CONCEPT AND DEMONSTRATION: A RECONFIGURABLE CONTROL SYSTEM FOR NUCLEAR POWER PLANTS

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Concept and Demonstration: A Reconfigurable Control System for Nuclear Power Plants

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Submitted to the Department of Nuclear Engineering on May 2, 1986 in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Nuclear Engineering

ABSTRACT

A closed-loop, digital reconfigurable control system based on fault tolerant systems technology is developed and experimentally demonstrated. Although the concept is implemented with specific emphasis on nuclear power plant systems, the general concept is applicable to other process applications as well.

There are two potential elements in reconfigurable control. These are the restructuring of the actuation schemes and the reformulation of the control strategies used in the system control. The focus of this work is on the latter element under non-emergency conditions.

A reconfigurable control strategy is devised in order to accommodate a wide range of plant operating conditions which include changes in the demand, plant dynamics, component status and alignment as well as anticipated failures in the sensors and plant components. The concept has been developed under the assumption that the hardware and software related to the controller are fault tolerant and that a Failure Detection and Isolation system is operational for components and sensors whose status or measurements are needed by the controller. The reconfigurable controller consists of a bank of diverse and complementary control laws and a reconfiguration scheme to select the control strategy for a given plant condition. It incorporates model-based and heuristic-based control schemes. The reconfiguration scheme is a multi-stage logic based on direct mapping between the identified plant operating condition and the control law and on-line performance evaluation of the previously implemented control actions. A decision and supervisory module is also incorporated to insure a safe operation of the controller.

The control concept was demonstrated on-line on the MIT Reactor. Computer simulation studies were conducted to test the software prior to on-line evaluation. The control strategy successfully reconfigured and controlled the MIT Reactor power during transients and steady state conditions within the specified requirements.

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CHAPTER 1. INTRODUCTION

The goal of this research is to develop and experimentally evaluate a generalized conceptual framework for a digital, closed-loop, reconfigurable control system based on fault tolerant systems technology. There are two potential elements in reconfigurable control. These are the restructuring of the actuation schemes and the reformulation of control laws or strategies used in the system control. The focus of the work is on the latter element.

The control concept is specifically demonstrated to nuclear power plants. A reconfigurable controller is designed to be operational during non-emergency conditions. The associated hardware and software architecture is not addressed. The purpose of this controller is to assist the plant operators in supervising the plant in order to improve its safety, availability, reliability, and performance. The concept is applicable to the overall plant control; though it is specifically applied here at the component and subsystem level.

In this chapter, an overview of the current research and advanced development work in the area of nuclear reactor instrumentation and control are presented. The need for better control systems and the issues in control system design are discussed. Finally, the scope and contribution of the research as well as the organization of this document are presented.

1.1 Overview: The Need for Improvement

In recent years, the nuclear power industry has been faced with greater demand to further improve its safety [Kemeny, 1979], [US NRC, 1980]. With escalating operating and capital cost, it is desirable to keep the plant on-line as much as posssible without compromising plant safety. There are various ways to meet these demands such as training, improved instrumentation and control, testing, inspection, and maintenace procedures, and management. To achieve this goal, this research addresses the area of improved plant control.

As an example of present day operator control requirements, consider the control of a typical feedwater system under non-emergency conditions - the feedwater system is only one of the many subsystems in a nuclear plant. In the event of failures, the operators need to diagnose the problem and proceed with the proper sets of actions in order to prevent a costly plant trip and the subsequent actuation of the plant safety system. Failures in this particular system can be classified into sensor, controller, actuator, and other component failures. These events must be manually handled by the operators to prevent a trip [Hammer et al., 1985]. In the case of a sensor input failure, the operator has to manually switch to the alternate sensor channel, while in the case of a controller failure, the auto/manual control switch has to be changed from automatic to manual and control is transferred to the operators. The same procedure is also followed when the controller is no longer in its range of applicability. In the case of actuator or other component failure, the backup one, if it is available, is activated; otherwise, the plant may have to be shutdown.

Plant control involves the orchestration of plant monitoring, diagnostics, and control decision making. Improvement in the area of plant control can drastically reduce the burden imposed on the operators and, thus, enhance their effectiveness in supervising, rather than directly controlling the plant. The systems needed to automate the task of data processing, monitoring, diagnosing, and control action decision making have to be reliable and valid over a wide range of operating conditions. A good interface between these systems and the operating crew is important. In addition, it is also important that these systems be able to tolerate failures and still continue to perform their functions. Improvement in the control area can be translated into the reduction of the significant number of plant trips that are attributed to spurious signals and improper operator control actions [Mueller et al., 1985], [Singh, 1985], [Nuclear News, July 1985]. However, the improvement must be approached cautiously. Careful considerations must be taken in integrating any automatic system in the plant. The issues of complexity, compatibility, and the need for a higher level of training have to be addressed.

The advancement in digital technology in the last few years has offered enormous promise for meeting the demand for better safety, reliability, and availability. Although the present analog systems satisfy their original specifications, they do not have many of the advantages and capabilities provided by the digital systems to meet the new needs [Baur, 1983], [Bozenhardt and Dybeck, 1985], [Chakroborty, 1985], [Divakaruni, 1985]. Digital systems offer the potential for greater flexibility, maintainability, compactness, realibility, and better user interface [Dennis, 1985], [Keiper et al., 1985], [Nauful et al., 1985].

To date, digital computers are primarily used for data acquisition and plant monitoring applications only [Divakaruni, 1985]. Because of the continuous evolution in digital technology and its potential role in meeting safety requirements and enhancing plant availability and reliability, there has been a growing interest in its application to plant instrumentation and control. This growing interest is evident from some of the recent meetings and symposiums [U.S. Nuclear Regulatory Commission, November 1984], [EPRI-Seminar, February 1985], [EPRI-Seminar, April 1985], [American Nuclear Society, September 1985]. As examples, recent trends and studies have been reported regarding the utilization of highly reliable computers [Lala, 1985], [Chisholm, 1985], software based diagnostic and surveillance systems [Ray et al.,1983A], [Good et al., 1981], and improved plant control system by implementing digital controllers [Divakaruni, 1985]. Several comprehensive surveys of the work on these areas are also presented in [Frogner et al., 1978], [Tylee et al., 1983], [Ebert, 1982].

1.2 Background and Motivation

1.2.1 The Need for Better Control Systems

As mentioned in the previous section, there has been a growing interest in improving the plant control system. In addition, the continuous evolution in digital technology has offered great promise in meeting these conditions.

In nuclear plant systems, the plant operation can be divided into two basic classes of control regimes. The first control regime involves the non-emergency control of specific plant variables. The control systems in this regime are primarily used to maintain the plant within well defined operating limits during normal operation. They are not relied upon to perform any safety functions during or following potential accidents, and they operate under the envelope of the plant safety systems at all times. In the U.S., this type of operation relies heavily on operators, and therefore in the past, any control improvement could be basically attributed to better operator training and operator interface systems. With increasing plant complexity, the operators face a tremendous control burden and therefore the presence of an improved control system is desirable in alleviating some of the control tasks imposed on the operators. Furthermore, there are concerns regarding the safety implications of these non-safety grade control systems (NRC's Unresolved Safety Issue, A-47) [Bruske et al., 1985], [Bickford et al., 1985].

In the second class of control regimes, the plant is automatically shutdown and the necessary emergency systems are automatically turned on if a safety limit has been violated. The emergency systems are designed to operate unattended over a relatively short period of time. The operators take over later or if these systems are not actuated automatically. This research will focus on the problems related to the first class of control regime. Hereafter, the word control system refers to the <u>non-emergency</u> control system.

Analog systems are widely used in today's power plants. However, the use of digital systems to automatically control the plant during non-emergency conditions is receiving increasing attention as a means of improving plant safety, reliability, availability, performance, and operating cost [Arlotto, 1984], [Divakaruni, 1985], [Kawakami et al., 1985], [Singh, 1985]. It appears, however, that there is still a long way to go before such new control schemes gain acceptance in the power industry [Smoak, 1976], [EPRI Seminar, April 1985, Panel Discussion]. Such schemes must provide better alternatives than current methods with which the industry has gained sufficient familiarity and experience. Analog control systems meet their original specifications or even the current safety requirements but they do not have the flexibilities offered by digital systems in meeting the ever increasing demand for better reliability and availability [Mehra et al., 1980]. Furthermore, analog systems use very primitive control algorithms that handle a limited range of operating conditions.

Current automatic control systems are normally used during steady state control operations and therefore they can only handle a limited range of plant conditions. The different control schemes that have been recently proposed have had varying degrees of success. In general, knowledge of the dynamic characteristics of the system and information about the process and measurement noise is often assummed. But during off normal conditions or in the presence of failures in the plant components, sensors, and actuators, the design assumptions used in the control scheme may no longer be valid. Furthermore, in typical power plant environment, the underlying process is highly non-linear and time varying. The structure of the governing plant model is expected to vary under different operating conditions. Then there is the problem of accommodating failures in the controller components, processing system, and other hardware systems.

In order to realize a control system that can enhance plant safety, availability, reliability, and performance, it is desirable that it has the ability to tolerate failure so that challenges to the safety systems and plant trips can be minimized. It is also desirable that the control system accommodates a wide range of operating conditions in order to alleviate some of the control tasks imposed on the operators. Such qualities are lacking in today's power plant control systems.

Various techniques based on digital technology have been reported for nuclear power plant applications to alleviate many of these problems. A common approach is to implement the control algorithm in several independent processing channels [Chakraborty et al., 1985], [Kawakami et al., 1985]. A voting circuit is used to eliminate the signal from the anomalous channels. The sensor inputs are also validated before they are used in the processing channels. This approach only addresses failures in the processing channel, associated hardware, and sensors. It does not account for the possible changes in the assummed plant model. Another approach is to design several control stategies to accommodate for the different operating conditions while using a similar aforementioned processing architecture. For example, in the feedwater level control, a "single element control" algorithm (proportional) is used for low power operation while a "three element controller" is used for high power operation [Mueller et al., 1985]. The presence of the operators is needed to switch over to the appropriate control strategy. A more elaborate control strategy has also been reported to accommodate for the broader operating conditions associated with the feedwater system [Broadwater, 1983]. For this application, a perfect knowledge of the plant operating condition is assummed. The issues of unmodeled failure conditions, failure identification uncertainties, and off-normal operations are not addressed.

1.2.2 Control System Design Issues

The control system design features that have been presented in the previous section have addressed various aspects of the problems. However, they failed to acknowledge an integrated view of the design issues in order to achieve a control system with high reliability, availability, and improved safety and performance. In this section, the issues in control system design based on digital technology are addressed.

The control system is designed to control a plant or process. It consists of sensors, controllers, actuators, and the reference input signal. It is important that the control system be able to tolerate a specified number of failures of its components so that challenges in the safety systems and plant trips are minimized. Furthermore, the controller has to be able to accommodate a wide range of operating conditions which include changes in the plant demand, plant dynamics, and component status and alignment as well as failures in the plant components, actuators, and sensors.

The design issues in a highly reliable and available control system based on digital technology has four parts. The first part involves the validation of information that is used in the controller. Information validation prevents control system failure as a result of erroneous and spurious input signals to the controller. Such information includes component status and alignment as well as measurements and estimates of plant process variables. The second part is the design of a hardware architecture to prevent a failure of the control system as a result of failures in the processing channel used in the controller, actuator mechanisms, and other hardware interface components. The third part, which is the one that is often overlooked, is the avoidance of control system failures that can be attributed to software failure. As a controller strategy becomes more sophisticated, software faults can be an important factor in determining the reliability of the control system. Software faults can be due to failures to acknowledge the software limitations for various plant conditions, incomplete requirement statements, or design changes. The last part involves the capability of the control strategy used in the controller to accommodate different types of plant operating conditions. The realization of this last control system design issue is very much dependent on the first three.

