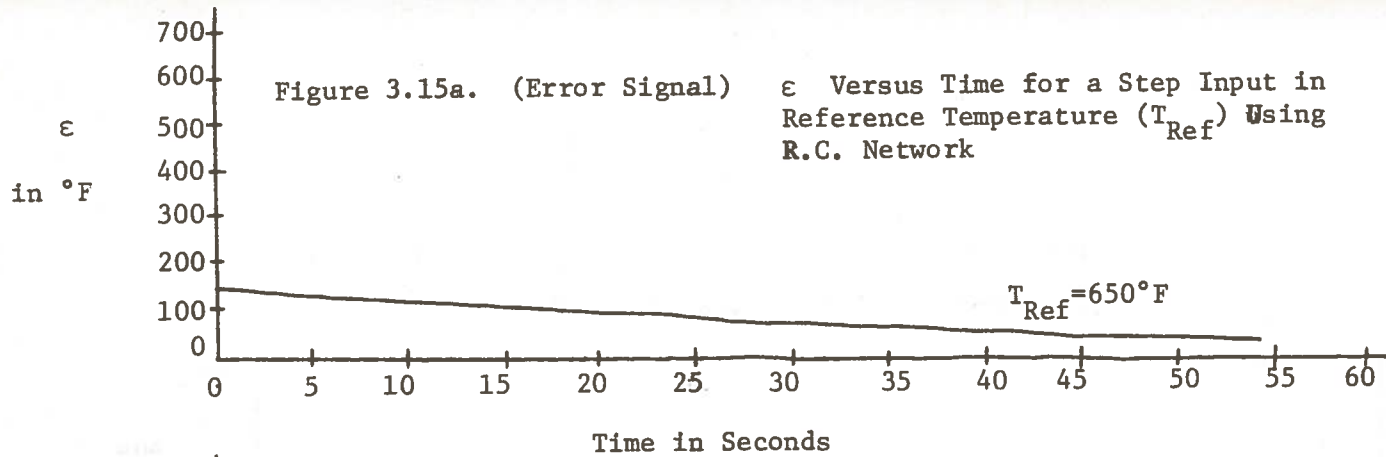


Figure 3.16. T_c , T_x , and T_f Versus Time for Step Input in T_{Ref} Using R.C. Network

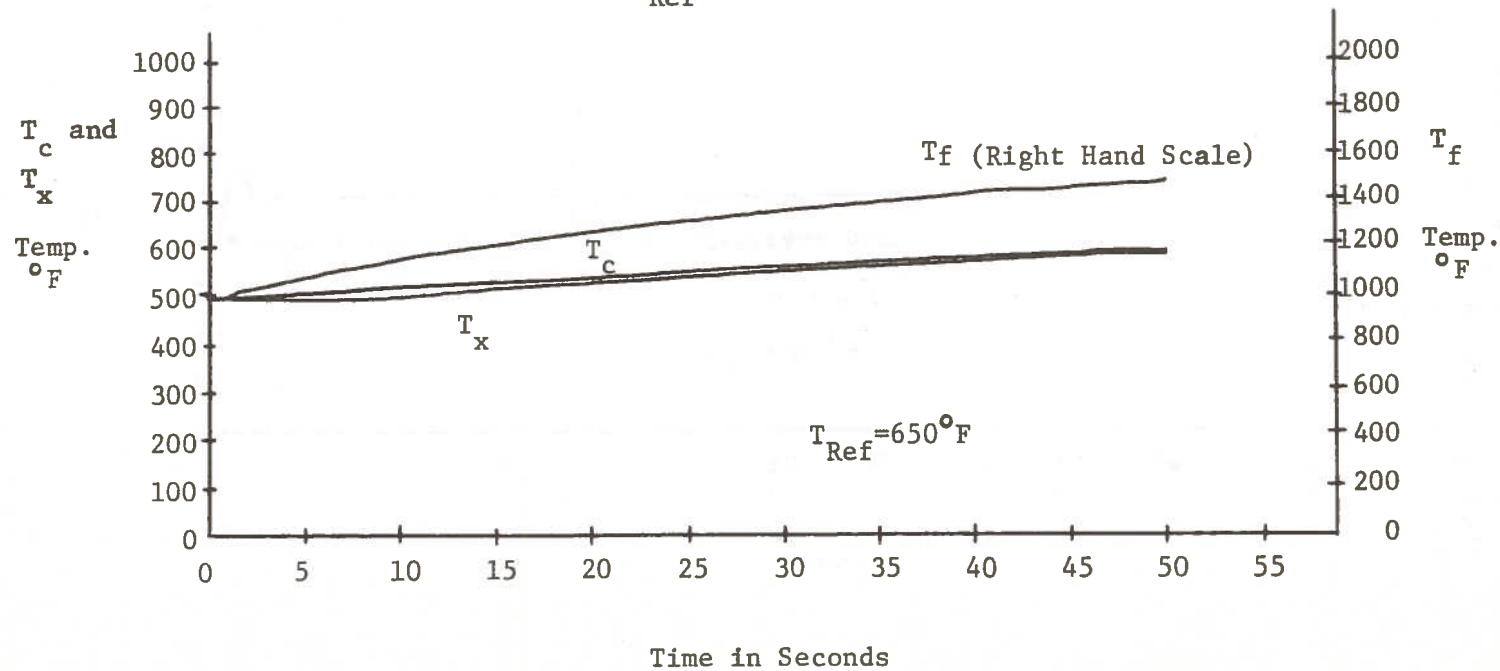


Figure 3.17. n^* Versus Time for Step Input in Reactivity With R.C. Network

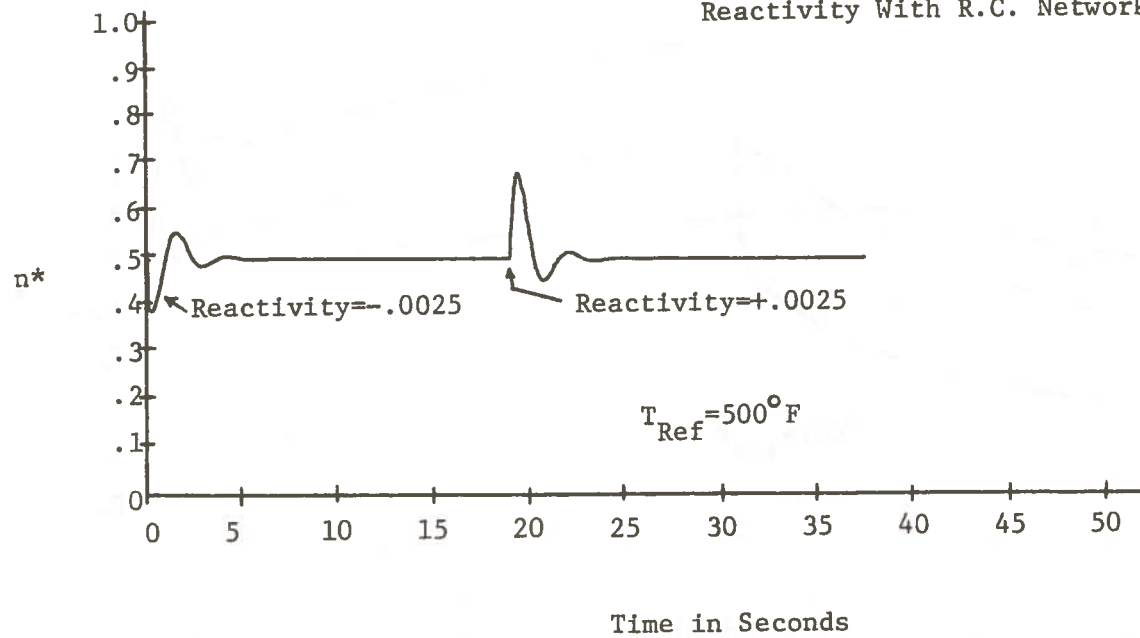
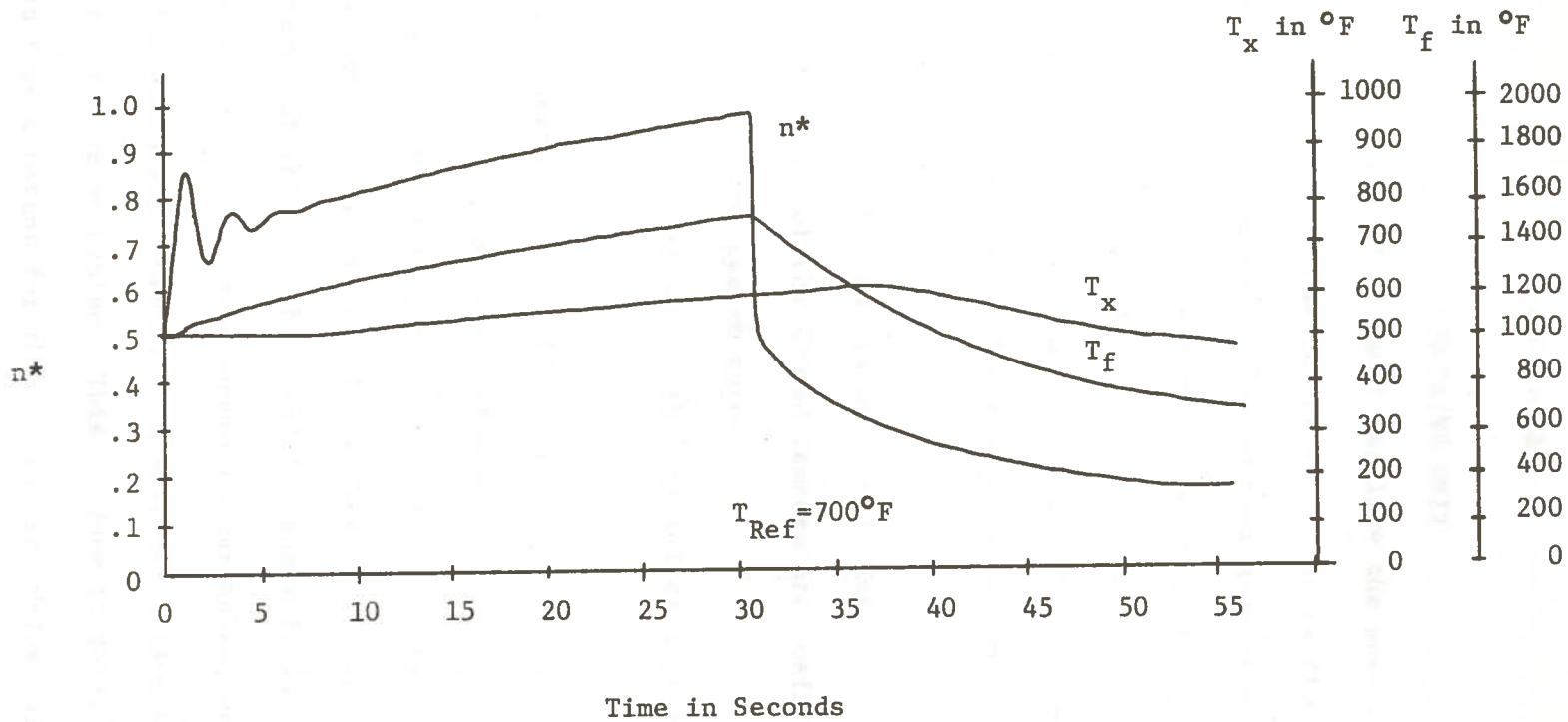


Figure 3.18. Effect of "Scramming" on n^* , T_x , and T_f Versus Time Using R.C. Network



CHAPTER FOUR

CONTROL ROD DRIVE UNIT

Basically, the control system must regulate the power reactor so that power is delivered to meet the demand. The reactor and the power plant must be sufficiently stable and must have good transient performance. Also, the range of system variables must be compatible with the limitations of the equipment and materials.

It can now be seen that to study this reactor-control-system completely requires an understanding of the effects and optimization of the following seven variables:¹²

1. The magnitude of the temperature coefficient.
2. The time constant of the lumped temperature coefficient.
3. K_m , the control rod system gain.
4. f_n , the natural frequency of the controller system.
5. ζ , the damping ratio.
6. f_o , the integrating break frequency.
7. The shape of the transient disturbance.

To determine the stability and to solve for the transient responses for a range of values of all the various parameters within reason for a system of this sort by stability analysis is a long and tedious procedure. With this large number of variables, an empirical approach by using an analog computer is a very attractive method to study the control rod servo system. This is done to determine the proper gain and time constant for the control rod drive unit.

In general, this is done by examining the following four criteria:¹³

1. Absolute stability. This criteria means that no exponentially increasing oscillations can exist.
2. Relative stability. What is the number of oscillations before a transient has died out?
3. Maximum power-level excursion. The peak power reached by the reactor for a fixed-shaped input disturbance.
4. The settling time of the system. The time for the response to achieve a given absolute percentage of the steady-state value.

As shown in Figure 3.13, the normalized neutron concentration versus time for various step inputs of reference temperature is well behaved. The initial oscillations immediately after the step inputs are caused by the control rod movement. The determination of the control rod drive unit time constant and the control rod drive unit gain is accomplished by observing the response of the reactor-power systems to various step disturbances caused by changing the reference temperature. The value chosen for the ratio of the control rod drive unit gain and of the control rod drive unit time constant is .08. The value chosen for the inverse of the control rod drive is 4.0.

The values chosen insure the response shown in Figure 3.13. Increasing the ratio K_m/τ_m while maintaining τ_m constant results in further oscillations. Increasing K_m/τ_m while maintaining K_m constant results in a higher frequency of oscillation.

The control rod drive unit coefficients are not optimal. Optimal conditions can be established by conducting further studies on the

response of the system to control stimuli.

The system is composed of three main parts, consisting of the control system, the plant, and the feedback system. This feedback system is formed by the output of the plant, which is compared with the reference input to determine the error signal. The error signal is then used to adjust the control signal to improve the system's performance.

Such a system is known as a closed-loop system, and it is characterized by its ability to maintain a desired level of performance despite disturbances. The control signal is generated by the controller, which receives the error signal and produces the control signal to drive the plant. The plant is the part of the system that produces the output, and the feedback system is the part that measures the output and compares it with the reference input.

by Figure 1. Figure 2 shows the block diagram of the system, and Figure 3 shows the transfer function of the system.

The transfer function of the system is given by $T(s) = \frac{Y(s)}{U(s)}$, where $Y(s)$ is the output and $U(s)$ is the input. The transfer function is a function of the complex frequency s , and it describes the relationship between the input and the output of the system. The transfer function is used to analyze the system's response to different inputs, and it is a key tool in the design of control systems.

CHAPTER FIVE

SECONDARY LOOP

The results shown in Chapters Two and Three are obtained by assuming that the average steam temperature in the heat exchanger is constant throughout all transients encountered in the primary loop. This restriction limited the simulation to the primary loop. It is found, however, that this restriction seriously impedes performance of the reactor-power-systems simulator as a dynamic tool in the study of pressurized-water reactors.

Shown schematically in Figure 5.1 is the block diagram representation of the PWR with primary-loop control. In this figure is shown a plug-in value which represents the constant steam temperature found in the heat exchanger. The model represented by Figure 2.1 depicts a PWR system that is more typical of the actual system than is the model in Figure 5.1. The comparison of the two systems is made by contrasting the results obtained by the model represented by Figure 2.1 and the results obtained by the model represented by Figure 5.1.

The results to be compared are found in Figures 5.2 through 5.4 and Figures 3.13 through 3.18. The results found in Figures 3.13 through 3.18 represent those obtained by the model of the PWR with primary loop control shown schematically in Figure 5.1. The results found in Figure 5.2 through 5.4 represent those obtained by the model of the PWR plant and control systems shown schematically

- | | |
|-------------------------------------|----------------------------|
| 1. Reactor Core | 8. Control Rods |
| 2. Reactor Vessel | 9. Control Rods Drive Unit |
| 3. Inlet Plenum | 10. Control System |
| 4. Outlet Plenum | 11. Comparator |
| 5. Heat Exchanger | 12. Reference Temperature |
| 6. Primary Loop Pump | 13. Averaging System |
| 7. Reactor Kinetics (Neutron Level) | 14. Steam Temperature |

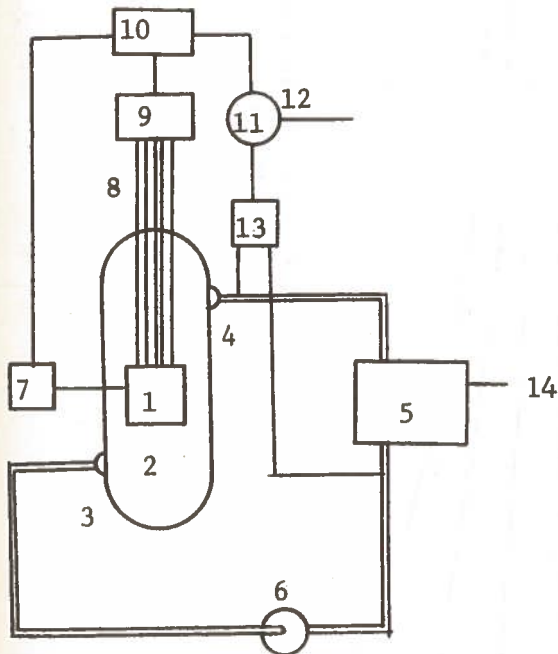


Figure 5.1.

Block Diagram PWR with Primary Loop Control

Figure 5.2. n^* Versus Time for Various Step Changes in Reference Temperatures (T_{Ref})

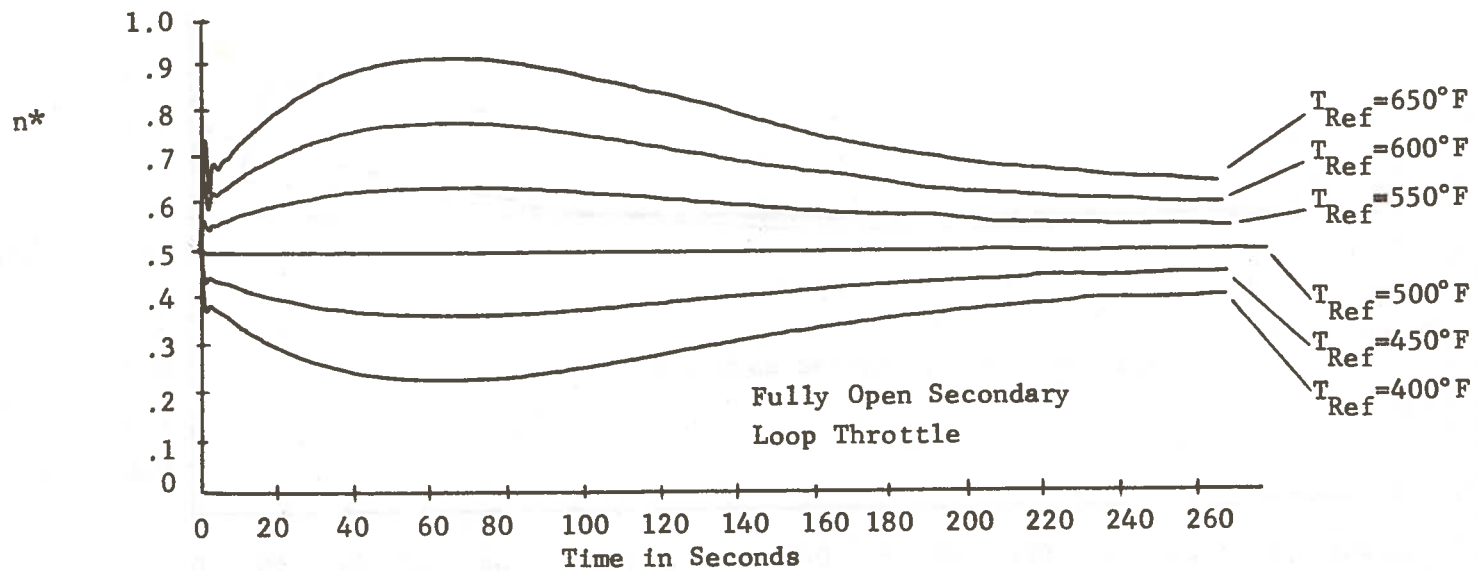


Figure 5.3a. Reactivity, δK , Versus Time for Various Step Increases in Reference Temperature (T_{Ref})

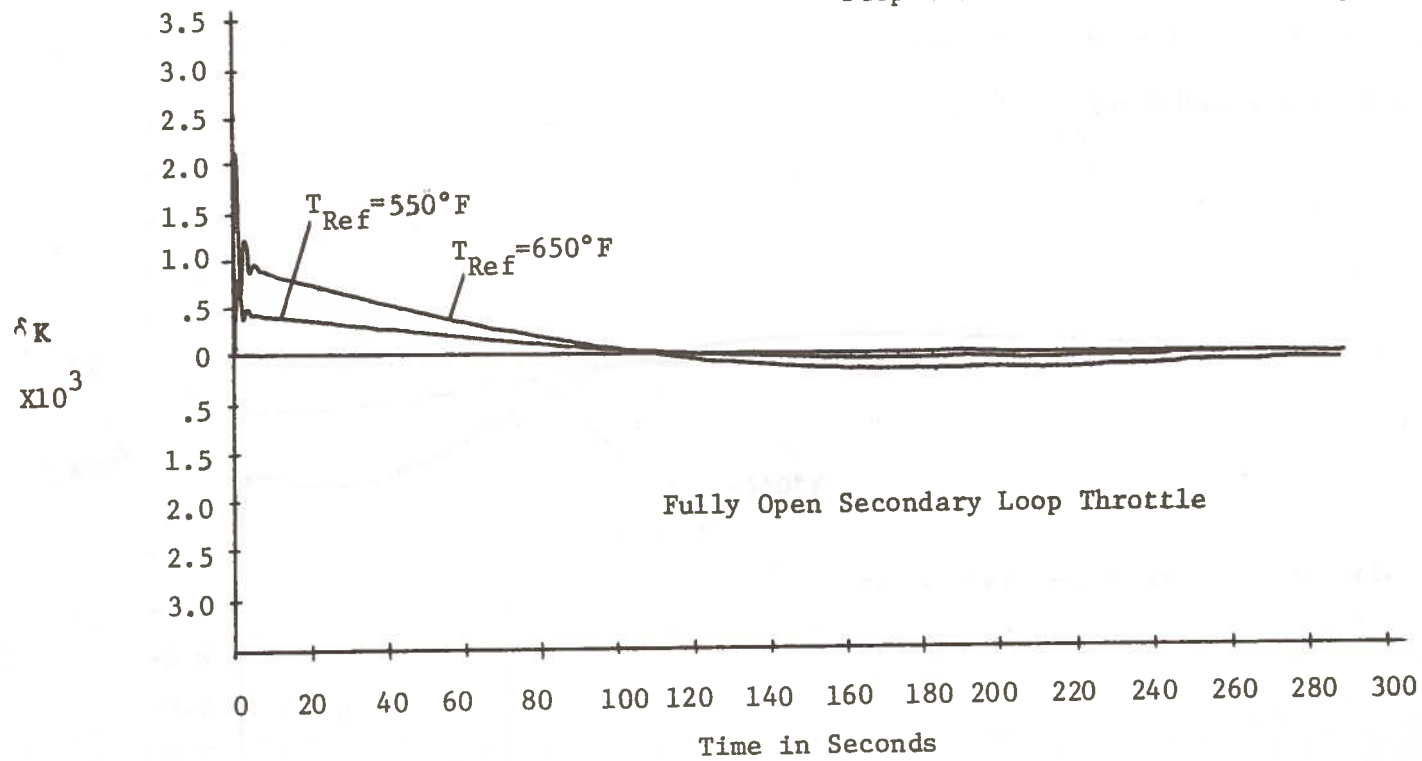


Figure 5.3b. Reactivity, δK , Versus Time
for Various Step Decreases in
in Reference Temperature (T_{Ref})

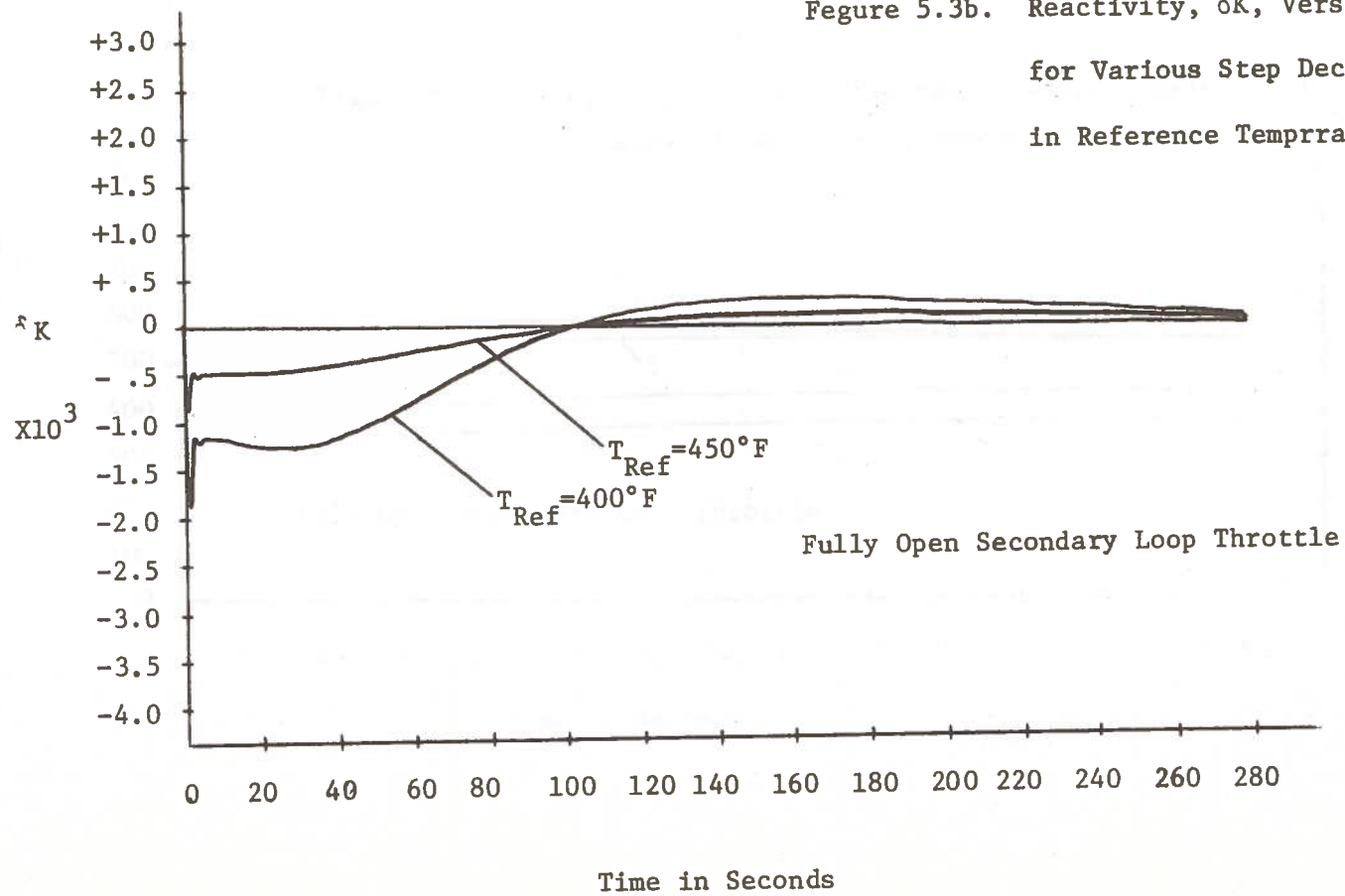


Figure 5.4a. T_c , T_{ic} , T_s , and T_f Versus Time for a Step Increase in Reference Temperature to 550°F

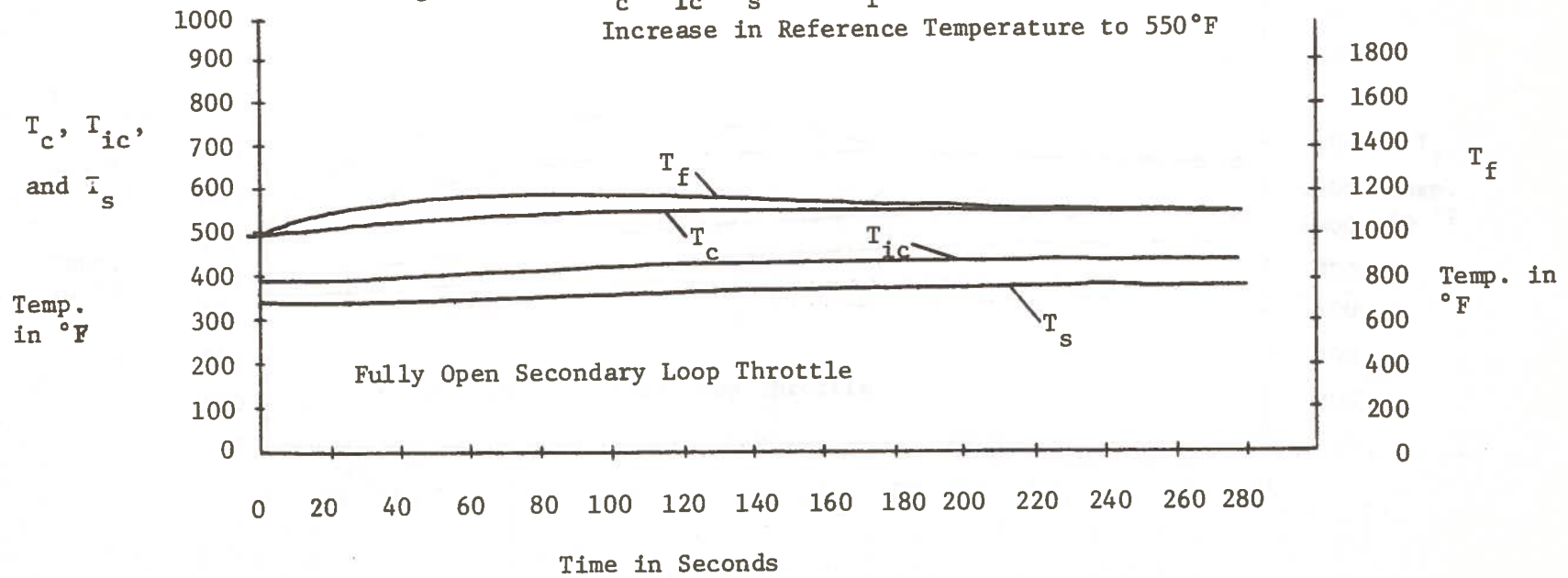


Figure 5.4b. T_c , T_{ic} , T_s , and T_f Versus Time for a Step Increase in Reference Temperature to 650°F

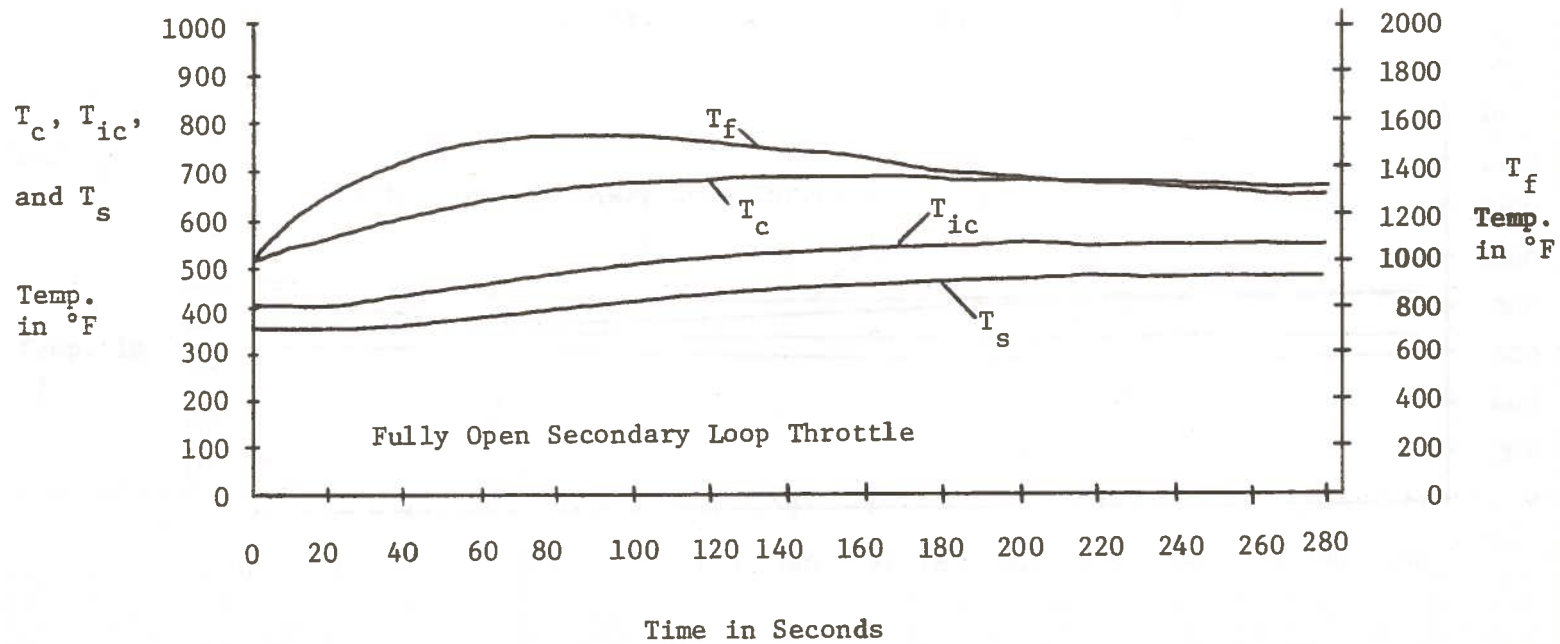


Figure 5.4c. T_c , T_{ic} , T_s , and T_f Versus Time for a Step Decrease in Reference Temperature to 450°F

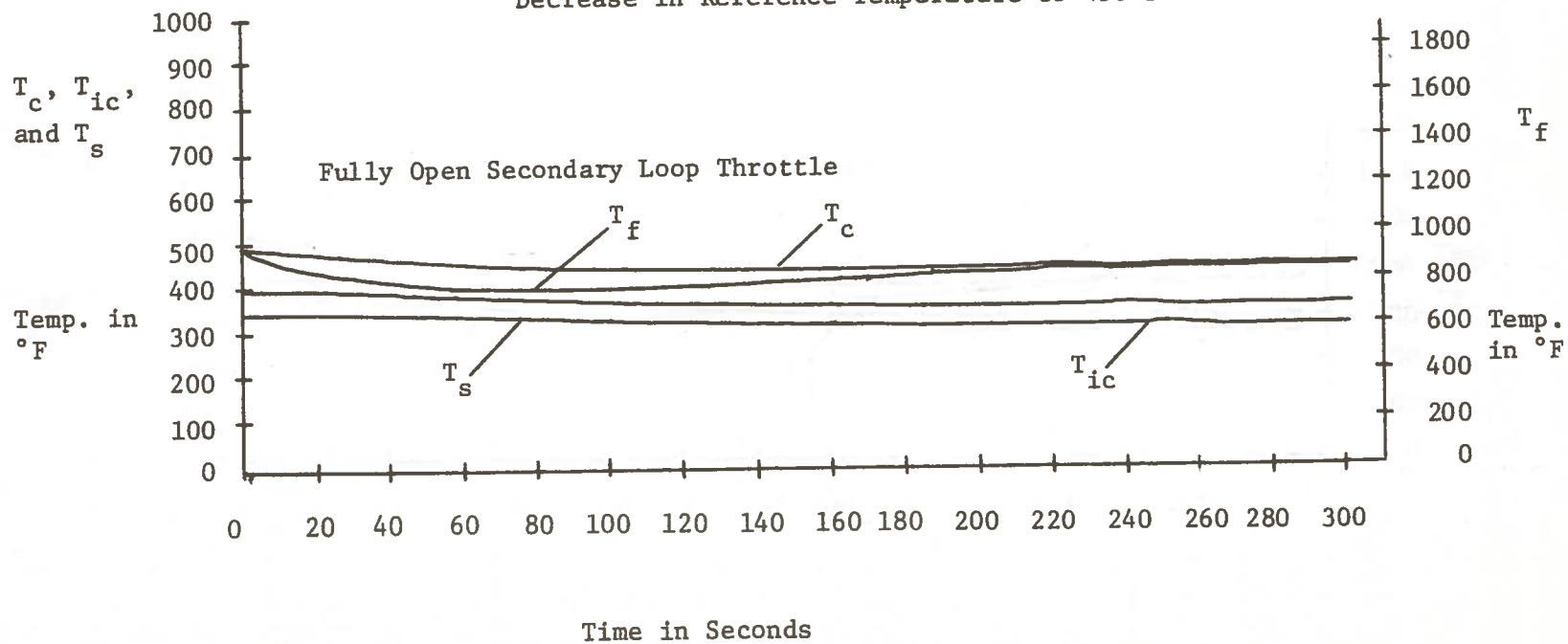
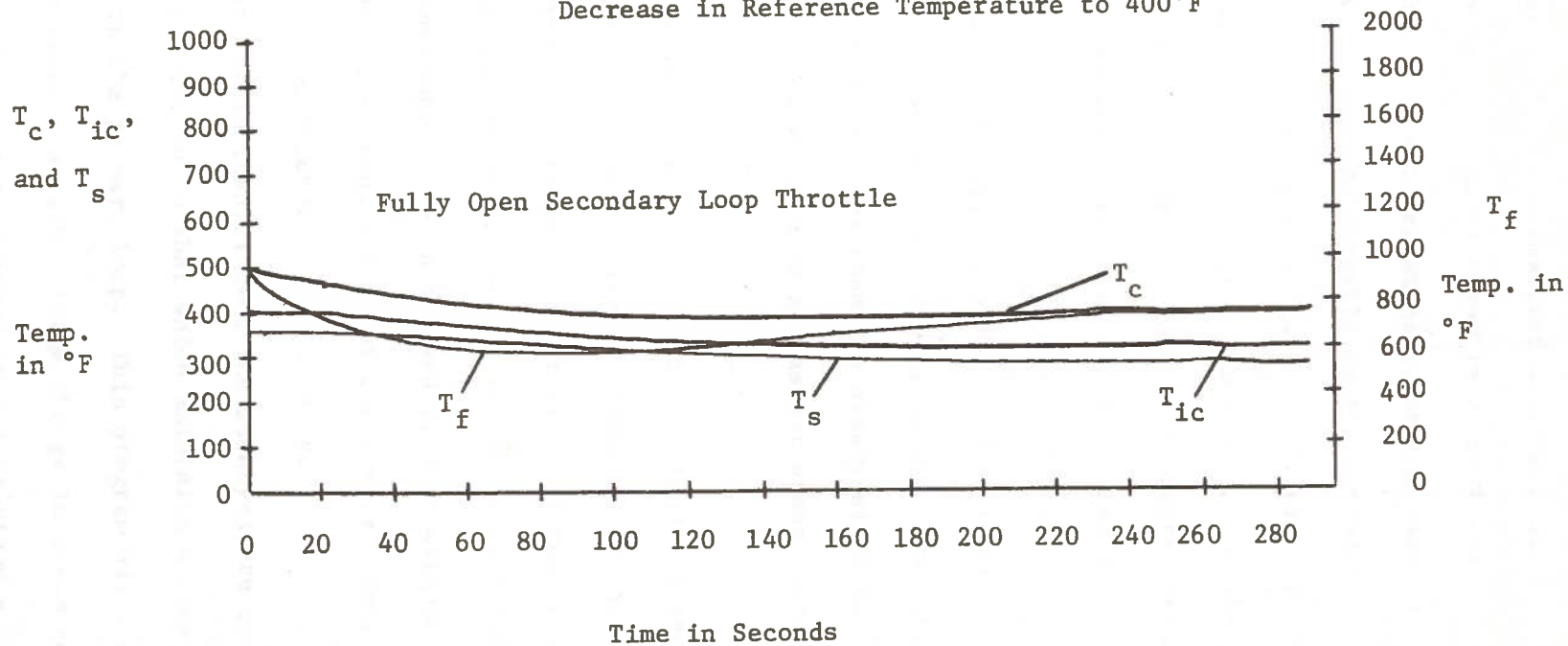


Figure 5.4d. T_c , T_{ic} , T_s , and T_f Versus Time for a Step Decrease in Reference Temperature to 400°F



in Figure 2.1.

As shown in Figure 5.2, the normalized neutron concentration (i.e., power level since the reactor power is proportional to the neutron population) has a direct dependence upon the secondary loop steam temperature even though the throttle on the secondary loop is maintained fully open. Comparing this figure to Figure 3.13 of Chapter Three, it is found that with a constant steam temperature the reactor power level reaches a steady-state condition in a shorter period of time than does the reactor power level of the system that allows the steam temperature to vary as shown schematically in Figure 2.1. It is found that the reactor power level obtained by the model in Figure 2.1 overshoots its steady-state condition and then settles at a power level that is much lower than the steady-state power level obtained by the model which uses a constant steam temperature on the secondary loop.