The control system has to account for plant operating conditions which include anticipated changes in demand, plant dynamics, component status and alignment, and failure conditions. It should be noted that a failure in the sensors, actuators, and other plant components which incorporate redundancy in their architecture is treated as a "normal" condition in the point of view of the controller. Failure to implement an appropriate control algorithm for a given plant condition can compromise the plant safety. This situation arises due to misidentification of the actual plant condition because of uncertainties or little knowledge of the plant model. It can be also due to failure to anticipate the range of operating conditions. Therefore, the controller strategy has to possess a certain level of "intelligence" to acknowledge and anticipate the various operating conditions based on all the available plant information.

The incorporation of fault tolerant techniques can alleviate many of the problems associated with the first three design issues. In general, **fault tolerance** is the inherent capability of a system to automatically adapt itself to failures of its elements in order to continuously maintain a specified level of operational integrity [Schabowsky et al., 1985]. While fault tolerance is related to reliability, the two concepts are not the same. High reliability does not imply fault tolerance. One way of using fault tolerance to improve the system or component reliability is by employing redundancy techniques.

A carefully designed fault tolerant system, in general, can offer a significant increase in system reliability and safety which can be translated to greater availability and reduced operating cost [Laduzinsky, 1985]. Because of the control system's implication in the plant safety and reliability, the incorporation of fault tolerance in its design is very important. In the other extreme, indiscriminate use of fault tolerant design may not be cost effective and it may result to increase cost and complexity which can lead to decrease availability and maintainability [Crew et al., 1985]. It is therefore very important to evaluate the system in order to determine the area in which a fault tolerant design can offer significant benefits.

1.2.3 Problem Statement

The research described in this report is focused on the problem regarding the fourth design issue in the control system design - the capability of the controller to accommodate various operating conditions. These conditions include anticipated changes in plant dynamics, demand, component status and alignment as well as anticipated failure conditions. The problems regarding the first three design issues which are information validation, hardware failures, or software failures are not included in the scope of this work.

There are several ways to address the problem regarding the capability of the controller to accommodate various plant operating conditions. In power plant applications, single control laws are not generally operable over a wide range of operating conditions as discussed earlier. If such a robust control law exists, the performance penalties during normal operation are expected to be excessive.

The approach that will be taken in this research is based on the concept of control law reconfiguration. There are two potential elements in reconfigurable control. In the first element, the control system is reconfigured by restructuring the actuating system (i.e., the physical device) as a result of failure. In the second element, on the other hand, the control system is reconfigured by reformulating the strategies or algorithms used in the system control as a result of changes in the plant operating conditions. A different actuating device may be used as a result of the control law reformulation. The focus of this work is on the latter element.

In reconfigurable control, the control strategy is derived from a bank of diverse and complementary control laws. A reconfiguration scheme governs the switching from one control law to another as a result of a change in the plant operating condition. It is used to select the most "appropriate" control law for the given condition. The controller that implements this control concept is referred to as a reconfigurable controller. It will be assumed that a Failure Detection and Isolation (FDI) System is operational for actuators, plant components, and sensors whose status or measurements are needed by the control algorithm. The problem is that given a set of "perfect" FDI information, devise a scheme to reconfigure the control strategies in the event of 1) anticipated changes in plant operating conditions (i.e., changes in plant dynamics, component status and alignment, and demand) and 2) failures in the sensors, plant components, and actuators that have been detected but cannot be isolated. The design involves the development of a bank of control laws for all the anticipated conditions along with a reconfiguration logic. Furthermore, the design is based on the incorporation of fault tolerant systems technology.

Several generalized reconfiguration schemes have been proposed for systems where the plant condition is "perfectly" known [Birdwell, 1978], [Chizeck, 1982], [Gross, 1984], [Looze, et al., 1985], [Ostroff et al., 1984], [Vandervelde, 1984]. Most of these schemes are based on the assumption that the system is linear. The use of rule-base system along with statistical hypothesis testing has been reported to identify the system's operating condition and to reconfigure the control scheme [Handelman, 1984]. For nuclear plant applications, a deterministic mapping between the plant operating condition and the control law has been reported [Broadwater, 1983]. In power plant environments, uncertainties exist in determining the actual plant operating condition, and therefore the assumption that the plant condition is perfectly known is not valid. Furthermore, the plant model under some conditions is not accurately known. Also, the use of statistical approaches in the reconfiguration may be difficult to implement since the necessary distribution functions are not well known. Failure to acknowledge these problems can result in unnecessary switch over from one control to another or implementation of a wrong control action.

Although, given that this research will focus on the problem regarding the capability of the controller to accommodate various operating conditions, the design issues regarding information validation, hardware failures, or software failures are also important. The objective of the following discussion is to review some of the work that had been reported on these other three problem areas.

In terms of information validation, self test, limit check, consistency test, sequential test, and probability ratio test are some of the general techniques that can be used [Willsky, 1976]. Several works have been reported on this area for nuclear power plant applications [Ray and Desai, 1984], [Deutsch et al., 1984], [Tylee et al., 1983]. With regard to protection against hardware failures, a common practice is to design a multiply redundant system. For processing systems, a dual, triple, and quadruple redundant architectures have been suggested [Lala, 1985]. The processors are operated in tight synchronism, use congruent inputs, and perform identical operations on the inputs by excuting identical software. A bit-for-bit test and voting procedure are used to detect and isolate failures. Regarding software fault tolerance, the two commonly reported approaches [Hecht, 1985] are N-version programming [Avizienis and Chen, 1977] and recovery blocks [Randell, 1975]. In N-version programming, several independently coded versions of a given program are run in parallel. A consistency test on the outputs is used and a majority answer is chosen as the result. In recovery blocks, an architecture which consists of three independent sections is used. The first part is the primary routine which normally performs a given task. The second part is an acceptance test which checks the results of the primary routine. The third part is an alternate routine which is used to execute the task in a totally independent manner if the acceptance test detects that the result obtained from the primary routine is incorrect. Total independence is achieved in a variety of ways such as changing the order of mathematical operations or deriving a result from several independent physical inputs.

1.3 Objective

The specific objective of this research is to develop and evaluate a methodology to reconfigure various control laws for a digital controller in nuclear power plants. This controller is design to be operational during non-emergency conditions as opposed to emergency conditions where the plant protection system takes over. The control concept is limited to the component and subsystem level (e.g., feedwater control system, reactor power control system) although it may be extended to the overall plant control. The main purpose of this controller is to assist the plant operators. The expansion of the automatic control regime will greatly relieve the operator of the burden of being a major part of the control loop and therefore enhance their role in the plant supervision. The other purpose of this controller is to interface with other operator assistance systems (i.e. plant monitor, diagnostics, and display system) in order to enhance the plant safety, reliability, and availability.

As mentioned earlier, there are four issues to address in order to design a highly reliable and available control system based on digital technology, namely: the validation of information used in the controller, controller and actuator hardware failure, controller software failure, and the capability of the control strategy to accommodate various operating conditions. This research only concentrates on the last problem area. However, an architecture will be suggested on how to integrate all four issues in the design. In this research, an FDI system for sensors, plant components, processor hardware and software, and actuators is assumed operational.

A control strategy that can accommodate a wide range of plant operating conditions plays an important role in the control system availability and reliability. A systematic approach is needed to accomplish this task in power plant environment where commonly made assumptions, as discussed above, may not be valid. The reconfiguration scheme has to be based on a decision algorithm that does not depend on restricted assumptions. For this research, the control laws are assumed available and little emphasis will be dedicated to their detailed design procedures. However, several control methodologies are presented in the Appendix A.

As part of the on going work at the C. S. Draper Laboratory and the MIT Nuclear Reactor Laboratory, the feasibility of the proposed reconfiguration scheme has been investigated via computer simulations and on-line implementation on the 5 megawatt (MW) MIT Reactor. The proposed scheme has been demonstrated to control the reactor power over the range of 20 to 100 %.

1.4 Contributions

The main accomplishment of this research is the conceptual development of a generalized framework for a digital reconfigurable controller based on fault tolerant systems technology. It involves the organization of the available plant information, the definition and the identification of the plant operating conditions, the selection of the "appropriate" control law for the given operating condition, and the verification of the control choice through on-line performance evaluation. The design framework also allows the specification of which components and measurements require a Failure Detection and Isolation System.

The other major accomplishment is the experimental evaluation of the methodology on the MIT Reactor in controlling the reactor power.

In the course of the experimentation, minor modifications and improvements have been made in some of the control algorithms that had already been proven on the MIT reactor. Furthermore, simulation and experimental studies on reactivity estimation, using reactivity balance and inverse kinetics models for control purposes, have also been conducted. These issues are discussed in Appendices C and D respectively.

1.5 Organization of Report

In Chapter 2, the conceptual design of the reconfigurable controller is presented. The functional description and the design guidelines are discussed. The implementation of the design concept on the MIT Reactor (MITR) is presented in Chapter 3. The results of the simulation and on-line evaluation of the reconfigurable controller on the MITR are given in Chapter 4. The research is summarized in Chapter 5. Conclusions and recommendations are presented in Chapter 6. Discussions of related topics and additional details for the research are presented in various appendices.

CHAPTER 2. CONCEPTUAL DESIGN OF THE RECONFIGURABLE CONTROLLER

In this chapter, a conceptual design of a reconfigurable controller is presented. The design incorporates the capability of the controller to accommodate various plant operating conditions through on-line reconfiguration of the control strategy. It involves the identification of plant operating condition and the selection of the "most" appropriate control action for that condition. The reconfiguration logic and the rationale used in the controller design are discussed.

It is assumed that a Failure Detection and Isolation (FDI) System is operational for sensors and other plant components whose status and measurements are needed by the control algorithms. As discussed later, the proposed framework provides a guideline for specifying the requirements for the minimum scope of such a fault tolerant FDI system. The hardware and software systems used in the controller are assumed to be designed in fault tolerant fashion. Thus, failures in such systems are not considered.

2.1 Motivation for the Conceptual Design

The dynamics of nuclear power plants and other process plants are highly complex, nonlinear, and time varying. The governing process models are expected to change during the course of operation, and therefore the plant dynamics are often difficult to model analytically. Some plant variables are also not measurable or, worse yet, not observable [Kwakernaak and Sivan, 1972] under certain conditions. Furthermore, the available measuring devices exhibit nonlinear characteristics. Even if perfect measurements of the plant process variables and component status were available, a complete body of knowledge about the plant operating condition is not guaranteed because of the uncertainty in the plant model. The control of the plant becomes more complicated in the event of sensor or component failures. The plant operators are trained to respond under these various conditions. The automation of the plant control would require an integration of the various tasks that the operators perform in operating the plant.

A controller has to be stable at all times. It is also desirable that it be robust without greatly compromising its performance. In the event of failures, degraded performance may be tolerated to prevent challenges of the safety system.

The control methodologies presented in Appendix A are ideal for certain control applications. Each one, however, suffers certain limitations. For example, the underlying assumptions used in the design may be true only under limited number of operating conditions. One approach to the solution of this problem is to try to develop a control strategy that can accommodate any plant conditions without the need for reconfiguration. Such a solution may or may not exist. If it exists, the performance penalties during normal operation are expected to be excessive.

The following sections discuss the formulation of the problem and the presentation of the conceptual design.

2.2 Formulation of the Problem

The problem of selecting the appropriate control action for a given condition can be stated as follows: given a set of plant information including measurements and FDI information

$$z = \{ z_1, z_2, \ldots\ldots\ldots, z_{nz} \}$$

define a set of plant operating conditions

$$\Phi = \{ \phi_1, \phi_2, \ldots\ldots\ldots, \phi_{nc} \}$$

then map a set of control laws or control procedures

$$u = \{ u_1, u_2, \ldots\ldots\ldots, u_{nu} \}$$

onto a set of plant operating condition.

The major assumption is that the set of information used to define operating conditions is valid, reliable, and sufficiently inclusive to be able to distinguish between operating conditions.

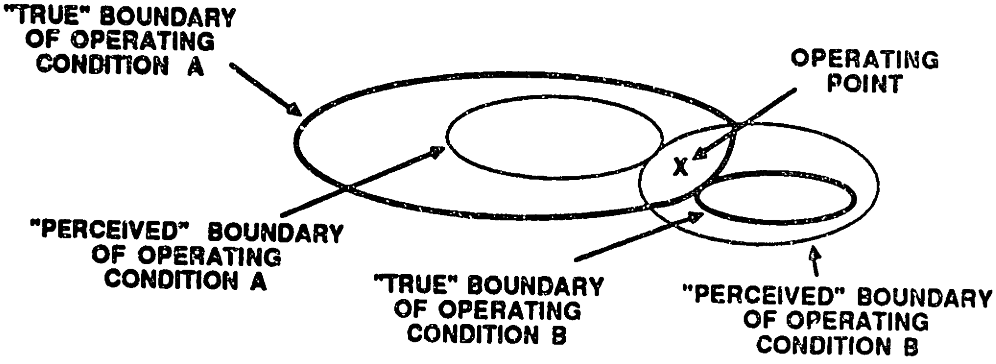
The set of plant information, z, is defined as the <u>information vector</u>. It consists of measured as well as, if required, estimated information, plant demand signals, and component status and alignment. Uncertainty may exist regarding this set of information because of noise, disturbances, and modeling errors despite the assumption of information validity. Further, it is assumed that the plant model and the statistics associated with the plant information are not accurately known.

The set of control laws consists of model-based algorithms as well as heuristic-based control procedures or a combination of both. Heuristic-based procedures are formulated based on rules of thumb, plant operating guidelines, procedures, or operators' recommendations.

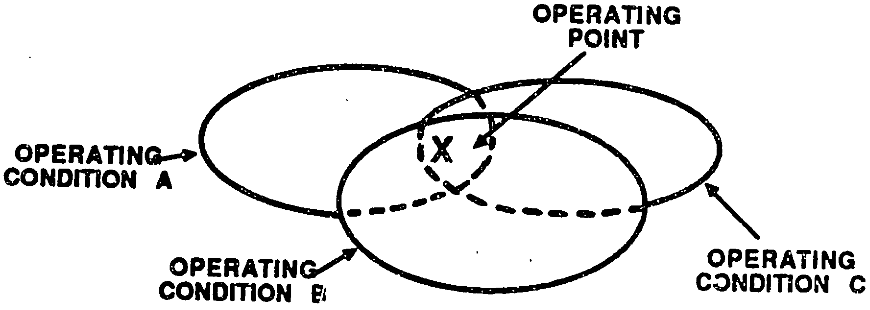
There are several problems that are associated with the formulated problem. First, the definition of the set of plant operating conditions, based on the information vector, poses a practical decision problem. An exhaustive enumeration of the different possible combinations of the available plant information will result in the combinatorial expansion in the number of plant operating conditions and control actions.

Another problem associated with the definition of plant operating conditions is that the set of operating conditions may not be complete. An unaccounted for condition, ϕ_m where $m > n_c$, may actually exist. Failure to acknowledge such condition may lead to undesirable consequences. A safety measure should be invoked if a ϕ_m condition occurs.

The uncertainties that exist in the information vector and plant model can affect the definition of some of the plant operating condi-



UNCERTAINTIES IN THE PLANT OPERATING CONDITIONS



OVERLAP BETWEEN PLANT OPERATING CONDITIONS

Figure 1. Uncertainties and Overlap Between Plant Operating Conditions

tions. The boundaries and models associated with these conditions may not be well defined and therefore the control laws or actions mapped onto these conditions may not perform satisfactorily. "Overlap" between various plant conditions may also exist and this can result in unnecessary switch over from one type of action to another. A representation of the uncertainties and overlap between operating conditions is depicted in Figure 1.

2.3 Functional Description of the Reconfigurable Controller

A general schematic diagram of the control system is shown in Figure 2. It consists of sensors, actuators, an FDI system, display system, and the reconfigurable controller. The sensors provide measurements related to the process, plant components, and actuators. The FDI system generates reliable information needed by the controller. This architecture exhibits the separability between the control logic, the FDI system, and person-machine interface system. The control strategy used in the controller is derived from a bank of control algorithms for the various operating conditions and a reconfiguration logic as shown in Figure 3. The task of the reconfiguration logic is to use the available information about the plant state variables, component status and alignment, and plant demands in order to determine the "most appropriate" control law for the given situation.

The reconfiguration logic is based on a multi-stage logic. Its objective is to select the "most" appropriate control law for the given situation without compromising the controller stability and therefore the plant safety. It incorporates a higher level of "intelligence" in order to orchestrate the various tasks that the operators perform while operating the plant under various conditions. Such tasks involve the organization of the plant information and the identification and classification of the plant operating condition. The correct execution of these tasks depends upon the knowledge of the plant characteristics and dynamics, plant operating guidelines, technical specifications (Tech Specs), and the limitations of the sensing, actuating, and control devices. The reconfiguration logic incorporates model-based controller designs as well as heuristic-based concepts. In perspective, the reconfiguration logic consists of a plant operating condition identifier, performance evaluator, and a decision and supervisory logic.

A block diagram of the overall control system which shows the components of the reconfiguration logic is presented in Figure 4. The opera-

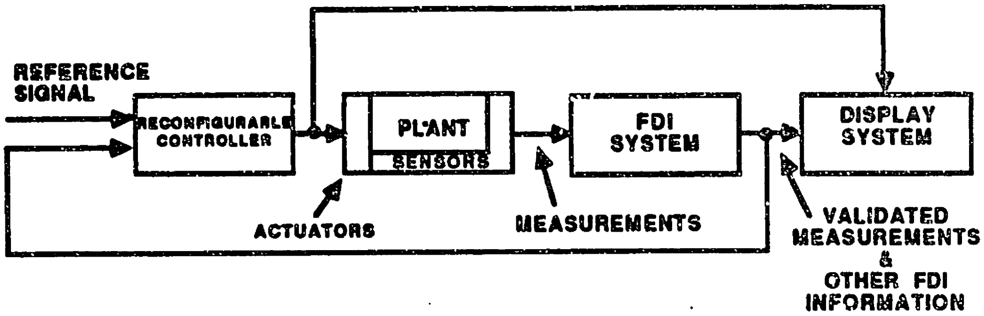


Figure 2. General Schematic Diagram of the Control System

tion of the components of the reconfiguration logic can be briefly described as follows:

1. The plant operating condition identifier maps the available information onto a set of plant operating conditions which are defined a priori. A set of control laws is then mapped onto the set of plant operating conditions. The control selection is based on the identification of the plant operating condition.
2. The performance evaluator (PE) then verifies whether or not the selection made based on the identified plant operating condition satisfies the desired performance criterion for the given condition. An adaptation scheme which is driven by the results of the PE is used to re-adapt the control selection if the previously implemented control option fails to satisfy the performance criterion. The alternative control options for a given plant operating condition are chosen a priori.
3. The decision and supervisory logic (DSL) supervises and overrides the recommendations made in the first two stages of the reconfiguration logic, if the need arises. It interfaces with a knowledge base which supplies the necessary procedures in order to insure a safe operation of the controller. The DSL serves as the last resort for the controller. It should be noted, however,

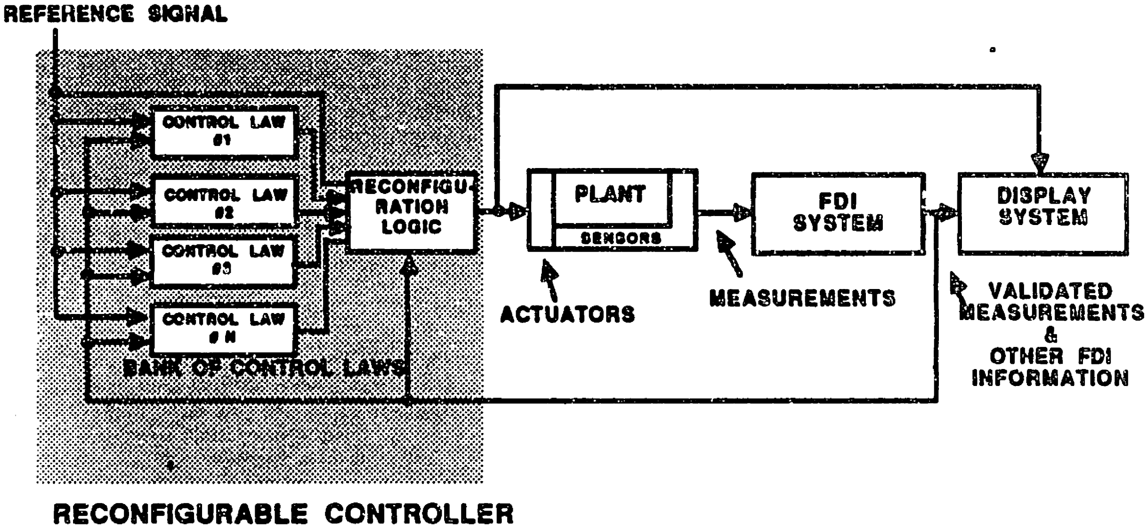


Figure 3. Block Diagram of a Reconfigurable Controller

that the proposed reconfigurable controller operates under the discretion of the human operators and the plant safety systems.

The details and philosophies behind each of the components of the reconfiguration logic are discussed in the next sections.

2.4 Reconfiguration Logic

The reconfiguration logic consists of three components: the plant operating condition identifier, performance evaluator, and decision and supervisory logic. A description of each component is presented below.

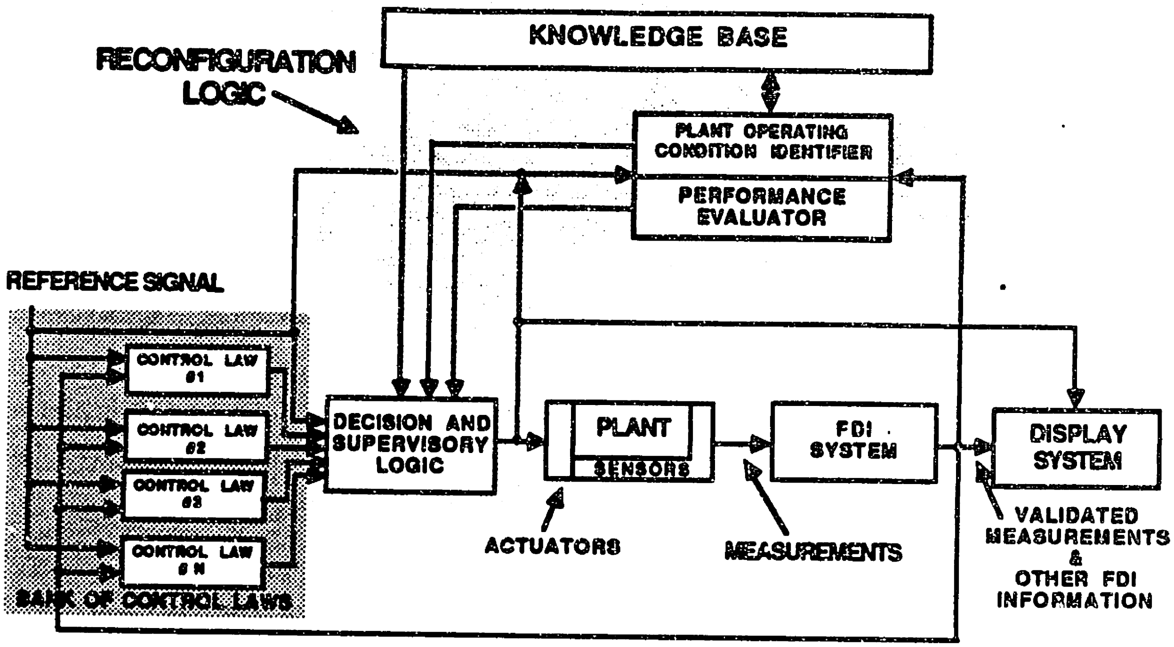


Figure 4. Block Diagram of the Reconfiguration Logic

2.4.1 Plant Operating Condition Identifier

The function of this component is to identify the plant operating condition (POC) by examining all available information about the plant. To facilitate the identification procedure, a framework is presented within which the available information is organized. By knowing the specific POC, one can then map it to a control law or a set of procedures that specifically applies to this condition. This component represents the first level of the multi-stage reconfiguration logic. Its functions and design procedure are discussed below. In this section, two main issues are addressed - the definition and the identification of the POC's.