The above results are attributed to the fact that the secondary loop steam temperature is allowed to vary. Figures 5.4a, 5.4b, 5.4c, and 5.4d illustrate the temperature profiles of the reactor system due to various step increases in the reference temperature. As observed, the steam temperature is allowed to vary without the use of any control on the secondary loop of the system. This allows the pressure in the secondary loop to vary.

As discussed earlier in Chapter Two, the steady-state control program used in the simulation is that which maintains a constant average temperature in the primary loop. This program has a disadvantage in that it permits a rather large change in steam temperature over the power range of interest as shown in the previously mentioned

figures. The large change in steam temperature also contributes to a proportionate change in steam pressure. A wide pressure range means larger and heavier piping, automatic throttling devices, and special turbines, and leads to boiler-fuel pump problems. Methods of compromise between a constant-average-temperature program and a constant-pressure program are not found in the simulation for reasons discussed in Chapter Two. For a more complete discussion of control methods, an excellent reference is the book Control of Nuclear Reactors and Power Plants by M. A. Schultz (see reference number two).

The results obtained by varying the secondary loop throttle are shown in Figures 5.5 through 5.9. Figure 5.5 indicates the effect of throttling on the power level of the reactor. Reducing the secondary-loop steam flow reduces the amount of power that is withdrawn from the primary-loop coolant, causing an increase in the average primary-loop coolant temperature. The reactor power is decreased according to the new demand, which allows the average primary-loop coolant temperature to return to its initial state. The sooner the reactor power equals the steam demand, the shorter the duration of this transient.

Figure 5.7 represents the increase of normalized reactor power following a change in the secondary loop throttle from being fully closed to being fully open. As depicted, the normalized power level of the reactor rises above the steady-state value of 0.5, and then stabilizes to a steady-state condition in approximately 800 seconds. The transient response of the system is representative of that which could be expected during the operation of a PWR having a constant average-temperature control program.

Figures 5.8 and 5.9 illustrate the effects of varying the steam flow in the secondary loop on the temperature profiles of the system. Figure 5.8 illustrates the rise in steam temperature with various throttle reductions from the fully open position. As can be seen with a 100% reduction in the throttle (fully closed) the steam temperature approaches 500°F, representing zero heat transfer between the primary coolant and the secondary steam.

Figures 5.9a, 5.9b, and 5.9c illustrate the effects of varying the steam flow in the secondary loop from full flow to 25% full flow, 50% full flow, and 75% full flow. With each variation, the average coolant temperature rises initially but then reaches a steady-state condition at its initial value. Also with each variation, the fuel temperature is seen to decrease and the inlet coolant temperature is seen to increase until each reaches a steady-state condition in which the reactor power equals the steam demand.

With the secondary loop throttle fully open and by using the one group delayed neutron approximation, the differential normalized neutron concentration and the inverse reactor period versus time results for various step changes in reference temperature are shown in Figures 5.10 and 5.11, respectively.

Figure 5.6. ΔX Versus Time for Various Step

Figure 5.5. n^* Versus Time for Various Step Changes in Secondary Loop Flow from Full Flow Using R.C. Network

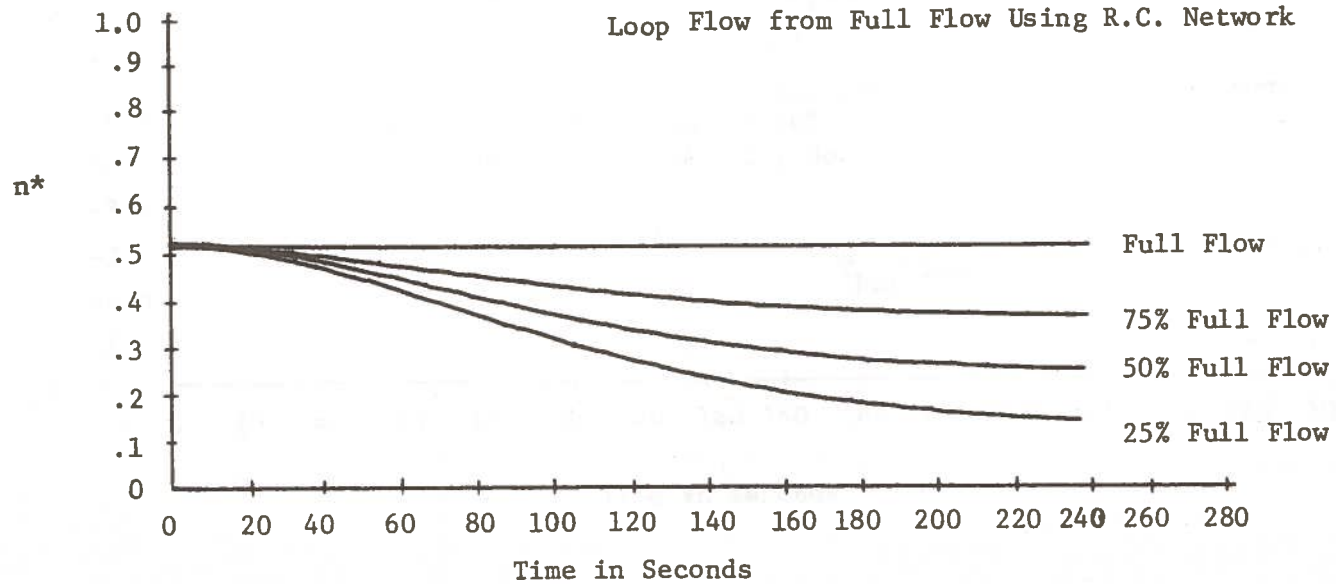
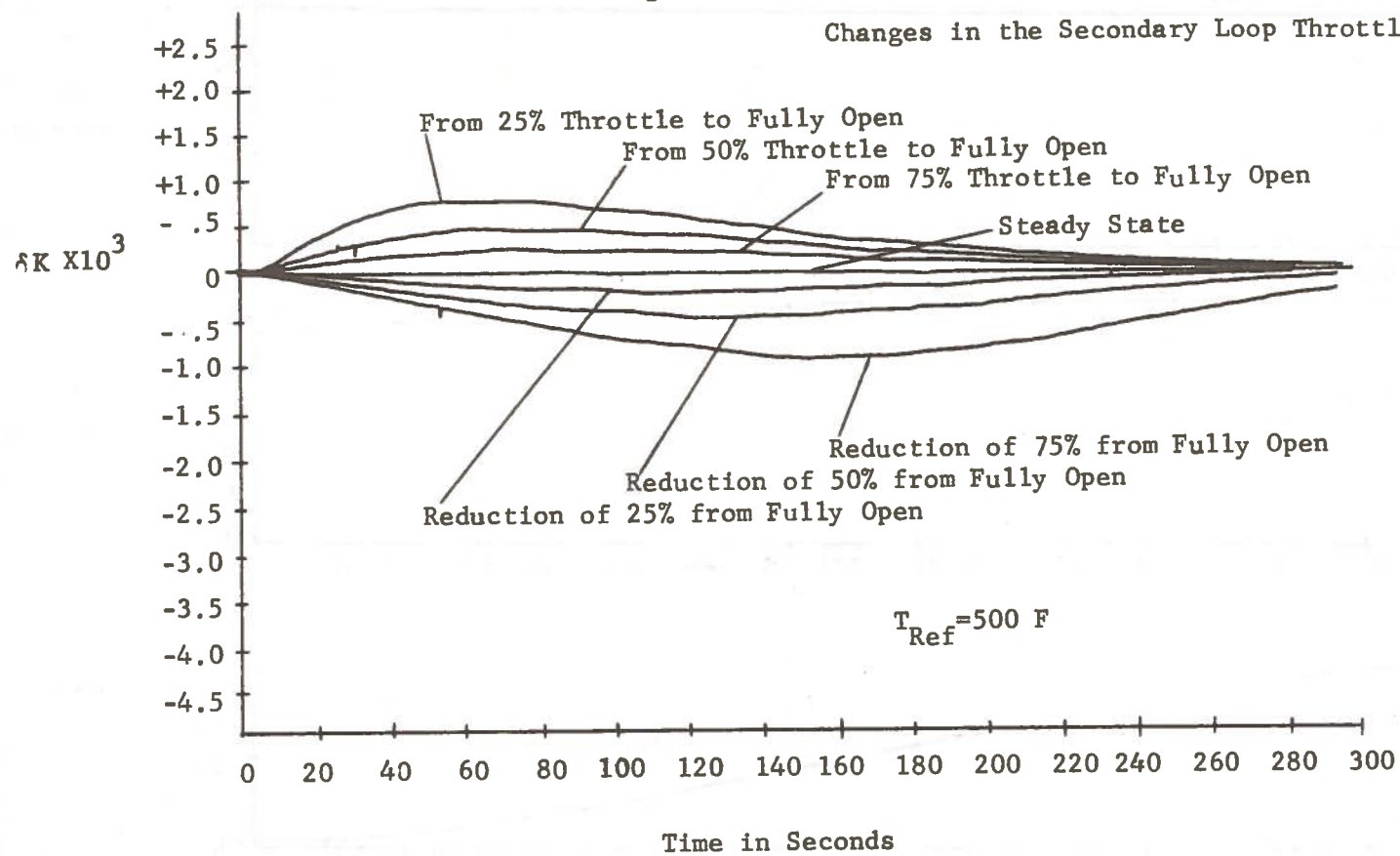
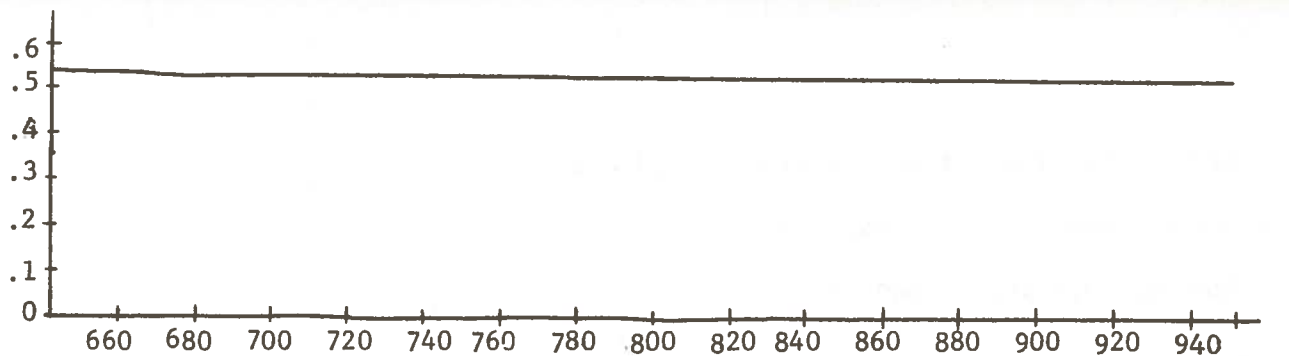


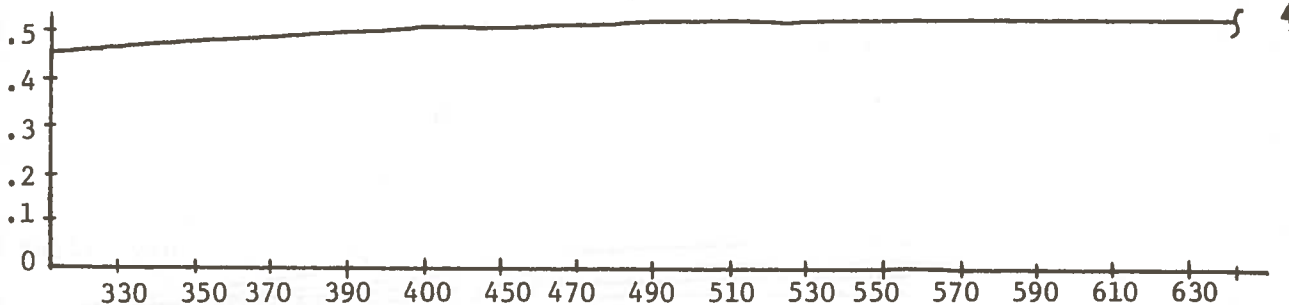
Figure 5.6. δK Versus Time for Various Step Changes in the Secondary Loop Throttle



n*
Continued



n*
Continued



n*

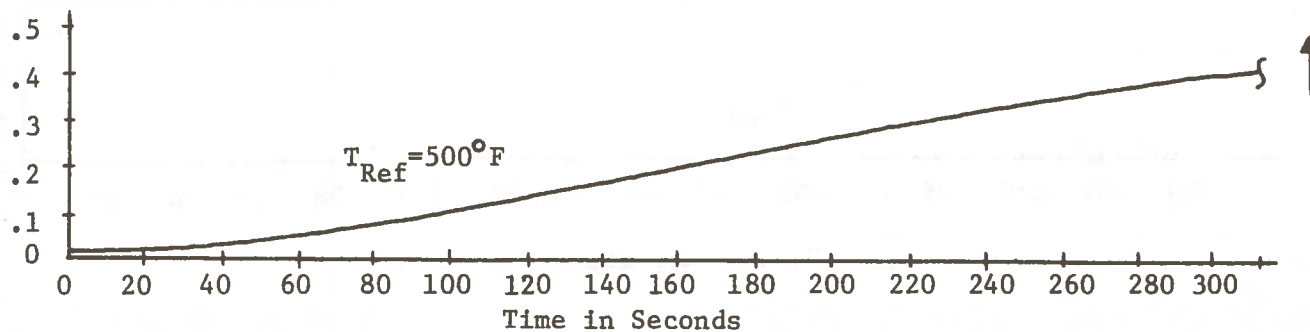


Figure 5.7. n* Versus Time For a Step Increase in the Secondary Loop Throttle From Zero To Fully Open

Figure 5.8. T_s Versus Time for Various Step Decreases
in the Secondary Loop Throttle Setting
from Fully Open Using R.C. Network

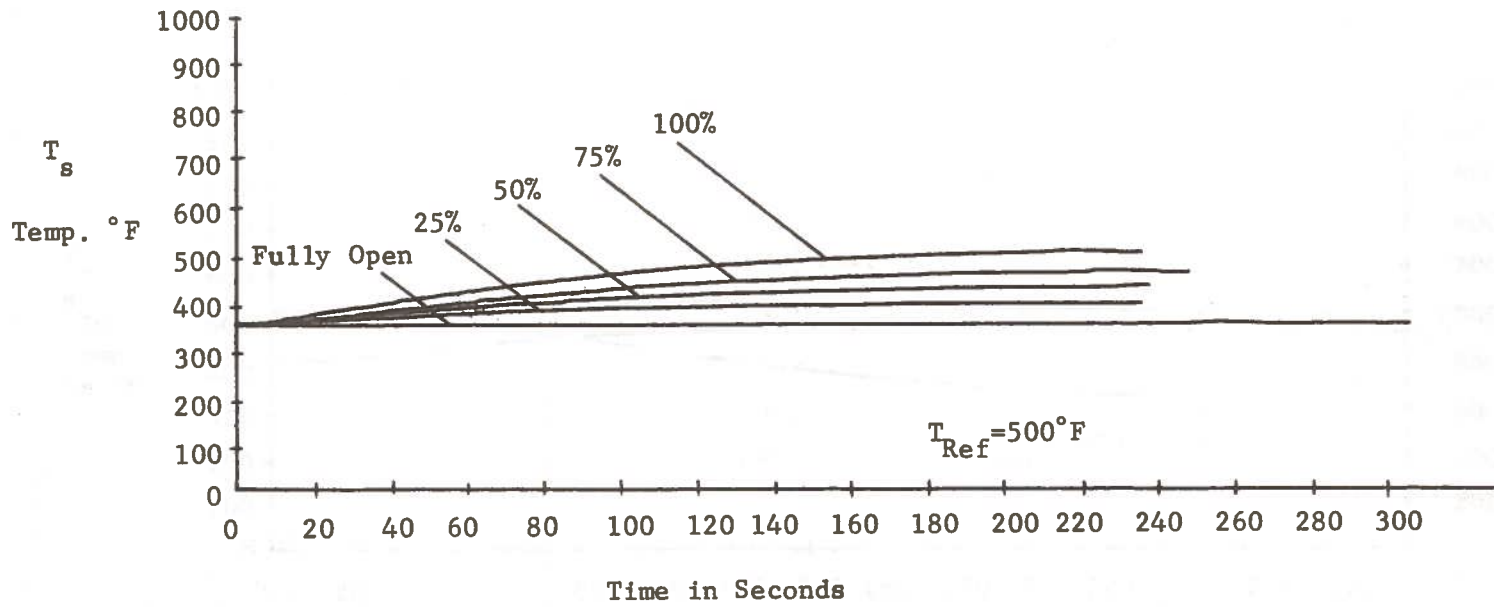


Figure 5.9a. T_c , T_{ic} , and T_f Versus Time for a 75%
 Decrease in the Secondary Loop Throttle from
 Fully Open

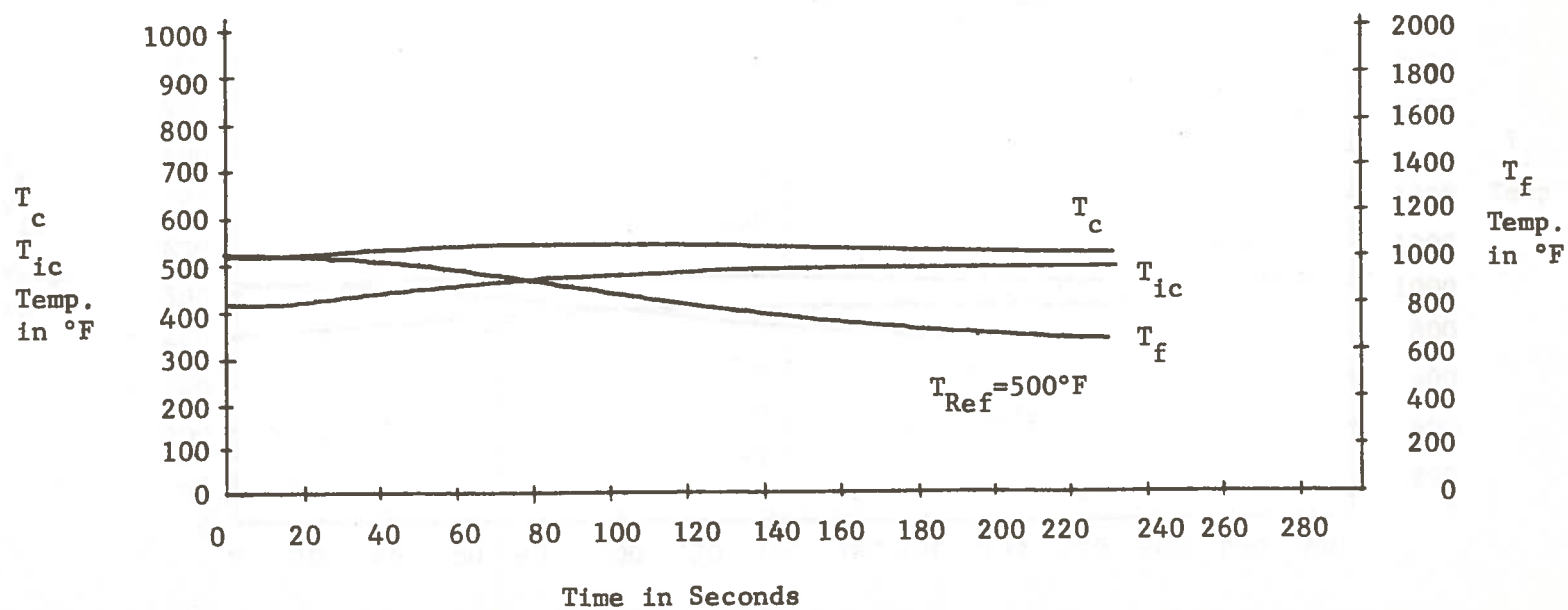


Figure 5.9b. T_c , T_{ic} , and T_f Versus Time for a 50%
 Decrease in the Secondary Loop Throttle
 from Fully Open

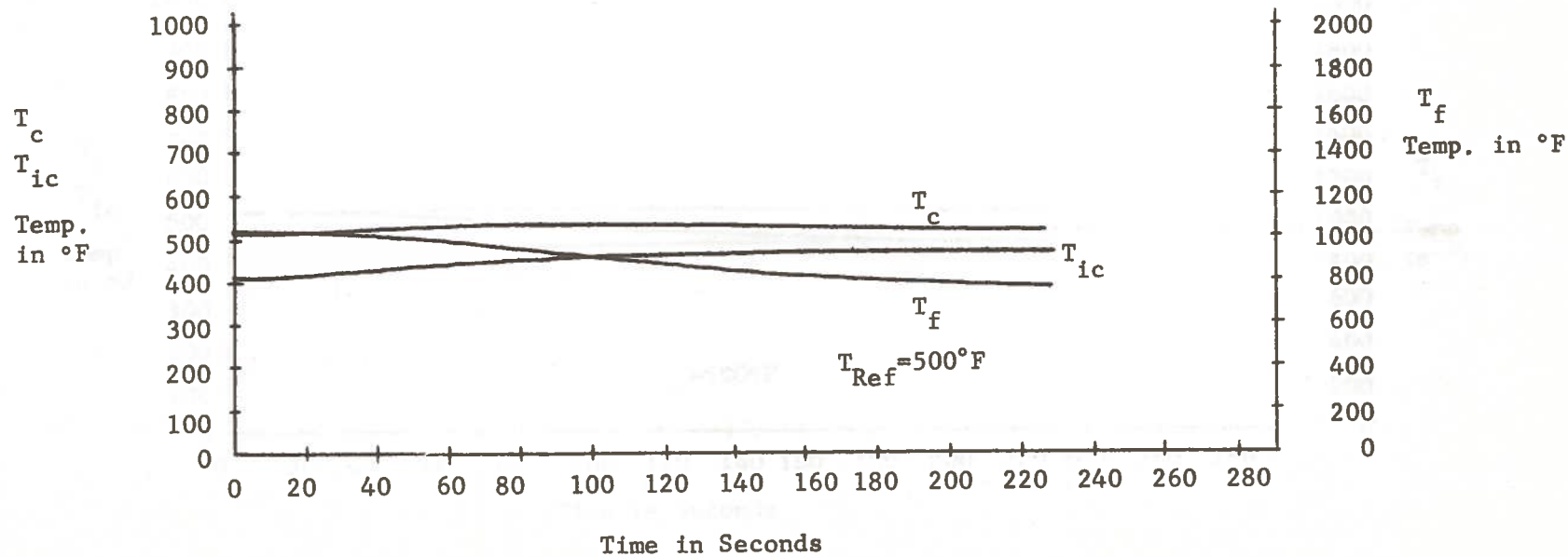
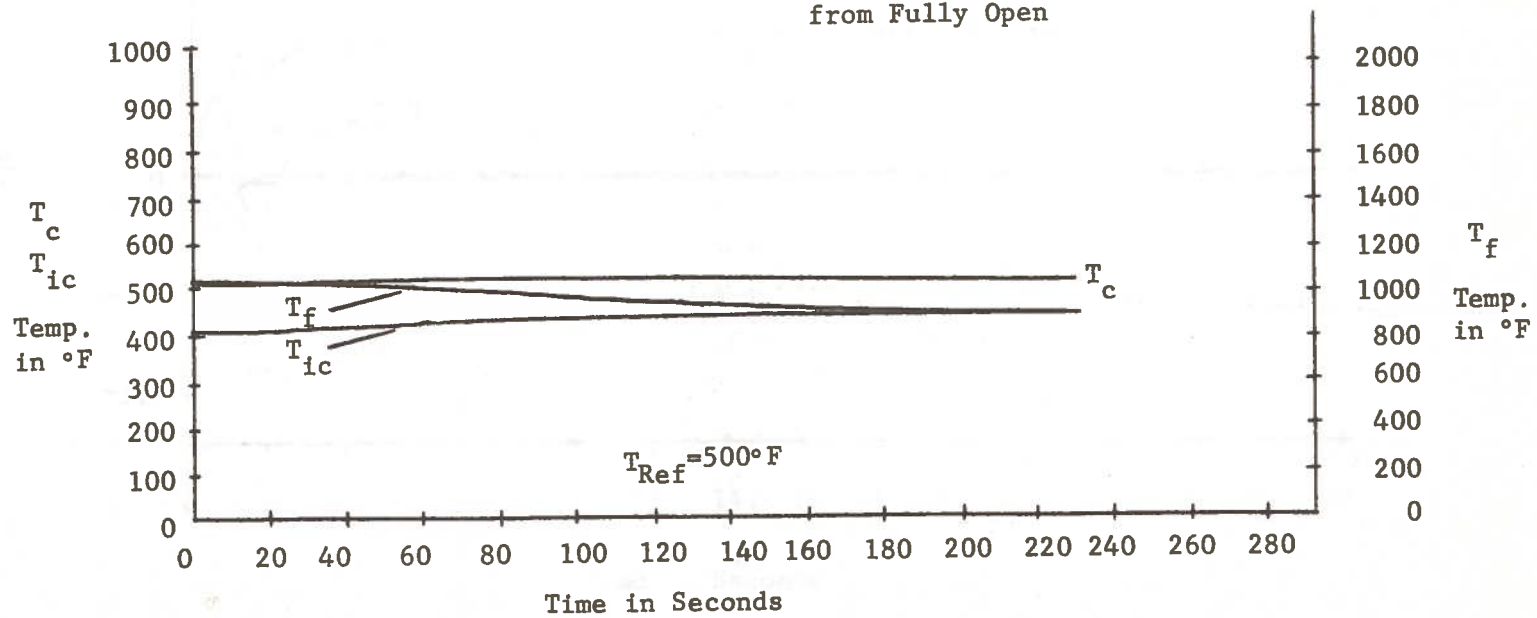
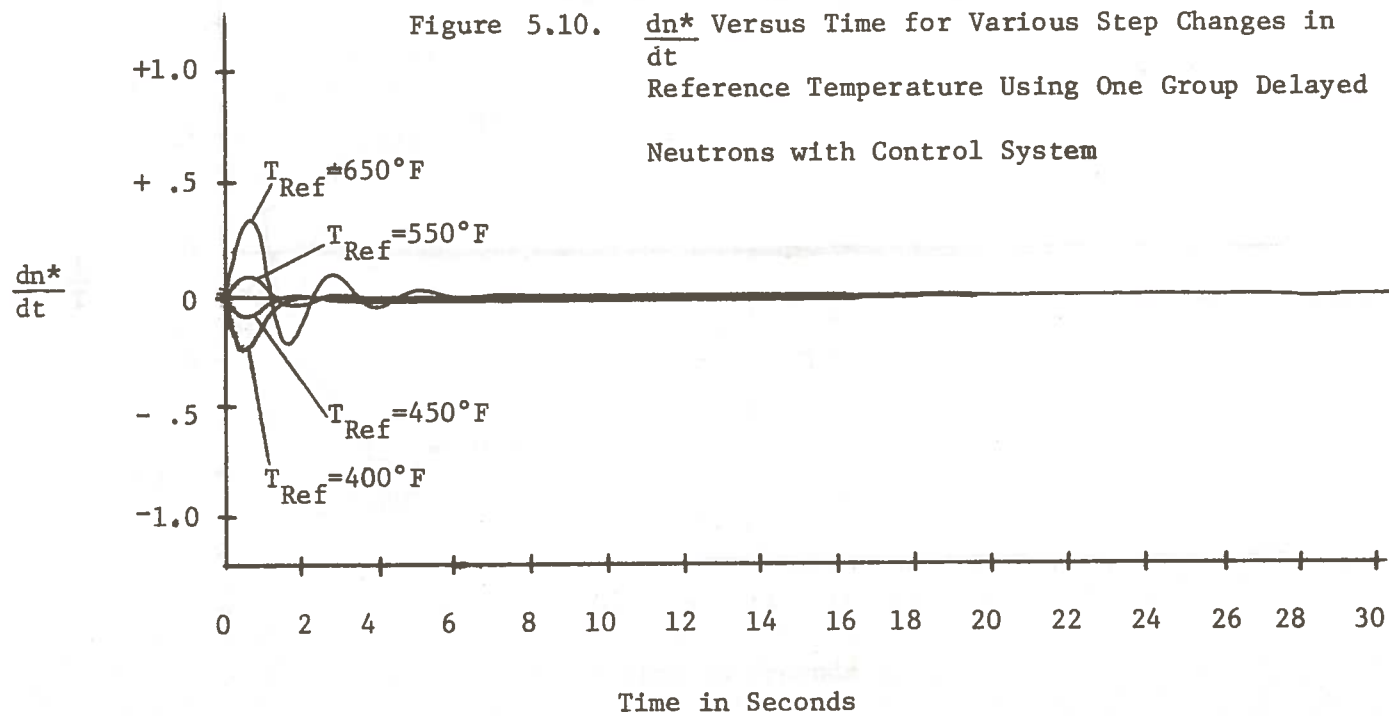
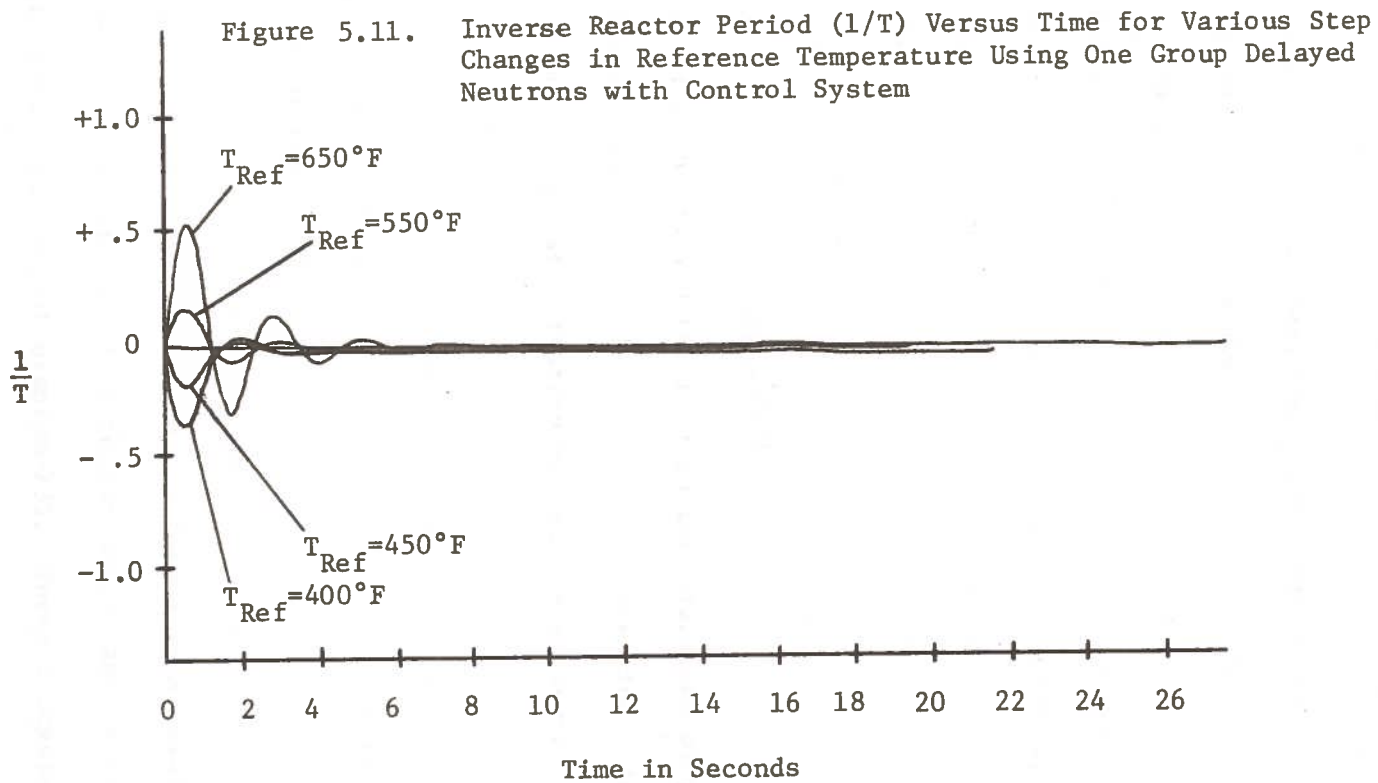


Figure 5.9c. T_c , T_{ic} , and T_f Versus Time for a 25%
Decrease in the Secondary Loop Throttle
from Fully Open







CHAPTER SIX

XENON POISONING

As mentioned in Chapter Two, the xenon start up and shut down problem is simulated as a separate problem. The reason is that the long time constants found in the problem require time scaling. Since two hours of real time are studied in one second, the reactor power systems which are studied in real time must be separated from the xenon problem. As mentioned earlier, the reactor power systems include a xenon poison contribution that remains constant during full-power systems operation.

6.1 The Theory of Xenon Poisoning^{15,16}

An effect that plays a vital role in the operation of power-producing thermal reactors is fission-product poisoning. As the reactor continues to operate, fission products are created in the fuel elements. Some fission products have large absorption cross sections for neutrons and thus can act as poisons. If these poisons are produced in appreciable amounts, they affect the overall neutron multiplication of the reactor.

Of particular interest in the study of poisons are the nuclides xenon-135 and samarium-149. Xenon-135 is formed as a result of the decay of the direct fission product tellurium-135 and is also formed as a direct fission product of uranium-235. These processes and their half-lives are summarized below:

where: I = number of I-135 atoms present per cubic centimeter;

γ_I = fractional yield of I-135 from the direct fission process,

= .056 atoms per fission;

Σ_f = macroscopic fission cross section of the fuel;

Φ = thermal neutron flux;

λ_I = decay constant of I-135,

= 2.9×10^{-5} seconds⁻¹.

One atom of xenon-135 is formed with the decay of each atom of iodine-135 so that the total rate of formation of xenon-135 is

$$\lambda_I I + \gamma_X \Sigma_f \Phi, \quad (6.2)$$

where γ_X is the fission yield of the xenon. The xenon-135 disappears both as the result of its natural radioactive decay and also because of neutron absorption. Therefore, the mathematical description of the xenon concentration in a reactor at any time during operation becomes:

$$\frac{dX}{dt} = (\gamma_X \Sigma_f - \sigma_X X) \Phi + \lambda_I I - \lambda_X X, \quad (6.3)$$

where: X = number of atoms of xenon-135 present per cubic centimeter;

σ_X = microscopic thermal-neutron absorption cross section of xenon-135,

= 3.5×10^{-18} cm²;

λ_X = decay constant of xenon-135,

= 2.1×10^{-5} seconds⁻¹;

γ_X = .003 atoms per fission.

To a good approximation, the only effect of fission product poisons on the multiplication factor appears in the thermal utilization factor, f . Thus the reactivity equivalent of poisons in a previously critical reactor can be written as

$$P = \frac{K'_\infty - K_\infty}{K'_\infty} = \frac{f' - f}{f'}, \quad (6.4)$$

where the primes refer to the poisoned reactor. In the absence of poisons, f is given by

$$f = \frac{\Sigma_{af}}{\Sigma_{af} + \Sigma_{am}}, \quad (6.5)$$

where: Σ_{af} = macroscopic thermal absorption cross section of the fuel,

= 678 barns for uranium-235;

Σ_{am} = macroscopic thermal absorption cross section of the moderator.

With poisons present, f becomes

$$f' = \frac{\Sigma_{af}}{\Sigma_{af} + \Sigma_{am} + \Sigma_{ap}}, \quad (6.6)$$

where: Σ_{ap} = macroscopic cross section of the poison.

= $\sigma_X X$.

Thus from the equation defining the reactivity with a poison one obtains the relation

$$P = \frac{f' - f}{f'} = \frac{-\Sigma_{ap}}{\Sigma_{af} + \Sigma_{am}}. \quad (6.7)$$

Looking at only the magnitude of P and ignoring the absorption in the moderator as compared to that in the fuel:

$$P = \frac{\Sigma_{ap}}{\Sigma_{af}} = \frac{\sigma_X X}{\Sigma_{af}} \quad (6.8)$$

Defining

$$I' = \frac{\sigma_X I}{\Sigma_{af}} \quad (6.9)$$

one can then rewrite Equations 6.1 and 6.3 in terms of the derivatives of P and I' . Thus, multiplying equations 6.1 and 6.3 by σ_X / Σ_{af} , one obtains:

$$\frac{dP}{dt} = (\Sigma_f \sigma_X \gamma_X / \Sigma_{af} - P \sigma_X) \Phi + \lambda_I I' - \lambda_X P \quad (6.10)$$

and

$$\frac{dI'}{dt} = \Sigma_f \Phi \gamma_I \sigma_X / \Sigma_{af} - \lambda_I I' \quad (6.11)$$

To observe shut down operations, one merely permits the flux term in Equations 6.10 and 6.11 to equal zero. Thus shut down can be simulated with

$$\frac{dP}{dt} = \lambda_I I' - \lambda_X P \quad (6.12)$$

and

$$\frac{dI'}{dt} = -\lambda_I I' \quad (6.13)$$

Because iodine-135 has a shorter half-life than xenon-135, the conditions are suitable for the xenon concentration to increase to a maximum after the reactor is shut down completely. This occurs because the iodine-135 present at shut down forms xenon-135 by radioactive decay at a rate that is initially greater

than the rate of decay of xenon-135, and because almost none of the xenon-135 is now being lost by neutron capture.

If equilibrium is attained before shut down, the concentration of iodine-135 at any time t_s after shut down is given by

$$I = I_0 e^{-\lambda_I t_s}, \quad (6.14)$$

in which I_0 is the equilibrium iodine concentration before shut down. Solving Equation 6.12 for the xenon poison level after shut down by substituting Equation 6.14 into 6.12 after noting that $I_0' = \sigma_X I_0 / \Sigma_{af}$, one obtains the well known relation¹⁷

$$P = \frac{\lambda_I}{(\lambda_X - \lambda_I)} I_0' (e^{-\lambda_I t_s} - e^{-\lambda_X t_s}) + X_0' e^{-\lambda_X t_s}, \quad (6.15)$$

where: $X_0' = X_0 \sigma_X / \Sigma_a$.

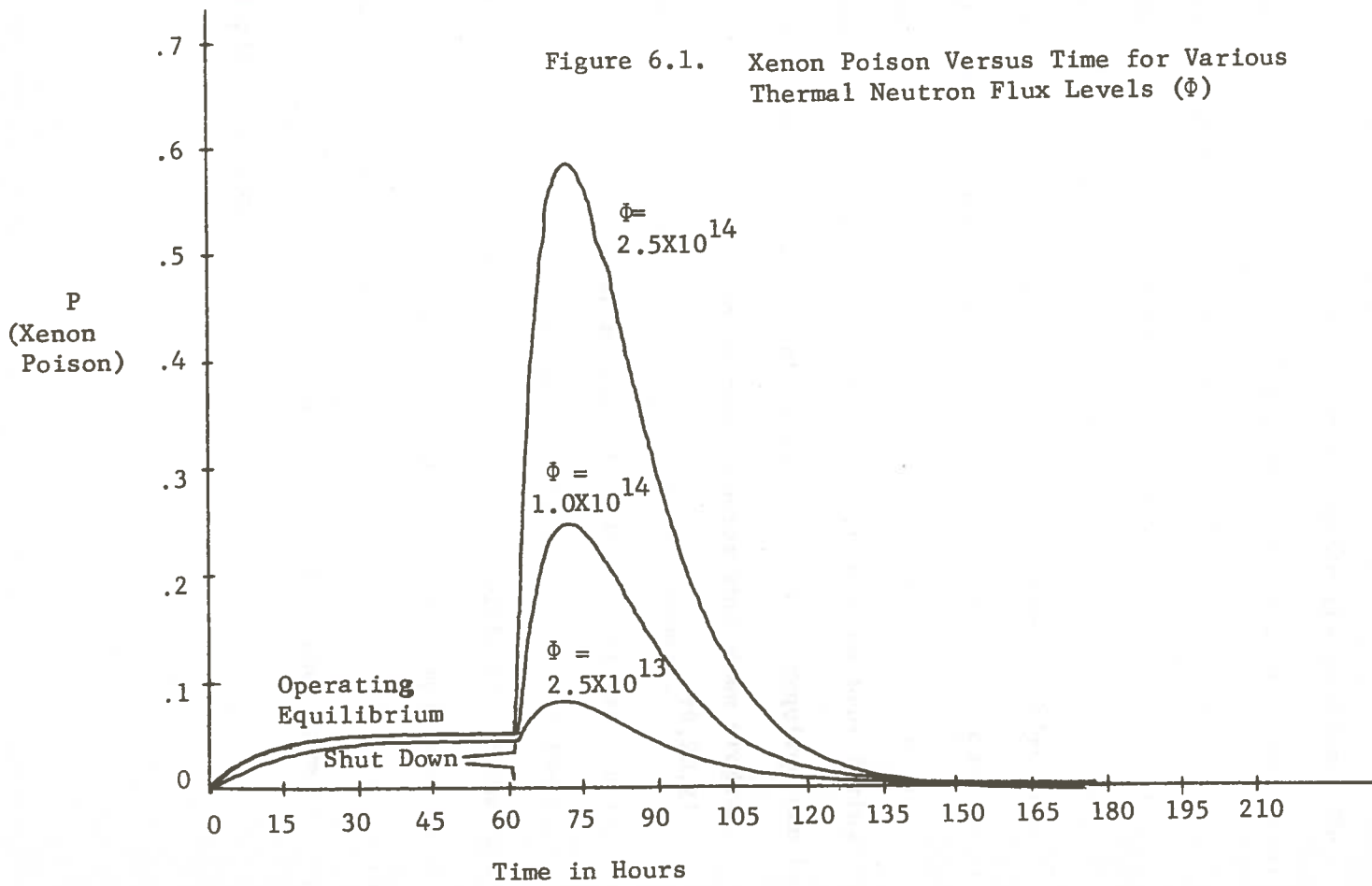
X_0 = equilibrium xenon concentration before shut down.