The available plant information is described by an information vector $z = \{ z_1, z_2, \ldots\ldots, z_{nc} \}$. The elements of this vector consist of measured as well as estimates of plant process variables (e.g., temperature, pressure, power), component status and alignment (e.g., pump on or off, available or failed, valve open or closed), and demand signals (e.g., raise or lower power, shutdown). As mentioned earlier, the elements of the information vector are assumed reliable and valid. Uncertainties may exist in the elements of the information vector because of noise, disturbances, or modeling errors.

A decision tree is used to organize the elements of the information vector. The branches of the decision tree are obtained by mapping the information vector onto a set of POC's. An end branch of the decision tree represents a specific POC in which a control law is mapped onto it as shown in Figure 5.

The information vector contains a large number of elements. In reality, a large number of POC's can be generated if one uses exhaustive enumeration of the various possible combinations of plant component status and alignment plant demand, and measurements as well as estimates of process variables. This procedure will produce a very large tree which will require a large number of control laws. Plant operators are trained to respond to these conditions. To automate this procedure would require a machine with very large computing capability in order to model the control selection task. Therefore, a scheme to prevent this expansion has to be devised. The discussion presented below addresses this issue.

There are two issues to consider in developing the decision tree namely: the definition of the POC's that will be included in the design and the search procedure involved in identifying the POC.

There are two ways to define the set of POC's. A specific POC can be defined by a top-down or bottom-up approach. In a top-down approach,

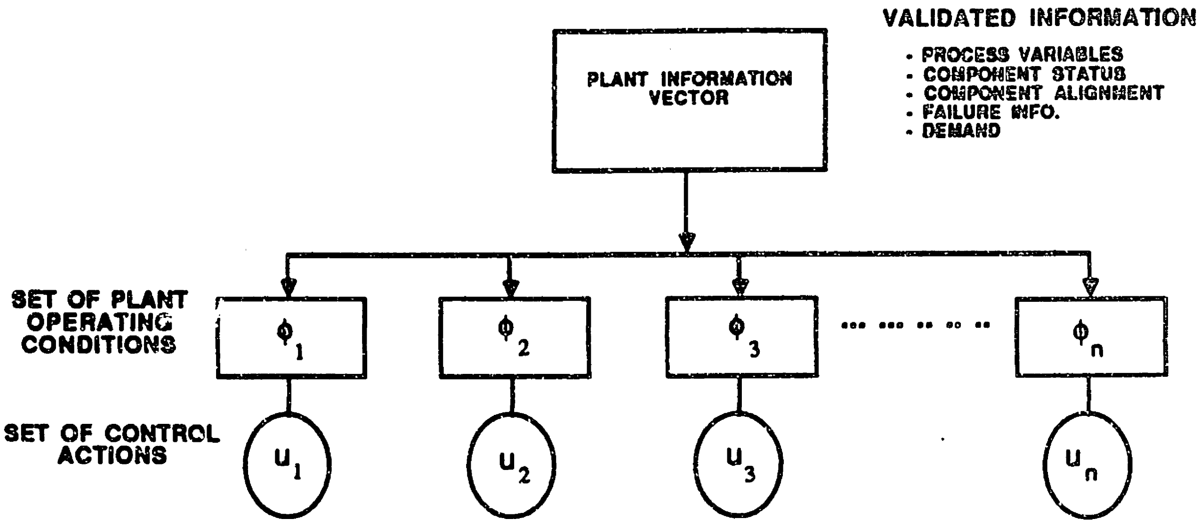


Figure 5. The Decision Tree Concept

the specific features are grouped together to define a POC whereas in the bottom-up approach, a specific POC is first defined and its features are enumerated. The plant information vector defines the features of a given POC.

Regardless of which approach is used to define the set of POC's, the amount of information has to be reduced in order to make the identification problem and the development of the decision tree more manageable. Two types of procedures are suggested. The first one involves the partitioning of the information and the second involves the aggregation of the information into a reduced set of features. The information vector can be divided into continuous (measurements or estimates of pressure, temperature, and power, for example) and discrete information (such as status and alignment). The partitioning of the information only applies to the continuous information. This is accomplished by discretizing the operating range associated with the continuous information into various discrete ranges such as low, middle, or high. The discretization process can be approached by using a deterministic or statistical procedures or by using fuzzy logic [Zadeh, 1984]. The rationale for partitioning the information is that neighboring points within a given discrete range should behave similarly and, therefore, requires similar control choices.

The aggregation procedure can be applied to discrete information. The information is grouped together to form a higher level of information. One way of doing this is to aggregate various information so that the system's functional description remains equivalent despite the grouping. For example, consider a "component" which consists of a pipe and two valves in series. The function of this component is to provide a flow path. In order for it to perform its function, both valves have to be open given that there is no break in the pipe. The information regarding the position of the valves can be grouped together so that a set of higher level of information can be generated to indicate whether or not the component is an available flow path. By aggregating the discrete information in the functional sense, the number of possible POC can be reduced systematically.

Based on either the top-down or bottom-up definition of the POC's, a hierarchial scheme is used in the decision tree to further organize the features of the POC's into various levels of categories in order to enhance the identification of the POC. It is the task of the controller designer to specify the set of features and conditions which best describe each level of categories. Some of these features may be very general and easy to identify while others may be too specific, and therefore cannot easily be identified. The goal of the hierarchial scheme is to separate the general from the specific features. The hierarchy is arranged so that the top levels are represented by very broad and general features of the POC's, while the lower levels are represented by more specific ones. Therefore, the top level category of POC provides a coarse characterization of the POC while the low level category provides more detailed characterization. With this hierarchial framework, the identification involves a top-down search of the associated features which define a specific POC. The rationale for organizing the information in a hierarchial structure is that "general" features can be more easily identified than "specific" features. Thus, once a specific condition is identified, then the control law is directly identified.

The techniques discussed above are incorporated in the design of the POC Identifier module in order to systematically classify the plant information vector into various categories. For power plant applications, four levels of categories are introduced: plant operating mode, plant operating configuration, plant operating state, and plant operating substate. Therefore, a specific POC is determined by identifying the mode, configuration, state, and substate that the plant is in. A generalized decision tree diagram of the different level of categories of POC is shown in Figure 6.

Plant operating mode is used to define the top category of POC. It is described by a very generalized set of features that is common to all the conditions that belong to this category. The plant operating power, presented in discrete range (e.g., high, low, etc.), and power demand are perhaps the two most distinguishing features of the plant operating mode. Some examples of plant operating modes, based on the above definition, may be called startup, shutdown, and power operation.

The second level in the hierarchy is the plant operating configuration. It is defined by the status and alignment of various components. A judicious aggregation of this type of information, based on the function of the components under consideration, is necessary in preventing a combinatorial expansion in the number of possible plant operating configurations.

The third level is the plant operating state. It is defined by the errors associated with the magnitude and rate of change of the variable or variables that are being controlled relative to their desired demand setpoints. The plant operating state is classified as either steady

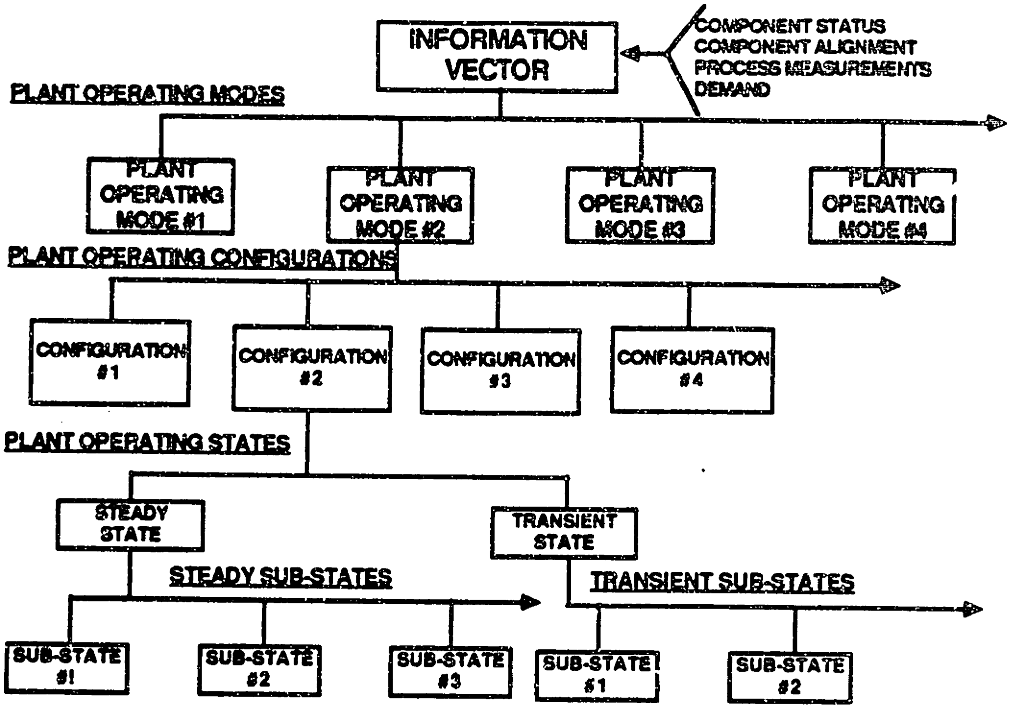


Figure 6. Hierarchy of Plant Operating Conditions

state or transient state. The criterion for "true" steady state is not easy to define. For this application, the plant operating state is said to be in steady state if the following generalized conditions are satisfied:

$$|f(x - x_{set})| \leq f^* \quad \text{and}$$

$$|g(\dot{x})| \leq g^*$$

where x	represents the variable or variables that is being controlled,
x_{set}	is the desired set point for x
$\dot{x}$	represents the rate of change of x
f, g	are functions which represent the error function and the rate of change of x respectively
f^*, g^*	are the desired values of f and g respectively.

In general, the criterion can be cast into the form:

$$|| W_f f(x - x_{set}) + W_g g(\dot{x}) || \le \epsilon$$

where W_f and W_g are weighting functions and ϵ is a threshold. The selection of the weighting functions and ϵ is left to the designer's judgement. Based on this generalized criterion, the concept of steady and transient plant operating states is presented in Figure 7.

The fourth level is the substate category. Substates are defined by the information related to plant process variables which are associated with the variable or variables that are being controlled. Such information may include magnitude, rate of change, validity, or past history of these variables. The features of the substate categories are more subjective and less defined than the plant operating state category to which they are attached. Therefore, boundaries between substates are much more obscure and the problem of POC overlap and uncertainties may be more predominant at this level of the decision tree.

Once the decision tree has been developed, the next step is to map each of its end branches onto a specific control law in a direct or one-to-one fashion. The rationale for choosing a deterministic mapping is based on the assumption of the existence of an FDI system that provides a "perfect" information about the plant. Furthermore, deterministic mapping also provides a good and simple representation of how human operators respond to a given set of conditions. The recommendation presented by the decision tree provides a quick and one pass first stage decision.

There are several issues that need further clarification regarding the definition and identification framework. First of all, given that there are n_c specific POC's and n_u available control laws or procedures, the mapping, however, does not necessarily imply that the number of POC's, is equal to the number of control laws. A given control law may apply to various branches of the decision tree. Thus, it also does not necessarily mean that a change in the POC as identified in the decision tree will result in a change or jump in the control. For example, given that the POC is described by the same configuration, state, and substate, a control law can be designed so that it applies in between two

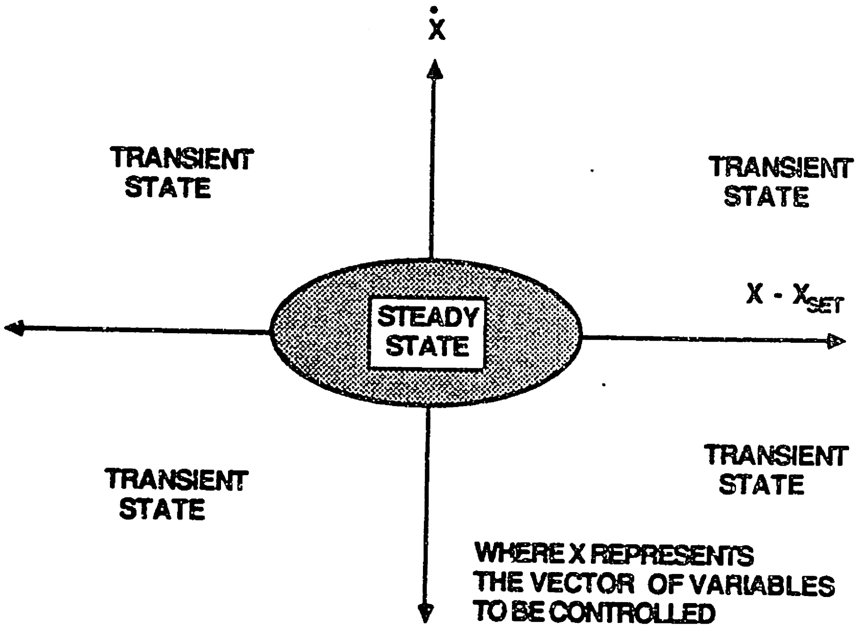


Figure 7. Definition of Plant Operating States

"adjacent" modes. Under this condition, there could be a change in the plant operating mode but the same control law still applies.

Furthermore, based on the decision tree architecture presented above, it does not necessarily mean that n_c is equal to the number of substates. The decision tree may be truncated at any level without the need to go down to the lowest level of category (i.e., the substate level) if the same control law or procedure applies to all the categories of POC's below this given level. Therefore, the n_c conditions can be defined either in the substate, state, configuration, or even in the mode level in some cases.

In the presence of noise, disturbance, and other uncertainties, a measure has to be taken to prevent unnecessary transition from one condition to another or possible misidentification. Filtering of the appropriate signals may be necessary. A multiple consecutive occurence

(MCO) test may be also used to declare the occurence of a given condition. The mechanics of this test is similar to that of the sequential test reported in [Fisher et al., 1984]. Because of noise, a declaration of a condition based on a single test may be unacceptable. The MCO criterion requires that a given condition be satisfied for a specified consecutive number of time steps before such condition is declared. A counter is incremented if a given condition is satisfied and decremented if it is violated. The counter threshold is chosen as a trade off between time delay and false declaration.

This proposed design framework offers some flexibility. It can accommodate direct and deterministic schemes as well as statistical and fuzzy schemes. In a determistic approach, the use of boolean logic, table look-up, or deterministic pattern recongnition technique [Fu, 1968] can be used to identify the mode, configuration, state, and substate. More sophisticated statistical and hypothesis testing schemes can be used to determine the probability that the plant is operating in a given condition [Lancraft and Caglayan, 1982]. Fuzzy logic [Zadeh, 1984] can be also used to account for the "fuzzy" boundary in between adjacent modes, states, and substates.

The search process based on the decision tree provides a simple scheme to determine the "most appropriate" control law for the given POC. Furthermore, the decision tree design provides a guideline for specifying which components and measurements must minimally be covered by an FDI system. The major drawback of this procedure lies on its major assumption - by knowing the POC, the control law selection can be directly made. This assumption may not be true under certain circumstances. In the presence of uncertainties, plant modeling errors, overlap between POC's, and anomaly in the control law (e.g. improperly tuned), the control law which is assigned to a given POC a priori may not perform its function satisfactorily. For this reason, the performance of the selected control law has to be monitored on-line in order to make a change in the control law selection if the need arises. The scheme to accomplish this procedure is presented in the next section.

2.4.2 Performance Evaluator

The uncertainties in the information vector can lead to uncertainties in the identification of the POC. Because of these uncertainties, the control laws that are a priori mapped to the POC's may or may not work satisfactorily. As a next stage of the decision process, the performance evaluation (PE) module is introduced.

The performance evaluation (PE) module determines how well the selected control algorithm for a given POC is performing its function based on on-line measurement of the plant response. It serves as a consistency or rationality check in order to determine how the system response relates to the desired performance conditions. Appropriate actions are taken if such conditions are not satisfied.

The PE consists of a performance criterion (PC) for a given condition and a performance adaptive or "reinforcement" scheme, as discussed later, to modify the selection made by the decision tree if that control law fails to meet the desired performace criterion (PC). The choice is made from an alternative set of control laws that is assigned a priori. The use of performance adaptive or reinforcement scheme in selecting an appropriate control law is viable under the assumption that the process dynamics is slower than the decision and control cycle.

The role of the performance evaluator is different from that in conventional control systems, where the system is designed to meet certain performance specifications under "perfectly" known plant operating condition. Such performance specifications are not evaluated on-line. Therefore, if plant conditions are changed, then the expected performance conditions may not be satisfied. Furthermore, it should be noted that the control law designed for a given plant condition has been designed to meet certain performance specifications which are not necessarily the same as those used in the PE module.

The result of the PE is used to direct the control selection process. A probability is assigned to each alternative control option for a given POC. The probability distribution is initialized so that the control that is a priori chosen from the decision tree is set to one and the rest to zero. It is updated based on a performance adaptive or reinforcement scheme [Barto et al., 1981], [Fu, 1970], [Mendel and Fu, 1970], [Narendra et al., 1974], (also see Appendix B). The choice of the algorithm depends on the specific application. An example is presented in Chapter 3 for the MIT reactor power controller.

The idea behind the adaptation scheme is rather simple. The probability of using a control choice for the given POC is increased or decreased depending on whether or not the previously selected control action satisfied the desired PC. The selection for the next time step is made according to the new set of probabilities and the process repeats itself. A maximum likelihood criterion is used. A probability weighted decision is not implemented because this approach may lead to instabilities. Furthermore, it will make the performance evaluation untractable because one cannot directly attribute the causality-effect relationship between the weighted control action and plant response.

The set of admissible control choices for a given POC is chosen a priori. It consists of control laws which are associated with the POC's that may overlap with the current condition. The admissible control choices may also include control laws that are designed for other operating conditions but may also work suboptimally in the POC under consideration.

The performance criterion can be formulated relative to a desired performance condition. Such criterion may be goal or constraint oriented. Often, the overall performance specifications cannot be formulated or evaluated precisely. The quality of the control law can, however, be monitored over short intervals of time. The performance specifications can be formulated over short time intervals so that they are related to the overall objective. The rationale for this formulation is that by satisfying the performance measure at each decision interval the overall goal can be eventually satisfied. Furthermore, such formulation is compatible with that of the performance adaptive or learning scheme. For power plant application, the plant performance based on power production, maneuverability, or efficiency may be sacrificed under certain plant conditions in order to insure plant safety.

Performance criterion used in the PE can be formulated in terms of magnitude and rate constraints on the important process variables, ξ,

$$J: \quad \xi_l < \xi(t) < \xi_u$$

$$\dot{\xi}_l < |\dot{\xi}(t)| < \dot{\xi}_u$$

where J is the performance criterion
ξ is the variable or variables of interest
ξ_l is the lower bound limit on ξ
ξ_u is the upper bound limit on ξ
$\dot{\xi}$ is the rate of change of ξ
$\dot{\xi}_l$ is the lower bound on the rate
$\dot{\xi}_u$ is the upper bound on the rate.

The upper and lower bounds presented above are primarily used in the performance evaluation and these are not equivalent to the alarm setpoints associated with ξ. In addition to these constraint conditions, a verification can be made to determine whether or not the process variable being controlled, $x(t)$, is moving towards its desired set point, x_{set},

$$|x(t) - x_{set}| < |x(t-1) - x_{set}|.$$

The criterion presented above can be used along with a set of heuristic rules. In general, the formulation of the performance criterion depends on the POC.

2.4.3 Decision and Supervisory Logic

The role of the decision and supervisory logic (DSL) is to orchestrate and supervise the operation of the plant operating condition (POC) identifier and the performance evaluator (PE) modules of the reconfiguration logic in order to insure a safe operation of the controller. It acts as a "safety jacket" for the controller [Astrom, 1985].

As discussed in the previous sections, the control selection process starts by identifying the POC and directly selecting the control law that is a priori mapped for this POC. This procedure is accomplished by using a decision tree. The control law that has been derived from the decision tree is then implemented and its performance is evaluated based on the plant response. If this control law satisfies the desired performance criterion for the given POC, then it is again implemented in the next time step. Otherwise, the search process is directed by a performance adaptive scheme to modify the control law selection. The adaptation scheme modifies the control choice by updating the probability distribution associated with the set of control laws for the given POC. The update procedure is based on the performance of the control option that has been previously implemented. A maximum likelihood criterion is used to select the best control action. If convergence to a desired control law is not achieved after a specified number of time intervals, then one of the tasks of the DSL is to take over and implement the most conservative control action. The DSL also overrides the decision made by the POC identifier or PE module in cases when the plant is approaching an unsafe condition or certain physical constraints, such as saturation of the actuators, are about to be violated.

The DSL interfaces with a knowledge base to generate the necessary actions. A knowledge base contains a general knowledge of the plant and the control problem at hand. It consists of general qualitative as well as quantitative information. The technical specification (Tech Specs) requirements, limits and constraints on various process variables, operating guidelines, operating rules of thumb, information about the POC (mode, configuraton, state, substates), and the limitations of each control law are some of the types of information that are included in the knowledge base. The POC identifier and the performance evaluator provide the input needed by the knowledge base.

Since there are numerous conditions in power applications that are quite difficult to quantify, the presence of the knowledge base as a part of the reconfiguration logic is very important in alleviating some of these problems. The rules or heuristics used in the knowledge base can drastically limit the search for the appropriate control action. These rules are domain specific. However, they do not guarantee optimal choices. A useful heuristic offers an action which is "good enough" to keep the plant operating in a safe condition. For example, the knowledge base can provide a contingency control action if a ϕ_m operating condition, where $m > n_c$, occurs. It is also used to override earlier decisions in cases when the plant is identified to be approaching an undesirable or unsafe condition. The knowledge base is, therefore, used as the last resort if a satisfactory selection cannot be obtained via the decision tree model and performance adaptive scheme.

There are several ways a knowledge base can be represented and organized [Winston, 1984]. The most common way to represent knowledge is derived from simple "if-then" statements or production rules. Such systems are called rule-based systems. The "if" part of the rule specifies the condition while the "then" part specifies the action. A rule is selected or "triggered" when all conditions in the if part are satisfied by the current situation. The rule is said to be "fired" when the actions are performed. In some cases, several rules may be satisfied simultaneously but it does not mean that they all "fire." A conflict resolution procedure is used to decide which rule actually gets fired. For power plant applications, the selection of the "most conservative" rule may be one of the ways to resolve the conflict.

For this design concept, the knowledge base is only updated manually. The implementation of the knowledge base is discussed in the later chapters.

2.5 Summary

This chapter presents the design of a controller that has a capability of accommodating various plant operating conditions. The design concept is based on the reconfiguration of diverse and complementary control laws or control procedures. The reconfiguration logic consists of a plant operating condition identifier, performance evaluator, and the knowledge base. This technique is implemented on the MIT reactor power control system as discussed in the next chapter.

CHAPTER 3. IMPLEMENTATION OF THE DESIGN CONCEPT ON THE MIT REACTOR

This chapter discusses the design guidelines for the MIT Reactor (MITR) reconfigurable power controller based on the concept discussed in Chapter 2. This research is part of an on-going effort between the C.S. Draper Laboratory (CSDL) and the MITR Laboratory to demonstrate the concept of an integrated fault tolerant control system on the MITR. The MITR is a research reactor with operating characteristics close to that of commercial power reactors. The experience gained from this system is important to extending this control concept to other plant subsystems and to other nuclear plants. A brief description of the MITR, its relevant instrumentation, the reactor power control system design, and other interfacing systems are presented. The controller is designed over the range of 20 to 100% power.