The time at which the maximum xenon concentration after shut down occurs is given by the equation¹⁸

$$t_{\max} = \frac{1}{\lambda_X - \lambda_I} \ln \frac{\lambda_X}{\lambda_I} \left(1 - \frac{\lambda_X - \lambda_I}{\lambda_I} \frac{X_0}{I_0} \right). \quad (6.16)$$

6.2 After Shut Down Buildup

A major limitation on the maximum operating power of a high-power thermal reactor is its large concentration of xenon-135. The concentration can correspond to hundreds of dollars of negative reactivity in such a reactor following immediate shut down. Reduction of the reactivity override by xenon poisoning following shut down of a high-power thermal reactor is an intriguing problem. Figure 6.1 illustrates the problem. In this figure, xenon poison concen-



trations after shut down are found for a reactor operating at flux levels of 2.5×10^{14} , 1.0×10^{14} , and 2.5×10^{13} neutrons/cm²-sec. One should observe the buildup following shut down of the reactor before which an equilibrium xenon concentration is attained.

A number of alternatives exist to handle the problem. The obvious solution is to accept the situation that the reactor cannot start up until the xenon poison concentration has had time to decay. A second, more expensive alternative is to provide sufficient excess positive reactivity such that the xenon poisoning cannot override the available excess positive reactivity. However, even these reactors lose their override capabilities toward the end of core life. A more imaginative solution in those cases where xenon poison concentrations after shut down cannot be tolerated is to program the neutron flux during a finite shut down period so that excess reactivity required can be minimized by determining an optimum reactor shut down program.

These methods are discussed by several authors.^{19,20,21}

An attempt at producing an optimal shut down is illustrate in Figure 6.2 and 6.3. One observes in Figure 6.2 that a two pulse on-off control of the neutron flux level significantly reduces the xenon buildup after shut down in comparison to a rapid shut down. As shown in Figure 6.3, a single pulse on-off control of the neutron flux level also reduces the xenon buildup after shut down in comparison to a rapid shut down.

Figure 6.2. Xenon Poison Versus Time Showing the Effect of a Two Pulse Shut Down in Comparison to a Rapid Shut Down

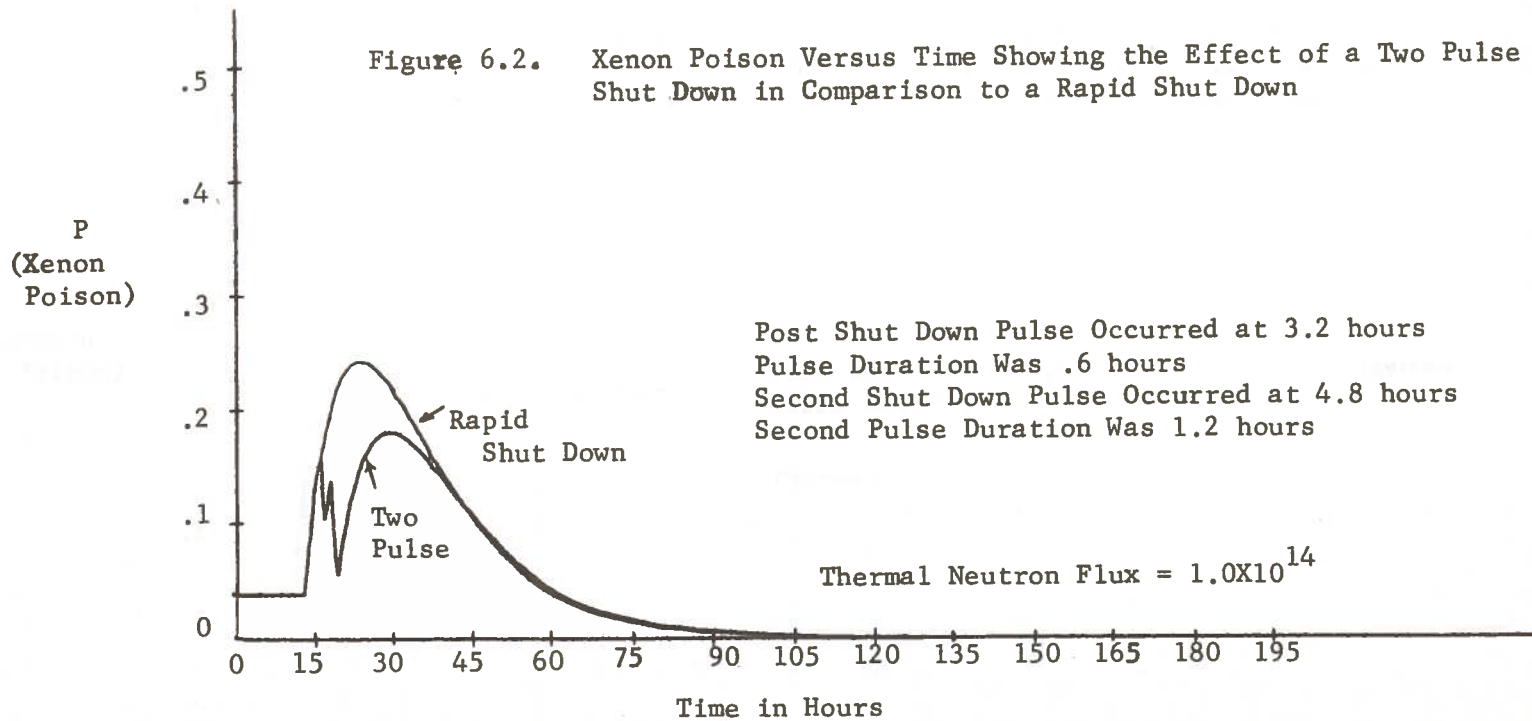
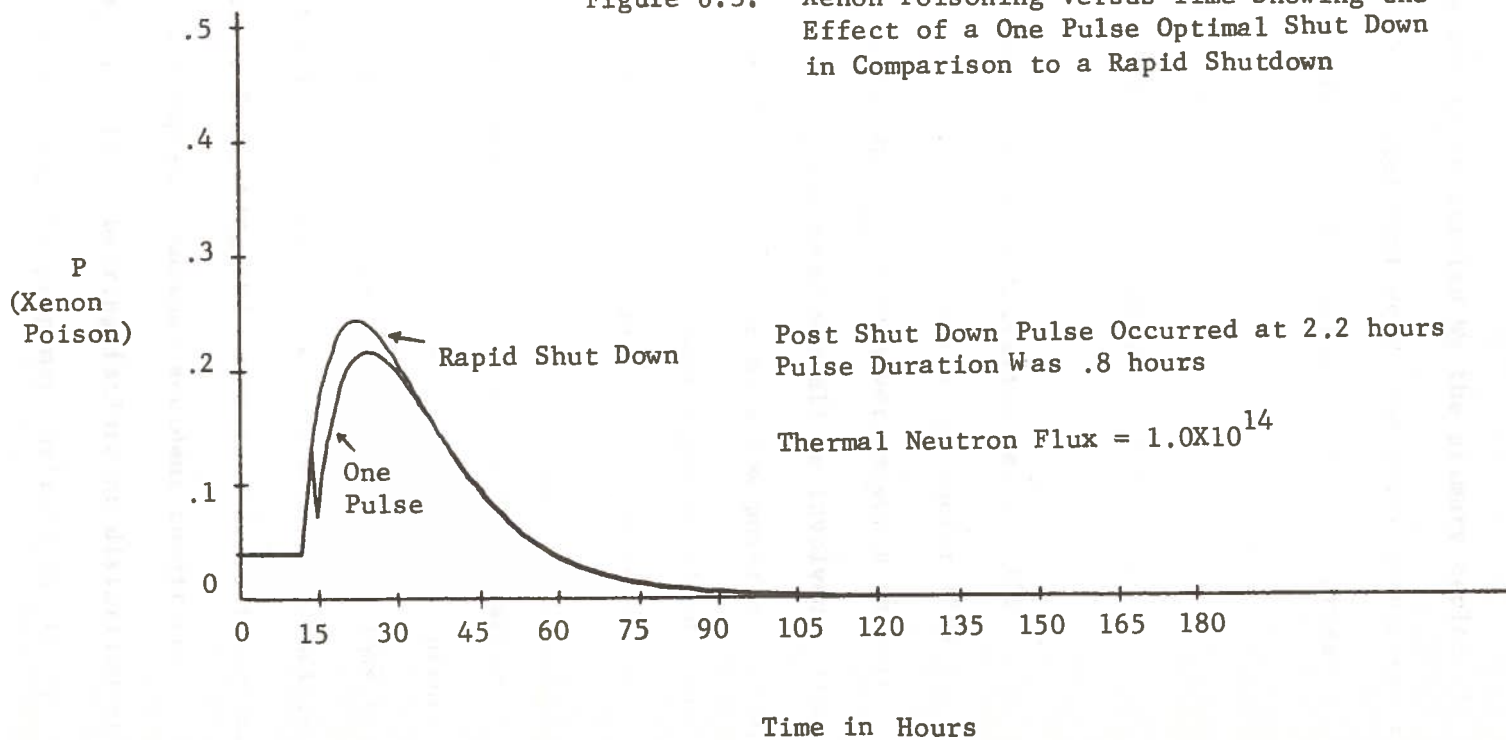


Figure 6.3. Xenon Poisoning Versus Time Showing the Effect of a One Pulse Optimal Shut Down in Comparison to a Rapid Shutdown



CHAPTER SEVEN

COOLANT FLOW CONSIDERATIONS

The rate at which energy is carried by the primary coolant from the reactor to the heat exchanger must equal the power generated by the reactor. This is called "the heat balance" and is expressed by the relation

$$P = F(T_{oc} - T_{ic}),$$

where: P = power output of the heat exchanger,

F = constant,

T_{oc} = temperature of coolant leaving reactor ($^{\circ}F$),

T_{ic} = temperature of coolant entering reactor ($^{\circ}F$).

There may be several reasons why T_{oc} must never exceed a certain value. Problems of stress, corrosion, and wear may all be involved. Also, it is inefficient to operate the primary loop at a low power output with the flow needed for full power output. These considerations require that some form of flow control is necessary in nuclear reactor power systems.

Along with the above considerations, a method illustrating the reduction of the primary coolant flow is necessary. The occurrence of several accident conditions causes a reduction or complete loss of coolant flow through the reactor core. One such accident condition is that the electrical power furnishing the power to operate the primary coolant pumps may be interrupted. Another accident condition is that the pumps may stop as a result of bearing failure or distortion of the pump rotor or casing. Also, the pump may cavitate as the result

of low system pressure after a loss of pressure accident. The primary coolant flow could also be interrupted by rupture of a main coolant line. Of these several possibilities, the most probable situation is the loss of pump power.

7.1 Loss of Coolant Flow

After a loss of power to the primary coolant pumps, the flow is reduced to zero. The above situation is depicted in Figure 7.1 and 7.2d. As can be observed in Figure 7.2d, the average coolant temperature and the fuel temperature rise after a loss of coolant accident. This is the first effect. The second effect is observed in Figure 7.1. In this figure, it is observed that the normalized power level decreases after a loss of coolant accident. This is caused by the negative temperature coefficient of the fuel and the constant average temperature control program of the control system. It is observed, however, that the reduction in reactor power does not effect the rise of the average coolant temperature significantly.

For this reason it is found that another method of controlling the reactor power level during loss of coolant accidents is necessary. A method of accomplishing the above is to control the scram rod insertion by a relay that would become energized upon loss of power to the pumps.

Another accident condition involves the reduction of the coolant flow to one half of its original value. This situation is illustrated in Figures 7.1 and 7.2c. As in the case of zero flow, the normalized power level is found to decrease for a 50% reduction of flow. This is shown in Figure 7.1. Figure 7.2c illustrates the rise in fuel temperature and in average coolant temperature with a 50% reduction of

primary coolant flow.

7.2 Flow Considerations in Reactor Control

As mentioned before, it is inefficient to operate the primary loop at low power output with the flow needed for full power output. Also, for several reasons mentioned earlier in this chapter, it is necessary to assume that T_{oc} must never exceed a certain value.

As shown in Figure 7.1, the reactor power level can be varied by varying the primary coolant of the reactor while maintaining a constant power output level at the heat exchanger. The data in Figure 7.1, indicates that increasing the flow by 25% (to 125%) causes the normalized reactor power level to increase. While decreasing the flow by 25% (to 75%) causes the normalized reactor power level to decrease. Figures 7.2a and 7.2b shows that an increase or decrease in primary loop coolant flow results in the increase or decrease respectively of the inlet coolant temperature of the reactor. Note that the fuel temperature remains constant and the coolant temperature reaches a steady state condition equal to its initial value before the change of flow is initiated.

The power which is extracted from the reactor remains constant, however. A reduction in the coolant flow causes a reduction in the inlet coolant temperature and an increase in the outlet coolant temperature. An increase in the coolant flow causes an increase in the inlet coolant temperature and a decrease in the outlet coolant temperature.

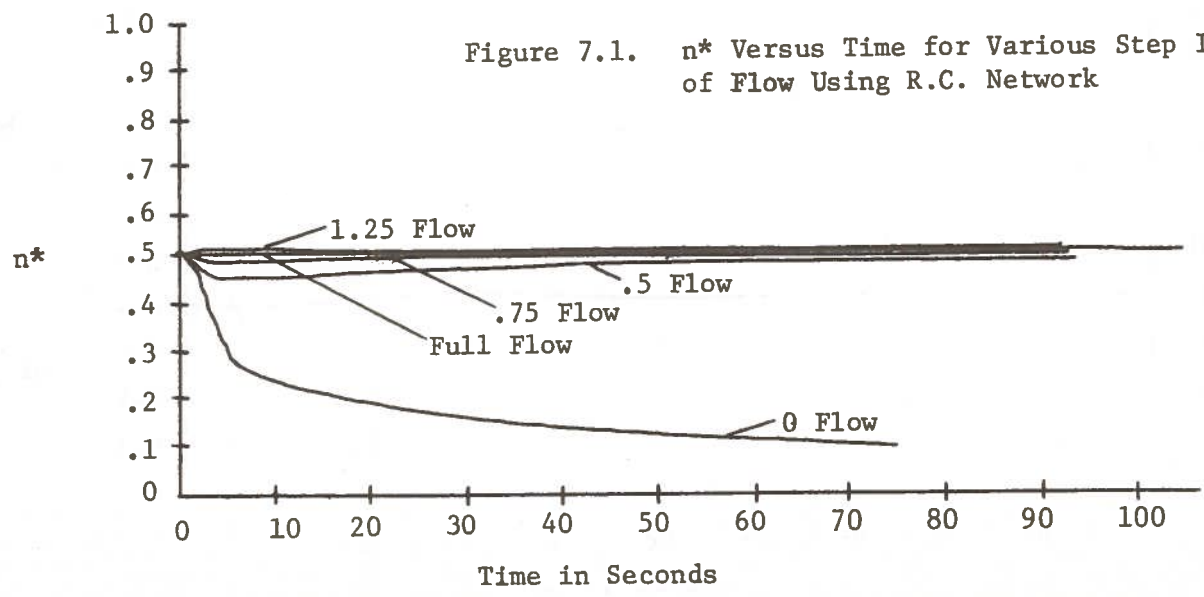


Figure 7.2a. T_c , T_{ic} , and T_f Versus Time for a Step Increase in Primary Loop Coolant Flow from Full Flow to 125% Full Flow Using R.C. Network

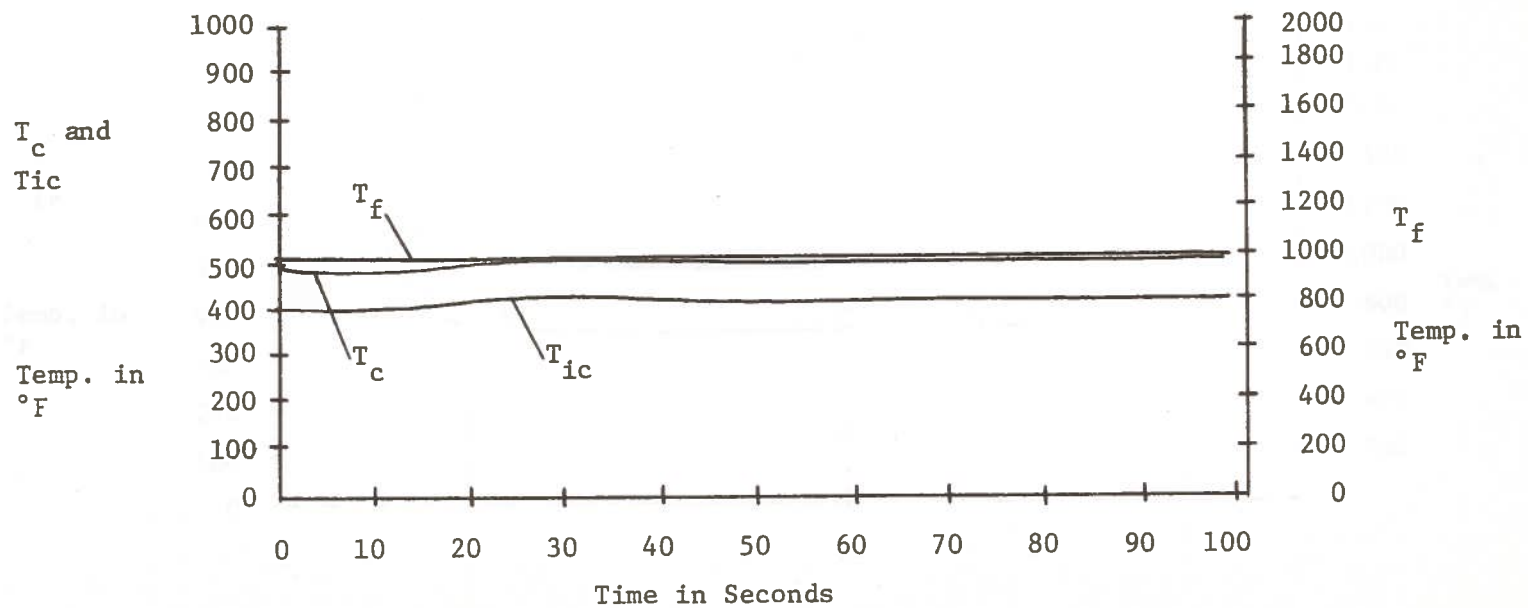


Figure 7.2b. T_c , T_{ic} , and T_f Versus Time for a Step
 Decrease in Primary Loop Coolant Flow from
 Full Flow to 75% Full Flow Using R.C. Network

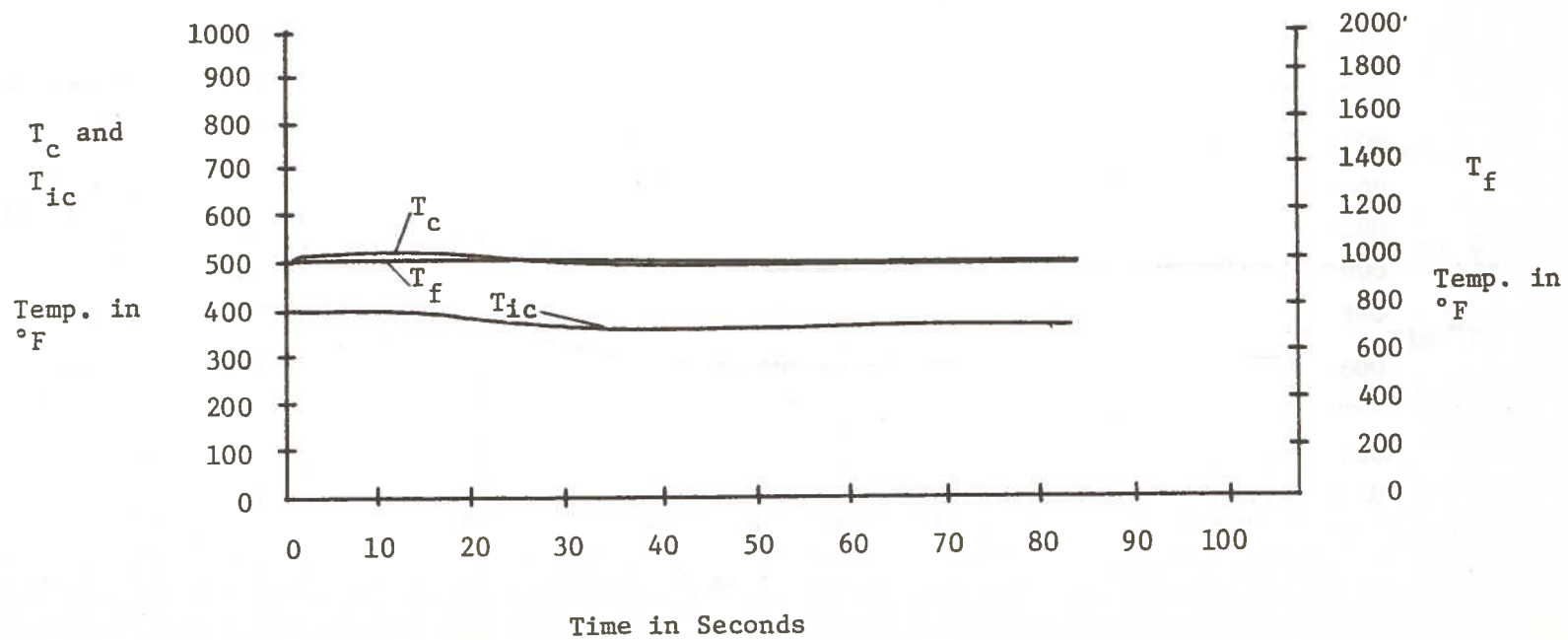


Figure 7.2c. T_c , T_{ic} , and T_f Versus Time for a Step Decrease in Flow from Full Flow to One Half Flow Using R.C. Network

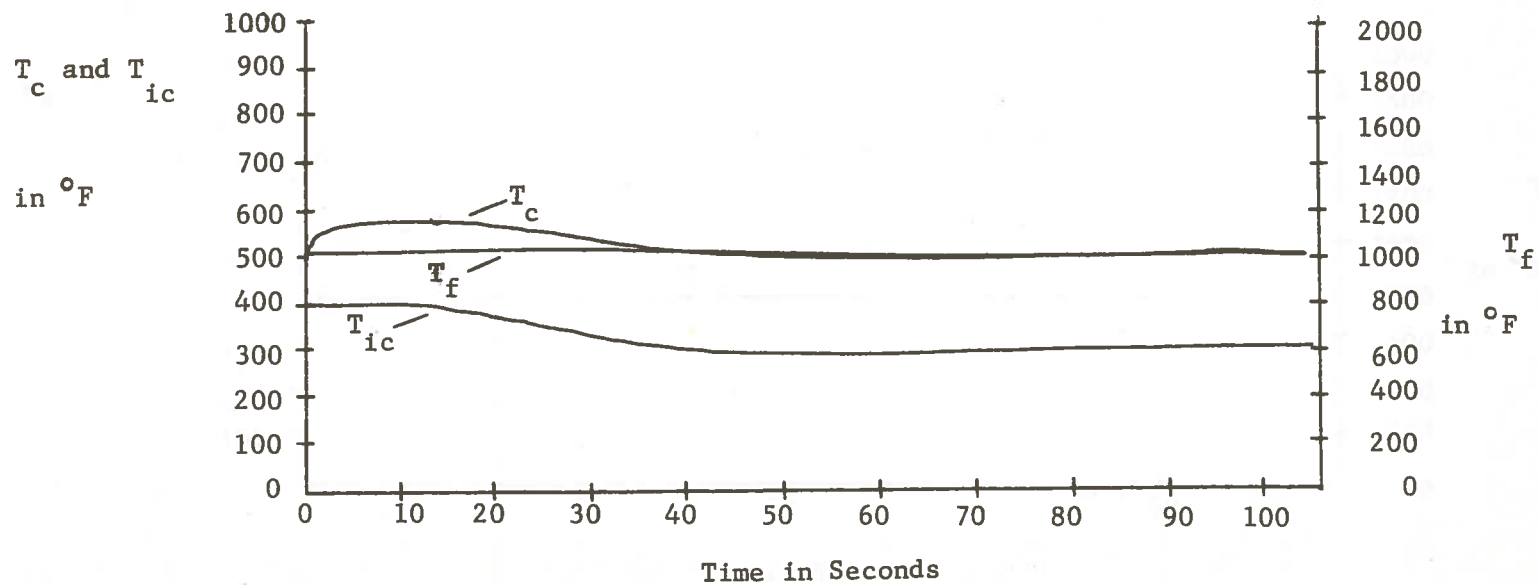
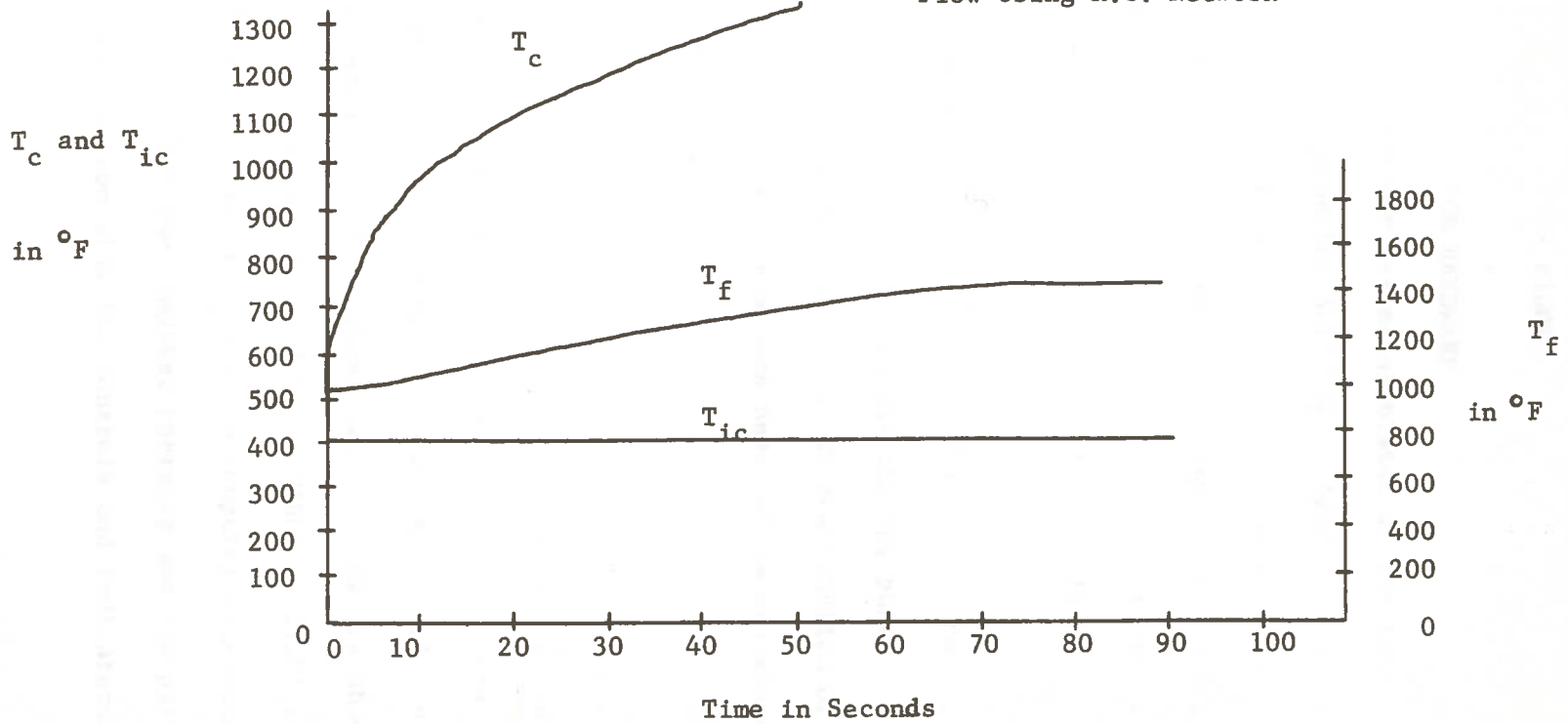


Figure 7.2d.

T_c , T_{ic} , and T_f Versus Time for a Step Decrease in Flow from Full Flow to Zero Flow Using R.C. Network



CHAPTER EIGHT

SIMULATOR HARDWARE

The site of the reactor-power systems simulator is the Louisiana State University Chemical Engineering Building. Figure 8.1 shows the layout of this hybrid computer facility. It shows the EAI 693 Data Conversion System, the EAI 680 Computing System (Analog Computing System), the EAI 8881 Monitor Scope, the EAI 8850 Variplotter, the XDS* Sigma 5 Digital Computer, the XDS Card Reader, the XDS Line Printer, the teletype, and the key punch.

The equipment of major interest to one at this time however, excludes the EAI 693 Data Conversion System and the key punch. These two pieces of equipment play an important part in the function of the reactor simulator; however, their operations need not be explained to the operator of the simulator.

8.1 XDS Sigma 5

The components of the XDS Sigma 5 Digital Computer are shown schematically in Figure 8.1. A process control panel is located nearest the teletype on one unit of the Sigma 5. The process control panel has two distinct functional sections. These two sections are shown in Figure 8.2. The upper section (labeled MAINTENANCE SECTION) is reserved for controls and indicators related to computer maintenance and diagnostic operations. For the computer operator and for program debugging, the lower section contains the controls and indicators.

* Xerox Data System

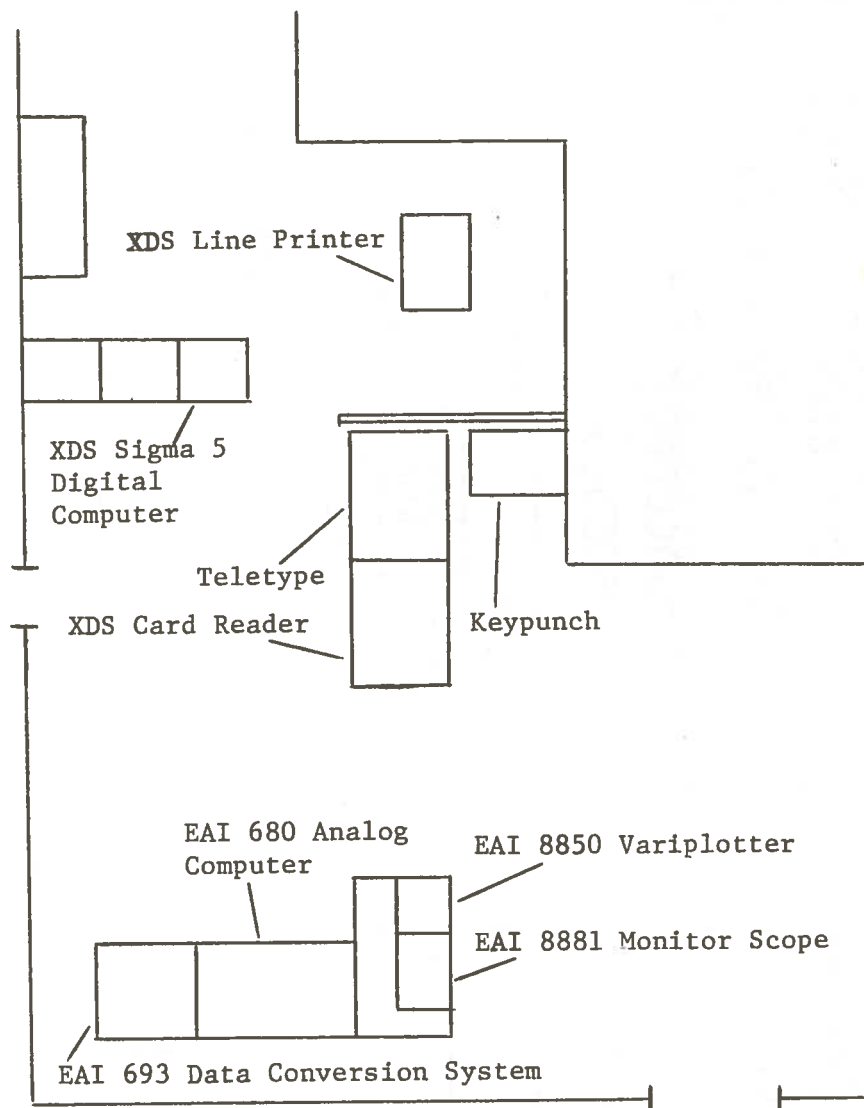


Figure 8.1. Hybrid Computing Facility

* Permission to reproduce this figure is granted by Xerox Data Systems, El Segundo, California.

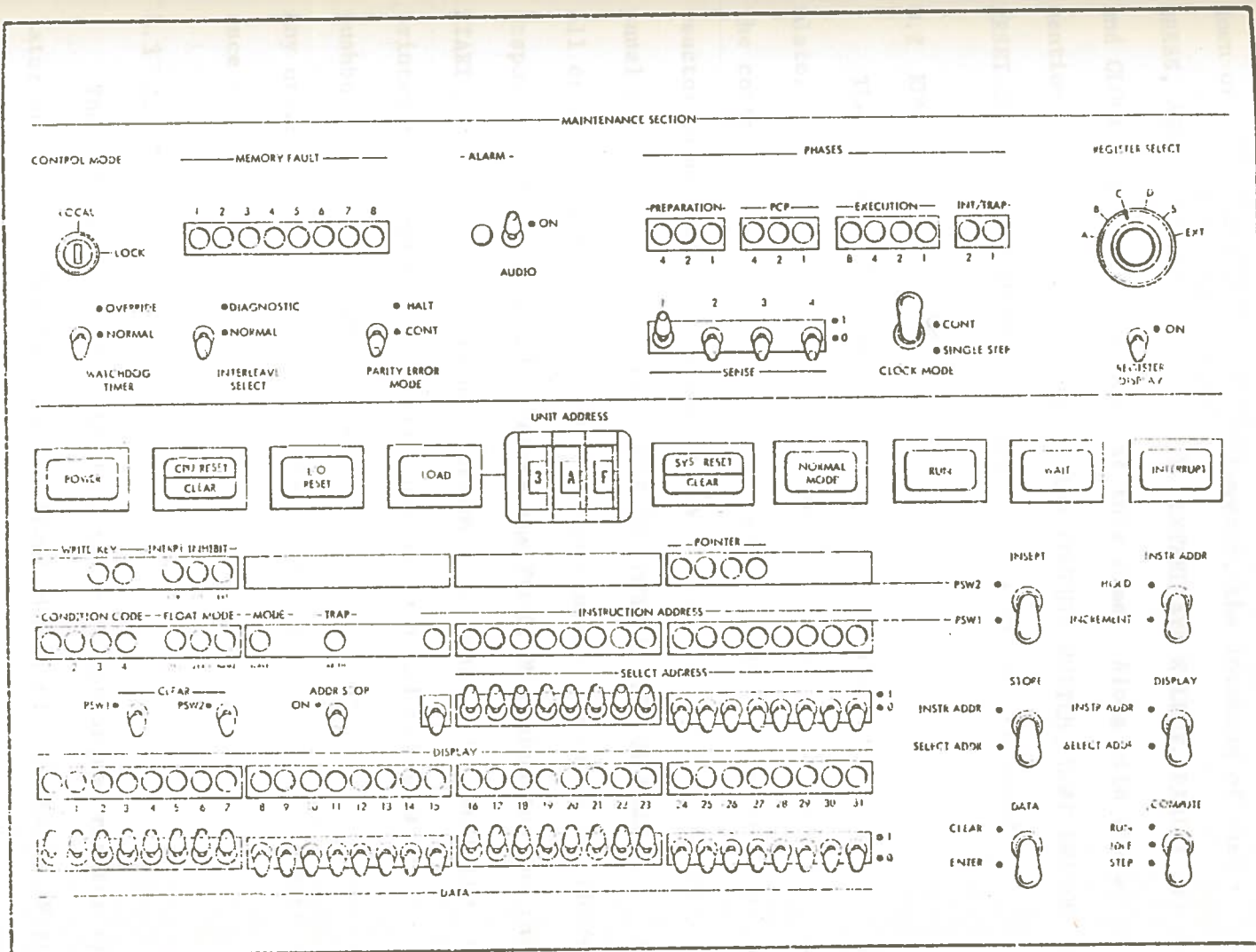


Figure 8.2. Process Control Panel

The operation of the process control panel will be discussed in detail in this chapter in the section involving the start up and shut down of the reactor simulator. However, the location of the UNIT ADDRESS, ADDR STOP, WATCH DOG TIMER, INTERLEAVE SELECT, PARITY ERROR MODE, and CLOCK MODE should be noted at this time. Along with the above mentioned items, the location of the COMPUTE SWITCH, LOAD SWITCH, SYS RESET/CLEAR, and INTERRUPT PUSHBUTTON should also be noted.

8.2 XDS Line Printer

The XDS Line Printer is used by the operator of the reactor simulator only during the initial phases of operation. Figure 8.3 shows the control panel for the line printer. During the operation of the reactor simulator, the following pushbuttons on the printer control panel should be functional: POWER ON, OPER'L, TOP OF PAGE, and START. All other pushbuttons should be nonfunctional. To cause the above response, one presses and releases the POWER ON pushbutton and the START pushbutton if it is not already functional. To cause the line printer to become nonfunctional, one presses and releases the STOP pushbutton and the POWER ON pushbutton if it is already functional. Any other functions desired of the line printer require the assistance of the hybrid computer technician.

8.3 XDS Card Reader

The XDS Card Reader is used by the operator of the reactor simulator only during the initial and final phases of operation. Figure 8.4 shows the control panel for the card reader. The pushbuttons of interest are the following: POWER, RESET, START, and STOP. The card reader becomes functional by pressing and releasing the POWER push-

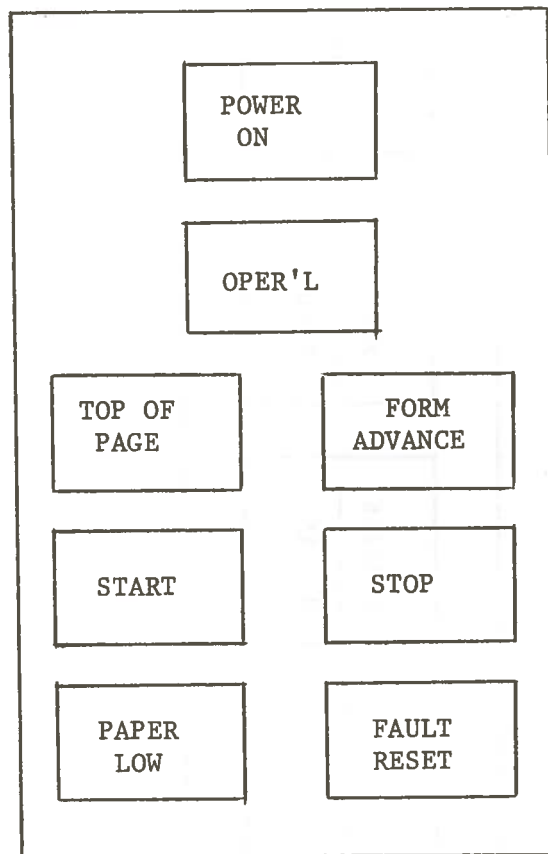


Figure 8.3. Line Printer Control Panel

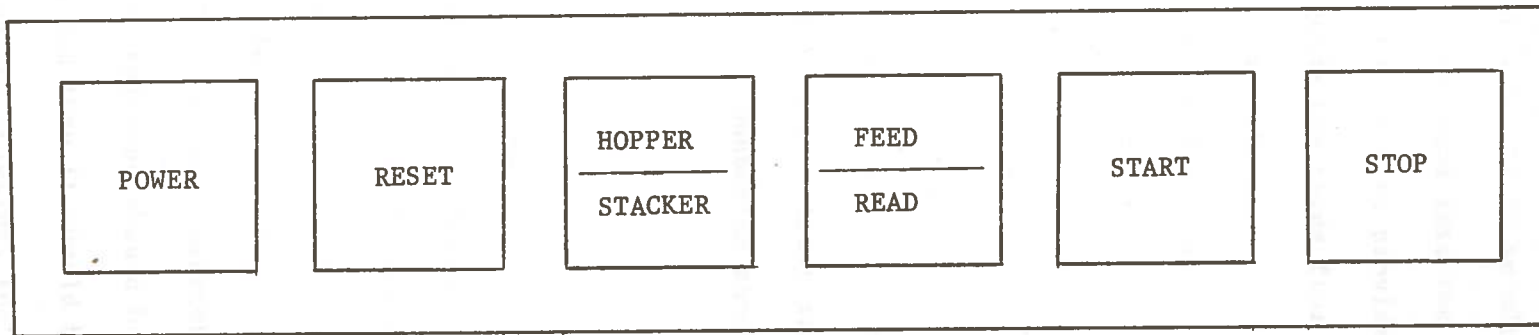


Figure 8.4. Card Reader Control Panel

button and the START pushbutton if it is not already functional. The card reader becomes nonfunctional by pressing and releasing the STOP pushbutton and the POWER pushbutton if it is already functional.

The loading of the computer cards into the card reader is done by placing the stack of cards into the slot provided. This is done by lifting the weight used to guide the cards from the slot and placing the cards in its place, such that the face of the card stack is down with column one of the face to the right and row one of the face in the lower position. After placing the card stack into the slot provided, the weight used to guide the cards onto the card stack is replaced.

Several situations may require the use of the RESET pushbutton. The RESET pushbutton is pressed and released after an incorrect entry is made on the process control panel. After pressing and releasing the RESET pushbutton, the START pushbutton should be pressed and released.

8.4 Teletype

The Teletype is used by the operator of the reactor simulator only during the initial and final phases of operation. The teletype is not shown schematically, for it resembles the keyboard of an ordinary typewriter with few exceptions. During the operation of the reactor simulator, the functional role of the teletype is in giving instructions to the operator and in accepting instructions from the operator. To accomplish this task, the teletype should have its POWER switch turned to the ON position, and then it should be placed in the ON LINE mode. When one is not using the teletype, the POWER switch should be

turned to the OFF position.

8.5 EAI 680 Computing System²²

The EAI 680 Computing System is of major importance to the user of the reactor simulator. It is this system upon which the majority of the reactor-power-systems-simulator is modeled. An overall view of the 680 Console is given in Figure 8.5. In this figure one can observe the areas of major significance. The LOGIC READOUT PANEL, HANDSET POTS, OVERLOAD INDICATORS, PATCH PANEL, LIMITERS IN UPPER DRAWER, CONTROL KEYBOARD, and ANALOG READOUT PANEL are the areas of interest.

8.5.1 Logic Readout Panel

The Logic Readout Panel contains indicators that show the state of each logic element. This panel is shown schematically in Figure 8.6. When the element is in the ONE state, the corresponding indicator is lit. Most of those indicators are pushbuttons as well, allowing the logic element to be set or reset manually.

Of particular interest at this point however, is the DIGITAL PUSHBUTTONS. Six general purpose pushbuttons are provided. Each button provides a zero or a one at an output termination on the patch panel. Each output corresponds to a pair of buttons. Depressing the button on the left side sets the output to ONE; depressing the button on the right sets the output to ZERO. The button on the left acts as an indicator; it is lit when the output is set to ONE.

8.5.2 Analog Readout Panel

Figure 8.7 depicts the Analog Readout Panel and the handset pot strip. The panel contains the Digital Voltmeter (DVM) display, display

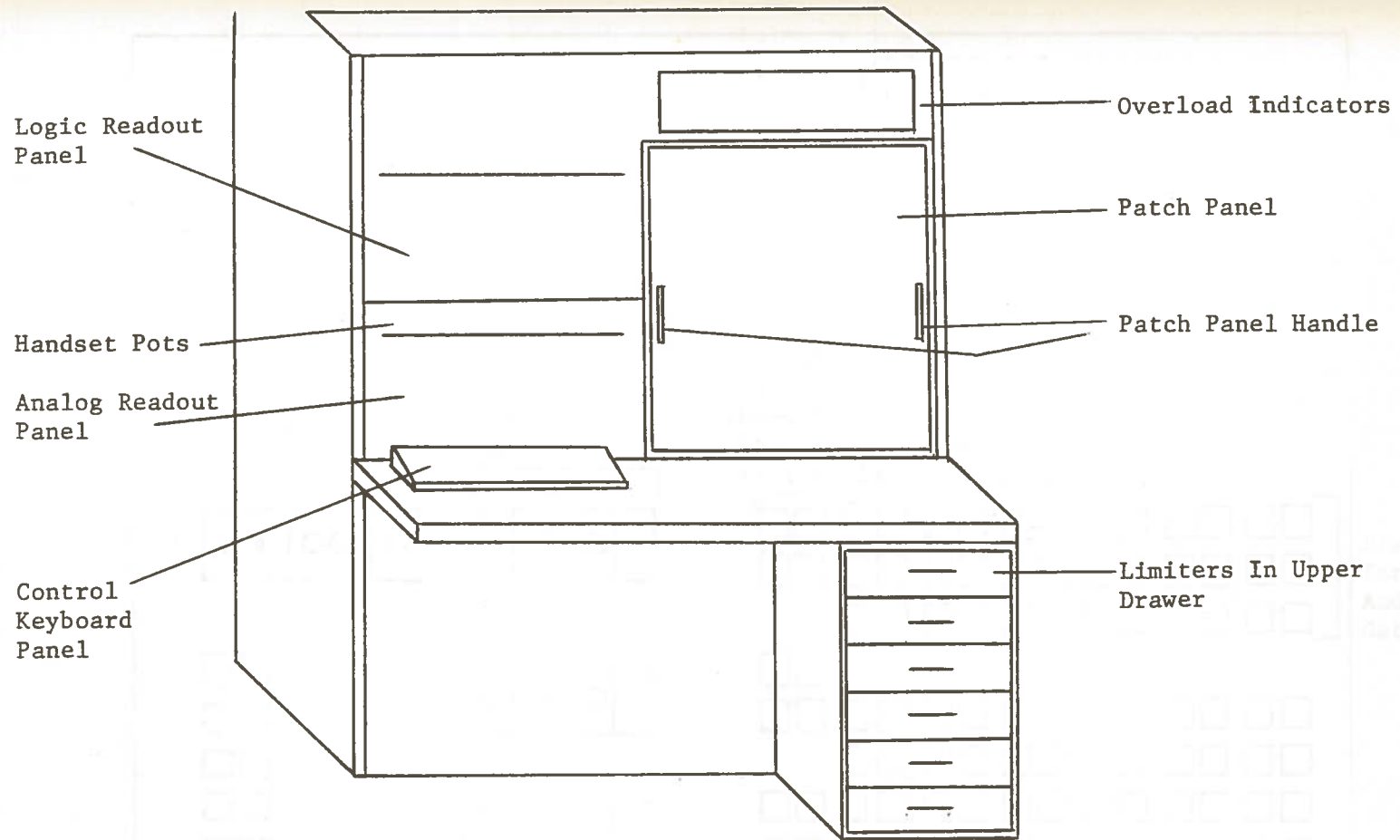


Figure 8.5. Overall View of the 680 Analog Computer

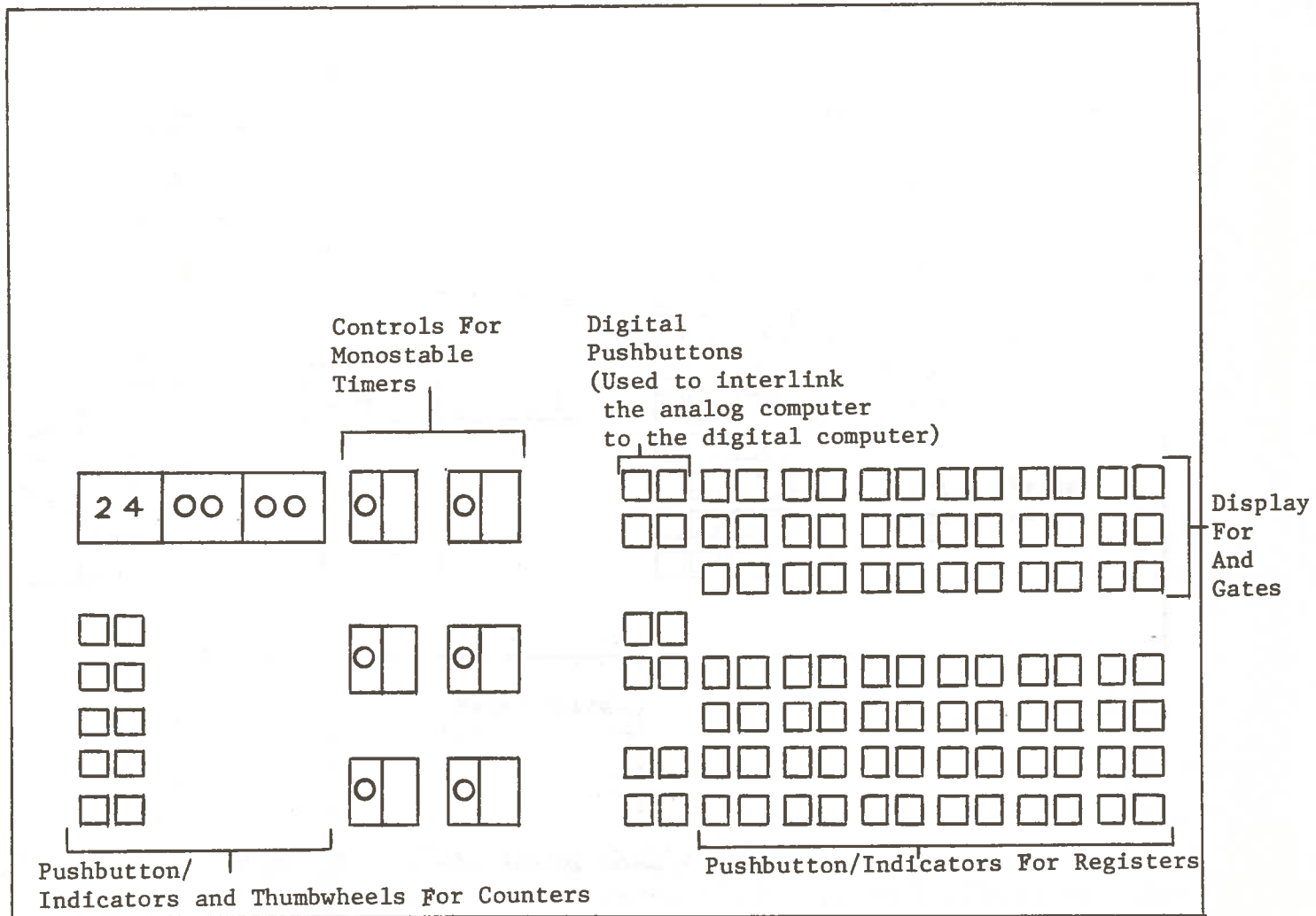


Figure 8.6. The Logic Readout Panel

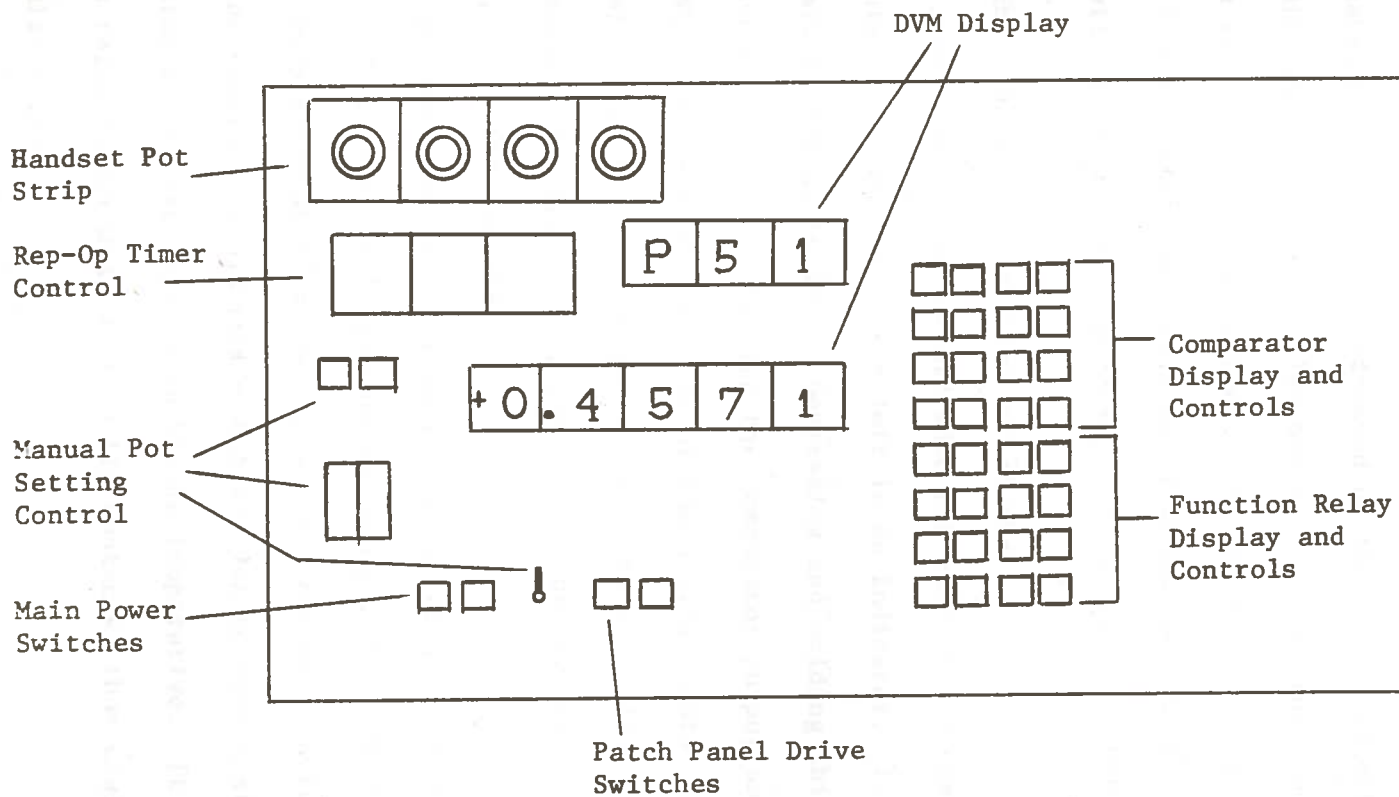


Figure 8.7. The Analog Readout Panel

for comparators and function relays, and other controls. The handset pot strip contains four handset potentiometers. The handset pot strip is discussed in detail in Section 8.5.6.

8.5.2a DVM Display

This displays the address (e.g., A35) and value (e.g., + .3926) of whatever component is addressed on the signal selector. Values are displayed on a unit-scaled basis; that is, reference voltage is taken as the unit of measurement. Hence, plus reference is displayed as + 1.0000 units. An overrange of 20 per cent is provided; i.e., the DVM will measure values up to + 1.1999 units (+ 11.999 volts).

8.5.2b Comparators and Function Relays

A pair of buttons is provided for each of the comparators in the computer. The button on the left is an indicator. It lights when the comparator output is ONE. Depressing and holding this button will set the output flip flop, forcing the comparator output on the patch panel to ONE regardless of the state of the analog inputs. Similarly, depressing the other button forces the output to ZERO. When the finger is removed from the button, the comparator reverts to the normal operation, following its analog signal.

The operator of the simulator is interested in comparator number four. This is the only comparator being used at the present time. This comparator when in the ONE state executes a "scram" signal. It causes function relays number 64A and 94A to open their contacts, thus causing the control system to become inoperative. It also causes function relay number 04A to close its contacts, thus causing the "scram" simulation.

A similar arrangement is provided for each of the function relays. When a relay is in the "ONE" state, the button on the left is lit. This button, when pressed and held, forces the relay into the "ONE" state independently of the patched logic inputs. The button on the right, when depressed, forces the relay into the ZERO state. These relays are driven by flip-flops, so that if no logic signal is patched in, they remain in the state into which they are manually set. Hence, if no logic inputs are patched, the relay may be used as a manual function switch.

In the reactor simulator, function relays number 34 and 9 are manual function switches. Function relays number 4, 64, and 94 are controlled by logic signals.

8.5.2c Main Power Switches

These switches apply power to the analog computer. Depressing the ON button turns the analog computer on; the OFF button turns it off.

8.5.2d Patch Panel Drive Switches

These switches, marked ENG and DIS are for insertion and removal of the motor-driven patch panel. A detailed discussion of mounting the patch panel onto the analog computer will be presented in this chapter.

8.5.2e REP-OP Timer Controls

These controls determine the deviation of the computing intervals in the Rep-Op mode. The operator is not concerned with these thumb-wheels.

8.5.2f Manual Pot Setting Control

In the lower left-hand corner of the panel are a pair of push-buttons marked POT ADDRESS and a set of thumbwheels marked MANUAL SELECTOR. Below the DVM is a lever marked POT CONTROL. These controls allow manual setting of the servo-set pots. For normal servo-setting operation, the POT ADDRESS should be in the KEYBOARD mode.

8.5.3 Control Keyboard

The Control Keyboard is located on the shelf below the analog readout panel. Its main functions are mode control, signal selection, and pot setting. Figure 8.8 depicts the various control areas found on the control keyboard. There are four areas of major importance to the operator of the simulator. From left to right, these areas will now be discussed in detail.

8.5.3a Logic Mode Control and Clock Rate Selection

The buttons marked ST, 10, 10^5 , and 10^6 select the clock rate for the synchronized logic elements. Depressing and releasing one button lights it and extinguishes the others. The button that is lit determines the clock rate. The rate used by the operator of the simulator is 10^6 pulses per second (one clock pulse every micro-second).

Located below the clock rate controls is the Digital Mode Control group. Depressing and releasing one button lights it and extinguishes the others. The button that is lit determines the mode. The buttons marked C, S, and R put the logic into the CLEAR, STOP, and RUN modes respectively. In the CLEAR mode, all flip-flops are cleared (reset to ZERO) and the system clock is stopped. In the STOP mode, the clock is stopped. In the RUN mode, the system clock is running at a fre-

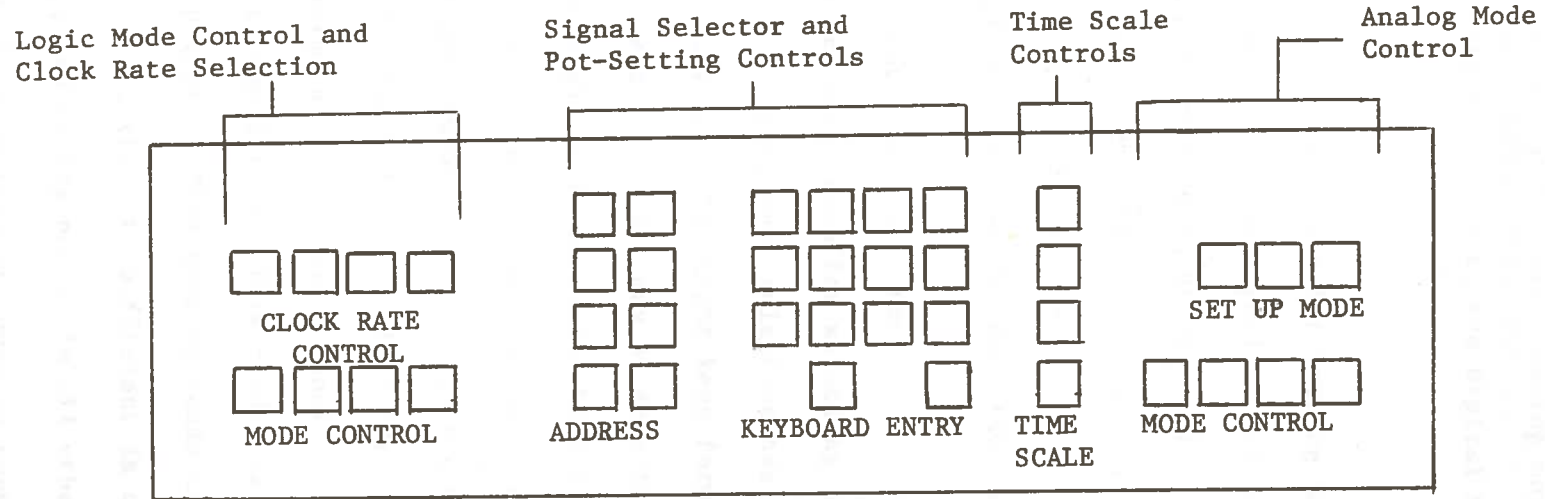


Figure 8.8. The Control Keyboard

quency determined by the Clock Rate group of buttons mentioned above. The PP button in the logic mode control group allows control of the logic mode by the patch panel. During normal operation of the reactor-power-systems simulator, the Digital Mode Control is in the RUN mode.

8.5.3b Signal Selector and Pot Setting Controls

These controls allow signal selection (i.e., addressing an amplifier or pot for readout by the DVM) and setting of servo-set pots. The entire group consists of 22 buttons; the eight marked A, P, D, P/10, T, PP, F, and Q; the ten numerical keys (marked 0-9); and the four control keys (marked CL, DAC, INC, and GO).

8.5.3c Component Selection Key

There are eight keys for selecting the type of component addressed. Once a component selection has been made, it remains in force until changed. The eight keys form a mutually-exclusive group; only one type of component may be selected at a given time. The buttons do not light up to indicate which type has been selected; this is unnecessary since the entire address is displayed on the DVM windows.

The eight component characters are defined below:

PP (Patch Panel). This key connects the DVM to the DVM input terminal on the patch panel.

A (Amplifier). This reads the amplifier output.

P (Pot). This address reads the servo-set pots. In the SP or PC mode, the pot coefficient is displayed (reference voltage is applied to the pot). In all other modes, the pot output is displayed (the regular input is connected to the pot).

D (Derivative). This address applies to all integrators. When a derivative is addressed, the appropriate summing junction is switched from the amplifier to the DVM. The DVM displays the sum of the inputs (multiplied by the appropriate gains) without sign inversion. An interlock is provided to prevent accidental addressing of a derivative in the IC or OP modes.

D/10 (Derivative /10). This address performs the same function as the "D" address, but with a change in gain within the DVM. The display output is reduced by a factor of 10.

T (Trunk). This key allows readout of any of the trunks.

F (Function Generators). This key allows readout of any of the variable DFG's.

Q (Handset Pots). This address is used for the handset pots. In the SP and PC modes, reference voltage is applied to the pot so that the displayed value is the pot coefficient. In all other modes, the output is displayed with the actual input connected.

8.5.3d Ten Numerical Keys (0 through 9)

These keys are used for entering the numerical portion of an address, and also (in the SP mode) for entering the desired value for pot setting. Numerical Keyboard entries are shifted in from the right on the DVM. This eliminates the need for entering leading zeros in addressing.

8.5.3e Control Keys (CL, DAC, INC, GO)

These Control Keys are used in conjunction with the numerical entry keys for readout and/or pot setting:

CL (Clear). This key is used primarily to correct mistakes,

and almost exclusively in the SP mode. It returns the keyboard to its initial state, ready to accept the first digit of an address. It is also useful in case a pot fails to set correctly (e.g., due to servo failure, open winding inside the pot, etc.). In such a case, the servo will continue to attempt to set the pot, and the CLEAR key may be used to disengage the servo and allow further addressing.

DAC (Digital to Analog Converter). This key allow numerical data to be entered into the DAC in modes other than SP.

INC (Increment). This key advances the address register to the next sequential address. Thus, if a large number of amplifiers are to be read out in sequence (or a large number of pots set in sequence), it is not necessary to re-enter the complete address each time.

GO. This key serves two functions: acknowledgement of an address and setting a pot. After each address has been entered, the address is displayed on the DVM address display area but the DVM value is blanked. This means that the address register contains the address of the desired component, but that the readout relay for that component has not actually been energized. Acknowledging the address with the GO key closes the appropriate relay, connecting the address component to the DVM. This feature prevents the accidental addressing of components and the consequent display of erroneous values.

In the SP mode, the GO key also controls the function of the numerical keyboard entry. After a pot is entered, the GO key is used to acknowledge the address in the usual way, and in addition,

it prepares the keyboard to interpret the next entry as an analog value (desired pot setting). The value is then entered, and the GO key is depressed a second time. This action actually sets the pot, displays its setting on the DVM, and prepares the keyboard to accept a new address. Further details on the pot setting procedure are given later in this chapter.

8.5.3f Time Scale Control (N, F, SEC, MS)

These buttons control the feedback capacitor values on the integrators and the rate at which the rep-op timer runs. Selecting the N and SEC provides the standard feedback capacitor value. The operator is to operate the simulator in the above mode (i.e., N and SEC), at all times.

8.5.3g Analog Mode Control Buttons

These seven buttons form a mutually-exclusive set. The modes are as follows:

PC (Pot Coefficient). This is the standard quiescent mode. Every amplifier is provided with feedback by means of a relay to prevent overloads. Hence, the analog computer should be in this mode whenever it is "at rest", or unattended. If a pot is addressed in this mode, the pot coefficient (setting) will be displayed.

SP (Set Pots). This mode provides feedback for every amplifier to prevent overloads, and also puts reference on the input of an addressed pot. It differs from the PC mode in that it is possible to set pots in this mode; that is, the servo setting system is energized. Hence, the SP mode should be used only

during actual pot settings.

ST (Static Test). This mode forces all integrators into the IC mode. It also energizes the \pm Test Reference voltage terminals. In addition, it allows derivative readout for integrators.

IC, H, OP (Initial Condition, Hold, and Operate). When one of these modes is selected, all integrators are put into that mode except those that have different mode control logic individually patched. The operator seldom places the simulator in the Hold mode.

PP (Patch Panel). When this button is depressed and released, the mode of the analog computer is controlled from logic signals on the patch panel. In this simulation, the operator seldom places the simulator in the Patch Panel Mode.

8.5.4 Patch Panel

For ease in programming, assigning components, and locating components for patching, the 680 patch panel is arranged in a symmetric manner. The analog portion of the patch panel is divided into 24 nearly-identical areas called fields. Thus, the programmer need only learn the basic pattern for a single field.

Each field on the 680 patch panel is divided into five trays. The tray is the basic 680 patching area, and contains a number of closely related components. A typical tray face is shown in Figure 8.9. Each tray is numbered for ease of identification. The upper area of the tray is used to define the use of the tray. These holes determine the function the tray will perform (i.e., integrator, summer, or high gain amplifier). The present use of the

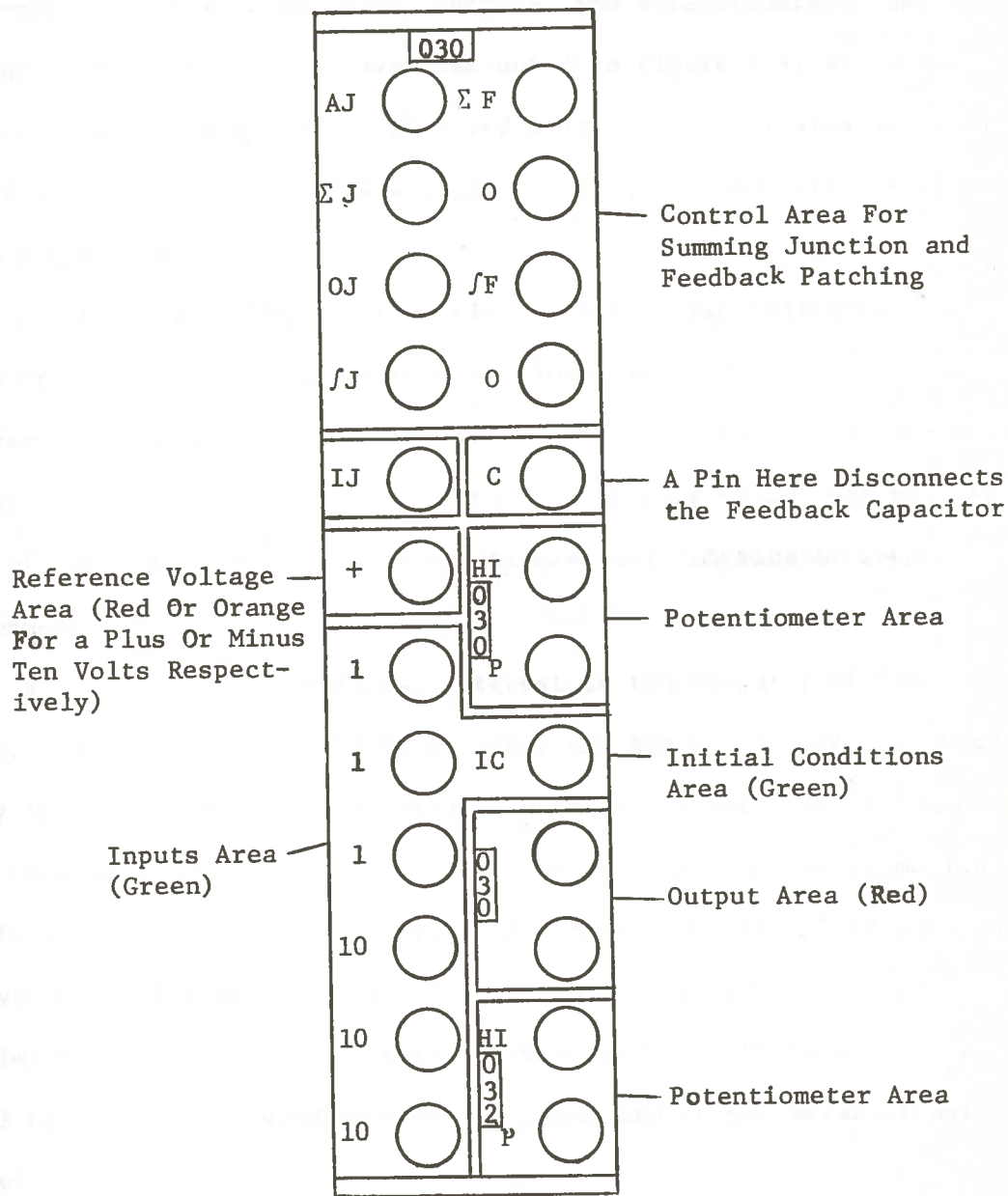


Figure 8.9. A Typical Patching Area

reactor simulator does not require the operator to be concerned with the above area.

The section immediately below the area mentioned above is of more interest to the operator. It is this section that determines the inputs, initial conditions, outputs, and potentiometers that a computing component is to have. As noted in Figure 8.9, an output area is always color coded with a red color. An input area is color coded with a green color. Also, an initial conditions area is coded with a green color.

The hole marked by either a plus or minus sign indicates a positive or negative 10 volts reference. These reference signals located on various patching areas are used frequently. They are of particular interest to the operator of the reactor simulator since this will be one of the few areas in which the operator will physically remove and reconnect wires.

Another area of particular interest to the operator of the reactor simulator will be the input areas and the output areas of each tray in use. The input area will be used by the operator to change the reactor kinetics from a one group delayed neutron approximation to a six group delayed neutron approximation by using the RC network and conversely. The output area will be used by the operator in the experimental analysis of the reactor-power-systems. Physical wiring will have to be executed in both the input and output areas of particular trays.

The patch panel is shown in Figure 8.10. The patch panel is divided into five horizontal ROWS of 30 trays each. Between rows of trays, there are horizontal STRIPS or BARS, two holes high. In the

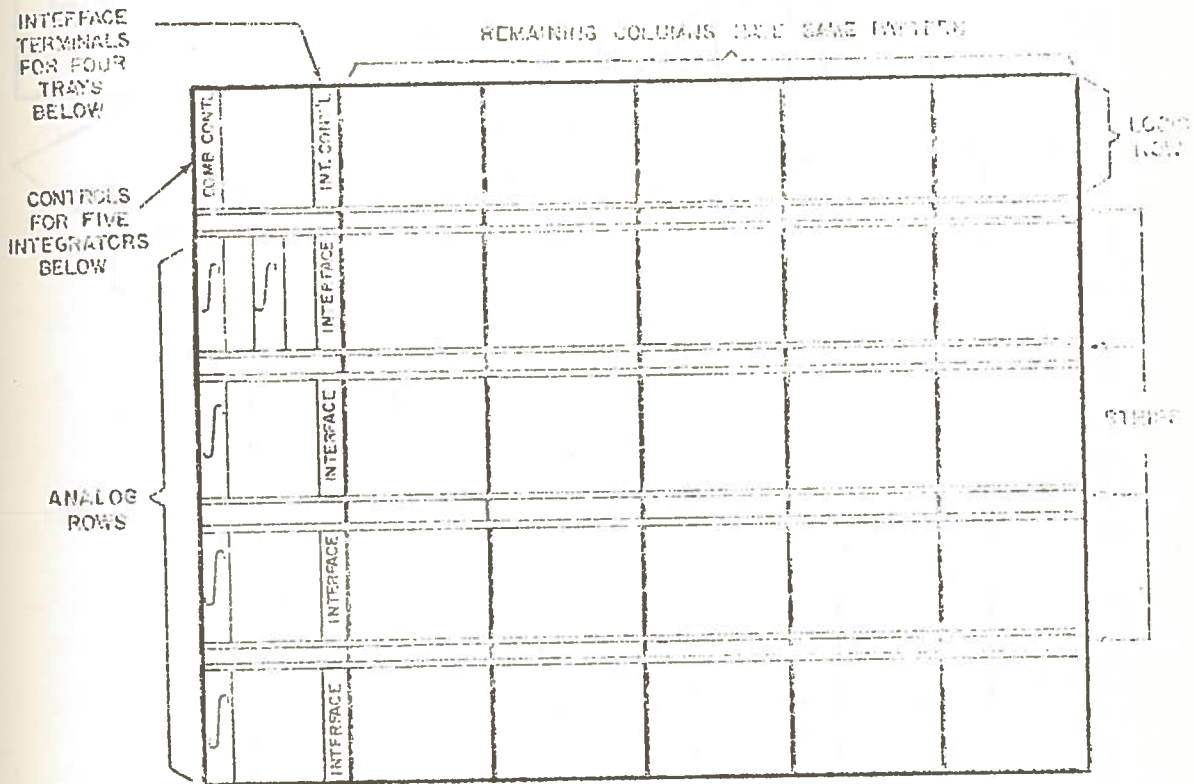
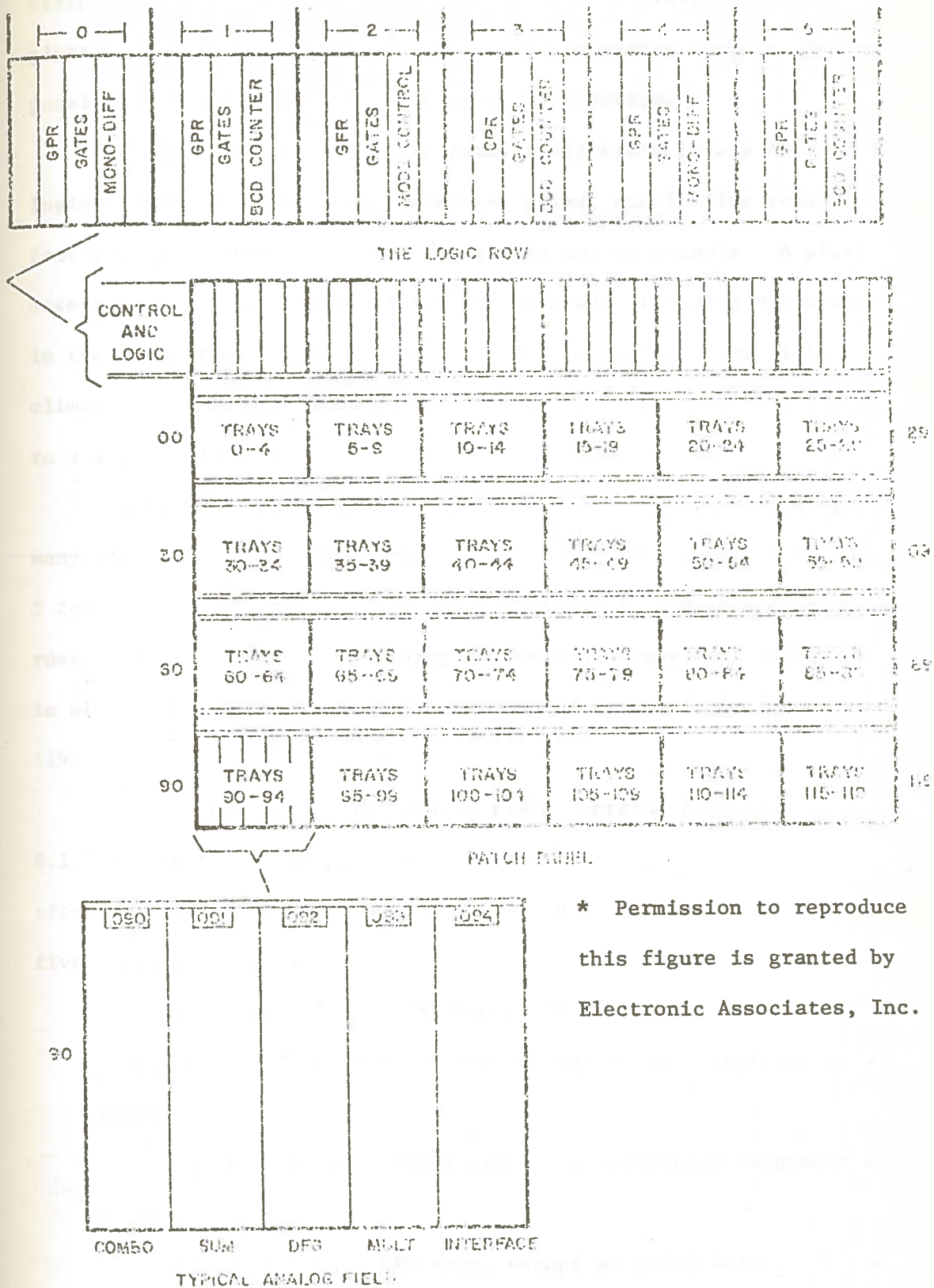


Figure 8.10. Patch Panel Layout, Showing Rows, Strips, and Fields

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Figure 8.11. Detailed Patch Panel Layout

strip area are located the trunks, reference terminations, ground, plotter, and scope connections, the noise generator outputs, DVM patch panel input, and similar miscellaneous terminations.

The upper row and the strip immediately below it are devoted to logic elements (flip-flops, registers, gates, etc.). The remaining four rows and three strips are devoted to analog signals. A plastic insert in each logic terminal prevents the use of analog patchcords in the logic area or logic patchcords in the analog area, virtually eliminating the possibility of accidental patching an analog signal to a logic component.

Figure 8.10 can be used to show that there are four times as many analog trays as logic trays. The logic rows contain 6 fields of 5 trays each for a total of 30 trays; the analog area has four such rows, giving a total of 24 analog fields of 5 trays each (120 trays in all). The analog trays are all numbered sequentially from 0 to 119.

As mentioned above, the analog field contains five trays. Figure 8.11 depicts the patch panel layout in detail. Each tray is named after the principle type of component or components it contains. The five types of trays are as follows:

Tray 0 or 5 is a COMBO tray. Its principle component is a combination amplifier which can be used as an integrator or a summer.

Tray 1 or 6 is a SUMMER tray. Its principle component is a summing amplifier.

Tray 2 or 7 is a DFG tray, except as noted below. It contains the termination for a ten segment variable DFG (which is

remotely located), and one or two fixed DFG's (located on the tray). In addition each tray contains an amplifier, which may be used either as an inverter or as the output amplifier for one of the fixed DFG's (the variable DFG's have their own built-in output amplifiers).

Tray 3 or 8 is a MULTIPLIER tray. It contains a quarter-square multiplier with its output amplifier. The output amplifier may be disconnected from the multiplier if desired.

Tray 4 or 9 is an INTERFACE tray. It contains the components that interface with the logic area (an electronic comparator, an electronic switch, and a relay which may be positioned by logic signals). The logic terminations for this tray are in the logic tray immediately above. In addition, an interface tray contains an amplifier, which is not an interface element. To summarize, the pattern of analog trays is as follows:

Trays ending in 0 or 5 are COMBO trays.

Trays ending in 1 or 6 are SUMMER trays.

Trays ending in 2 or 7 are either COMBO trays (2-27) or DFG trays (32-117).

Trays ending in 3 or 8 are MULTIPLIER trays.

Trays ending in 4 or 9 are INTERFACE trays.

The logic components, like the analog components, are arranged in as symmetric a manner as possible. There are six fields of 5 trays each, for a total of 30 trays. Figure 8.11 is used to describe the logic row. The logic tray of particular interest to the operator of the reactor simulator is the last tray within a field. The last tray is an INTERFACE tray. It contains the logic terminals for the com-

parators, electronic switches, and relays in the four analog trays below it.