3.1 Overview of the Fault Tolerant Control Research on the MITR

The MITR is one of the few research reactors in the U.S. that is being used as a testing ground of the various fault tolerant control concepts for nuclear power plants [Bernard et al., 1984], [Bernard et al., 1985], [Lanning et al., 1985], [Ray et al., 1983A], [Ray et al., 1983B], [Ray and Desai, 1984], [Deutsch et al. 1982]. This research is part of an on-going effort between CSDL and MITR to experimentally evaluate an integrated fault tolerant control methodology on the MITR power control system.

The major objective of this on-line fault tolerant reactor power control system relative to the MITR [Bernard, 1984] are:

- The regulation of reactor power under both steady state and transient conditions. The transient conditions include xenon induced effects, coolant temperature variations, and operator-induced load changes.

- On-line detection and isolation of faulty sensors, actuators, and control algorithms without interruption of plant operation.
- On-line information display of the critical plant variables, sensor and equipment diagnostics, and the control system decision and control output.

The CSDL/MIT concept is incorporated in the sensors, actuators, and control laws. The application of fault tolerance in sensors involves the development of an on-line digital Signal Validation algorithm to detect and isolate failures in redundant sets of sensors and to provide validated measurements [Ray and Desai, 1984]. The validated measurement is based on a set of redundant measurements which consist of directly and analytically derived measurements. To achive fault tolerance in the actuators, direct redundancy is used. It involves the installation of redundant components and sensors and the implementation of a failure detection and isolation (FDI) logic to monitor the operation of the actuators [Lanning et al., 1985]. Regarding the control laws, various control strategies have been investigated for different operating conditions which include sensor and actuator failures and anticipated as well as operator induced changes in the plant operating conditions.

As part of the CSDL/MIT effort to develop and evaluate an integrated fault tolerant control methodology for the MITR, this research attempts to design a safe and reliable controller for various operating conditions. The concept of control law reconfiguration presented in Chapter 2 is used. The control strategies that have been previously evaluated are incorporated in the reconfigurable controller design. A future effort is planned to implement the controller and the FDI System in a fault tolerant computer system as a next step in achieving an integrated fault tolerant control system.

3.2 Description of the MITR and its Instrumentation

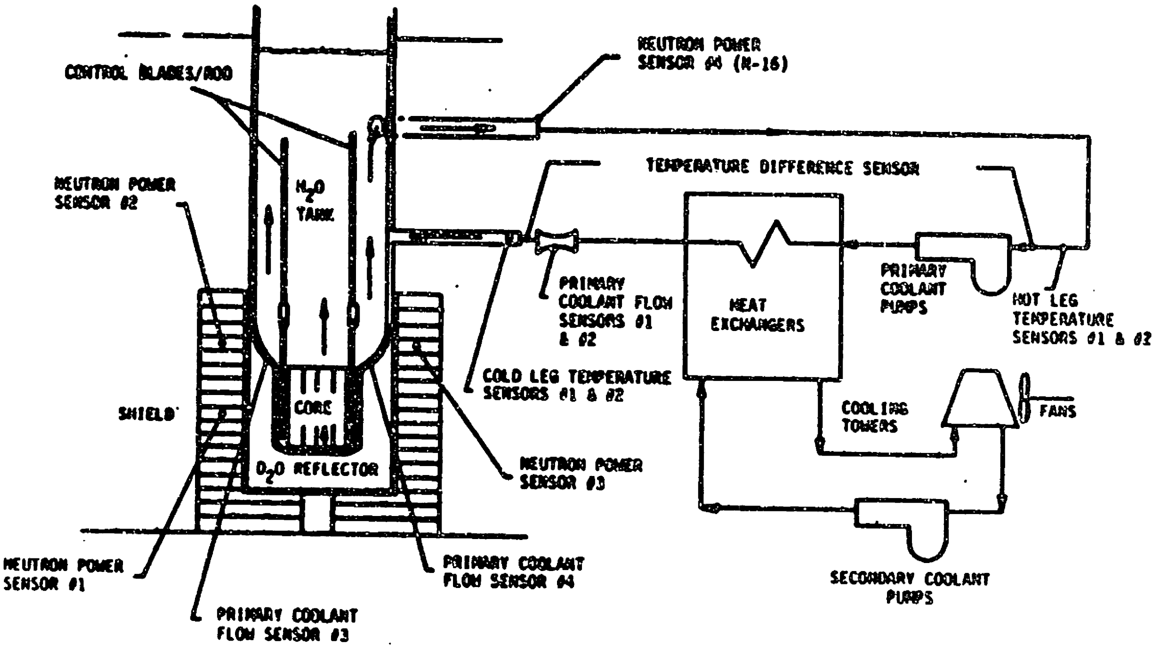


Figure 8. Simplified Process and Instrumentation Diagram for MITR

The MITR is a 5 MW thermal fission reactor that is heavy-water reflected and light-water cooled and moderated. It consists of a primary and secondary loop. The primary loop operates at atmospheric pressure and the primary coolant temperature is limited to 55 deg-C. A simplified diagram of the process and the relevant instrumentation for the reactor power control demonstration is given in Figure 8. The MITR is normally operated at full power 24 hours a day. It is started up every Monday and shutdown on Friday. Xenon is expected to build up as the week progresses. A detailed description of the system configuration and instrumentation is given in the MITR-II Reactor Systems Manual [MIT Nuclear Reactor Laboratory, 1980]. The discussion presented below is relevant to the digital control work in this thesis.

3.2.1 Process Instrumentation

As a plant design requirement, the sensors that form the MITR's safety system must be isolated from the control system. For this application, three neutron flux sensors and a gamma-ray sensor, that correlates the neutron power with the N-16 activity in the primary coolant, are used to measure the reactor power. There are two temperature sensors at the hot leg, two at the cold leg, and one sensor which measures the temperature difference between the legs. There are four independent measurements of primary coolant flow. These measurements are obtained from the pressure differences across orifices. Presently, there are two reg rod position sensors and one position sensor each for shim blade #1 and shim blade #4. All these sensors are hard-wired to an LSI-11/23 minicomputer through appropriate isolators, signal conditioners, and A/D converters. Each sensor is conditioned so that each has an analog output in the range of 0 to 10 volts. There are presently 18 multiplexer ports for the analog signals. The signal that corresponds to each port is listed in Table 1.

3.2.2 Control Mechanism

The MITR power can be controlled by using six shim blades and one regulating rod (reg rod). The shim blades are used for coarse power control and the reg rod for fine adjustments. All control mechanisms can be controlled manually.

The original control system was designed so that the reg rod can be automatically controlled by using an analog feedback controller which uses a single power sensor for steady state power control only. The servo mechanism energizes a 3-position relay to drive a constant-speed motor that can move the reg rod up or down at rate of 108 mm/min (4.25 inches/min). There is no automatic analog control capability in the shim blades. They are manually positioned but only one can be moved at a given time. The six shim blade drive motors are all constant speed

Table 1. MITR Instrumentation: These are the signals that are presently connected to the plant computer (Nov. 1985).

A to D port	Description of the Signal
1	Ch-7 Power sensor
2	Ch-8 Power sensor
3	Ch-9 Powersensor
4	N-16 Power sensor
5	Primary flow sensor
6	Primary flow sensor
7	Primary flow sensor
8	Primary flow sensor
9	Difference between hot leg and cold leg temperature (ΔT sensor)
10	Set Point for digital control
11	Hot leg temperature
12	Hot leg temperature
13	Cold leg temperature
14	Cold leg temperature
15	Shim blade #1 position
16	Reg Rod position
17	Reg Rod position
18	Shim blade #4 position

drive motors similar to that for the reg rod. Both the shim blade and reg rod reactivity worth curves are non-linear functions of position. Each shim blade has an integral and maximum differential reactivity worths of about 1985 millibeta (1.56 % $\Delta k/k$) and 135 millibeta/inch (0.106 % $\Delta k/k$/inch) respectively, where beta is equal to 0.00786 for the MITR. The corresponding values for the reg rod are 204 millibeta (0.16 % $\Delta k/k$) and 30 millibeta/inch (0.023 % $\Delta k/k$/inch).

As part of the on-going CSDL/MITR effort, the reg rod and the shim blades can be also positioned via computer control. Presently, only one shim blade is available for this application (shim blade #4). The remaining five are planned to be connected in the near future. The reg rod can accommodate two types of actuating motors for computer control. The first actuating mechanism is a fixed speed motor which is also used by the analog system. The second one is a variable speed stepping motor. The maximum speed of this motor is limited to that of the fixed speed motor. A dually redundant variable speed drive motor system exists for the reg rod. However, it is not going to be utilized for the proposed controller design. Based on the present design, the drive belt that links the control rod drive shaft and the motor shaft has to be manually moved to switch from one motor to another. Regarding the shim blade mechanism, only a fixed speed motor is currently available.

3.2.3 Processing System

An LSI-11/23 computer and a data acquisition system have been installed on the MITR. Presently, both systems are not designed in a fault tolerant fashion. The computer may malfunction in the event of a single failure in the hardware and software and its periperals. However, the control system is designed to trip to manual mode in the event of a hardware or software failure in the computer system.

The present computer system consists of a single string processor, memory, real-time clock, and A/D and D/A converters. The LSI-11/23 machine can accomodate a real-time FORTRAN program (in machine executable form) requiring a memory of about 50 kilobytes. This program also includes FORTRAN libraries and a special real-time MACRO subprogram package (DTLIB of Data Translation). The real-time subprogram package that accessed the data from the A/D converters runs asynchronously with the control program.

3.2.4 Interfacing Systems

The digital controller interfaces with a signal validation system (SVS) and a real time display system. The SVS provides a reliable set of plant measurements. The display system, on the other hand, presents the operating crew with real time information generated by the SVS and the reactor control system.

The MITR Signal Validation System (SVS) performs on-line calibration and fault detection and isolation of faulty sensors [Ray et al., 1983A]. It generates a validated estimate of a process variable based on the available redundant measurements which are directly measured or analytically derived. Presently, the MITR SVS provides a validated estimate of reactor power, primary coolant flow, and primary coolant temperature. The details of the technique are described in [Ray et al., 1983A]. The same technique is used in an on-going effort to validate important PWR and BWR process variables [Deutsch et al., 1984].

3.3 Reconfigurable Controller Design for the MITR

This section discusses the assumptions made in developing the reconfigurable controller for the MITR power control system. The same assumptions apply to the simulation and on-line evaluation studies. The guidelines in designing the controller are also presented in this section. The conditions that are accommodated in the design include anticipated changes in demand, plant dynamics, component status and alignment. Possible failure conditions in the actuators and plant components, that have been detected but not isolated, are also included.

3.3.1 Design Assumptions

Several assumptions are made in implementing the design concept on the MITR because of the present instrumentation and processing limitations. The following assumptions are made:

- The design will cover the range of 20 to 100% power. This range will be referred to, as discussed later, as the power operation mode. Startup and shutdown conditions are not considered.

- All measurements used in the controller are assumed valid despite the fact that the current Signal Validation System (SVS) only validates the reactor power, the reactor coolant temperature difference across the core, and the reactor coolant flow.
- Computer hardware and software failures are not considered. The controller will be implemented in an LSI-11/23 computer with all the associated peripherals and hardware interfacing components. The control signal will be generated at the rate of once a second because of timing constraints.
- All reactor coolant pumps are assumed available. The rationale behind this assumption is that the allowable reactor power operating range is dictated by the reactor coolant pump configuration. Based on this assumption, the reactor power can be freely adjusted within the 20 to 100% range.
- The reg rod is connected to a variable speed drive motor. It is assumed that the status of the motor, the motor speed, and the reg position are known at all times. The design can accommodate reg rod failure.
- The shim blades can be adjusted by using a fixed speed drive motor. It is assumed that the motor status and its speed are always known. Only one shim blade can be adjusted at a time. The current hardware does not allow for an automatic selection of which one of the six shim blades will be adjusted at a given time step. Because of this feature, only shim blade #4 will be used. As an operating requirement, the other five blades have to be at the same height within a specified bound. The blade that is being adjusted has to be within a given distance away from the shim bank position. Based on the list of available measurements (see Table 1), the shim blade #1 position sensor will be used as the shim bank position indicator.
- Based on the Technical Specification (Tech Specs) requirement, the plant can be operated with one inoperable shim blade as long as its height is equal to or greater than that of the shim bank. Since there is only one shim blade that is available for digital

control, this condition will not be considered. Manual control will be used in the event of shim blade mechanism failure.