8.5.5 The \pm Feedback Limiter, Found in the Upper Drawer

The 680 has provisions for twelve feedback limiters. Every tray whose address ends in 1 may contain a feedback limiter. These limiters are used to limit the output of any of these amplifiers to some positive and negative voltage.

The two limit points (positive and negative) are set independently. For each limiter, the limits are controlled by two potentiometers. The potentiometers are in the upper-most slide-out drawer to the right of the Control Keyboard.

To set a limiter, the analog computer is placed in the PC mode, and the GO pushbutton located on the Control Keyboard is depressed. The upper-most drawer mentioned above is then opened. To set the negative limit, depress and hold the button marked "-" adjacent to the numbered limiter knob, and adjust the knob until the appropriate limit value appears on the DVM. Then release the button and adjust the "+" limit similarly. For example, if the limits are to be set to + 1.0 and - 1.0 machine units, then the output of the desired amplifier to which the limiter is patched will be limited between + 10.0 and - 10.0 volts.

8.5.6 Handset Pots

The 680 has four handset pots addressed with the letter Q. The schematic diagram showing the location for the handset pots is found in Figure 8.7. The pots are terminated in the "extra" COMBO trays in the top row (i.e., trays 2 and 7). There are two handset pots in each

of these trays, which makes the patch panel area for these integrators identical with the corresponding area for other integrators.

Handset pots may be set in any mode. If it is desired to set them to a specific coefficient, then the PC mode is recommended. The SP mode should not be used for these pots because the GO key alternates the keyboard function between the address and value mode. Since no values are entered digitally for handset pots, the PC mode is used to allow the entry of addresses only.

8.5.7 Overload Indicators

Directly above the patch panel are the overload indicators. The area housing overload indicators can be seen schematically in Figure 8.5. When an amplifier overloads, the appropriate light on the above mentioned area glows. The overload indicator for the amplifiers are laid out in four rows, similar to the patch panel itself. Only the last digit identifying the overloaded amplifier appears to glow. The first two digits are common to a block of 10 AMPLIFIERS.

8.6 Monitor Scope²³

The digital (or monitor) scope shown schematically in Figure 8.12 displays up to four logic signals at a time. It can also be used to display analog signals. The operator of the reactor simulator is concerned only with the display of the analog signal.

Two horizontal inputs to the monitor scope are provided for this purpose. The horizontal inputs to the monitor scope are designated H4 (Channel 1) and H5 (Channel 2). The two terminals for these inputs appear beneath interface tray 79 and interface tray 99.

The present design of the reactor simulator includes a provision

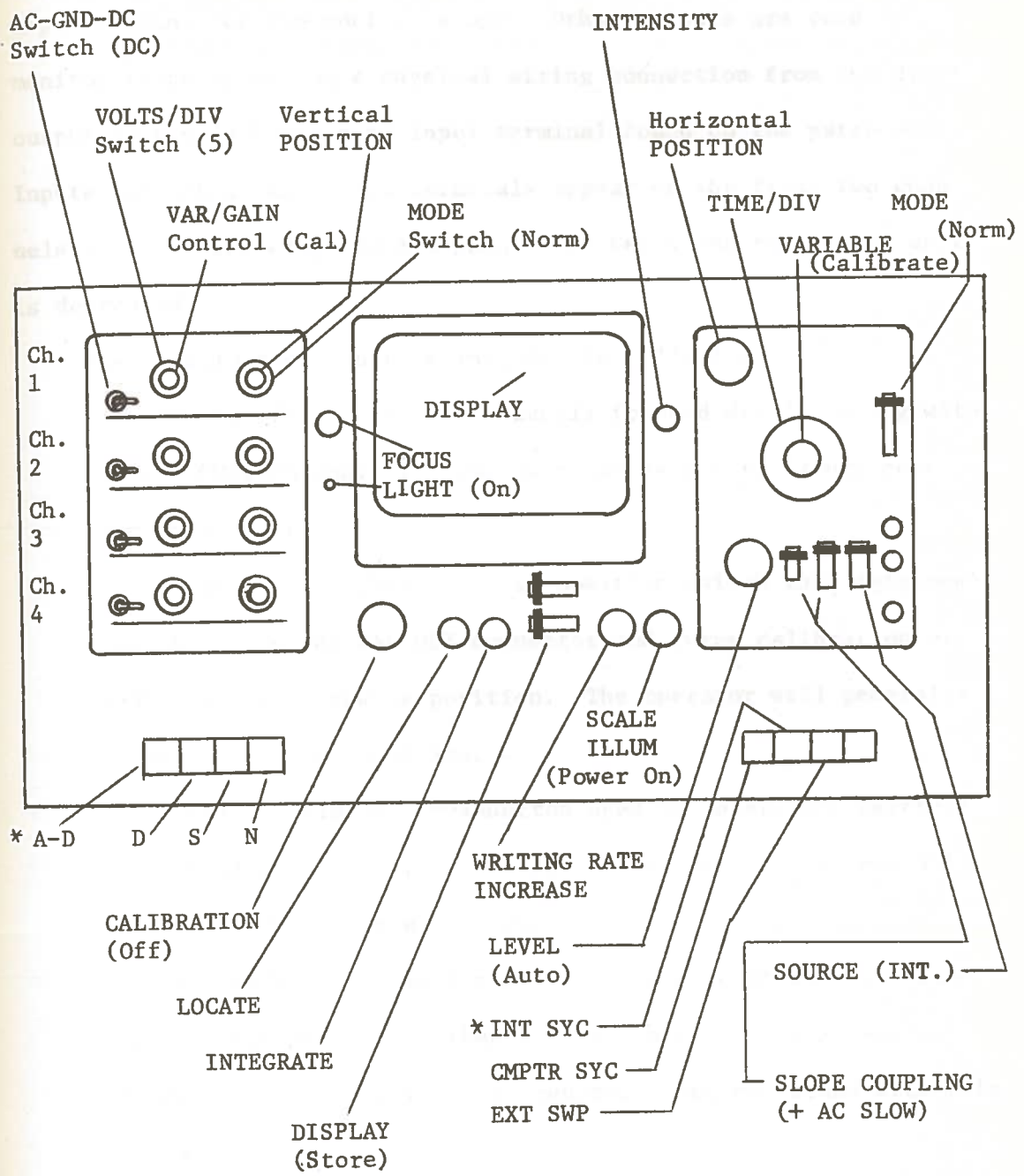


Figure 8.12. Monitor Scope

for monitoring any amplifier output. Whenever an amplifier is addressed, the output of the amplifier is read on the H4 horizontal input terminal of the monitor scope. Other outputs are read on the monitor scope by making a physical wiring connection from the desired output to the H5 horizontal input terminal found on the patch panel. Inputs patched to these two terminals appear on the first two channels of the scope when the A-D pushbutton below the four trace unit is depressed.

The oscilloscope controls include the following:

FOCUS. This controls an evenly focused display along with the **ASTIGMATISM** control. The operator is generally not concerned with this control.

CALIBRATION. This is a six position switch that sets peak-to-peak voltage at CAL OUT connector and turns calibration off in fully counter-clockwise position. The operator will generally operate in the OFF position.

LOCATE. This is a pushbutton used to locate the vertical position of display before storing. The operator is generally not concerned with this control.

INTEGRATE. This is a pushbutton used to store repetitive displays that are faster than the instrument's normal stored writing rate. The operator is generally not concerned with this control.

LOWER. NONSTORE: Lower half of CRT will not store.

STORE: Lower half of CRT stores.

ERASE: Lower half of CRT erases when switch is pressed and released.

The operator will generally operate the monitor in the STORE mode.

SCALE ILLUM. This switch controls the illumination of the graticule lines and the power to the scope. The operator is to operate the monitor by turning this switch clockwise.

WRITING RATE INCREASE. This is a pull-on switch with an adjustable potentiometer. It is used to store non-repetitive displays that are faster than the normally stored writing rate of the instrument. The operator is generally not concerned with this control.

UPPER. NONSTORE: Upper half of CRT will not store.

STORE: Upper half of CRT stores.

ERASE: Upper half of CRT erases when switch is pressed and released.

The operator will generally operate the scope in the STORE mode.

Also shown in Figure 8.12 to the left of the oscilloscope is the Four Channel Oscilloscope Control. The important features of this unit are the VOLTS/DIV switch, the VAR. GAIN switch, AC-GND-DC switch, the VERTICAL POSITION CONTROL, and the MODE switch.

The operator of the reactor simulator will generally have the above switches and controls in the following positions:

VOLTS/DIV: 5 volts/division

VAR. GAIN: CAL

AC-GND-DC: DC

VERTICAL POSITION: Manipulated until desired output is located
in desired location on the oscilloscope screen

MODE: Channel 1-NORM.

Channel 2-Off if the scope is not being used with the H5

terminal on the patch panel.

Channel 3-OFF.

Channel 4-OFF.

The Time Base Unit is found on the right of the oscilloscope. This unit is depicted in Figure 8.12 also. This unit controls the time base deflection for the X axis of the scope. The important features of this unit are the HORIZONTAL POSITION Control, the TIME/DIV switch, the VARIABLE TIME/DIV Control, the MODE switch, the SOURCE switch, the COUPLING switch, the SLOPE switch, and the LEVEL switch.

The operator of the reactor simulator will have the above switches in the following positions:

HORIZONTAL POSITION: Manipulated until desired output is located in desired location on the oscilloscope screen.

TIME/DIV: 1 or 2 seconds per division.

VARIABLE TIME/DIV: CALIBRATED

MODE: NORM

SOURCE: INT.

COUPLING: AC SLOW

SLOPE: + (POSITIVE)

LEVEL: AUTO

Below the Four Channel Oscilloscope Controls are four pushbuttons labeled A-D, D, S, and N. These pushbuttons are also shown in Figure 8.12.

When A-D is depressed, the first two channels of the scope are set to monitor the H4 and H5 input terminals from the analog section of the patch panel. The operator of the simulator operates the monitor with

it in the A-D mode.

Beneath the Time Base Unit are four buttons. Three of them are labeled CMPTR SYC, INT SYC, and EXT SWP. The blank button is not used. The buttons mentioned above are shown in Figure 8.12. If INT SYN, internal synchronization, is depressed, sweep along the X axis is triggered by the internal synchronization in the Time Base Unit. The operator of the simulator operates the monitor with it in the INT SYN mode.

8.7 Servo-Set Pots²⁴

The Servo-Set Potentiometers are not shown in Figure 8.5. These pots, however, play an important part in the overall operation of the reactor simulator. The operator of the reactor simulator should be capable of changing the coefficient on any of the servo-set pots.

To set a pot from the keyboard, the following steps are undertaken:

1. Make certain that the analog computer is in the SP mode.
2. Make certain that the POT ADDRESS controls (lower left-hand corner of the analog readout panel) are in the KEYBOARD mode.
3. Make certain that the green light is in the ADDRESS DISPLAY portion of the DVM, (the upper windows of the DVM). If it is not, depress and release the CLEAR button. The presence of a green light in the upper window indicates that the keyboard entry will be interpreted as an address.
4. Enter the desired address (e.g., P15). Leading zeros may be omitted, but will do no harm if entered (e.g., P015 would address the same pot). Entering this address entails pressing and releasing P on the ADDRESS and 0, 1, and 5 on the KEYBOARD

ENTRY. After doing the above, the operator presses and releases the GO button on the KEYBOARD ENTRY.

5. The green light should now have moved to the lower row of the windows (the DVM VALUE display). This indicates that the next keyboard entry will be interpreted as a pot coefficient. Enter the desired value (4 digits) by pressing and releasing the desired pot setting numerals on the KEYBOARD ENTRY. Press and release GO. This should set the pot and return the green light to the upper row of windows, indicating the keyboard is ready to accept the next address.
6. As the pot sets, a red light may come on momentarily in the lower left-hand window on the DVM. This is a normal indication of the necessary servo error during the setting process. When the pot is set correctly (to within 0.0001), the light will go out, the servo will be automatically disengaged, the actual pot-setting will be displayed on the DVM, and the keyboard will be ready to accept the address of the next pot to be set.
7. If the light remains on for any considerable length of time, it is an indication that the pot has not been set correctly (the maximum setting time for maximum pot travel, from 0.0000 to 0.9999, is one second). Depressing the CL key will terminate the pot-setting procedure and will allow other pots to be set.

Although the above explanation is somewhat lengthy, the actual process goes quite rapidly. As an example, consider the steps required to set the following pots to the desired values:

scope (1)	P0	3842
the ampli	P1	9980
procedur	P2	0047
The	P14	5069
the w	P20	4831
analog	P21	1117

The sequence of operations would be as follows:

1. Select SP modes.
2. Make certain that the POT ADDRESS is in the KEYBOARD mode.
3. Make certain that the green light is in the upper right-hand DVM window (in ADDRESS DISPLAY area).
4. Make the following entries:

P0	GO	3842	GO	(This sets P0)
INC	GO	9980	GO	(This sets P1)
INC	GO	0047	GO	(This sets P2)
14	GO	5069	GO	(This sets P14)
20	GO	4831	GO	(This sets P20)
INC	GO	1117	GO	(This sets P21)

Note that some of the pots are in sequence (e.g., P0, P1, P2) and others are not. Note also that even the out of sequence pots do not require reselection of the "P" portion of the address.

8.8 Readout Procedure²⁵

Along with the procedure involved in setting pots, the operator is interested in the procedure for obtaining the readout of data on various potentiometers and amplifiers. As mentioned earlier, the addressing of an amplifier and the subsequent readout of that amplifier on the DVM permits one to monitor the output of that amplifier on the

scope if it is functioning. Thus the operator has a visual display of the amplifier output on the scope and on the DVM involving a simple procedure.

The readout procedure of an amplifier or pot output is to enter the appropriate address on the DVM and to press and release GO. The analog computer may be in any mode, with the following exceptions:

1. The SP mode should be avoided unless it is actually desired to set pots. As mentioned earlier in the previous section, the GO key in this mode will prepare the keyboard to interpret the next entry as a pot setting, rather than an address. To readout pot coefficients without disturbing them one should use the PC mode.
2. As discussed in paragraph 8.5.3c, the D and D/10 keys do not function in the IC and OP modes.
3. In the PC mode, it is possible to read amplifier outputs, but not informatively, since all amplifiers have a small feedback resistance connected around them in this mode, thus preventing overloading and keeping the output near zero.

As an example of the readout procedure, consider A0, A1, A2, A13, A14, A15, P20, P21, and P22 to be read out. The following sequence would be used:

A0	GO	Address and Output of A0 are displayed.
INC	GO	Address and Output of A1 are displayed.
INC	GO	Address and Output of A2 are displayed.
13	GO	Address and Output of A13 are displayed.
INC	GO	Address and Output of A14 are displayed.
INC	GO	Address and Output of A15 are displayed.

P20 GO Address and Output (if in the PC mode the pot coefficient is read instead of the pot output), of P20 are displayed.

INC GO Address and Output of P21 are displayed.

INC GO Address and Output of P22 are displayed.

8.9 Start Up Procedure

A thorough review of each of the sections found in this chapter is vital to the operation of the reactor simulator and to the understanding of the following procedures.

The analog computer may be turned on by depressing the "POWER ON" button on the analog readout panel. When the power comes on, there will be overloads initially, but these should vanish in about 10 to 20 seconds if the computer is placed in the PC mode. It is recommended that the indicators on the analog control panel be placed in the following modes during warmup (20 minutes):

Analog Mode-PC

Logic Mode-CLEAR

Signal Selector-CLEAR, then address a pot, then GO.

Pot Address Control (on analog readout panel)-KEYBOARD position.

After applying the power to the analog computer, one then engages the reactor simulator patch panel. To engage any patch panel, the following is executed by the operator:

1. Hold patch panel in both hands and squeeze the spring-loaded levers in the handles.
2. Insert the patch panel straight into its position. Do not "pivot" the panel into position.
3. Once the panel is in position, release the levers in the

handles. The panel should now be latched into position securely. The patchcords will not make electrical contact with the terminals in the patch bay until the drive motor is engaged.

4. Depress and hold the "PATCH PANEL ENGAGE" button on the analog readout panel until the light on this button appears. When the patch panel is engaged, this button will light.

If a patch panel other than the one mentioned above is found on the analog computer, disengage the other patch panel to permit the engaging of the reactor simulator patch panel. To disengage any patch panel the following is executed by the operator:

1. Depress and hold the "PATCH PANEL DISENGAGE" button on the analog readout panel until the light on this button appears. When the patch panel is disengaged, this button will light.
2. Hold the patch panel in both hands and squeeze the spring-loaded levers in the handles.
3. Remove the patch panel straight from its position. Do not "pivot" the panel from position.
4. Once the panel is removed from position, release the levers in the handles. The panel should now be removed from the analog computer.

After engaging the reactor simulator patch panel one then connects either a one group delayed neutron approximation or a six group delayed neutron approximation in the reactor kinetics section of the reactor simulator as described below.

The one group delayed neutron results are obtained by connecting the outputs of amplifiers 4 and 5 to the desired patch panel compo-

nents used in the simulation, making certain that the outputs of amplifiers 105 and 100 are disconnected from the above mentioned patch panel components used in the simulation. The six group delayed neutron results obtained by using the RC network are observed by connecting the RC network as shown in Appendix B, by making certain that the outputs of amplifiers 105 and 100 are connected to the desired patch panel components used in the simulation, and by making certain that the outputs of amplifiers 4 and 5 are disconnected from the above mentioned patch panel components used in the simulation.

The steps in connecting the RC network to the patch panel are as follows:

1. From the output of amplifier 8 connect a yellow analog patch panel wire to the terminal labeled INPUT on the face of the RC network.
2. From the terminal marked OJ on amplifier 105 connect a yellow analog patch panel wire to the terminal labeled AMP INPUT on the face of the RC network.
3. From the terminal marked O on amplifier 105 connect a yellow analog patch panel wire to the terminal labeled AMP OUTPUT on the face of the RC network.

If the RC network is to be used in the study of the reactor-power-systems, the following steps should be taken:

1. Disconnect the wire labeled AMP 4 OUTPUT found near the top of the patch panel from the top terminal of the output (red) area found nearest the input (green) area on amplifier 4.
2. Disconnect the wire labeled AMP 5 OUTPUT found near the top of the patch panel from the top terminal of the output (red)

- area found nearest the input (green) area on amplifier 5.
3. Connect the wire labeled AMP 100 OUTPUT found near the bottom of the patch panel to the top terminal of the output (red) area found nearest the input (green) area on the amplifier 100.
 4. Connect the wire labeled AMP 105 OUTPUT to the top terminal of the output (red) area found nearest the input (green) area on amplifier 105.

If the one group delayed neutron approximation to the reactor kinetics equation is to be used in the study of the reactor-power-systems, the following steps should be taken:

1. Disconnect the wire labeled AMP 100 OUTPUT found near the bottom of the patch panel from the top terminal of the output (red) area found nearest the input (green) area on amplifier 100.
2. Disconnect the wire labeled AMP 105 OUTPUT found near the bottom of the patch panel from the top terminal of the output (red) area found nearest the input (green) area on amplifier 105.
3. Connect the wire labeled AMP 4 OUTPUT found near the top of the patch panel to the top terminal of the output (red) area found nearest the input (green) area on amplifier 4.
4. Connect the wire labeled AMP 5 OUTPUT found near the top of the patch panel to the top terminal of the output (red) area found nearest the input (green) area on amplifier 5.

At this point, the operator should be certain that the Pot Address Control, which is located on the analog readout panel, is in the KEY-

BOARD position. The CLOCK RATE CONTROL, MODE CONTROL, and SET UP MODE on the control panel are 10^6 , R, and PC respectively. The limits of ± 10 volts on amplifier number 21 is then obtained by adjusting the feedback limiter number 21 in the upper drawer (see Section 8.5.5).

The handset pots should be adjusted after carefully following the procedure mentioned above. On the control panel, the operator presses and releases the "Q" address, the KEYBOARD ENTRY number, and then GO. The pot setting is read out on the DVM while the appropriate pot coefficient is being obtained by rotating the dial on the handset pot. The handset pot coefficients during the initial phases of the reactor simulator operation are critical to the overall performance of the system. Therefore, the handset pots should be set very carefully. The various "Q" pot coefficients are as follows:

Q02	.9999	Q07	.5000
Q04	.4000	Q09	.0163

The next step in the procedure to operate the reactor simulator is to turn on pushbuttons number 0 and 1 which are found on the Logic Read-out panel of the analog computer. This action initiates the condition necessary to interlink the Sigma 5 Digital Computer and the EAI 680 Analog Computer.

After initiating the above condition, the operator is then in a position to read in the digital program to be used in the reactor simulator. The operator places the cards into the card reader. At this time, the card reader is made functional as described in Section 8.3.

The operator then places the COMPUTE switch on the Sigma 5 process control panel in the IDLE position. The operator then presses and releases the INTERRUPT pushbutton on the Sigma 5 process control panel.

The operator then returns to the card reader. The RESET and START buttons on the card reader are then pressed and released sequentially.

The operator returns to the Sigma 5 process control panel after causing the XDS Line Printer and the teletype to become functional. At the Sigma 5 process control panel, the operator then initiates a checkout procedure on the process control panel to assure that the following areas are in the following modes:

UNIT ADDRESS: OFO
ADDR STOP: OFF
WATCH DOG TIMER: NORMAL
INTERLEAVE SELECT: NORMAL
PARITY ERROR MODE: CONT

After this careful checkout, the operator then proceeds to do the following:

1. Make certain that the COMPUTE switch is in the IDLE position.
2. Press and release the SYS RESET/CLEAR pushbutton.
3. Press and release the LOAD pushbutton.
4. Set COMPUTE switch to RUN.
5. Read teletype and allow it to finish typing.
6. Press and release the INTERRUPT pushbutton.
7. After the teletype prints "!! KEYIN", type, "C" on the teletype.
8. Depress the NEW LINE key on the teletype.
9. After the servo-set pots are set automatically, read the teletype for any error messages. An error message stating that a pot did not set correctly, requires the operator to

approach the EAI 680 Analog Computer Control Keyboard and to set the pot using the servo-set pot system. The values of the pot coefficients are given in Appendices A and C.

10. If any other error message occurs, consult either the computer manuals or the computer technician for assistance.

After initiating the above procedures, the operator then goes to the analog control panel. The Logic Mode Control is placed in the RUN mode.* The Analog Set Up Mode Control is then placed in the Static TEST mode. In this mode either a one group delayed neutron approximation or a six group delayed neutron approximation is used in the reactor kinetics section of the reactor simulator. A static test on the entire system is then undertaken.

A static check is performed by the operator by addressing each amplifier and each potentiometer that is listed in the "Amplifier Assignment Sheet and Static Check" and "Potentiometer Static Check" tables found in Appendix A. The static check used in the xenon poisoning problem is found in Appendix C. Where notes are provided, (e.g., amplifier 0 requires a + 10 volts reference to be patched into the initial conditions hole), the instructions found in the notes should be executed. An example of the procedure in initiating a static check follows for amplifier 0 and 1 and potentiometers 0 and 1:

1. Address amplifier 0 (see Section 8.8).
2. Patch a + 10 volts reference into the I.C. terminal on amplifier 0.

* Make certain function relay 04 is off; function relays 34, 64, 94 and 09 are on; and comparator 04 is off.

3. Read the DVM.
4. The DVM reads - 1.000 (- 10.00 volts).
5. Unpatch the + 10 volts reference from the I.C. terminal on amplifier 0.
6. Address amplifier 1.
7. Read the DVM.
8. The DVM reads + .3247 (+ 3.247 volts).
9. Address potentiometer 0.
10. Patch a + 10 volts reference into the I.C. terminal on amplifier 0.
11. Read the DVM.
12. The DVM reads - .0766 (- .766 volts).
13. Unpatch the + volts reference from the I.C. terminal on amplifier 0.
14. Address potentiometer 1.
15. Push in the wire terminating at the + 10 volt reference which is numbered 009.
16. Read the DVM.
17. The DVM reads + .5000 (+ 5.000 volts).
18. Pull out the connector of the wire terminating at the + 10 volt reference numbered 009 approximately half way. Do not unpatch this wire from the patch panel; an open circuit is created by slightly withdrawing the connector.

The outputs read out for each amplifier on the DVM should coincide with the voltage outputs labeled in the above mentioned tables. If a readout does not meet the above condition, the operator should consult someone familiar with analog computations to remedy the prob-

lem before proceeding to other areas of study in the reactor simulator.

After successfully completing a static check, the next step in the procedure to operate the reactor simulator is to press and release the "PC", "IC*", "R", and "OP" ANALOG MODE CONTROL buttons on the Control Keyboard sequentially. When this is done, the analog computer will overload momentarily. A thirty second period should lapse from the time the "OP" button is depressed. This period allows the simulator to stabilize at its new operating position.

Upon the completion of the thirty second waiting period mentioned above, the operator initiates the final step in starting the reactor simulator. This is the pressing and releasing of function relay number 64 display button to cause it to glow. The reactor simulator is now functional.

8.10 Shut Down Procedure

Assuming that the ANALOG MODE CONTROL of the Control Keyboard is in the "OP" mode, the operator initiates the shutdown procedure by pressing and releasing the "IC" and "PC" ANALOG MODE CONTROL buttons on the Control Keyboard sequentially.

The operator then separates the analog computer from the digital computer by turning off pushbuttons number 0 and 1 which are found on the Logic Readout Panel of the analog computer.

The above action will process a "!FIN" card on the card reader

* In the "IC" mode make certain that certain function relay 34, 94 and 09 are ON, that function relay 04, and 64 are OFF, and that comparator 04 is OFF.

and will release the digital computer from service with the analog computer. The operator then removes the RC network from the patch panel and removes the patch panel from the analog computer, after which the maintenance patch panel is placed on the analog computer. The operator then depresses the "POWER OFF" button on the analog readout panel. This action turns the analog computer off.

After this procedure the line printer, the card reader, and the teletype are all made nonfunctional as described previously in this chapter. The operator then places the COMPUTE switch on the Sigma 5 process control panel in the IDLE position.

8.11 Review of the Simulator Results

The various figures shown in Chapters Five, Six, and Seven are easily reproduced on the reactor simulator by manipulation of certain control stimuli. The control stimuli of interest are:

1. Variation of the reference temperature.
2. Variation of the secondary loop steam throttle.
3. Variation of the primary loop coolant flow rate.
4. Variation of xenon buildup after start up and shut down.

Figures 3.1 through 3.6 and Figures 3.13 through 3.18 are obtained by observing various control variable changes which are caused by variations in the reference temperature while maintaining a constant steam temperature. Figures 3.1 through 3.6 are obtained by using the one group delayed neutron approximation. Figures 3.13 through 3.18 are obtained by using the six group delayed neutron approximation with the aid of the RC network discussed in Chapter Three.

These figures were produced to compare the external RC network that simulated all six groups of delayed neutrons with the one group

delayed neutron approximation model. The steps to generate these figures are not mentioned in this chapter. However, the production of similar figures while using the variable steam temperature which is associated with the secondary loop model is discussed.

Figures 5.2 through 5.4 are obtained by observing various control variable changes which are caused by variations in the reference temperature with the secondary loop included in the model of the reactor power systems. Figures 5.2 through 5.4 are obtained by using the RC network discussed in Chapter Three. Figures similar to the above can also be obtained by using the one group delayed neutron approximation as mentioned in Chapter Three.

Figures 5.5 through 5.9 are obtained by observing various control variable changes which are caused by variations in the secondary loop throttle. These figures are obtained by using the RC network. Similar results can be obtained by using the one group delayed neutron approximation.

Figures 6.1 through 6.3 are obtained by observing the xenon poison concentration during start up and shut down of a reactor with various flux levels.

Figures 7.1 through 7.2d are obtained by observing various control variable changes which are caused by variations in the primary loop flow rate. These figures are obtained by using the RC network. They can also be obtained by using the one group delayed neutron approximation.

Shown in Figures 5.10 and 5.11 is the one group differential normalized neutron concentration, and the one group inverse reactor period versus time, respectively, for various changes in the reference temperature.

8.11.1 Procedure

Before considering the following procedures which are used to obtain the above mentioned results, a thorough review of Chapter Two and Three is recommended. A study of the equipment used, their function, and their operation as presented in this chapter is vital in understanding this section. A study of the model described in Chapter Two along with the RC network described in Chapter Three is recommended. An understanding of the simulator start up and shut down procedure found in this chapter is necessary. Also, an understanding of the procedure found in this chapter to set the pots and to address various patch panel components is required. The monitor scope, and DVM operation found in this chapter should be fully realized.

8.11.1a Basic Steps

To summarize, the basic steps in preparing the reactor simulator for operation are the following:

1. Obtain the RC network from the area near the line printer.
2. Remove the PWR digital computer cards from the RC network storage area.
3. Start the reactor power systems as outlined in this chapter.
4. Start the scope as outlined in this chapter.
5. After pressing function relay 64, wait five minutes for the system to stabilize. If the RC network is used in the simulator as discussed in Chapter Three, observe the output of amplifier 105 (normalized neutron concentration) by addressing amplifier 105 on the Control Keyboard during this time. Amplifier 105 is observed on the DVM and on the scope. If the one group delayed neutron concentration is used in the simu-

lator as discussed in Chapter Three, observe the output of amplifier 4 (normalized neutron concentration) by addressing amplifier 4 on the Control Keyboard during this time. Amplifier 4 is observed on the DVM and on the scope.

6. After the steady state conditions are reached, the systems are capable of being studied.

8.11.1b Experimental Results

The experimental results are obtained by observing eight fundamental rules. These rules are as follows:

1. One should not press any button unless told to do so explicitly in the instructions.
2. No wires are removed from the patch panel unless specifically told to do so.
3. No wires are connected to the patch panel unless specifically told to do so.
4. Any amplifier can be read out on the DVM at any time when in the OPERATE mode.
5. The output of each amplifier is in voltage units. The conversion of these voltage units to physical units is discussed in Section 2.1.1a and 2.1.1b.
6. A constant overload horn is heard if an amplifier overloads. During start up, one should expect this overload signal as explained in this chapter. During operation of the reactor power systems, this overload signal may be encountered during "scram" conditions. The key to understanding the overload signal is found in the time period that this signal endures. Overload conditions may exist momentarily, but these condi-

tions should not be allowed to persist for time periods greater than 30 seconds. To overcome the overload state, one simply depresses the IC pushbutton on the Control Keyboard and then the PC mode control pushbutton on the Control Keyboard.

7. During a "scram" condition, function relay pushbutton 04 turns on automatically. In this condition, one should depress the IC and PC pushbuttons on the Control Keyboard to eliminate the overload condition encountered during a scram condition. As mentioned previously, an overload condition may exist for 30 seconds before the above sections need be initiated.
8. The reactor power systems simulator is made operational after the above "scram" procedure by placing the reactor power systems in the mode that it is in before the mode that caused the "scram". The function relays are then placed in the following states:

04 - off

34 - on

64 - off

94 - on

09 - on

The IC and OP pushbuttons are then depressed sequentially. A period of 30 seconds is allowed to pass after the OP pushbutton is depressed. At the termination of this period, the function relay 64 pushbutton is turned on. A period of five minutes is then allowed to pass to permit the reactor power

systems to stabilize.

8.11.1c Various Reference Temperatures

The study of the reactor power systems after a step change in the reference temperature is initiated by observing Figures 5.2 through 5.4. In these figures, normalized neutron concentrations, reactivity, average coolant temperature, temperature of the coolant entering the reactor, secondary loop steam temperature, and fuel temperature are observed after a disturbance to the systems. The disturbance is the step change in reference temperature.

The normalized neutron concentration of the reactor power systems versus time as shown in Figure 5.2 is obtained by executing the following on the reactor simulator:

1. Turn off function relay number 64. This will open the circuit to the proportional-plus-integral controller thus allowing the error message to be zero during the adjustment of the reference temperature.
2. Address handset pot Q07 as described in Section 8.9.
 - a. Observe the handset pot coefficient on the DVM window.
 - b. Adjust handset pot Q07 until the desired reference temperature value is attained (i.e., the DVM will give the value of the reference temperature divided by 1000. If the window reads .6000, the value of the reference temperature is 600°F.).
3. Address amplifier number 105 if the RC network is used to simulate the reactor kinetics equation as discussed in Chapter Three. The addressing of any amplifier is discussed in this chapter.

- a. Observe the steady state normalized neutron concentration on the DVM.
 - b. Observe the steady state normalized neutron concentration on the scope, the operation of which is described in this chapter. One should be concerned with the TIME BASE of the scope.
 - c. Patch a yellow analog patch panel wire from the terminal labeled "10N RC NETWORK N" to the "Y" terminal of an "X - Y" plotter if the RC network is used as mentioned above (optional).
4. Turn on function relay number 64.
 5. Observe the transient response of the system.
 6. Allow the systems to reach a steady state condition.
 7. If the system "scrams", press IC and PC. Also, turn off function relay 04, turn on function relay 94, and address handset pot Q07. Adjust Q07 such that the reference temperature is 500°F. At this point, depress IC and OP. Allow thirty seconds to pass. After this thirty second period, turn on function relay number 64. Allow the systems to reach a steady state condition through a period of five minutes.
 8. Address Q07, and adjust Q07 such that the reference temperature is 500°F.
 9. Allow the system to reach a steady state condition.
 10. Repeat steps 1-9 for various reference temperatures.

The reactivity of the reactor power systems versus time shown in Figures 5.3a and 5.3b is obtained by executing the following on the reactor simulator:

1. Repeat steps one and two as mentioned in the procedure to obtain the normalized neutron concentration found previously in this section.
2. Address amplifier number 21.
 - a. Observe the steady state reactivity level on the DVM.
 - b. Observe the steady state reactivity level on the scope, the operation of which is described in this chapter. One should be concerned with the TIME BASE of the scope.
 - c. Patch a yellow analog patch panel wire from the terminal labeled "REACTIVITY" to the "Y" terminal of the "X - Y" plotter (optional).
3. Repeat steps four through ten as mentioned in the procedure to obtain the normalized neutron concentration.

The average coolant temperature, T_c ; fuel temperature, T_f ; secondary loop steam temperature, T_s ; and coolant temperature entering the reactor, T_{ic} , versus time shown in Figures 5.4a, 5.4b, 5.4c, and 5.4d are obtained by executing the following:

1. Repeat steps one and two as mentioned in the procedure to obtain the normalized neutron concentration found previously in this section.
2. Address one of the following amplifiers:

Amplifier 64 - T_c

Amplifier 85 - T_s

Amplifier 34 - T_f

Amplifier 62 - T_{ic}

- a. Observe the steady state value of the above control variable on the DVM.

- b. Observe the steady state value of the above control variable on the scope, the operation of which is described in this chapter. One should be concerned with the TIME BASE of the scope.
- c. Patch a yellow analog patch panel wire from the "Y" terminal of the "X - Y" plotter to the appropriately labeled terminal as shown below and found on the patch panel (optional):

T_c - "COOLANT AVE. TEMP."

T_s - "SECONDARY LOOP STEAM TEMP."

T_f - "FUEL TEMP."

T_{ic} - "INLET COOLANT TEMP."

3. Repeat steps four through nine as mentioned in the procedure to obtain the normalized neutron concentrations found previously in this section.
4. Repeat steps one, two, and three as mentioned above for various control variables.
5. Repeat steps one through four as mentioned above for various reference temperatures.

8.11.1d Various Secondary Loop Throttle Openings

A study of the reactor power systems after a step change in the secondary loop throttle opening is obtained by observing Figures 5.5 through 5.9. In these figures, normalized neutron concentration, reactivity, average coolant temperature, temperature of the coolant entering the reactor, secondary loop steam temperature, and fuel temperature are observed after a disturbance to the system. The dis-

turbance is the step change in the secondary loop throttle opening.

The normalized neutron concentration of the reactor power systems versus time as shown in Figure 5.5 is obtained by executing the following on the reactor simulator:

1. Address amplifier number 105 if the RC network is used to simulate the reactor kinetics equation as discussed in Chapter Three. The addressing of any amplifier is discussed in this chapter.
 - a. Observe the steady state normalized neutron concentration on the DVM.
 - b. Observe the steady state normalized neutron concentration on the scope, the operation of which is described in this chapter. One should be concerned with the TIME BASE of the scope.
 - c. Patch a yellow analog patch panel wire from the terminal labeled "10N RC NETWORK N" to the "Y" terminal of an "X - Y" plotter if the RC network is used as mentioned previously (optional).
2. Adjust handset pot Q02. The actual value found on the pot represents the per cent opening of the throttle. If the pot is turned counter-clockwise, the throttle opening decreases. Turning the pot fully clockwise or fully counter-clockwise fully opens the throttle or fully closes the throttle, respectively. The values read on the pot for various per cent throttle openings are the following:

% Fully Open	Pot Value
100 %	10.0
75 %	7.5
50 %	5.0
25 %	2.5

- a. The value of the above pot coefficient cannot be observed on the DVM window while in the OP mode. The value is observed by physically observing the handset pot. The observed value of the pot coefficient represents the throttle opening.
 - b. The pot should be turned as rapidly as possible to give an approximate step change in the secondary loop throttle opening.
3. Observe the transient behavior of the system.
 4. Allow the system to reach a steady state condition.
 5. Rapidly adjust handset pot Q02 to the fully clockwise position. This causes the throttle opening to be fully open.
 6. Allow the system to reach a steady state condition.
 7. Repeat steps 1-6 for various throttle openings.

The reactivity versus time as shown in Figure 5.6 is obtained by executing the following on the reactor simulator.

1. Address amplifier 21:
 - a. Observe the steady state reactivity level on the DVM.
 - b. Observe the steady state reactivity level on the scope, the operation of which is described in this chapter. One should be concerned with the TIME BASE of the scope.
 - c. Patch a yellow analog patch panel wire from the terminal

labeled "REACTIVITY" to the "Y" terminal on an "X - Y" plotter (optional).

2. Repeat steps two through five of the procedure used to obtain the normalized neutron concentration versus time found earlier in this chapter.
3. Observe the transient response of the system for an increase in the throttle opening to fully open.
4. Allow the system to reach a steady state condition.
5. Repeat steps 1-4 for various throttle openings.

The normalized neutron concentration versus time as shown in Figure 5.7 is obtained by executing the following procedure on the reactor simulator:

1. Repeat step one of the procedure used to obtain the normalized neutron concentration versus time as mentioned previously in this section.
2. Decrease the secondary loop throttle by rotating handset pot Q02 counter-clockwise to a position representing 20 per cent throttle opening (e.g., the pot setting will be 2.0).
3. Allow the systems to reach a steady state condition.
4. From the above throttle opening, decrease the throttle opening to 10 per cent by adjusting handset pot Q02 to a value of 1.0.
5. Allow the system to reach a steady state condition.
6. From the above throttle opening, decrease the throttle opening to 0 per cent by adjusting handset pot Q02 to a value to 0.0.

7. Allow the system to reach a steady state condition.
8. At this point, the normalized neutron concentration should be observed to be near zero representing a zero power level.
9. Increase the throttle to fully open by turning handset pot Q02 to the fully clockwise position.
10. Observe the transient behavior of the system.
11. Allow the system to reach a steady state condition.

The secondary loop steam temperature, T_s ; fuel temperature, T_f ; average coolant temperature, T_c ; and coolant temperature entering the reactor, T_{ic} , versus time shown in Figures 5.8, 5.9a, 5.9b, and 5.9c are obtained by executing the following on the reactor simulator:

1. Address one of the following amplifiers

Amplifier 64 - T_c

Amplifier 85 - T_s

Amplifier 34 - T_f

Amplifier 62 - T_{ic}

- a. Observe the steady state value of the above control variable on the DVM.
- b. Observe the steady state value of the above control variable on the scope, the operation of which is described in this chapter. One should be concerned with the TIME BASE of the scope.
- c. Patch a yellow analog patch panel wire from the "Y" terminal of the "X - Y" plotter to the appropriately labeled terminal as shown below and found on the patch panel (optional):

T_c - "COOLANT AVE. TEMP."

T_s - "SECONDARY LOOP STEAM TEMP."

T_f - "FUEL TEMP."

T_{ic} - "INLET COOLANT TEMP."

2. If T_s is observed, repeat steps two through seven of the procedure used to obtain the normalized neutron concentration versus time shown in Figure 5.5 as mentioned earlier.
 - a. For zero throttle opening, repeat steps two through nine of the procedure used to obtain Figure 5.7 while observing the transient response of the system.
 - b. When the throttle is reduced to zero without realizing the above procedure, oscillations in the reactivity occur. The oscillations are caused by the error associated with the difference between the steam temperature and the average heat exchanger temperature.
3. If either T_c , T_f , or T_{ic} , is observed, repeat steps two through six of the procedure used to obtain the normalized neutron concentration versus time as shown in Figure 5.5.
4. Repeat step one, two, and three of the above procedure for various control variables.
5. Repeat steps one, three, and four of the above procedure for various throttle openings.

8.11.1e Various Primary Coolant Flow Rates

A study of the reactor power systems after a step change in the primary loop coolant flow rate is obtained by observing Figures 7.1 through 7.2. In these figures, normalized neutron concentration, average coolant temperature, temperature of the coolant entering the

reactor, and fuel temperature are observed after a disturbance to the system. The disturbance is the step change in the primary loop coolant flow rate.