- All other components that can affect the power control system are assumed operational. Thus, based on the assumptions made regarding the pumps, the plant operating configuration will be defined solely based on the status of the reg rod and shim blade drive motors, as discussed later in this chapter.
- Because of computing limitations, the operation of the controller will be demonstrated in a selected number of operating conditions that have been identified in the design. The concept of control law performance evaluation and control selection adaptation will also be demonstrated for selected operating conditions.

In the next sections, the design guidelines for the proposed MITR reconfigurable power controller are presented. The elements of the information vector, the control laws used in the design, and the components of the reconfiguration logic are discussed.

3.3.2 Information Vector

The information vector contains the information needed by the controller. It consists of current and past process variable measurements, component status and alignment indications, and analytically estimated variables. The available measurements that are included in the information vector consist of the reactor power, reactor outlet temperature, one reg rod position, and shim blade #4 and shim blade #1 positions. All of the above measurements are assumed valid at all times. The information that is used by the controller and assumed available includes the status and speed of the reg rod and shim blade drive motors.

The information vector also contains elements that are not directly measurable. These elements are estimated based on physical models. One of these elements is reactivity. This variable provides an indication of the reactor power generation rate. The reactivity present in the core is estimated based on a reactivity balance model and an inverse kinetics model (see Appendix D). Under certain conditions, the two models may be inconsistent because of modeling errors which can be attributed to the reactivity coefficients, delayed neutron grouping, and dynamic effects of control mechanism motion. If this situation happens, the more conservative of the two is chosen. The logic used to validate the reactivity information is presented in Appendix D.

The instantaneous reactor period is another important element of the information vector. It provides an indication of the rate of change of power. This variable is estimated by using the reactor power history. For the case of the MITR, the rate of change of power is computed by directly taking the derivative of the power history. A digital low pass filter is used to minimize the noise in the power signal. The rate of change of power is also presented in terms of the startup rate which is inversely proportional to the reactor period.

Another important set of estimated variables is the result of the evaluation of the reg rod and shim blade reactivity constraint relationships [Bernard, 1984]. Reactivity constraint is based on the concept of restricting the total reactivity in the core so that it is always possible to change the direction of the power trajectory at the desired termination point of the transient by reversing the direction of the control mechanism that is associated with the controller. The reactivity constraint associated with a control mechanism is said to be satisfied if a reversal of the motion of this control mechanism provides a "sufficient" rate of reactivity change to reverse the direction of the rate of change of power. The reactivity constraint is evaluated for both the reg rod and the shim blades. It is obtained from the knowledge of the reactor power relative to a desired limiting power, the differential reactivity worth curve associated with the control mechanism, the total reactivity in the core, and the position of the control mechanism. For this application, two sets of shim blade and reg rod reactivity constraint relationships are evaluated. The first set is based on the desired set point which is used to identify a plant operating condition and the second is based on a limiting power, about 4200 KW. The latter set of constraints is referred to as the supervisory constraint which is used in the decision and supervisory logic as discussed later. The validity of the reactivity constraint depends on the validity of the inputs required to evaluate the reactivity constraint relationship. For this application, the reactivity constraint is assumed valid as long as the reactivity estimate is valid. However, regardless of the validity of the reactivity estimate, the conservative reg rod and shim blade reactivity constraints are evaluated all the time as discussed in Appendix D.

3.3.3 Control Laws

The controller is based on the reconfiguration of various control laws and sets of procedures for different operating conditions. It involves the identification of the plant operating condition and the performance evaluation of the selected control strategy.

There are five important control laws that are available for MITR power control over the range of 20 to 100%. The descriptions of the control laws are presented in Appendices C and E. A proportional-integral-derivative (PID) control law is used at steady state to adjust the reg rod [Ray et al., 1983C]. It may also be used to adjust the shim blades, but with a different set of gains. This control law is valid if the reactivity estimate is valid and the reactivity constraints are satisfied.

The Non-linear Digital Control (NLDC) [Bernard, 1984] algorithm is used under transient plant operating conditions with the assumption that the reactivity estimate is valid. It can be used to adjust the reg rod and the shim blades. It is also used at steady state to direct the necessary rules if the reactivity constraints based on the desired set point are not satisfied.

The third control law is the fuzzy control algorithm [Bernard et al., 1985]. Its current version is only applicable for power increase. It is designed to control the reg rod without relying on the reactivity estimate.

The fourth control law is called the relay control algorithm. It is based on a set of empirical switching curves with are defined by the deviation from the desired operating power and the rate of change of power. This control law can be used to adjust the reg rod or shim blade at steady state and transient conditions. However, its performance is not expected to be as "good" as that of the NLDC or fuzzy control algorithms during transients. The PID is also expected to perform better than the relay control during "ideal steady state" conditions.

The fifth type of control law or procedure is based on rules derived from operating guidelines and/or operator experience. These rules are specifically formulated for the MITR.

3.3.4 Reconfiguration Logic

The decision made by the controller is based on the identification of the plant operating condition, control law performance evaluation, and a decision and supervisory logic which supervises the operation of the controller. A simplified diagram of the MITR reconfigurable controller is shown in Figure 9. This diagram shows the bank of control laws and procedures and the components of the reconfiguration logic. The components of the reconfiguration logic are discussed below.

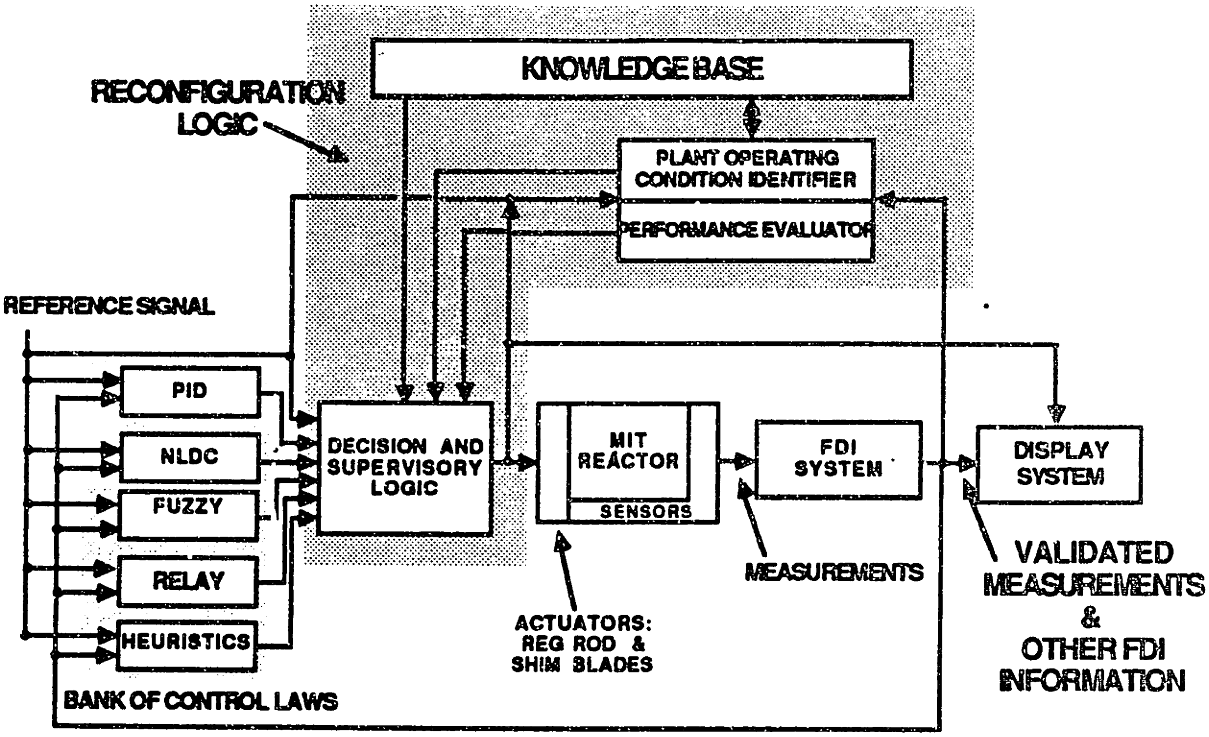


Figure 9. Simplified Diagram of the MITR Reconfigurable Controller

3.3.4.1 Plant Operating Condition Identifier

This section presents the scheme used to define and identify the operating conditions that are accommodated by the controller.

To organize the elements of the information vector in order to define and identify the set of plant operating conditions, a decision tree has been developed for the MITR Reactor Power Control System. For this design, a deterministic logic, as opposed to a statistical or fuzzy logic, has been used to partition some of the elements of the information vector into discrete regions. Furthermore, a deterministic logic is also used to define and identify the features of various plant operating conditions. The objective here is to define the plant operating modes, configurations, states, and substates based on the information vector. For this application, the set of plant operating conditions is defined so that the control laws that have previously been evaluated on the MITR (see Appendix C) can be directly used. The definitions of the plant operating conditions are also based on the design assumptions presented earlier.

Plant Operating Modes

The operating modes are startup, power operation, and shutdown. Because of instrumentation constraints, the startup and shutdown branches of the decision tree are truncated. Manual control is used for these operating conditions. Power operation mode is defined over the range of 20 to 100% of the MITR rated power. A power demand beyond this range is not included in this operating mode.

Plant Operating Configurations

Three configurations have been defined. The definition of a given configuration is based solely on the status of the reg rod and shim blade #4 drive motors as mentioned in the design assumptions. The power can be adjusted freely in the 20 to 100% range under the assumption that all the reactor coolant pumps are available. The description of each configuration is summarized in Table 2. The first configuration is an alignment where both the reg rod and shim blade drive motors are available. The second one is an alignment in which only the shim blade motor is available. Any other conditions that do not satisfy the above definitions are aggregated to the third configuration. Only the first two configurations are included in the automatic control regime; manual control is used in the third configuration. Failure of the shim blade drive motor is not considered in the design since only one shim blade is presently connected to the computer. However, Tech Specs requirement allows a single shim blade failure as long as its height is greater than or equal to that of the shim bank.

Table 2. MITR Plant Operating Configurations

Configuration	Description
A	Both reg rod and shim blade drive motors are available.
B	Only the shim blade drive motor is available.
C	At least, the shim blade drive motor is unavailable.

Plant Operating States

The plant operating states consist of steady and transient states. For the MITR demonstration, the plant operating state is defined by two quantities: the desired deviation from the demanded power level and the desired rate of change of power. The plant is considered to be in steady state if both quantities are close to zero within a specified set of bounds:

$$|\delta P| \leq \delta P^*$$

$$|SUR| \leq SUR^*$$

where P = Power

SUR = Startup Rate

$\delta P = (P - P_{set})/P_{set}$ = power deviation

P_{set} = Power setpoint

δP^* = desired δP

SUR^* = desired SUR

In order to alleviate the problem of unnecessary switch over from one state to another because of noise, a sequential test, based on consecutive occurences of a given state (i.e., Multiple Consecutive Occurrence criterion), is used. Furthermore, once the steady state condition is reached, a larger δP^* is chosen in order to prevent a switch over from steady state to transient due to external disturbances. The value of δP^* is chosen to be larger for shim blade control than for reg rod control. A diagram which shows the hierarchy of plant operating conditions for the MITR reconfigurable controller is shown in Figure 10.