The normalized neutron concentration of the reactor power systems versus time as shown in Figure 7.1 is obtained by executing the following on the reactor simulator:

1. Address amplifier 105 if the RC network is used to simulate the reactor kinetics equation as discussed in Chapter Three. The addressing of any amplifier is discussed in this chapter.
 - a. Observe the steady state normalized neutron concentration on the DVM.
 - b. Observe the steady state normalized neutron concentration on the scope, the operation of which is described in this chapter. One should be concerned with the TIME BASE of the scope.
 - c. Patch a yellow analog patch panel wire from the terminal labeled "10N RC NETWORK N" to the "Y" terminal of an "X - Y" plotter if the RC network is used as mentioned previously (optional).
2. Turn on the following Digital Pushbuttons found on the Logic Readout Panel as discussed in this chapter for the corresponding flow rate:

Pushbuttons 0-1		Full Flow
Pushbuttons 0-1-2	125%	Full Flow
Pushbuttons 0-1-3	75%	Full Flow
Pushbuttons 0-1-4	50%	Full Flow
Pushbuttons 0-1-5	0%	Full Flow

3. For each of the above flow rate step changes, observe the systems transient response.
4. Allow the system to reach a steady state condition for full flow, 125% full flow, 75% full flow, and 50% full flow.
5. Zero flow causes several analog computer components to overload,
 - a. After observing the transient behavior of the system to the above step change in flow, depress the IC and PC pushbuttons on the Control Keyboard.
 - b. Turn off Digital Pushbutton 5 found on the Logic Readout panel.
 - c. Make certain that the function relays are in the following states:
 - Function Relay 04 - off
 - Function Relay 34 - on
 - Function Relay 64 - off
 - Function Relay 94 - on
 - Function Relay 09 - on
 - d. Depress the IC and OP pushbuttons on the Control Keyboard.
 - e. Allow thirty seconds to elapse.
 - f. Turn on function relay 64.
 - g. Allow the system to reach a steady state condition for a period of five minutes.
6. After the system reaches a steady state condition, all Digital Pushbuttons found on the Logic Readout Panel, with the exception of Digital Pushbuttons 0 and 1, should be in the OFF state.

7. Allow the system to reach a steady state condition in the above mode.

The average coolant temperature, T_c ; fuel temperature, T_f ; and coolant temperature entering the reactor, T_{ic} , versus time shown in Figures 7.2a, 7.2b, 7.2c, and 7.2d are obtained by executing the following on the reactor simulator:

1. Address one of the following amplifiers:

Amplifier 64 - T_c

Amplifier 34 - T_f

Amplifier 62 - T_{ic}

- a. Observe the steady state value of the above control variable on the DVM.
- b. Observe the steady state value of the above control variable on the scope, the operation of which is described in this chapter. One should be concerned with the TIME BASE of the scope.
- c. Patch a yellow analog patch panel wire from the "Y" terminal of the "X - Y" plotter to the appropriately labeled terminal as shown below and found on the patch panel (optional):

T_c - "COOLANT AVE. TEMP."

T_f - "FUEL TEMP."

T_{ic} - "INLET COOLANT TEMP."

2. For each control variable, repeat steps two through seven of the procedure used to obtain the normalized neutron concentration versus time as mentioned previously in this section.

8.11.1f Xenon Poisoning

A study of xenon poisoning during start up and shut down is obtained by observing Figures 6.1, 6.2, and 6.3. In Figure 6.1, xenon poisoning versus time is shown before and after shut down of the reactor for various flux levels. Figures 6.2 and 6.3 show xenon poisoning versus time before and after shut down of the reactor for a flux level of 10^{14} neutrons/cm²-sec. Included in the above figures is a study of the effect that post shut down pulses of 10^{14} neutrons/cm²-sec. have upon the xenon poisoning.

The xenon poisoning versus time as shown in Figure 6.1 is obtained by executing the following on the reactor simulator:

1. Address amplifier 82. The addressing of any amplifier is discussed in this chapter.
 - a. Observe the steady state xenon poisoning level on the DVM.
 - b. Observe the steady state xenon poisoning level on the scope, the operation of which is described in this chapter. One should be concerned with the TIME BASE. One should also keep in mind that two hours of real time are obtained in one second of computer time for this problem as discussed in Chapter Six.
 - c. Patch a yellow analog patch panel wire from the terminal labeled "XENON POISONING" to the "Y" terminal of an "X - Y" plotter (optional).
2. Turn off function relay 09. This action is representative of the action taken to shut down a reactor having a flux level of 10^{14} neutrons/cm²-sec.
3. Observe the systems transient response.

4. Allow the system to reach a steady state condition.
5. Turn on function relay 09. This action is representative of the action taken to start up a reactor having a flux level of 10^{14} neutrons/cm²-sec.
6. Observe the systems transient behavior.
7. Allow the system to reach a steady state condition.
8. Repeat steps one through seven for various flux levels by changing the pot setting on the servo-set pots to the values shown in Appendix C with the following procedure:
 - a. Depress the IC, PC, and SP pushbuttons on the Control Keyboard.
 - b. Set pots 15, 16, 17, 12, 41, 20, and 22 to the values listed for the desired flux level as shown in Appendix C. The above servo-set pots are set by executing the procedure as outlined in this chapter.
 - c. Depress the PC pushbutton on the Control Keyboard.
 - d. Check the function relays for the following modes:
 - Function Relay 04 - off
 - Function Relay 34 - on
 - Function Relay 64 - off
 - Function Relay 94 - on
 - Function Relay 09 - on
 - e. Depress the IC and OP pushbuttons on the Control Keyboard.
 - f. Allow thirty seconds to pass.
 - g. Turn on function relay 64.
 - h. Allow five minutes to pass thus permitting the system to reach a steady state.

- i. The system is now ready for further study with the new flux level.

The xenon poisoning versus time plots showing the effect of a two pulse and a one pulse shut down in comparison to a rapid shut down shown in Figures 6.2 and 6.3, respectively, are obtained by executing the following on the reactor simulator:

1. To reproduce Figure 6.2, the following procedure is used:
 - a. A flux level of 10^{14} neutrons/cm²-sec. is used as mentioned in the above procedure.
 - b. Repeat steps one, two, and three of the previously mentioned procedure. Turn off function relay 09 at the same point on the plot that the relay is turned off in step "a" above.
 - c. Turn on function relay 09 after a period of 1.6 seconds is passed from the time at which the relay is turned off in step "b". This action gives the reactor a pulse of flux that reduces the xenon poisoning. This pulse is for a period of .3 seconds after which function relay 09 is turned off.
 - d. Turn on function relay 09 after a period of 2.4 seconds is passed from the time at which the relay is turned off in step "b". This pulse is for a period of .6 seconds after which function relay 09 is turned off.
 - e. The above procedure requires precise timing. Practice is required to press the ON and OFF pushbuttons of function relay 09 at the times required.
2. To reproduce Figure 6.3 the following procedure is used:

- a. With a flux level of 10^{14} neutrons/cm²-sec., as mentioned in the procedure to reproduce Figure 6.1, repeat steps one through seven.
- b. Repeat steps one, two, and three of the procedure used to reproduce Figure 6.1. Turn off function relay 09 at the same point on the plot that the relay is turned off in step "a" above.
- c. Turn on function relay 09 after a period of 1.1 seconds is passed from the time at which the relay is turned off in step "b". This action gives the reactor a pulse of flux that reduces the xenon poisoning. This pulse is for a period of .4 seconds after which function relay 09 is turned off.
- d. The above procedure requires precise timing. Practice is required to press the ON and OFF pushbuttons of function relay 09 at the times required.

8.11.1g Reactor Period Studies

A study of the derivative of the normalized neutron concentration versus time, and of the inverse reactor period versus time is obtained by observing Figures 5.10 and 5.11, respectively. The above results are obtained by connecting the one group delayed neutron approximation to the patch panel as discussed in Section 8.9. One must remember to disconnect the RC network normalized neutron concentration from the patch panel as discussed in the above mentioned section.

The study of the derivative of the normalized neutron concentration versus time is obtained by executing the following on the reactor simulator:

1. Repeat steps one, and two of the procedure used to obtain the normalized neutron concentration of the reactor power systems versus time as shown in Figure 5.2 and discussed in Section 8.11.1c.
2. Address amplifier number 39. The addressing of any amplifier is discussed in this chapter.
 - a. Observe the steady state normalized neutron concentration on the DVM.
 - b. Observe the steady state normalized neutron concentration on the scope, the operation of which is described in this chapter. One should be concerned with the TIME BASE of the scope.
 - c. Patch a yellow analog patch panel wire from the terminal labeled "DERIVATIVE N ONE GROUP" to the "Y" terminal of an "X - Y" plotter (optional).
3. Repeat steps four through ten of the procedure used to obtain the normalized neutron concentration of the reactor power systems versus time as shown in Figure 5.2 and discussed in Section 8.11.1c.

The study of the inverse reactor period versus time is obtained by executing the following on the reactor simulator:

1. Repeat steps one, and two of the procedure used to obtain the normalized neutron concentration of the reactor power systems versus time as shown in Figure 5.2 and discussed in Section 8.11.1c.
2. Address amplifier number 2. The addressing of any amplifier is discussed in this chapter.

- a. Observe the steady state normalized neutron concentration on the DVM.
 - b. Observe the steady state normalized neutron concentration on the scope, the operation of which is described in this chapter. One should be concerned with the TIME BASE of the scope.
 - c. Patch a yellow analog patch panel wire from the terminal labeled "REACTOR PERIOD" to the "Y" terminal of an "X - Y" plotter (optional).
3. Repeat steps four through ten of the procedure used to obtain the normalized neutron concentration of the reactor power system versus time as shown in Figure 5.2 and discussed in Section 8.11.1c.

8.11.1h Additional Studies

The study of the reactor power systems after a step change in the reference temperature is obtained by observing Figures 5.2 through 5.4. A further study of the system can be obtained by observing Figures 3.14, 3.15a, 3.16, 3.17 and 3.18 after a step change in reference temperature. Similar results can be obtained on the reactor simulator.

The effect of control rod failure on the normalized neutron concentration is seen in Figure 3.14. The reproduction is obtained by following the procedure used to produce the normalized neutron concentration of the reactor power system versus time as shown in Figure 5.2 as discussed in Section 8.11.1c. The only difference in procedure is the following:

1. Only a change in reference temperature from 500°F to 650°F is considered.

2. From the time the step change is initiated in step 4 of the above mentioned procedure, a period of 15 seconds is allowed to pass. At this instant, function relay 34 is turned off. This action simulates a control rod failure.

The error signal versus time for a step change in reference temperature from 500°F to 650°F is shown in Figure 3.15a. The reproduction is obtained by following the procedure used to produce the normalized neutron concentration of the reactor systems versus time as shown in Figure 5.2 as discussed in Section 8.11.1c. The only difference is that amplifier 61 is observed and addressed. The patch panel terminal for this amplifier is labeled "ERROR SIGNAL".

The average coolant temperature, T_c ; the average heat exchanger temperature, T_x ; and the fuel temperature, T_f , versus time for a step change in reference temperature from 500°F to 650°F is shown in Figure 3.16. The reproduction is obtained by following the procedure used to produce the normalized neutron concentration of the reactor power systems versus time as shown in Figure 5.2 as discussed in Section 8.11.1c. The only difference is that the following are observed and addressed:

<u>OUTPUT VARIABLE</u>	<u>AMPLIFIER</u>	<u>TERMINAL LABEL</u>
T_f	34	"FUEL TEMP."
T_c	64	"COOLANT AVE. TEMP."
T_x	112	"HEAT EXCHANGER TEMP."

The normalized neutron concentration, n^* ; the average heat exchanger temperature, T_x ; and the fuel temperature, T_f ; versus time for a step change in reference temperature from 500°F to 700°F is shown in Figure 3.18. The reproduction is obtained by following the procedure used to produce the normalized neutron concentration of the reactor

power systems versus time as shown in Figure 5.2 as discussed in Section 8.11.1c. The only difference is that the following are observed and addressed.

<u>OUTPUT VARIABLE</u>	<u>AMPLIFIER</u>	<u>TERMINAL LABEL</u>
n*	105	"10N RC NETWORK N"
T _x	112	"HEAT EXCHANGER TEMP."

The normalized neutron concentration, n*, versus time for a step change in reactivity ($\pm .0025$) is shown in Figure 3.17. The reproduction is obtained by executing the following procedure:

1. Address amplifier number 105 if the RC network is used to simulate the reactor kinetics equation as discussed in Section 8.9. The addressing of any amplifier is discussed in this chapter.
 - a. Observe the steady state normalized neutron concentration on the DVM.
 - b. Observe the steady state normalized neutron concentration on the scope, the operation of which is described in this chapter. One should be concerned with the TIME BASE of the scope.
 - c. Patch a yellow analog patch panel wire from the terminal labeled "10N RC NETWORK N" to the "Y" terminal on an "X - Y" plotter if the RC network is used as mentioned above (optional).
2. Push in the wire into the "009" + 10 volt reference found at the top of the analog section of the patch panel. The above action creates a .0025 negative reactivity step disturbance.
3. Observe the transient response of the system.

4. Allow the system to reach a steady state condition.
5. Disconnect the wire from the "009" + 10 volt reference found at the top of the analog section of the patch panel. The above action creates a .0025 positive reactivity step disturbance.
6. Observe the transient response of the system.
7. Allow the system to reach a steady state condition.
8. Do not remove the above mentioned wire from the "009" + 10 volt reference. Simply pulling the wire half of the way from the terminal hole will disconnect the wire.

8.11.1i One Group Approximation

The results obtained in Sections 8.11.1c through 8.11.1h can be approximated by using the one group delayed neutron approximation in place of the RC network. The procedure is the same with two exceptions. First, the one group delayed neutron approximation is connected to the patch panel in the place of the RC network as discussed in Section 8.9. Second, the address of the amplifier is found to be amplifier 4. This amplifier is addressed instead of amplifier 105. The terminal label found on the patch panel is also changed from "10N RC NETWORK N" to "ONE GROUP N 10 N". The addressing of amplifier 4 gives the one group normalized neutron concentration as observed on the DVM.

8.11.2 Shut Down Summary

The basic procedure used in shutting down the reactor simulator is summarized below:

1. Shut down the reactor power systems as described in Section 8.10.

2. Remove the RC network from the patch panel.
3. Place the PWR digital computer cards into the RC network storage area.
4. Turn off the power switch of the scope as shown in this chapter.
5. Remove the reactor simulator patch panel from the analog computer and place the maintenance patch panel on the analog computer as described in Section 8.9.

CHAPTER NINE

SUMMARY AND CONCLUSIONS

In a nuclear engineering curriculum and for public demonstrations, the simulation of the nuclear reactor power systems is useful in the behavioral study of the systems.

Classroom training in basic reactor control principles and reactor theory will be more meaningful to the student by his use of the simulator in an effort to gain practical exercise in the subject. The student will have a clearer understanding of control concepts after he observes the theoretical control process taught in the classroom on a working reactor model that closely reproduces the behavior of a power reactor.

In addition, the present simulator package can be modified to match the model of a specific PWR plant by adjusting the servo-set potentiometer coefficients to match the parameters of the given plant. This is beneficial in the study of systems behavior for various PWR plants. The only requirement of the systems operator is to physically change the cards of the digital computer data-section in which is found the address and coefficient of the potentiometers to the desired physical parameters of the plant. The physical interpretation of these potentiometer coefficients is found in Appendixes A, B, and C.

Along with the above modification, data logging of the systems dynamic behavior is another option that may be initiated. A full explanation of this option is presented in a thesis written by Ernest I. Hamilton, Jr., entitled Digital Computer Supervision of an Analog

Nuclear Power Plant Simulator.²⁸ Only minor variations in the present design of the simulator are expected.

Further studies in the area could include the following:

1. Secondary loop control.
2. Multi-region heat exchanger model.
3. Multi-region reactor vessel and reactor core model.
4. Load simulation along with a fault study on the load.
5. Digital control of the plant (closed loop).

The present system does not "feed back" the behavior of the secondary loop steam temperature to the control system. A direct method to regulate the secondary loop steam temperature could be explored.

The multi-region heat exchanger, reactor vessel, and reactor core model could be studied. The present model as mentioned earlier is a point representation of the heat exchanger, reactor vessel, and reactor core. A more detailed representation would include the spatial dependence of the systems by dividing them into regions from which the appropriate reactor kinetics model and heat transfer model is developed.

Spatial analysis could be performed with the present equipment by full utilization of the hybrid facility. A step in that direction would be to model the "transport delay" on the digital computer instead of on the analog computer. This step would permit the use of valuable analog computer components in modeling the heat transfer and reactor kinetics equations.

Load simulation on the present model is accomplished by varying the secondary loop throttle opening. A more detailed analysis of the load could be accomplished by building the appropriate mathematical

model of the turbine, generator, and condenser. From the generator, an electrical load could be demanded. A mathematical model of this load requires the expansion of the present analog computer to facilitate the modeling of the above mathematical representation. It is conceivable, however, that with the large time constant of the secondary loop, a method of digital computer simulation in conjunction with the present analog computer facility could be used.

The digital control of the plant could be realized. In this realization, the digital computer would control the operation of the simulator.

A block diagram of the PWR power plant and control systems with spatial dependence is shown in Figure 9.1. The modeling of this system on the hybrid computer is readily visualized. The methods used to model the system are areas of further study.

As of now, however, the hardware, software, and documentation in this investigation provide the Louisiana State University Nuclear Science Center with an extremely useful tool. Nuclear plant operation may be effectively studied by a large number of students at a minimal cost.

- | | |
|-------------------------------------|--|
| 1. Reactor Core | 9. Comparator |
| 2. Reactor Vessel | 10. Averaging System |
| 3. Inlet Plenum | 11. Pump for Primary Loop |
| 4. Outlet Plenum | 12. Boiler Feed Water Pump |
| 5. Control Rods | 13. Throttle |
| 6. Control Rods Drive Unit | 14. Turbine |
| 7. Control System | 15. Load (Electrical Generator) |
| 8. Reactor Kinetics (Neutron Level) | 16. Condenser |
| | 17. Digital Computer |
| | 18. Flow Regulation to Analog |
| | 19. Reference Temperature |
| | 20. Heat Exchanger |
| | 21. Spatial Dependence of Core |
| | 22. Spatial Dependence of Heat Exchanger |

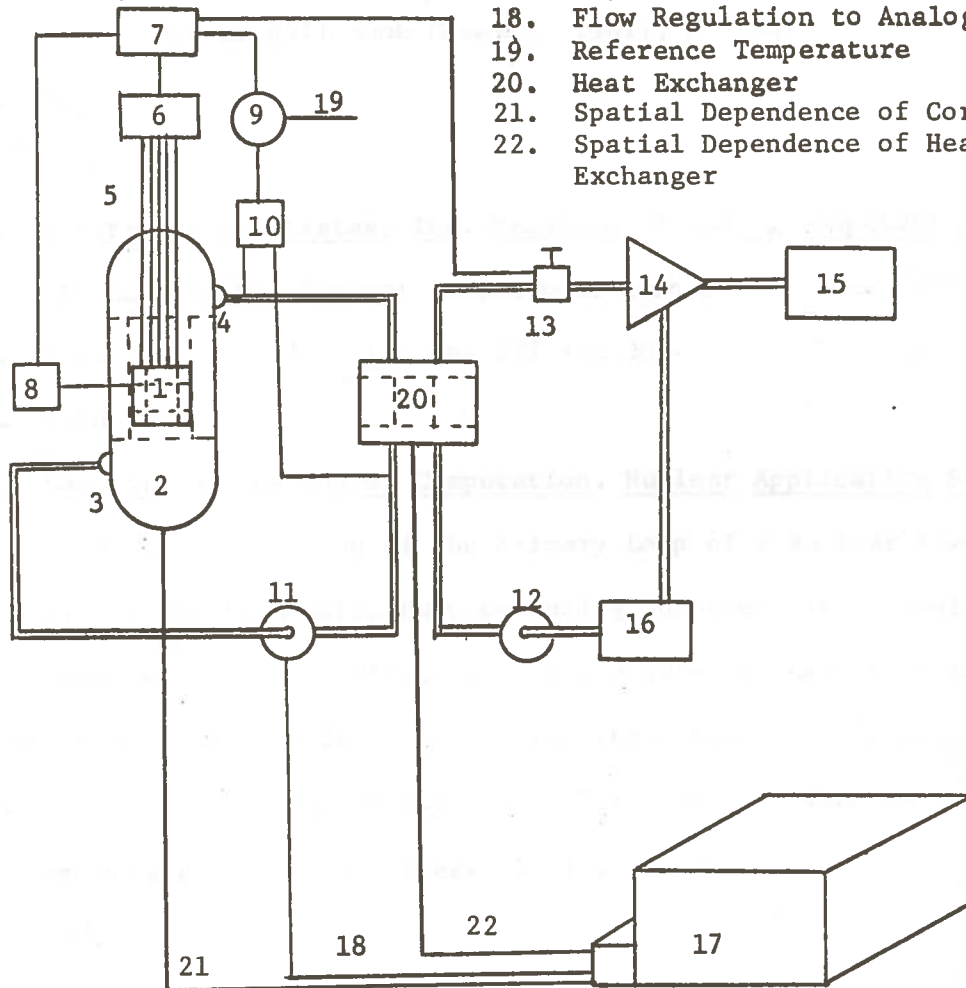


Figure 9.1.

Block Diagram Of PWR Power Plant And Control System
With Spatial Dependence

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APPENDIX A

SIMULATOR SCALED EQUATIONS AND ANALOG DIAGRAM²⁶

One Group Reactor Kinetics:

$$dn/dt = n\delta K/\ell - \beta K n/\ell + \lambda C;$$

$$\begin{aligned} d[10n^*]/dt &= 10[2000\delta K][10n^*]/(2000\ell 10) - \beta K[10n^*]/\ell \\ &+ 10(10\lambda)[C^*/10]. \end{aligned} \tag{A.1}$$

n = neutron concentration (neutrons/cc),

δK = reactivity,

ℓ = prompt (effective) neutron lifetime (sec.),

β = total delayed neutron fraction,

K = multiplication factor,

λ = effective decay constant ($1/13.04 \text{ sec.}^{-1}$),

n^* = n/n_m , normalized neutron concentration,

n_m = maximum practical neutron density (neutrons/cc),

C = delayed neutron precursor concentration (atoms/cc),

C^* = C/n_m , normalized precursor concentration.

Delayed Neutron Concentration:

$$dC/dt = -\lambda C + K\beta n/\ell;$$

$$d[C^*/10]/dt = -(\lambda)[C^*/10] + (K\beta/100\ell)[10n^*]. \tag{A.2}$$

Fuel Element Heat Transfer:

$$M_f C_f dT_f/dt = n \Delta H_f - UA[T_f - T_c];$$

$$\begin{aligned} d[T_f/200] &= (n_m \Delta H/M_f C_f 2000)[10n^*] - (UA/M_f C_f)[T_f/200] \\ &+ (UA/2M_f C_f)[T_c/100]. \end{aligned} \quad (A.3)$$

T_c = average coolant temperature in reactor ($^{\circ}\text{F}$),

T_f = average fuel temperature ($^{\circ}\text{F}$),

U = overall coefficient of heat transfer in the reactor core (BTU/sec.-ft.².- $^{\circ}\text{F}$),

A = heat transfer area in reactor (sq. ft.),

M_f = effective mass of fuel and moderator (lb.),

C_f = effective specific heat of moderator and fuel (BTU/lb.- $^{\circ}\text{F}$),

ΔH = heat of fission (BTU-cc/sec.-neutron).

Fuel Element to Coolant Heat Transfer:

$$M_c C_c dT_c/dt = UA(T_f - T_c) - W_c C_c (T_{oc} - T_{ic}),$$

and

$$M_c C_c dT_c/dt = UA(T_f - T_c) - W_c C_c (2T_c - 2T_{ic}),$$

where $T_{oc} = 2T_c - T_{ic}$,

$$\begin{aligned} d[T_c/100]/dt &= - (UA/M_c C_c)[T_c/100] - 10(2W_c C_c/10M_c C_c)[T_c/100] \\ &+ (2UA/M_c C_c)[T_f/200] + 10(2W_c C_c/10M_c C_c)[T_{ic}/100]. \end{aligned} \quad (A.4)$$

M_c = mass of coolant (lbs.),

C_c = specific heat of coolant (BTU/lb.- $^{\circ}\text{F}$),

W_c = mass flow rate of coolant (lbs./sec.),

T_{ic} = temperature of coolant entering reactor ($^{\circ}\text{F}$),

T_{oc} = temperature of coolant leaving reactor ($^{\circ}\text{F}$).

Temperature Out of Reactor Core:

$$T_{oc} = 2T_c - T_{ic};$$

$$[T_{oc}/100] = 10(.2)[T_c/100] - [T_{ic}/100]. \quad (\text{A.5})$$

Outlet Plenum - Mixing in Plenum Chamber:

$$M_o dT_o/dt = W_c [T_{oc} - T_o],$$

or,

$$M_o dT_o/dt = W_c [2T_c - T_{ic} - T_o]; \quad (\text{A.6})$$

$$d[T_o/100]/dt = (2W_c/M_o)[T_c/100] - (W_c/M_o)[T_{ic}/100] - (W_c/M_o)[T_o/100].$$

T_o = coolant temperature at the outlet of the reactor outlet chamber ($^{\circ}\text{F}$),

M_o = mass of coolant in outlet plenum chamber (lbs.).

Time Delay to Heat Exchanger:

$$T_{ix} = T_o(t - \tau_o);$$

$$[T_{ix}/100] = [T_o(t - \tau_o)/100]. \quad (\text{A.7})$$

T_{ix} = temperature of coolant entering the heat exchanger ($^{\circ}\text{F}$),

τ_o = time delay necessary for the coolant to flow from the outlet plenum chamber of the reactor core to the inlet of the heat exchanger,

$\tau_o = 4$ seconds,

t = time in seconds.

Heat Transfer in the Heat Exchanger:Primary Side:

$$M_x C_x dT_x/dt = W_c C_c [T_{ix} - T_{ox}] - U_x A_x [T_x - T_s],$$

where

$$T_x = (T_{ox} + T_{ix})/2,$$

$$M_x C_x dT_x/dt = 2W_c C_c T_{ix} - (U_x A_x + W_c C_c 2)T_x + U_x A_x T_s;$$

$$\begin{aligned} d[T_x/100]/dt &= (2W_c C_c / M_x C_x) [T_{ix}/100] - (2W_c C_c / M_x C_x) [T_x/100] \\ &\quad - 10(U_x A_x / 10M_x C_x) [T_x/100] + (U_x A_x / M_x C_x) [T_s/100]. \end{aligned} \quad (A.8)$$

M_x = mass of coolant in heat exchanger (lbs.),

U_x = overall coefficient of heat transfer in the heat exchanger (BTU/sec.-ft²-°F),

T_x = average coolant temperature in heat exchanger (°F),

T_s = average temperature of coolant entering the heat exchanger (°F),

T_{ox} = temperature of coolant leaving the heat exchanger (°F),

A_x = heat transfer area in heat exchanger (sq. ft.).

Out of Heat Exchanger Primary:

$$T_{ox} = 2T_x - T_{ix};$$

$$[T_{ox}/100] = 10(.2)[T_x/100] - [T_{ix}/100]. \quad (A.9)$$

Heat Transfer in Heat Exchanger Secondary:

$$(M_m C_m + M_s C_s) dT_s/dt = (U_x A_x) [T_x - T_s] - K_a A_p (T_s);$$

$$\begin{aligned} d[T_s/100]/dt &= (U_x A_x / (M_m C_m + M_s C_s)) [T_x/100 - T_s/100] \\ &\quad - (K_a / (M_m C_m + M_s C_s)) (A) [T_s/100]. \end{aligned} \quad (A.10)$$

M_m = mass of heat exchanger tube metal (lbs.),

M_s = mass of steam and water in heat exchanger tube metal
(lbs.),

C_m = specific heat of heat exchanger tube metal (BTU/lb.-°F),

C_s = average specific heat of steam and water in heat exchanger
(BTU/lb.-°F),

K_a = throttle constant (BTU/psia-sec.),

A = relative throttle opening (full open, $A = 1$),

$p(T_s)$ = pressure as a function of steam temperature ($p(T_s) = NT_s$),

N = one psia/°F.

Piping Delay from Heat Exchanger to Inlet Plenum:

$$T_i = T_{ox}(t - \tau_i);$$

$$[T_i/100] = [T_{ox}(t - \tau_i)/100]. \quad (A.11)$$

τ_i = time delay necessary for the coolant to flow from the
outlet of the heat exchanger to the inlet plenum chamber,
= 4 seconds;

T_i = coolant temperature at the input to the reactor inlet
plenum chamber (°F).

Inlet Plenum - Mixing in Plenum Chamber:

$$M_i dT_{ic}/dt = W_c [T_i - T_{ic}];$$

$$d[T_{ic}/100]/dt = (W_c/M_i)[T_i/100] - (W_c/M_i)[T_{ic}/100]. \quad (A.12)$$

M_i = mass of coolant in the inlet plenum chamber (lbs.).

Temperature Average:

$$T_{ave} = T_{ox}/2 + T_{oc}/2;$$

$$[T_{ave}/100] = (.5)[T_{ox}/100] + (.5)[T_{oc}/100]. \quad (A.13)$$

T_{ave} = average controller temperature ($^{\circ}F$).

Comparator - Error Signal:

$$\epsilon = T_{Ref} - T_{ave};$$

$$[\epsilon/100] = (T_{Ref}/1000)10 - [T_{ave}/100]. \quad (A.14)$$

ϵ = error signal ($^{\circ}F$),

T_{Ref} = reference temperature ($^{\circ}F$).

Proportional Plus Integral Controller:

$$n_o = \tau_c K_c \epsilon + K_c \int_0^t \epsilon dt;$$

$$n_o - n = \tau_c K_c \epsilon + K_c \int_0^t \epsilon dt - n;$$

$$[2(n_o^* - n^*)] = (200\tau_c K_c^*)[\epsilon/100] + (2K_c^*100) \int_0^t [\epsilon/100] dt - (.2)[10n^*]. \quad (A.15)$$

n_o = demand power level (neutrons/cc),

n_o^* = normalized demand power level,

K_c^* = normalized controller gain ($^{\circ}F\text{-sec.})^{-1}$,

K_c = controller gain (neutrons/ $^{\circ}F\text{-sec-cc}$),

τ_c = controller time constant (sec.).

Control Rod Movement:

$$d^2\mu/dt^2 = - (1/\tau_m)d\mu/dt + K_m/\tau_m [(n_o - n)/n];$$

$$d^2[20\mu]/dt^2 = - (1/\tau_m)d[20\mu]/dt + (K_m/\tau_m)[20(n_o^* - n^*)/n^*]. \quad (A.16)$$

μ = departure of control rod reactivity (dimensionless),

τ_m = control rod drive unit time constant (seconds),

K_m = modified gain constant (seconds⁻¹).

Reactivity:

$$\delta K = \delta K_f + \delta K_p + \delta K_T + \delta K_c.$$

δK_f = built in reactivity of fuel (It can be considered as a constant during short periods. It depends on fuel depletion, breeding, etc.);

δK_p = reactivity due to poison concentration (It can be considered to be constant for short transient periods of time);

(δK_p and δK_f changes have a negligible effect on overall reactivity compared to the effect of fuel temperature and control rod movement. It should be noted, however, that the effect of poisons is quite important during simulation of start up and shut down procedures.);

$$\delta K_T = \alpha [T_f - T_r],$$

T_r = temperature coefficient of reactivity reference temperature (temperature at which temperature contribution to reactivity is zero),

α = temperature coefficient of reactivity,

δK_T = reactivity contribution due to the fuel temperature;

$$\delta K = K_r + \alpha T_f + \mu,$$

$$\mu = \delta K_c - \delta K_{co},$$

$$K_r = \delta K_{co} + \delta K_p + \delta K_f - \alpha T_r;$$

δK = reactivity;

δK_c = reactivity contribution to control rod position;

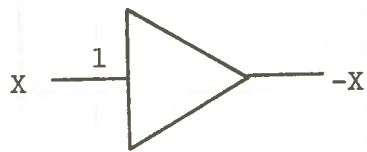
δK_{co} = initial reactivity contribution to control rods;

K_r = reactivity constant.

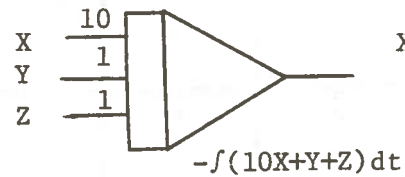
Therefore the reactivity equation becomes:

$$[2000\delta K] = 2000K_r + 2000\alpha T_f + 2000\mu;$$

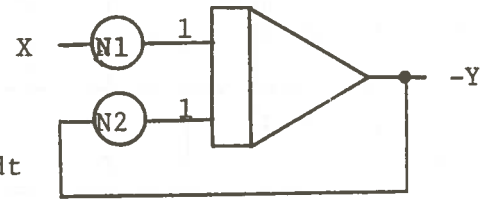
$$[2000\delta K] = 10(20K_r)10 + (4 \times 10^5 \alpha)[T_f/200] + 10[200\mu]. \quad (A.17)$$



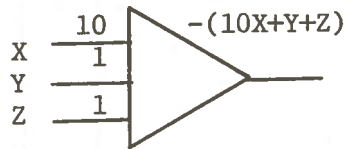
Inverter



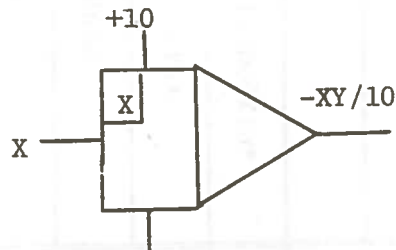
Summing Integrator



N1=a
N2=b



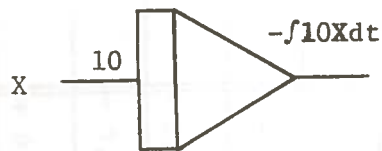
Summer



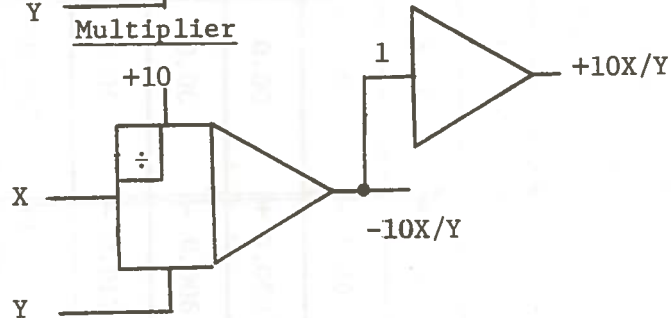
Multiplier

Example Problem:

$$dy/dt = (a)[X] - (b)[Y]$$



Integrator



Divider

Figure A.1. Standard Analog Patching Symbols

Table A.1.

Amplifier Assignment Sheet And Static Check

Amp	Use	Output Parameter	Static Check		Notes
			Calculated Value	Measured Value	
0	f	$-C^*/10$	-10.00	-10.00	+10 I.C. on Amp 0
1	Σ	$-dn^*/dt$	+ 3.25	+ 3.247	
2	-	$+dn^*/dt/n^*$	- 6.50	- 6.49	
4	-	$+10n^*$	+ 5.00	+ 5.00	
5	f	$-10n^*$	- 5.00	- 5.00	
6	-	$+0.5(2000\delta K)n^*$	0.00	+ 0.003	
8	M	$-2000\delta Kn^*$	0.00	- 0.006	
9	-	$-2000\delta K$	0.00	- 0.012	
11	-	$+C^*/10$	+10.00	+10.00	+10 I.C. on Amp 0
21	Σ	$+2000\delta K$	0.00	+ 0.012	
30	f	$-T_f/200$	- 5.00	- 5.00	
31	-	$+dn^*/dt/10n^*$	- 0.65	- 0.649	
34	-	$+T_f/200$	+ 5.00	+ 5.00	
35	f	$-T_c/100$	- 5.00	- 5.00	
38	M	$-dn^*/dt/10n^*$	+ 0.65	+ 0.649	
39	-	$+dn^*/dt$	- 3.25	- 3.247	

Table A.1. (continued)

Amplifier Assignment Sheet And Static Check

Amp	Use	Output Parameter	Static Check		Notes
			Calculated Value	Measured Value	
40	Σ	$-T_{oc}/100$	- 6.00	- 5.99	
45	f	$-T_o/100$	- 4.00	- 3.99	
50	f	$-T_x/100$	- 5.00	- 4.99	
51	Σ	$-T_{ox}/100$	- 6.00	- 5.99	
55	Σ	$+0.0117(T_s - T_x)/100$	- 0.0176	- 0.018	
60	f	$+0.02 \int \frac{\epsilon}{100} dt$	+10.00	+10.00	-10 I.C. on Amp 60
61	Σ	$+\epsilon/100$	- 1.00	- 0.999	
62	-	$+T_{ic}/100$	+ 4.00	+ 3.99	
64	-	$+T_c/100$	+ 5.00	+ 5.00	
65	Σ	$+(2n^* - 2n_o^*)$	+ 1.037	+ 1.03	
66	Σ	$+T_{ave}/100$	+ 6.00	+ 5.99	
68	M	$+(2n^* - 2n_o^*)/n^*$	+ 2.07	+ 2.063	
69	-	$-T_s/100$	- 3.50	- 3.49	
70	f	$-T_{ic}/100$	- 4.00	- 3.99	
71	Σ	$+T_i/100$	+ 6.00	+ 5.99	
72	-	$-T_{ix}/100$	- 4.00	- 3.99	

Table A.1. (continued)

Amplifier Assignment Sheet And Static Check

Amp	Use	Output Parameter	Static Check		Notes
			Calculated Value	Measured Value	
75	\int	$+d20\mu/dt$	+10.00	+10.00	-10 I.C. on Amp 75
80	\int	-200μ	-10.00	-10.00	-10 I.C. on Amp 80
85	\int	$+T_s/100$	+ 3.50	+ 3.49	
90	\int	Pade' Network	+10.00	+10.00	-10 I.C. on Amp 90
91	Σ	$+T_{ix}/100$	+ 4.00	+ 3.99	
92	-	$-\epsilon/100$	+ 1.00	+ 0.999	
94	-	$+0.02\epsilon/100$	- 0.02	- 0.019	
95	\int	Pade' Network	+10.00	+10.00	-10 I.C. on Amp 95
96	M	$-(2n^*-2n_o^*)/n^*$	- 2.07	- 2.063	
100	-	$-10n^*$ (RC Network)	- 5.00	- 5.00	
102	-	$+(2n_o^*-2n^*)$	- 1.037	- 1.03	
105	HG	$+10n^*$ (RC Network)	+ 5.00	+ 5.00	
110	\int	Pade' Network	+10.00	+10.00	-10 I.C. on Amp 110
112	-	$+T_x/100$	+ 5.00	+ 4.99	
115	\int	Pade' Network	+10.00	+10.00	-10 I.C. on Amp 115

Table A.2.

Potentiometer Assignment Sheet

Pot	Parameter Expression	Check Setting	Run Setting
0	λ	.0766	.0766
1	$2000\delta K/10$	.5000	.5000
2	$\beta/100\ell$	.065	.065
3	.100	.100	.100
5	.500	.500	.500
6	$1/2000\ell$	.500	.500
7	$\beta K/10\ell$	.650	.650
10	.950	.950	.950
11	10λ	.766	.766
21	$U_{x^x} A_x / 10 M_{x^c} C_x$	.040	.040
25	$U_{x^x} A_x / M_m C_m + M_s C_s$	.0117	.0117
27	W_c / M_i	.500	.500
30	$n_m \Delta H / 2000 M_f C_f$	.100	.100
31	.400	.400	.400
32	$U A / M_f C_f^2$	.100	.100
33	W_c / M_i	.500	.500

Table A.2. (continued)
Potentiometer Assignment Sheet

Pot	Parameter Expression	Check Setting	Run Setting
35	.500	.500	.500
36	$2W_{cc} / M_{cc}$	.250	.250
37	UA / M_{cc}	.500	.500
40	$2W_c / M_o$	1.000	1.000
42	.200	.200	.200
45	.400	.400	.400
46	W_c / M_o	.500	.500
47	W_c / M_o	.500	.500
50	.500	.500	.500
51	$2W_{cc} / M_{xc}$	.600	.600
52	$U A_{xxx} / M_{xxx}$	.400	.400
55	.500	.500	.500
57	$U A_{xx} / M_{mm} + M_{ss}$	.0117	.0117
60	$K_a / M_{mm} + M_{ss}$	.005	.005
62	$2000K_c^*$	.020	.020
63	$20\tau_{cc} K_c^*$	.020	.020

Table A.2. (continued)
Potentiometer Assignment Sheet

Pot	Parameter Expression	Check Setting	Run Setting
66	.500	.500	.500
67	.200	.200	.200
70	$UA/M_f C_f$	.200	.200
71	$|4 \times 10^4 \alpha|$	.800	.800
72	.200	.200	.200
75	$2W_c C_c / M_c C_c$	.600	.600
77	$1/10\tau_m$	.400	.400
80	.200	.200	.200
82	$1/\tau_i$	.250	.250
87	$1/\tau_i$	.250	.250
90	$1/\tau_o$	.250	.250
91	.200	.200	.200
92	$1/\tau_o$	.250	.250
95	$1/\tau_o$	.250	.250
96	$2W_c C_c / 10M_c C_c$	.250	.250
97	$3/5\tau_o$	.150	.150

Table A.3.

Potentiometer Static Check

Pot	Parameter Expression	Static Check		Notes
		Calculated Value	Measured Value	
0	λ	- .766	- .766	+10 I.C. on Amp 0
1	$2000\delta K/10$	+5.000	+5.000	Push in lead to +10 on 009 reference
2	$\beta/100\ell$	+ .325	+ .324	
3	.100	- .325	- .307	
5	.500	+5.000	+5.000	
6	$1/2000\ell$	0.000	-0.003	
7	$\beta K/10\ell$	-3.25	-3.25	
10	.950	-9.500	-9.500	
11	10λ	+7.660	+7.660	+10 I.C. on Amp 0
21	$U_{x x} A / 10 M_{x c} C_{x c}$	- .200	- .198	
25	$U_{x x} A / M_{m m} C_{s s} + M_{s s} C_{m m}$	+ .0585	+ .058	
27	W_c / M_i	+3.000	+3.000	
30	$n_m \Delta H / M_f C_f 2000$	+ .500	+ .497	
31	.400	+4.000	+3.990	
32	$U A / M_f C_f 2$	+ .500	+ .497	
33	W_c / M_i	-2.000	-1.990	
35	.500	+5.000	+5.000	

Table A.3. (continued)
Potentiometer Static Check

Pot	Parameter Expression	Static Check		Notes
		Calculated Value	Measured Value	
36	$2W_{c c} / M_{c c}$	+1.000	+ .999	
37	$U A / M_{c c}$	-2.500	-2.499	
40	$2W_c / M_o$	+5.000	+4.990	
42	.200	+1.000	+ .999	
45	.400	+4.000	+3.990	
46	W_c / M_o	-2.000	-1.990	
47	W_c / M_o	-2.000	-1.990	
50	.500	+5.000	+4.990	
51	$2W_{c c} / M_{x c}$	+2.400	+2.400	
52	$U A_{x x} / M_{x x}$	+1.400	+1.400	
55	.500	-5.000	-5.000	
57	$U A_{x x} / M_{m m} + M_{s s}$	- .0409	- .040	
60	$K_a / M_{m m} + M_{s s}$	+ .0175	+ .016	
62	$2000K_c^*$	+ .0200	+ .019	
63	$20\tau_c K_c^*$	+ .0200	+ .019	
66	.500	-3.000	-2.990	
67	.200	-1.000	-1.000	

Table A.3. (continued)
Potentiometer Static Check

Pot	Parameter Expression	Static Check		Notes
		Calculated Value	Measured Value	
70	$UA/M_f C_f$	-1.000	- .998	
71	$|4 \times 10^4 \alpha|$	+4.000	+3.990	
72	.200	+2.000	+2.000	-10 I.C. on Amp 115
75	$2W_c C_c / M_x C_c$	-3.000	-2.990	
77	$1/10\tau_m$	+4.000	+4.000	-10 I.C. on Amp 75
80	.200	+1.000	+1.000	
82	$1/\tau_i$	-1.500	-1.500	
87	$1/\tau_i$	+2.500	+2.500	-10 I.C. on Amp 110
90	$1/\tau_o$	-1.000	- .999	
91	.200	+2.000	+2.000	-10 I.C. on Amp 95
92	$1/\tau_o$	+1.000	+ .999	
95	$1/\tau_o$	+2.500	+2.500	-10 I.C. on Amp 90
96	$2W_c C_c / 10M_c C_c$	-1.250	-1.250	
97	$3/5\tau_o$	+1.500	+1.500	-10 I.C. on Amp 95
100	.500	+5.000	+4.990	
102	.500	-3.000	-3.000	
105	$10K_m / \tau_m$	+1.656	+1.655	

Table A.4.

Handset Potentiometer Assignment

Handset Pot	Parameter Description	Check Setting	Run Setting	Static Check Output
02	A	.999	Variable	+3.50
04	$20K_r$	.400	Variable	-4.00
07	$T_{Ref}/1000$	.500	Variable	-5.00
09	$2n_o^*/10$	.0163	Variable	+ .163

Table A.5.

Limiter Assignment

Limiter	Amp	Limited Variable	Check Setting		Run Setting	
			+	-	+	-
21	21	2000 δ K	10	10	10	10

Table A.6.

Multiplier Assignment

Mult	Use	Mult	Use
8	M	38	D
18	M	68	D

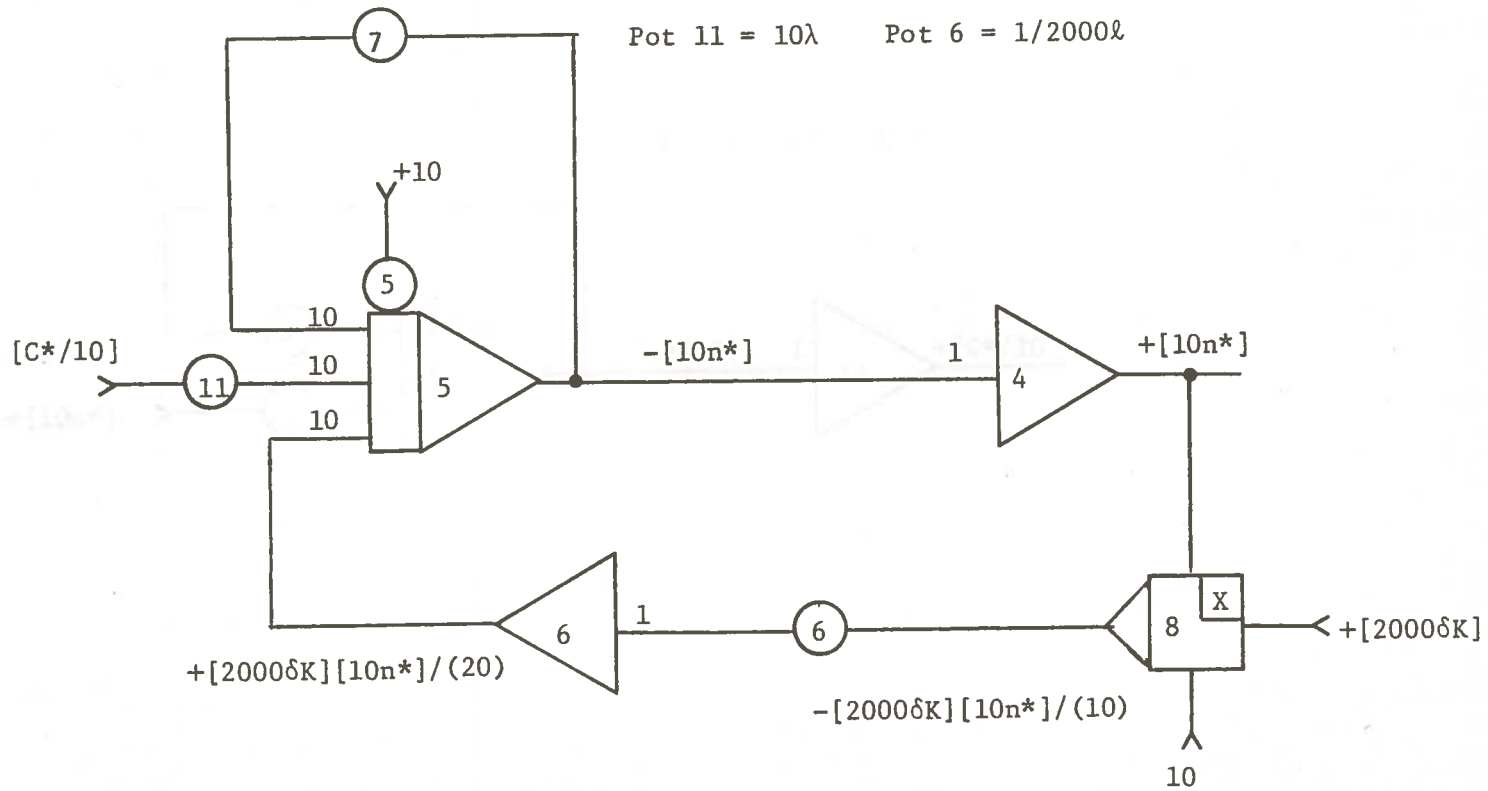
REACTOR KINETICS: EQUATION A.1

Pot 5 = .5

Pot 7 = $K\beta/10\ell$

Pot 11 = 10λ

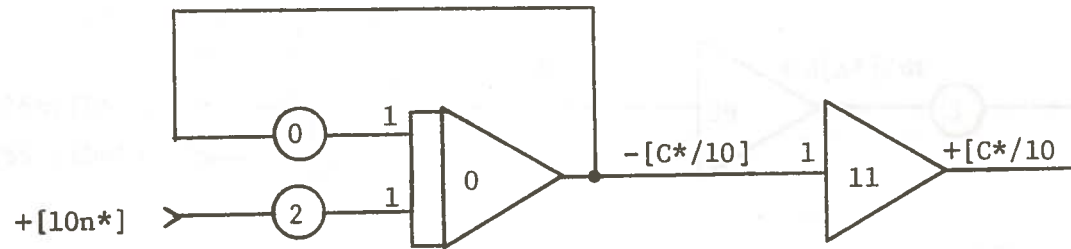
Pot 6 = $1/2000\ell$



DELAYED NEUTRON CONCENTRATION: EQUATION A.2

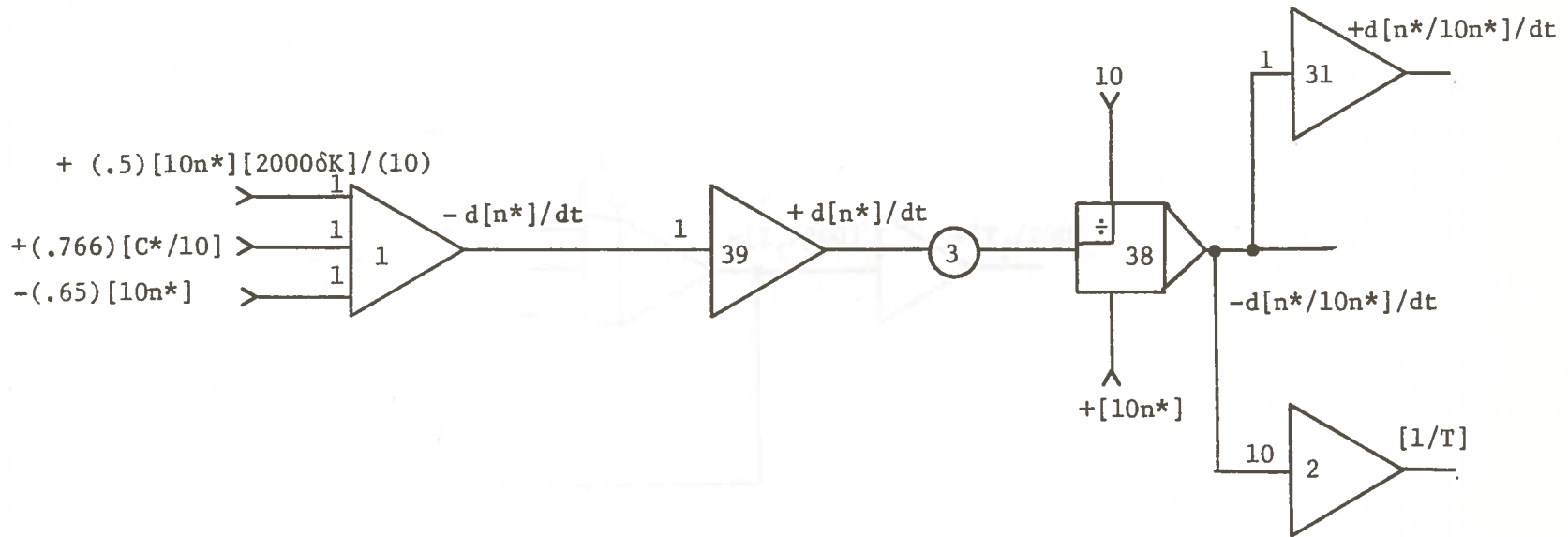
Pot 0 = λ

Pot 2 = $\beta/\lambda 100$



INVERSE REACTOR PERIOD

Pot 3 = .100



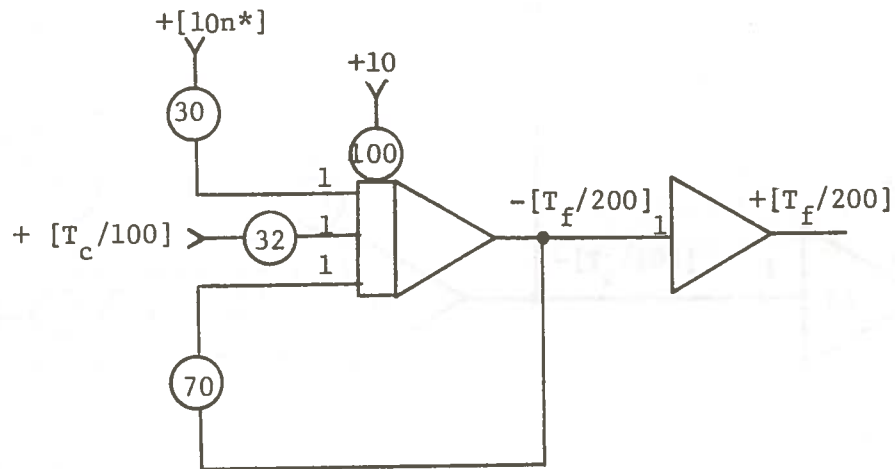
FUEL ELEMENT HEAT TRANSFER: EQUATION A.3

$$\text{Pot } 30 = n_m \Delta H / M_f C_f 2000$$

$$\text{Pot } 70 = UA / M_f C_f$$

$$\text{Pot } 32 = UA / M_f C_f^2$$

$$\text{Pot } 100 = .500$$



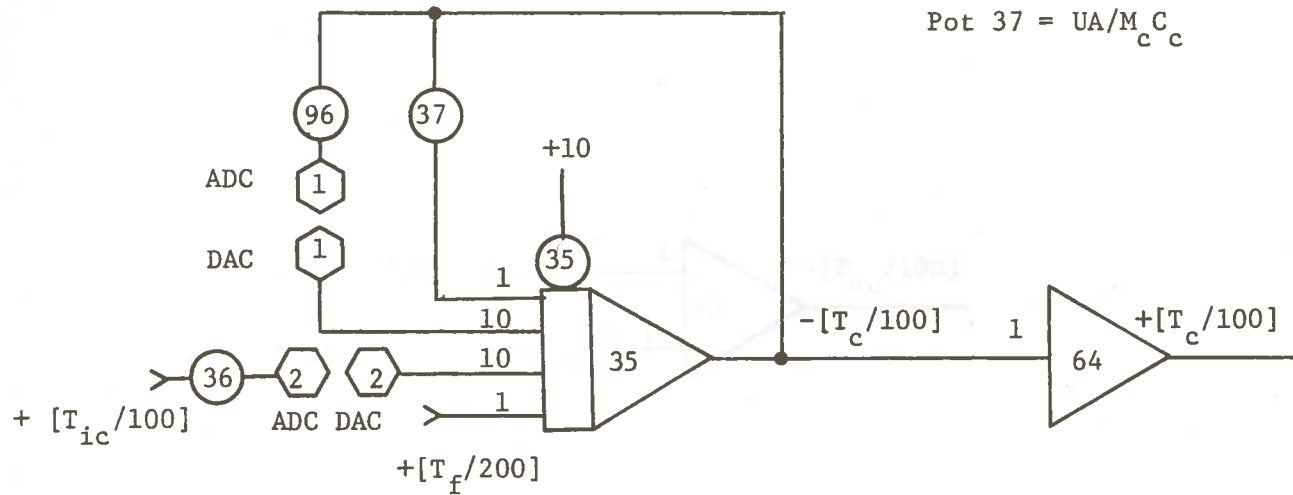
FUEL ELEMENT TO COOLANT HEAT TRANSFER: EQUATION A.4

$$\text{Pot } 96 = 2W_c C_c / 10M_c C_c$$

$$\text{Pot } 36 = 2W_c C_c / M_c C_c$$

$$\text{Pot } 37 = UA / M_c C_c$$

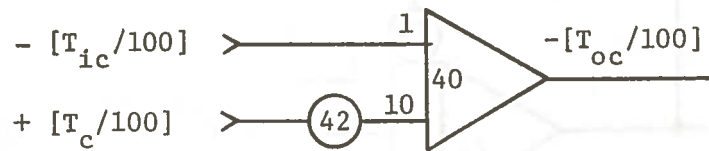
$$\text{Pot } 35 = .500$$



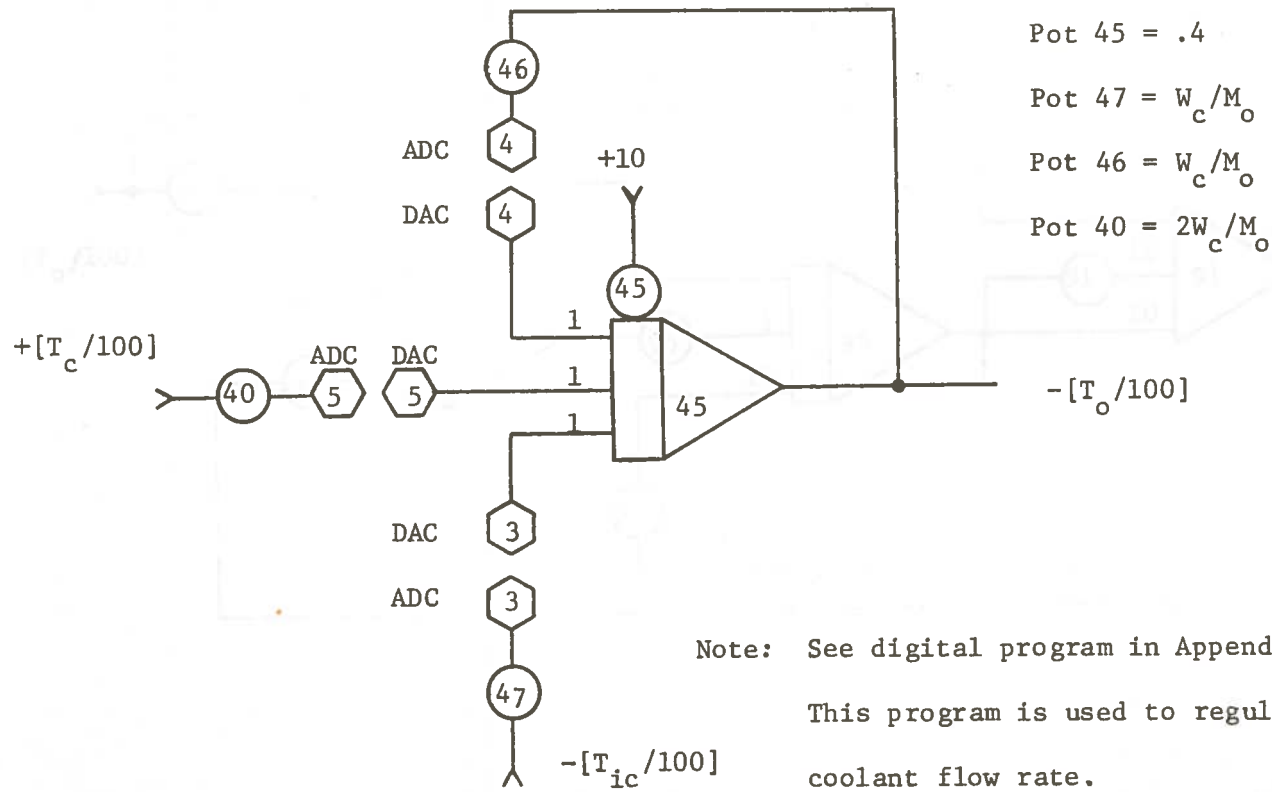
Note: See digital program in Appendix D for ADC-DAC. This program is used to regulate the primary coolant flow rate.

TEMPERATURE OUT OF REACTOR CORE: EQUATION A.5

Pot 42 = .200



OUTLET PLENUM - MIXING IN PLENUM CHAMBER: EQUATION A.6



TIME DELAY TO HEAT EXCHANGER - FOUR SECONDS: EQUATION A.7

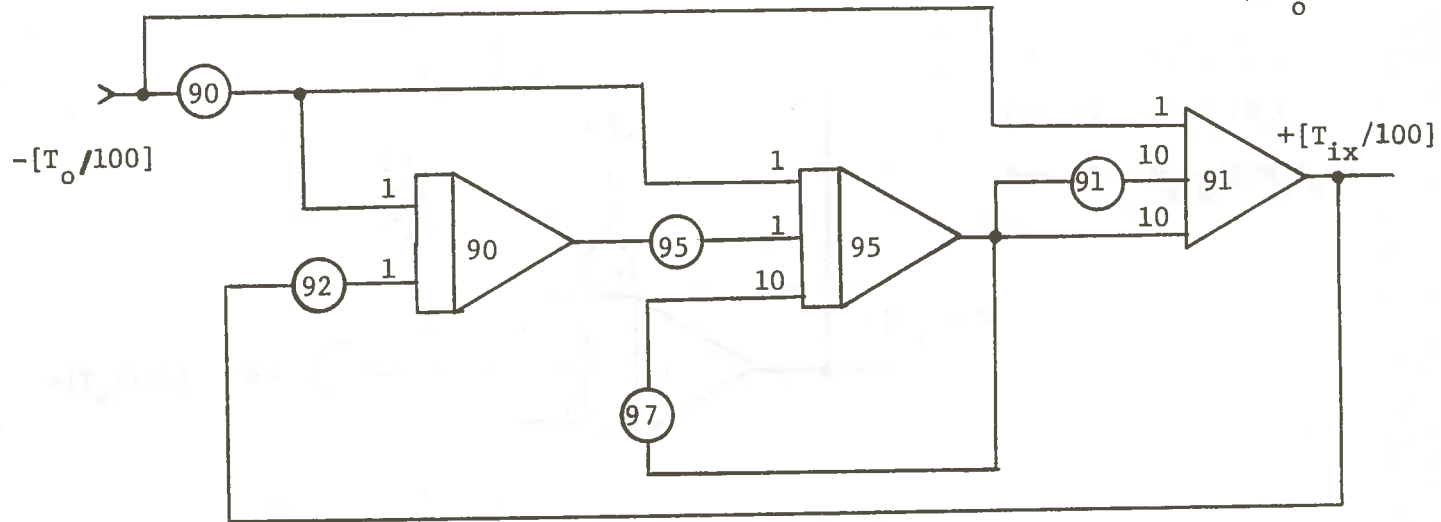
Pot 90 = $1/\tau_o$

Pot 95 = $1/\tau_o$

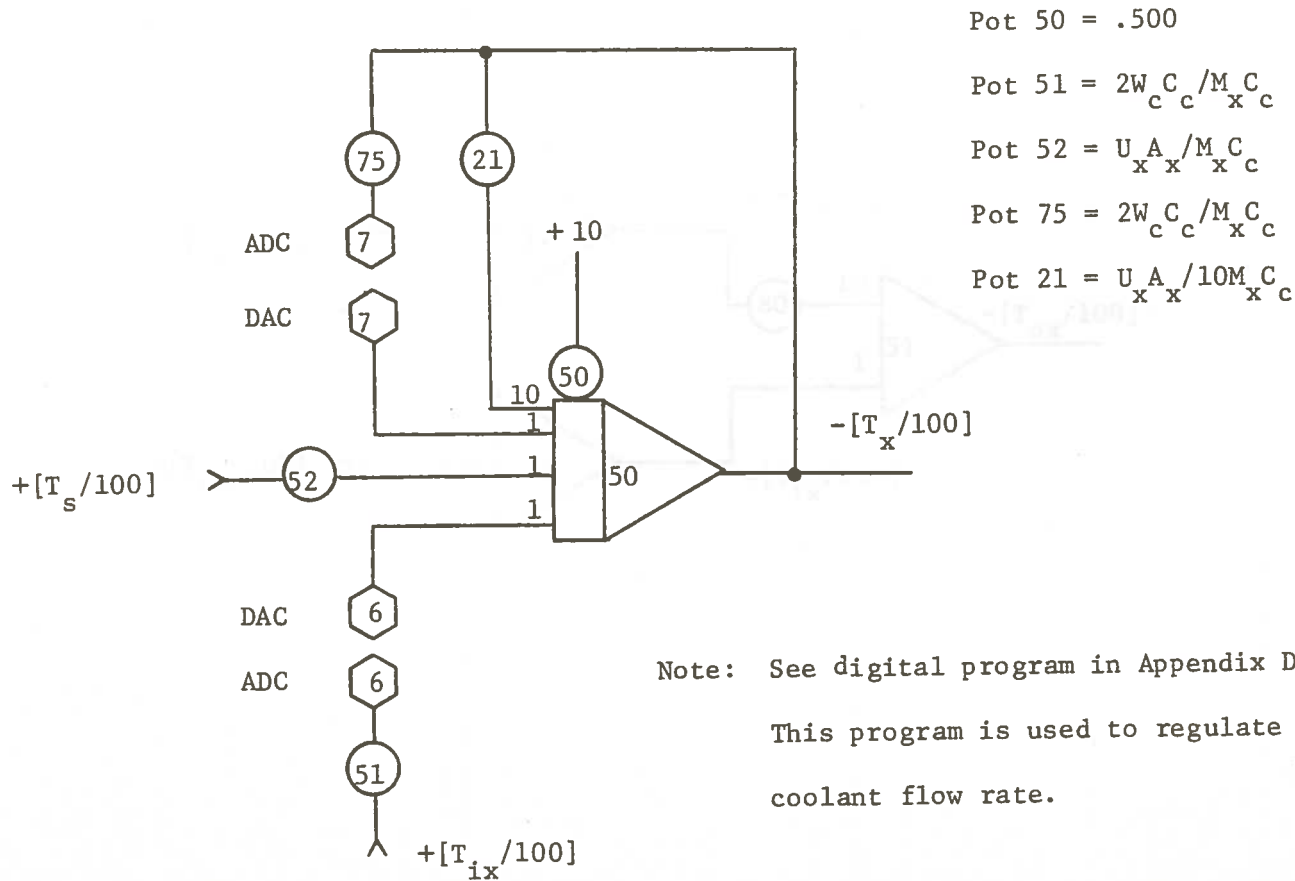
Pot 92 = $1/\tau_o$

Pot 91 = .200

Pot 97 = $3/5\tau_o$

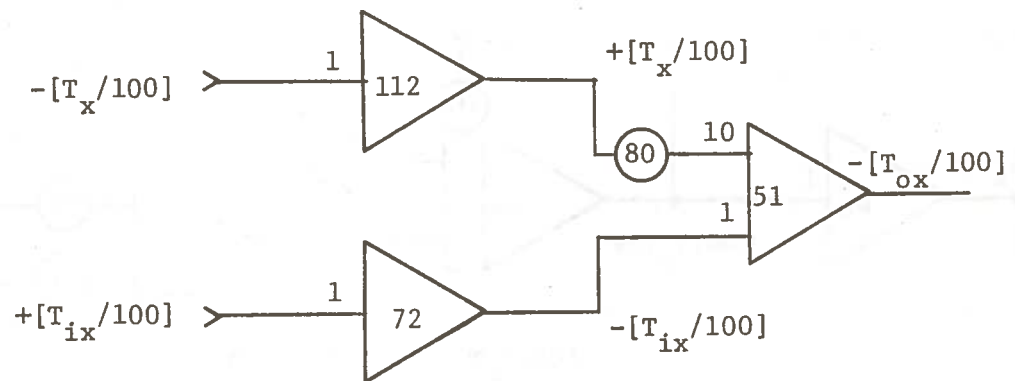


HEAT TRANSFER IN THE HEAT EXCHANGER - PRIMARY SIDE: EQUATION A.8



OUT OF HEAT EXCHANGER - PRIMARY: EQUATION A.9

Pot 80 = .2



HEAT TRANSFER IN HEAT EXCHANGER - SECONDARY: EQUATION A.10

$$\text{Pot 57} = U_x A_x / (M_m C_m + M_s C_s)$$

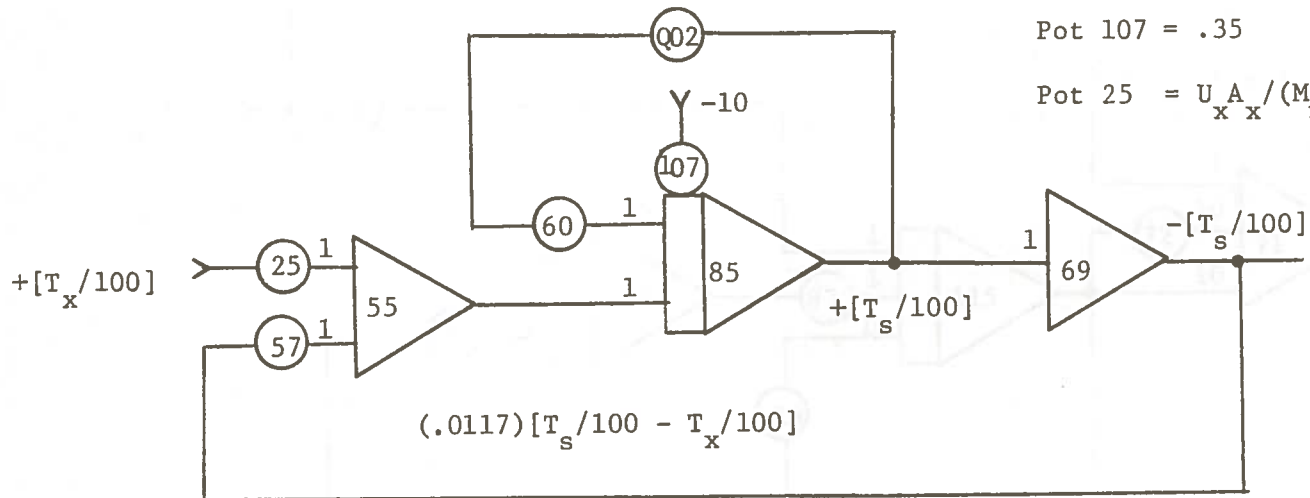
$$\text{Pot 60} = K_a / (M_m C_m + M_s C_s)$$

$$\text{Pot Q02} = \text{variable throttle setting} = A$$

$$= .999 \text{ during static check}$$

$$\text{Pot 107} = .35$$

$$\text{Pot 25} = U_x A_x / (M_m C_m + M_s C_s)$$



PIPING DELAY FROM HEAT EXCHANGER TO INLET PLENUM - FOUR SECONDS: EQUATION A.11

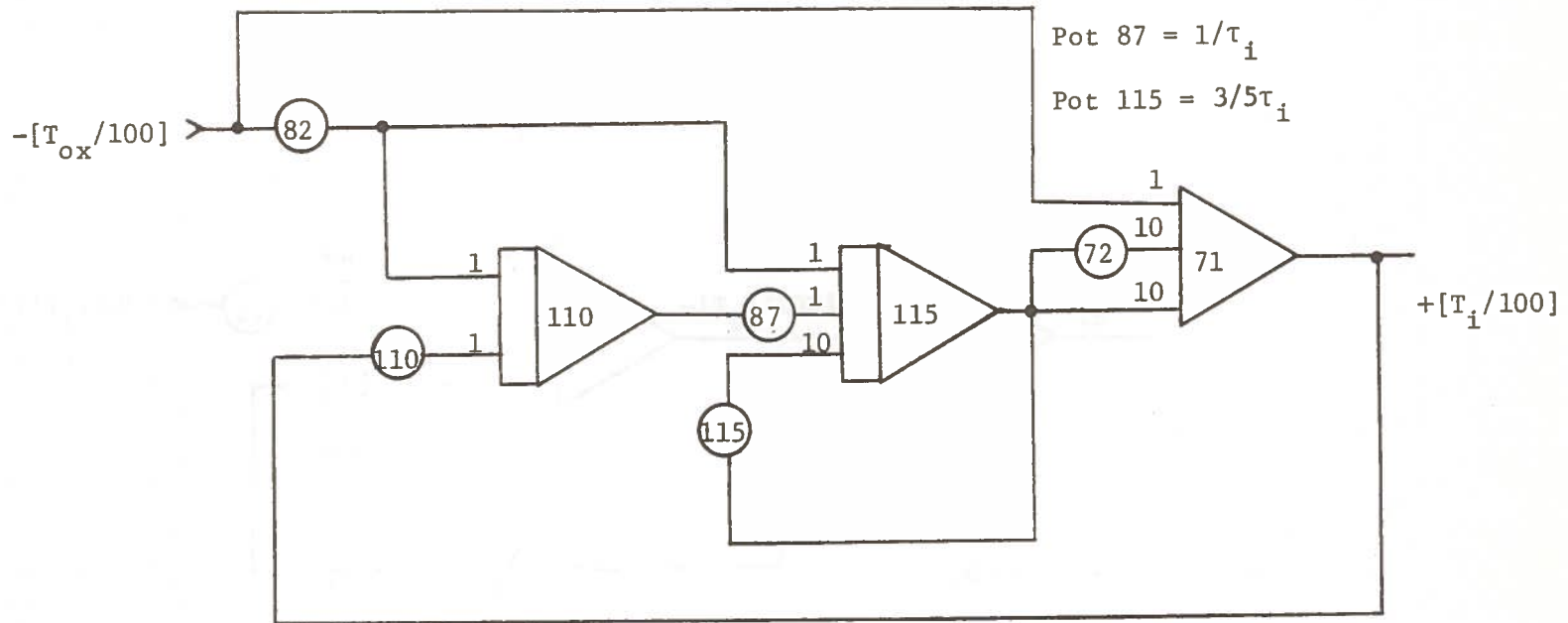
Pot 82 = $1/\tau_i$

Pot 72 = .200

Pot 110 = $1/\tau_i$

Pot 87 = $1/\tau_i$

Pot 115 = $3/5\tau_i$

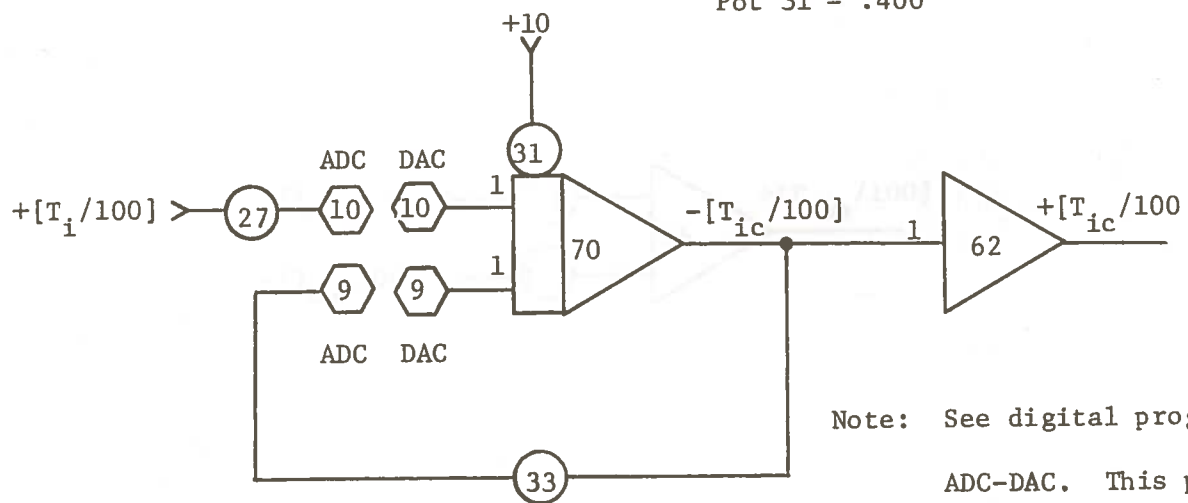


INLET PLENUM - MIXING IN PLENUM CHAMBER: EQUATION A.12

Pot 27 = W_c/M_i

Pot 33 = W_c/M_i

Pot 31 = .400

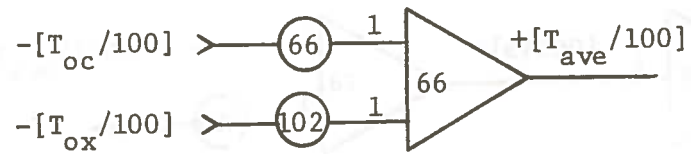


Note: See digital program in Appendix D for ADC-DAC. This program is used to regulate the primary coolant flow rate.

TEMPERATURE AVERAGE: EQUATION A.13

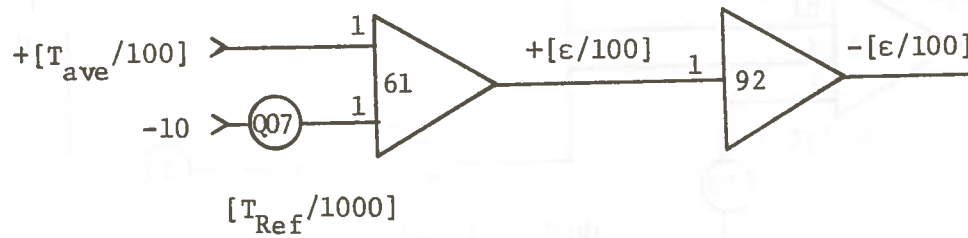
Pot 66 = .500

Pot 102 = .500

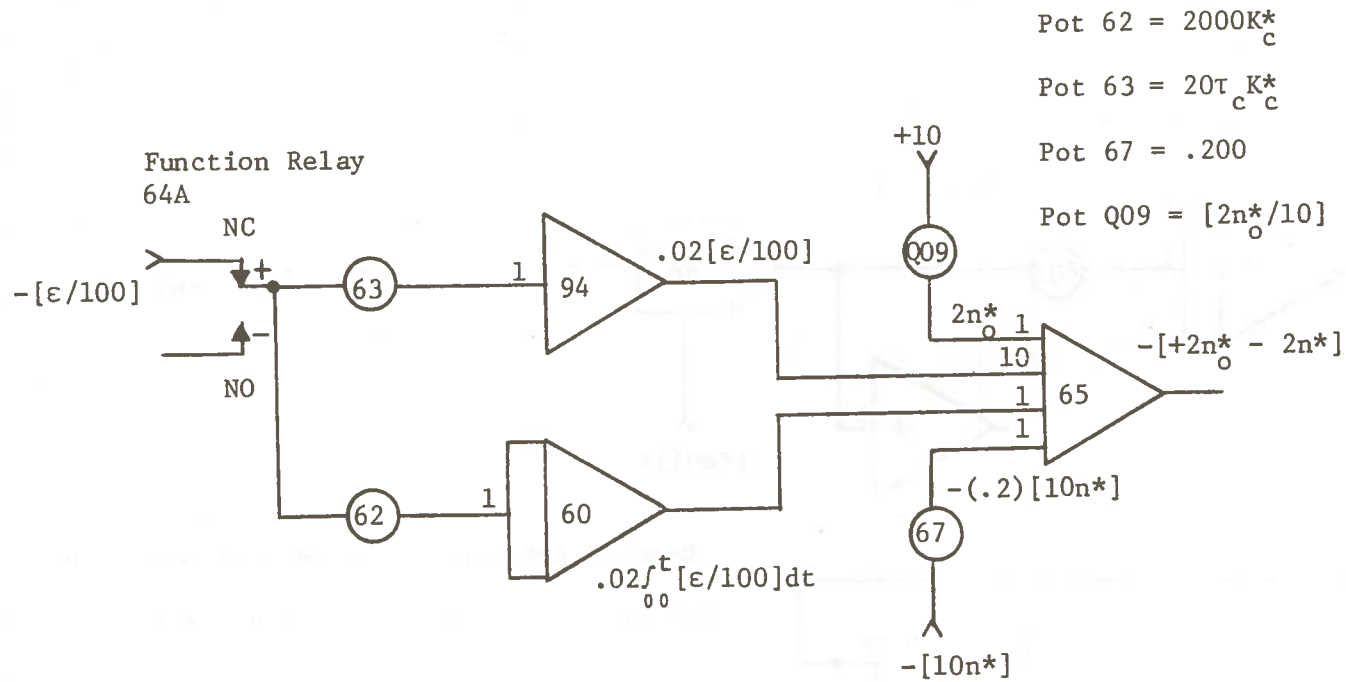


COMPARATOR - ERROR SIGNAL: EQUATION A.14

Pot Q07 = variable handset potentiometer to
obtain the reference temperature.
= .500 during static check



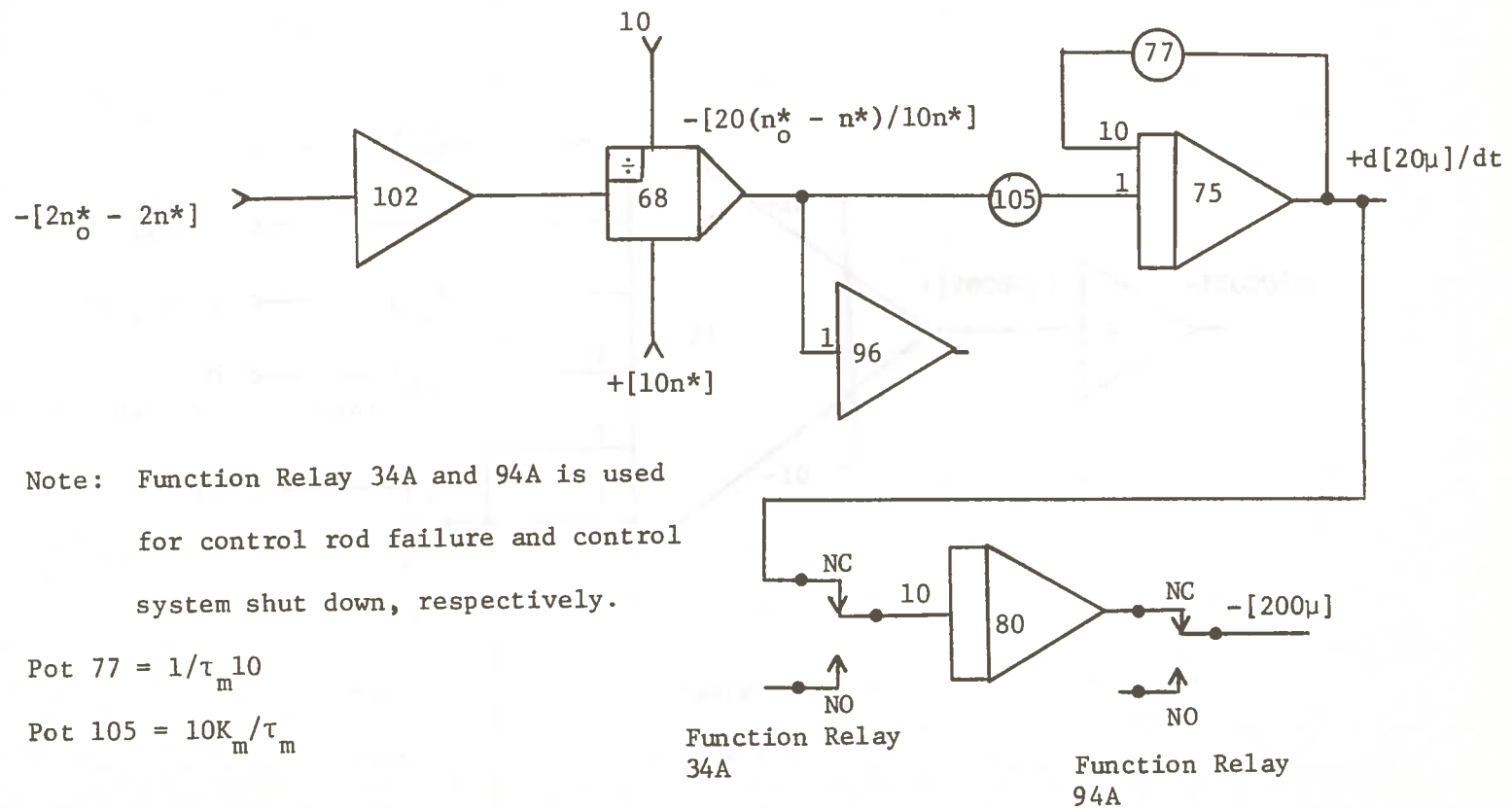
PROPORTIONAL PLUS INTEGRAL CONTROLLER: EQUATION A.15



Note: Function Relay 64A is open during step form IC to OP.

Opening this relay removes the error signal to the controller.

CONTROL ROD MOVEMENT: EQUATION A.16



Note: Function Relay 34A and 94A is used for control rod failure and control system shut down, respectively.

Pot 77 = $1/\tau_m$

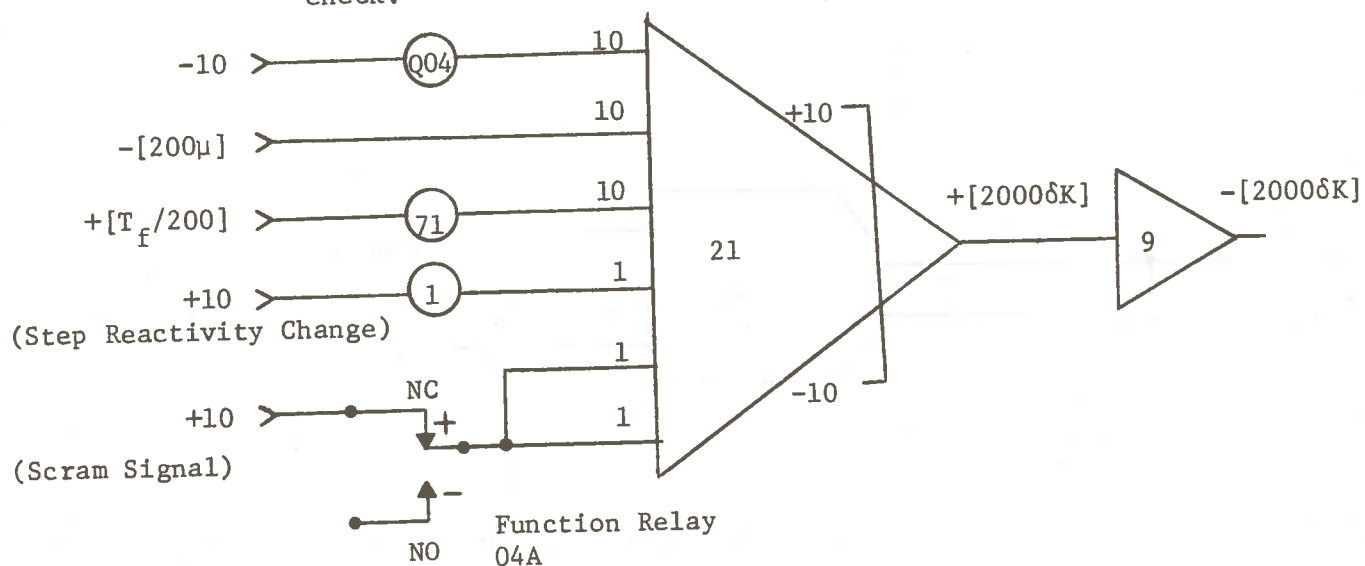
Pot 105 = $10K_m/\tau_m$

REACTIVITY: EQUATION A.17

Pot 1 = $|2000\delta K/10|$
 = .5 during static
 check.

Pot Q04 = $20K_r$ representing reactivity response.
 = .400 during static check.

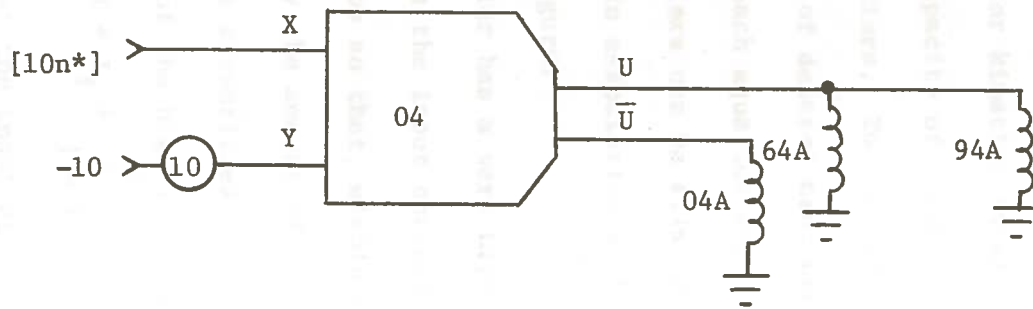
Pot 71 = $|+4 \times 10^4 \alpha| = .8$



Note: From 009 +10 volt reference to pot 1 input push lead into reference terminal for step negative reactivity change.

Function Relay 04A is used to initiate the "Scram" signal.

AUTOMATIC "SCRAM"



Note: $U = 1 (X + Y) > 0$

Pot 10 = .95

$U = 0 (X + Y) < 0$

$U \neq \bar{U}$

APPENDIX B

REACTOR KINETICS BY USE OF AN RC PASSIVE NETWORK

The passive network along with the associated high gain amplifier used to simulate the reactor kinetics equation is shown in Figure B.1.

An estimate of the capacity of a computer is often given by the number of high gain amplifiers. To simulate the reactor kinetics equation using six groups of delayed neutrons would require at least seven such amplifiers if each equation were to be modeled separately. Such costly use of amplifiers can be eliminated by the proper selection of components to be used in association with the amplifier shown in the above mentioned figure.

The high gain amplifier has a very high input impedance so that for all practical purposes the input current is negligibly small. The output impedance is low so that, within ratings, the output voltage is not affected by the amount of current being drawn from the amplifier. With the above properties and by using Kirchoff's current law at the input of the high gain amplifier one obtains:

$$I + I_f + \sum_{j=1}^6 I_j = 0. \quad (\text{B.1})$$

If one further assumes that the input of the high gain amplifier is at zero potential then Equation B.1 becomes:

$$\frac{e_I}{R_o} + C_o \frac{de_o}{dt} + \sum_{j=1}^6 I_j = 0. \quad (\text{B.2})$$

If the voltage across capacitor C_j is called e_j , and its charge

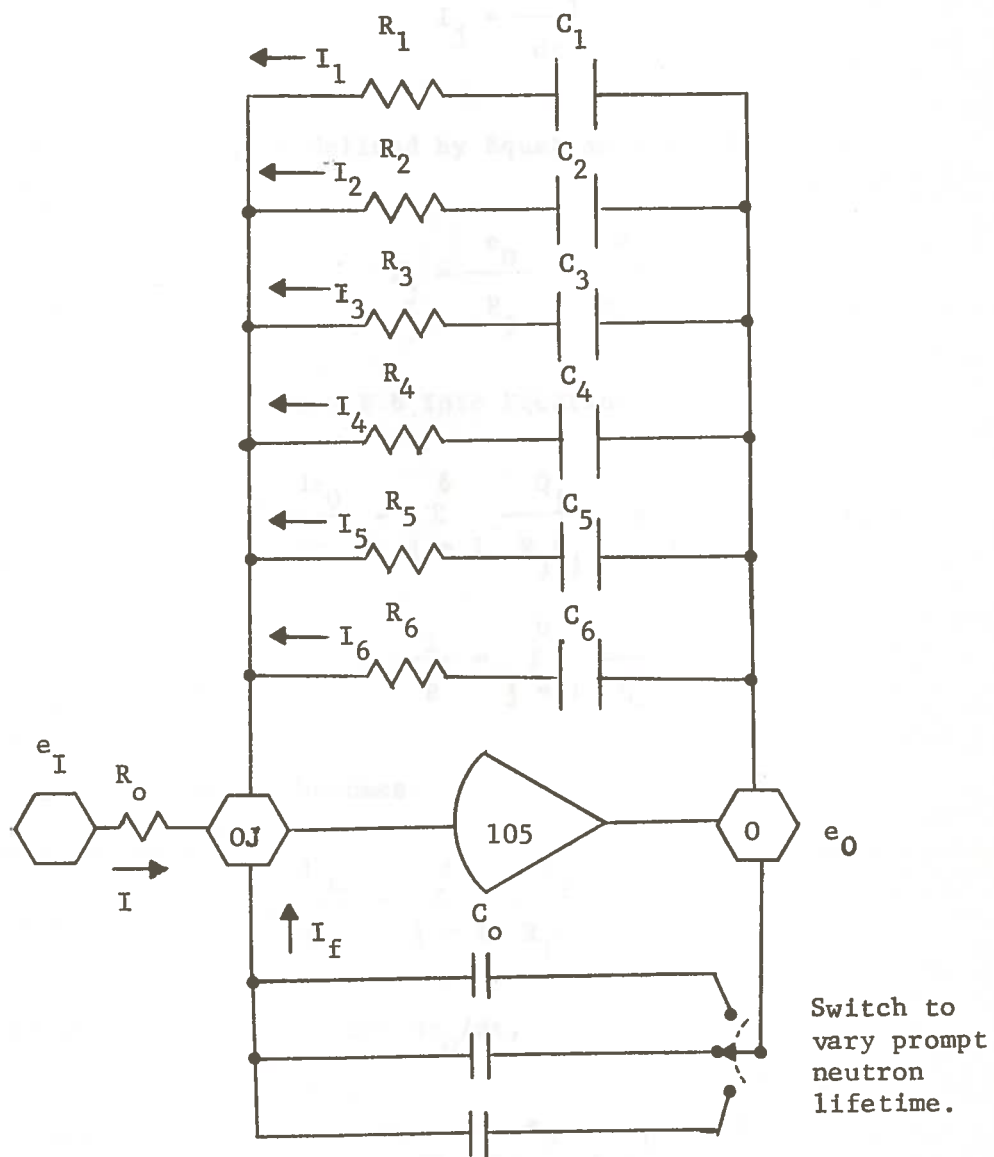


Figure B.1. Reactor Kinetics Simulation

Q_j , then with sign convention as shown above,

$$Q_j = C_j e_j, \quad (\text{B.3})$$

$$e_j + I_j R_j = e_0, \quad (\text{B.4})$$

and

$$I_j = \frac{dQ_j}{dt}. \quad (\text{B.5})$$

Substituting e_j as defined by Equation B.3 into Equation B.4 and solving for I_j ,

$$I_j = \frac{e_0}{R_j} - \frac{Q_j}{R_j C_j}. \quad (\text{B.6})$$

Substituting Equation B.6 into Equation B.2:

$$\frac{e_I}{R_0} + C_0 \frac{de_0}{dt} - \sum_{j=1}^6 \frac{Q_j}{R_j C_j} + \sum_{j=1}^6 \frac{1}{R_j} e_0 = 0. \quad (\text{B.7})$$

Letting

$$\frac{1}{R} = \sum_{j=1}^6 \frac{1}{R_j}. \quad (\text{B.8})$$

then Equation B.7 becomes:

$$\frac{e_I}{R_0} + C_0 \frac{de_0}{dt} - \sum_{j=1}^6 \frac{Q_j}{R_j C_j} + \frac{1}{R} e_0 = 0. \quad (\text{B.9})$$

Solving Equation B.9 for de_0/dt ,

$$\frac{de_0}{dt} = -\frac{e_I}{R_0 C_0} - \frac{e_0}{R C_0} + \frac{1}{C_0} \sum_{j=1}^6 \frac{Q_j}{R_j C_j}. \quad (\text{B.10})$$

Substituting equation B.5 for I_j into Equation B.6 and dividing equation B.6 by C_o , then

$$\frac{dQ_j}{C_o dt} + \frac{Q_j}{R_j C_j C_o} = \frac{e_o}{R_j C_o} \quad (\text{B.11})$$

Comparing Equations B.10 and B.11 with the reactor kinetics equations as shown below:

$$\frac{dn}{dt} = \frac{n\delta K}{\ell} - \frac{nK\beta}{\ell} + \sum_{i=1}^6 \lambda_i C_i, \quad (\text{B.12})$$

and

$$\frac{dC_i}{dt} = \frac{n\beta_i}{\ell} - \lambda_i C_i, \quad (\text{B.13})$$

where: $i = 1, 2, 3, 4, 5, 6$.

If one allows $-e_j$ to be proportional to $n\delta K$ and e_o to be proportional to n the equations will have the same form. The values of R_j , C_j , R_o , and C_o can be calculated in terms of the known constants λ_i , β_i , β , ℓ and the scale factors chosen for n , C_i , and δK .²⁷

The scaled equations are as follows:

$$\frac{d[10n^*]}{dt} = \frac{[10n^* 2000\delta K]}{2000\ell} - \frac{[10n^*]\beta}{\ell} + \sum_{i=1}^6 \lambda_i [10C_i^*],$$

and

$$\frac{d[10C_i^*]}{dt} = \frac{[10n^*]\beta_i}{\ell} - \lambda_i [10C_i^*].$$

Letting

$$-[n^* 2000\delta K] = e_1,$$

$$[10n^*] = e_o,$$

and

$$[10C_i^*] = Q_j/C_o \quad i, j = 1 \dots 6;$$

the corresponding coefficients are

$$2000\ell/10 = R_o C_o \quad (\text{B.14})$$

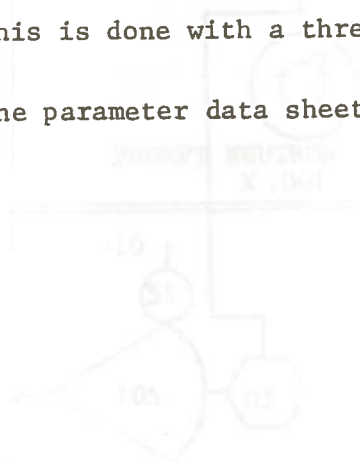
$$\beta/\ell = 1/RC_0 \quad (\text{B.15})$$

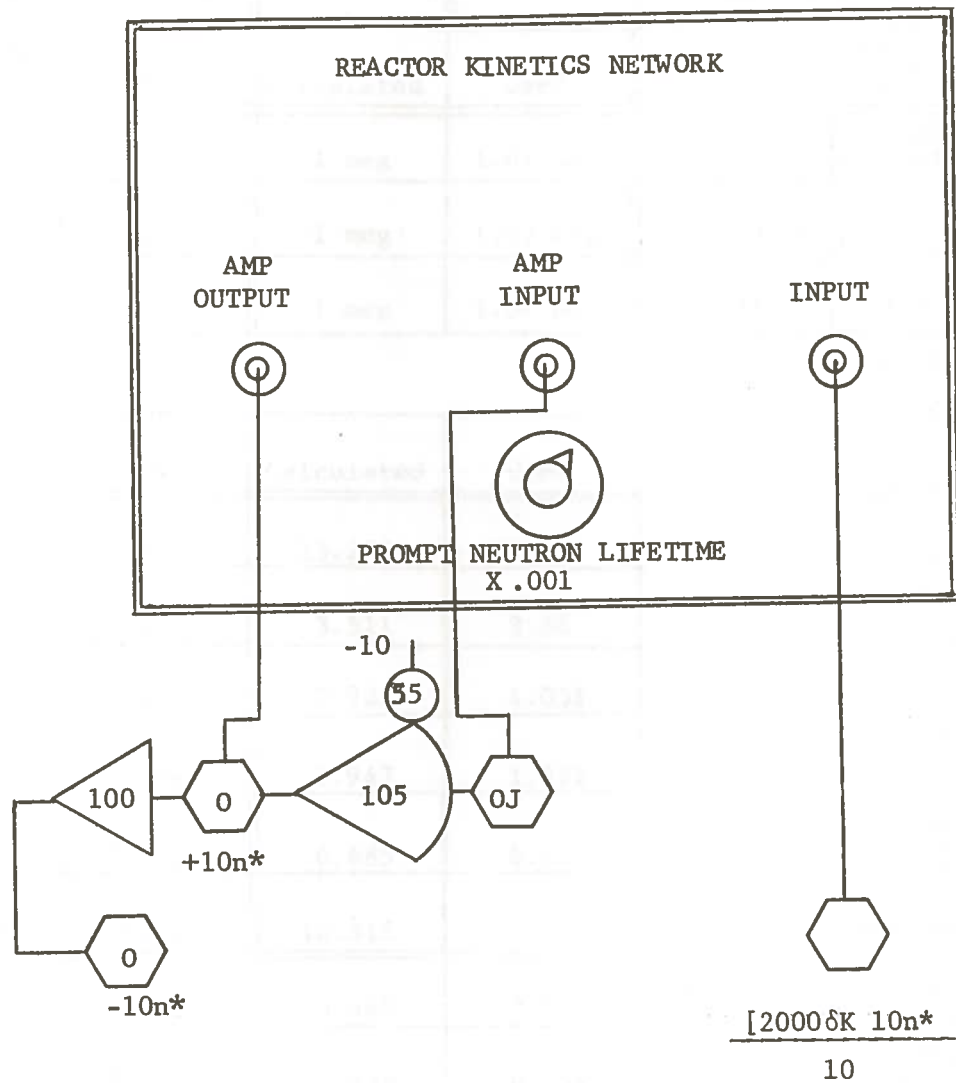
$$\lambda_i = 1/R_i C_i \quad (\text{B.16})$$

$$\beta_i/\ell = 1/R_i C_0 \quad (\text{B.17})$$

From Equations B.14, B.16, and B.17, the basic relationship between the physical reactor coefficients and the capacitor and resistor values is found. The proper components to use in the reactor kinetics network are determined if R_0 is allowed to be one megohm.

A feature which allows the observation of three distinct prompt neutron lifetimes of 10^{-3} , 10^{-4} , and 10^{-5} seconds is incorporated in the circuit design by noting that the value of ℓ can be adjusted by varying C_0 . This is done with a three position switch with C_0 values shown on the parameter data sheet.





Potentiometer 55 = .5

Amplifier 105 requires a pin in the "C" input, and a bottle plug from "fF" to "O".

Figure B.2. Reactor Kinetics (Six Group RC Network)

Physical Wiring Diagram

Table B.1.

Resistor and Capacitor Values for R.K.N. ^{235}U Fuel

ℓ	R_o		C_o	
	Calculated	Used	Calculated	Used
10^{-3}	1 meg	1.07 meg	.2 micro	.187 micro
10^{-4}	1 meg	1.07 meg	.02 micro	.0189 micro
10^{-5}	1 meg	1.07 meg	.002 micro	.00197 micro

R & C	Calculated	Used
R_1 meg	23.256	24.95
R_2 meg	3.511	3.56
R_3 meg	3.925	4.031
R_4 meg	1.947	1.972
R_5 meg	6.685	6.72
R_6 meg	18.315	18.7
C_1 micro	3.468	3.45
C_2 micro	9.338	9.428
C_3 micro	2.295	2.264
C_4 micro	1.706	1.694
C_5 micro	.1312	.1298
C_6 micro	.01814	.01811

Table B.2.

Reactor Kinetics Network Precision Analysis (^{235}U)

Delayed Neutron Parameters	Circuit Board Value	True Value	% Error	
λ_1	.0116	.0124	6.5%	
λ_2	.0298	.0305	2.3%	
λ_3	.1096	.111	1.26%	
λ_4	.2994	.301	0.5%	
λ_5	1.146	1.14	0.53%	
λ_6	2.95	3.01	1.99%	
β_1/ℓ	2.12	2.15	1.4%	$\ell = 10^{-4}$
β_2/ℓ	14.86	14.24	4.35%	
β_3/ℓ	13.13	12.74	3.1%	
β_4/ℓ	26.8	25.68	4.36%	
β_5/ℓ	7.87	7.48	5.2%	
β_6/ℓ	2.829	2.73	3.6%	
β_1/ℓ	.214	.215	.4%	$\ell = 10^{-3}$
β_2/ℓ	1.502	1.424	5.5%	
β_3/ℓ	1.326	1.274	4.1%	
β_4/ℓ	2.712	2.568	5.6%	
β_5/ℓ	.796	.748	6.4%	
β_6/ℓ	.286	.273	4.8%	
β_1/ℓ	20.34	21.5	5.4%	$\ell = 10^{-5}$
β_2/ℓ	142.6	142.4	.1%	
β_3/ℓ	125.9	127.4	1.1%	
β_4/ℓ	257.4	256.8	.23%	
β_5/ℓ	75.5	74.8	.9%	
β_6/ℓ	27.14	27.3	.58%	

$\frac{2000\ell}{10}$	Circuit Board Value	True Value	% Error
$\ell = 10^{-3}$	2.0009	2.000	0.04%
$\ell = 10^{-4}$.2022	.2000	1.1%
$\ell = 10^{-5}$.02107	.0200	5.35%

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Time scaling is indicated for this problem by the large time constants of the system, i.e. $1/\lambda_X = 13$ hrs. and $1/\lambda_I = 10$ hrs. Since these values would result in extremely long diagnostic studies involving xenon buildup, the time scale factor of $1/7200$ is chosen to allow two hours of reactor operation to be studied in one second on the computer.

Letting $\tau = \beta t$, and
 $\beta = 1/7200$,

then Equation C.3 can be written as

$$\begin{aligned} d[10P]/d\tau = & (\sigma_X \gamma_X 10 \Phi \Sigma_f / \Sigma_{af} \beta 10)(10) - (\sigma_X \Phi / 10\beta)[10P](10) \\ & + (10\lambda_I / 3\beta)[3I'] - (\lambda_X / \beta)[10P]. \end{aligned} \quad (C.4)$$

I' Concentration:

$$dI'/dt = \Phi \gamma_I \sigma_X \Sigma_f / \Sigma_{af} - \lambda_I I'. \quad (C.5)$$

Multiplying by the scale factor of three,

$$d[3I']/dt = \Phi \gamma_I \sigma_X 3 \Sigma_f / \Sigma_{af} - \lambda_I [3I']. \quad (C.6)$$

Time scaling the above equation and letting ten volts equal 10^{15} neutron/cm²-sec., the following equation is obtained:

$$d[3I']/d\tau = (\Phi \gamma_I \sigma_X 3 \Sigma_f / \Sigma_{af} \beta 10)(10) - (\lambda_I / \beta)[3I']. \quad (C.7)$$

APPENDIX C

SCALED EQUATIONS FOR XENON POISONING*

Letting the maximum flux level equal 5×10^{14} neutrons/cm²-sec., a maximum value of negative reactivity due to xenon buildup after shut down will approximate .54 for U-235 as the fuel. Along the same lines, the maximum iodine concentration will occur when the reactor operating time approaches infinity. From this consideration it can be calculated that the maximum I' value is 2.87.

From the above information concerning the maximum values for P and I' one obtains the analog scale factors of ten and three respectively.

The reduction of the describing equations in xenon poisoning to the scaled voltage equations used on the computer is shown below.

Xenon Reactivity:

$$dP/dt = [\sigma_X \gamma_X \Sigma_f / \Sigma_{af} - P \sigma_X] \Phi + \lambda_I I' - \lambda_X P. \quad (C.1)$$

Multiplying by the scale factor of ten,

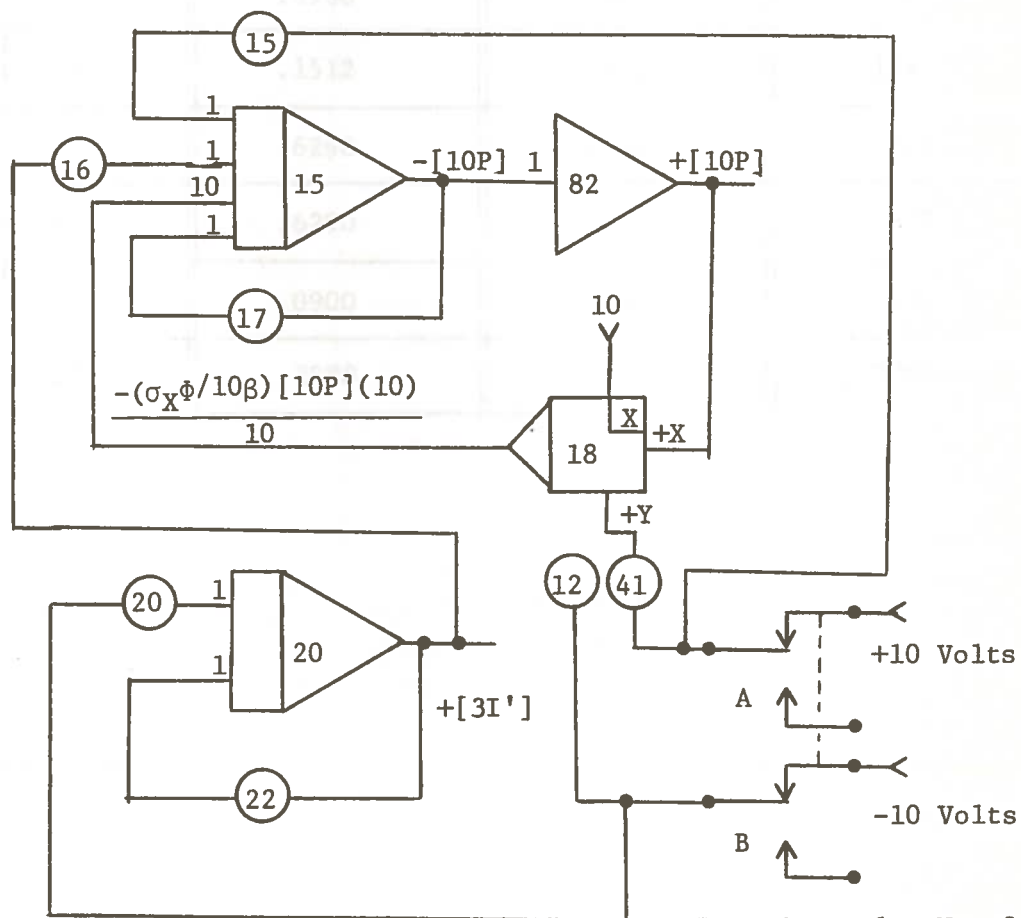
$$d[10P]/dt = [\sigma_X \gamma_X 10 \Sigma_f / \Sigma_{af} - [10P] \sigma_X] \Phi + \lambda_I 10 [3I'] / 3 - \lambda_X [10P]. \quad (C.2)$$

Letting ten volts equal 10^{15} neutrons/cm²-sec., the following equation is obtained:

$$d[10P]/dt = (\sigma_X \gamma_X 10 \Phi \Sigma_f / 10 \Sigma_{af}) (10) - (\sigma_X \Phi / 10) [10P] (10) + (\lambda_I 10 / 3) [3I'] - (\lambda_X) [10P]. \quad (C.3)$$

* The definition of the symbols used is found in Chapter Six.

Xenon Poisoning Analog Diagram:*



Pot 15 = $(\sigma_X \gamma_X \Phi \Sigma_f / \Sigma_{af} \beta)$

Pot 16 = $(10\lambda_I / 3\beta)$

Pot 17 = (λ_X / β)

Pot 12 = $(\sigma_X \Phi / 10\beta)$

Pot 22 = (λ_I / β)

Pot 20 = $(3\gamma_I \sigma_X \Phi \Sigma_f / \Sigma_{af} \beta 10)$

Pot 41 = $(\Phi \sigma_X / \beta 10)$

Function Relay No. 9

Normally Closed

Contacts

* The above analog diagram is representative of Equations C.4 and C.7

Table C.1. Pot Settings for Various Flux Levels.

Pot No.	$\Phi = 2.5 \times 10^{14}$	$\Phi = 1.0 \times 10^{14}$	$\Phi = 2.5 \times 10^{13}$
15	.0160	.0064	.0016
16	.6960	.6960	.6960
17	.1512	.1512	.1512
12	.6290	.2520	.0629
41	.6290	.2520	.0629
20	.0900	.0360	.0090
22	.2088	.2088	.2088

Table C.2. Xenon Static Check

Pot Or Amplifier	Measured Volts	Calculated Volts	Note * $\Phi = 2.5 \times 10^{14}$	
Pot 15	+ .160	+ .1600	+10 Volts IC Amp 15 -10 Volts IC Amp 20	
Pot 16	+ 6.959	+ 6.960	↑	
Pot 17	- 1.509	- 1.512		
Pot 12	- 6.367	- 6.290		
Pot 41	+ 6.438	+ 6.290		
Pot 20	- .896	- .900		
Pot 22	+ 2.087	+ 2.088		
Amp 15	- 9.990	-10.00		
Amp 82	+ 9.990	+10.00		
Amp 20	+ 9.990	+10.00		↓

APPENDIX D

DIGITAL PROGRAM USED ON HYBRID COMPUTER

In this appendix is found a listing of the program that is used in the control of the reactor-power-systems operation. The program is used in a number of ways. It is written to set the servo-set potentiometers automatically, and to position the function relays in the desired mode for start up of the simulator. It also places the simulator in several desired modes, thus eliminating the operational procedure necessary to obtain these modes manually.

Along with the above, the program is written to adjust the primary coolant flow rate. Several sense lines are used in conjunction with the program to accomplish this task. Pushbuttons numbered zero through five establish the mode of the sense lines one through six, respectively. If a pushbutton is made high, the corresponding sense line is also high. The mode of each sense line is checked in the digital program to establish the conditions of primary coolant flow rate within the simulator. The program has a number of comment listing to aid in understanding its use.

Glossary Of Subroutines Used

The hybrid linkage routines provide the FORTRAN programmer with general purpose subroutines which allow communication with the analog computer.

If an error is detected during execution of the routine, the following message is printed by the teletype and control is returned to the mainline program.

The various subroutines are listed below:

<u>PURPOSE</u>	<u>ROUTINE</u>
Select Analog Mode	SAMO ('M')
Set Analog Time Constant	STCO ('T')
Select Logic Mode	SLMO ('M')
Set Potentiometer	SPOT (I,C)
Test and Read Sense Line	TRSL (I)
Set Function Relay Plus	SSRP (I)
Set Function Relay Minus	SSRM (I)
Select, Convert, & Read ADC	CRAC (I,U)
Load & Transfer Dam	LTDA (I,C)

<u>FORTRAN NAME</u>	<u>PURPOSE AND COMMENTS</u>
<u>SAMO ('MODE')</u>	Set the analog mode on the 680 analog. MODE specifies: 'PC' = Pot Coefficient 'PP' = Patch Panel 'ST' = Static Test 'OP' = Operate 'HD' = Hold 'IC' = Initial Conditions 'SP' = Set Pot
<u>STCO ('TIME')</u>	Set the analog time constant on the 680 analog. TIME specifies: 'NS' = Normal-SEC 'FS' = Fast-SEC 'NM' = Normal-Millisecond 'FM' = Fast-Millisecond
<u>SLMO ('MODE')</u>	Set the logic mode on the 680 analog. MODE specifies: 'R' = Run 'S' = Stop 'C' = Clear
<u>SPOT (IPOT, COEFF)</u>	Set potentiometer (servo) <u>IPOT</u> specifies the integer patchboard address of the potentiometer to be set.

COEFF specifies the floating point value
(positive) of the desired pot coefficient.
Maximum value = 0.9999 analog machine
units.

NOTE: The pot setting tolerance = ± 0.0005
machine units.

TRSL (ISENSE) Test the specified sense line and return status
to the FORTRAN program. (The sense line is
reset if high when tested.)

SSRP (IRELAY) Set the specified function relay to the (+)
state.

IRELAY specifies the integer patchboard address
of the function relay to be set minus.

CRAC (ICHAN, UNITS) Initiate a conversion on the specified ADC
channel and return the converted value to
the calling program.

ICHAN specifies the ADC channel (0-23) to be
converted.

UNITS is the floating point value (in machine
units) of ICHAN. Maximum range = ± 0.9999
analog machine units.

LTDA (ICHAN, COEFF) Load and transfer the specified DAM with a
coefficient.

ICHAN specifies the DAM channel (0-11) to be
loaded and transferred.

COEFF specifies the floating point value
(in machine units) to be loaded into ICHAN
and transferred.

JOB

FORTRANH GO,LS

LOGICAL SS,TRSL

```
C *****
C *****
C DIGITAL PROGRAM TO BE USED WITH THE REACTOR SIMULATOR
C *****
C DIGITAL CONTROL ROUTINE TO REGULATE THE COOLANT FLOW AND TO
C SET THE ANALOG POTS AND MODE.
C *****
C *****
C THIS SECTION ESTABLISHES THE MODE OF THE ANALOG COMPUTER
C *****
C CALL STCO('NS')
C CALL SSRP(034)
C CALL SSRP(094)
C CALL SSRP(009)
C CALL SSRM(004)
C CALL SSRM(064)
C *****
C THIS SECTION SETS THE SERVO SET POTENTIOMETERS
C *****
9 CONTINUE
READ(5,10) IPOT,COEFF
10 FORMAT(6X,I4,F10.5)
IF(COEFF.LT.0.0) GO TO 11
CALL SPOT(IPOT,COEFF)
GO TO 9
11 CONTINUE
CALL SLMO('R')
CALL SAMO('PC')
C *****
C THIS SECTION ESTABLISHES THE CONDITION TO RUN HYBRID
C *****
20 CONTINUE
```

```

SS=TRSL(1)
IF(.NOT.TRSL(1)) GO TO 104
C *****
C THIS SECTION CHECKS IF THE FLOW SHOULD BE 125 PERCENT FULL
C *****
SS=TRSL(3)
IF(TRSL(3).AND.TRSL(2)) GO TO 2000
C *****
C THIS SECTION CHECKS IF THE FLOW SHOULD BE 75 PERCENT FULL
C *****
SS=TRSL(4)
IF(TRSL(4).AND.TRSL(2)) GO TO 3000
C *****
C THIS SECTION CHECKS IF THE FLOW SHOULD BE 50 PERCENT FULL
C *****
SS=TRSL(5)
IF(TRSL(5).AND.TRSL(2)) GO TO 4000
C *****
C THIS SECTION CHECKS IF THE FLOW SHOULD BE 00 PERCENT FULL
C *****
SS=TRSL(6)
IF(TRSL(6).AND.TRSL(2)) GO TO 5000
C *****
C THIS SECTION CHECKS IF THE FLOW SHOULD BE 100 PERCENT FULL
C *****
SS=TRSL(2)
IF(TRSL(2)) GO TO 1000
GO TO 20
C *****
C THIS SECTION RELEASES THE DIGITAL COMPUTER
C *****
104 CALL SAMD('PC')
CALL RELECE
1000 CONTINUE
DO 1001 I=1,11
CALL CRAC(I,X)

```

```
      X=X
      CALL LTDA(I,X)
1001  CONTINUE
      GO TO 20
2000  CONTINUE
      DO 2001 I=1,11
      CALL CRAC(I,X)
      X=1.25*X
      CALL LTDA(I,X)
2001  CONTINUE
      GO TO 20
3000  CONTINUE
      DO 3001 I=1,11
      CALL CRAC(I,X)
      X=.75*X
      CALL LTDA(I,X)
3001  CONTINUE
      GO TO 20
4000  CONTINUE
      DO 4001 I=1,11
      CALL CRAC(I,X)
      X=.5*X
      CALL LTDA(I,X)
4001  CONTINUE
      GO TO 20
5000  CONTINUE
      DO 5001 I=1,11
      CALL CRAC(I,X)
      X=0.0
      CALL LTDA(I,X)
5001  CONTINUE
      GO TO 20
      STOP
      END
OLOAD (GO),(UDCB,2),(LIB,USER,SYSTEM),(FORE,1600)
OASSIGN (F05,SI)
```


0ASSIGN (F06.LO)
ROV

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C *****
C THIS SECTION CONTAINS THE DATA TO SET THE POTS
C THE FIRST COLUMN REPRESENTS THE POT COEFFICIENT
C THE SECOND COLUMN REPRESENTS THE POT SETTING
C *****

0	.0766
1	.5000
2	.0650
5	.5000
6	.500
7	.6500
10	.9500
11	.766
21	.0400
25	.0117
27	.5000
30	.100
31	.4000
32	.1000
33	.5000
35	.5000
36	.2500
37	.5000
40	.9999
42	.2000
45	.4000
46	.5000
47	.5000
50	.5000
51	.6000
52	.4000
55	.5000
57	.0117
60	.0050
62	.0200
63	.0200

66	•5000
70	•2000
71	•8000
72	•2000
75	•6000
77	•4000
80	•2000
82	•2500
87	•2500
90	•2500
91	•2000
92	•2500
95	•2500
96	•2500
97	•1500
100	•5000
67	•2000
102	•5000
105	•8000
107	•3500
110	•2500
115	•1500

C

C

C

THIS SECTION REPRESENTS THE DATA FOR XENON POISONING

C

15	•0064
16	•6960
17	•1512
12	•2520
41	•2520
20	•0360
22	•2088

C

-1.0

FIN

VITA

The author was born on December 8, 1947 in Morgan City, Louisiana. He graduated from Morgan City High School in June, 1966. Upon graduation from high school, he enrolled in Louisiana State University to undertake a study in electrical engineering.

During his undergraduate studies, he was awarded a Louisiana Electric Utilities Research Scholarship. The author received his Bachelor of Science Degree in Electrical Engineering in January 1971. Along with the acceptance of this degree, the author received a Commission in the United States Army as a Distinguished Military Graduate.

Subsequent to his Bachelor of Science Degree, the author undertook a program of study leading to a Master of Science Degree in Nuclear Engineering. During his graduate studies, the author was offered a research and teaching assistantship with the Nuclear Science Center. During the summer of 1972, he was awarded a Louisiana State University Graduate Fellowship. At the present time, he is a candidate for the Master of Science Degree in Nuclear Engineering. Mr. Stansbury is a member of Phi Kappa Phi, Tau Beta Phi and Eta Kappa Nu.