Plant Operating Substates

The plant substates are defined by the information related to the variable or variables being controlled as well as past information regarding the plant operating conditions. To simplify the discussion, a naming convention for the substates is introduced. A plant operating substate is designated by three alphanumeric characters XCn

where	X	takes on the value of S or T to designate steady or transient substate
	C	takes on the value of A, B, or C to designate the configuration (see Table 2)
	n	takes on the value of 1, 2, 3, ... to designate a substate in a given state and configuration.

Thus, the first steady substate in configuration A is labelled as SA1. The plant operating substates that have been defined for the MITR controller are summarized in Table 3 and Table 4. Figure 11 shows the corresponding trees.

Eight steady substates have been defined: four in Configuration A and four in Configuration B. Substate SA1 is a condition where the reg rod and shim blade reactivity constraints are satisfied given that the reactivity estimate is valid. A PID control law is used to drive the reg

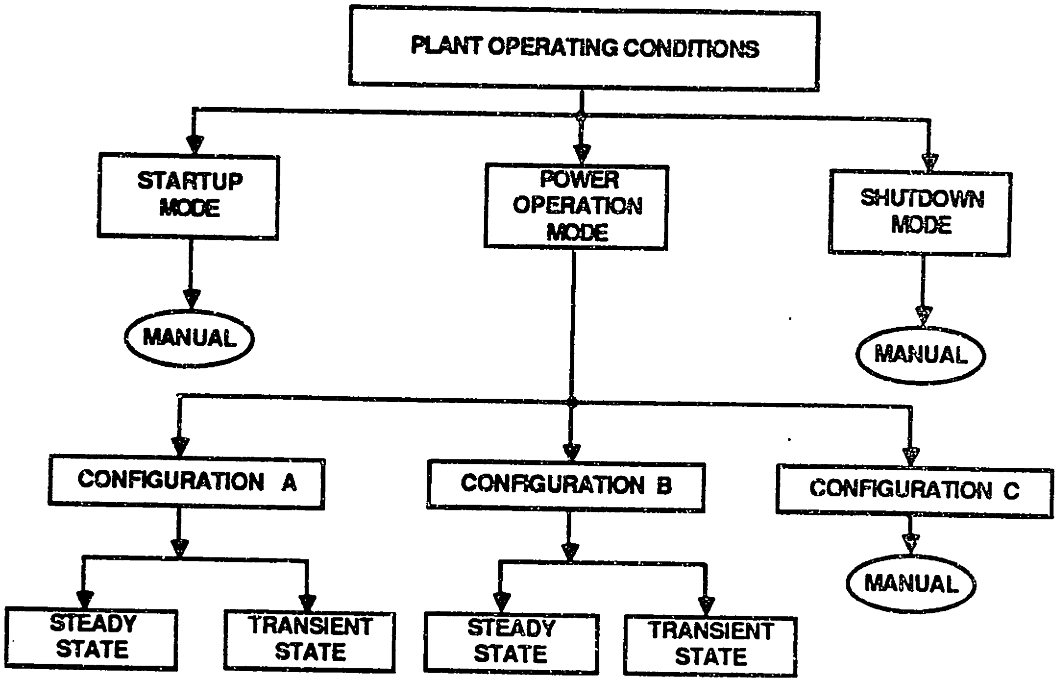


Figure 10. Hierarchy of Plant Operating Conditions for the MITR

rod under this condition. As discussed later, the PID may not work well if it is not properly tuned. The other possible control laws that can be used include the fuzzy and relay control algorithms.

Substate SA2 is a condition where the reg rod or shim blade reactivity constraint is not satisfied, given that the reactivity estimate is valid. This situation can occur if the power is just levelling off just after a transient and the desired power deviation and the rate of change of power conditions are both satisfied (especially if the shim blade has been used earlier to adjust the power). To prevent possible overshoot or undershoot, the reg rod and the shim blade are adjusted based on the

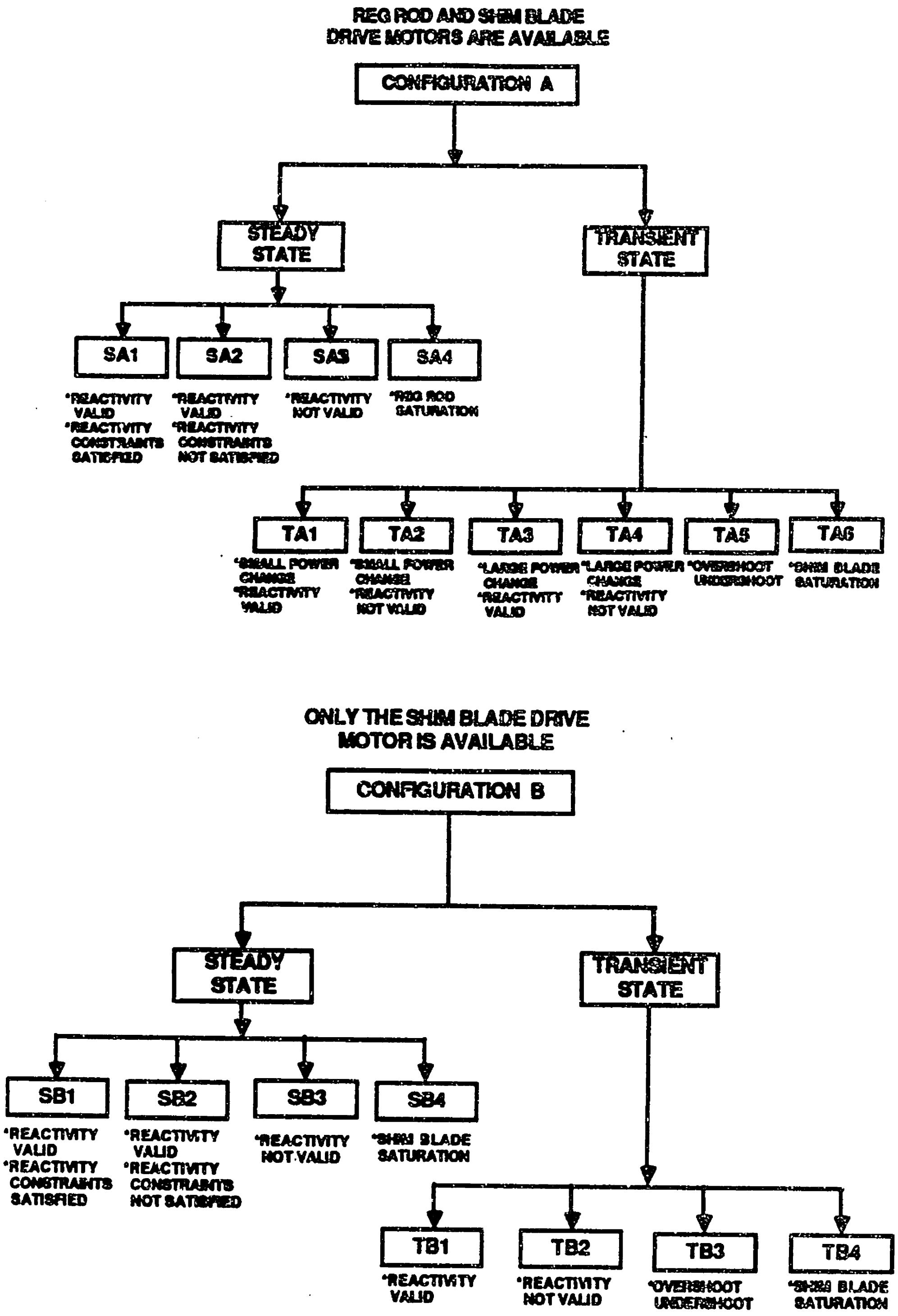


Figure 11. MITR Substates

Table 3. MITR Plant Operating Substates for Configuration A (Part 1 of 2): Both reg rod and shim blade drive motors are available.

Steady Substates	Description	Control Law	Control Mechanism
SA1	reactivity is valid and reactivity constraints are satisfied	PID	Reg Rod
SA2	reactivity is valid and reactivity constraints are not satisfied	Heuristics based on reactivity constraints	Reg Rod and Shim Blade
SA3	reactivity is not valid	Heuristics and Relay	Reg Rod and Shim Blade
SA4	Reg Rod hits In/Out Limit	Heuristics	Reg Rod and Shim Blade

reactivity constraints and heuristic logic. The logic used is presented in Appendix E.

Substate SA3 is a condition where the reactivity is not valid. The relay algorithm and heuristics are used to control the reactor power under this condition. After a prolong operation at steady state, the information regarding the status of the reactivity estimate is disregarded. This substate is then reclassified as SA1. The rationale for this is that a smoother power regulation can be achieved by making such assumption. As mention above, the PID is used in substate SA1. This control law is no longer sensitive to the magnitude of the reactivity once the power has levelled off. The reactivity is only used to provide

Table 3. MITR Plant Operating Substates for Configuration A (Part 2 of 2): Both reg rod and shim blade drive motors are available.

Transient Substates	Description	Control Law	Control Mechanism
TA1	reactivity is valid, small power change	NLDC	Reg Rod
TA2	reactivity is not valid, small power change	Fuzzy, Relay	Reg Rod
TA3	reactivity is valid, large power change or reshim	NLDC & Heuristics	Reg Rod and Shim Blade
TA4	reactivity is not valid, large power change or reshim	Relay & Heuristics	Reg Rod and Shim Blade
TA5	Overshoot or undershoot	Heuristics, Relay and NLDC	Reg Rod and Shim Blade
TA6	Shim Blade hits In/Out Limit	Heuristics or Manual	Reg Rod and Shim Blade

the derivative signal. For this application, the reactivity estimate obtained from the inverse kinetics model is used in the PID.

Substate SA4 is a condition where the reg rod hits its in-out limit. This is referred to as a saturation condition in the reg rod. A procedure based on heuristics is used to provide the control action for this substate. The shim blade is adjusted while the reg rod is moved away

Table 4. MITR Plant Operating Substates for Configuration B: Only the shim blade drive motor is available.

Steady Substates	Description	Control Law	Control Mechanism
SB1	reactivity is valid and reactivity constraints are satisfied	PID	Shim Blade
SB2	reactivity is valid and reactivity constraints are not satisfied	Heuristics based on reactivity constraints	Shim Blade
SB3	reactivity is not valid	Heuristics and Relay	Shim Blade
SB4	Shim blade hits In/Out Limit	MANUAL	Shim Blade

Transient Substates	Description	Control Law	Control Mechanism
TB1	reactivity is valid	NLDC	Shim Blade
TB2	reactivity is not valid	Relay	Shim Blade
TB3	Overshoot or undershoot	Heuristics, Relay, & NLDC	Shim Blade
TB4	Shim Blade hits In/Out Limit	Heuristics or Manual	Shim Blade

from its limiting position. The details of this procedure are presented in Appendix E.

The steady substates in Configuration B are very similar to those in Configuraton A. Of course, only the shim blade is used to adjust the power.

The transient substates are described in Table 3 and Table 4. There are various conditions to consider in defining the transient substates for the MITR. These conditions include: reactivity information, the magnitude of the power change, the positions of the control mechanisms, the power history, and the previous plant operating state. The details involved in defining and identifying these conditions are presented in Appendix E.

The reactivity information consists of the validity of the estimate and the results of the reactivity constraint evaluation for both the reg rod and shim blade (see Appendix D). The magnitude of the desired power change is also an important factor. It dictates whether the power should be changed by adjusting the reg rod or the shim blade. Another important set of conditions includes the initial power level and the initial positions of the control mechanisms. For example, a 3 to 4 megawatt (MW) change would require less time than would a 1 to 2 MW change. The reason for this is that the power level and period are exponentially related. Hence, given that the reg rod is initially at a "low" position, a 1 MW change at higher power level can be easily accommodated by the reg rod. It should be noted that there is a "strong" negative temperature feedback on the MITR at high power level. However, it is not "strong" enough to overcome the effect of the exponential relationship between the power and period. An a priori knowledge of the plant characteristics is used to differentiate between a "large" and "small" power change. Furthermore, for "small" power changes, the reg rod position is important in deciding whether the power should be changed by adjusting the reg rod or shim blade. For example, during a power increase, the reg rod should initially be at a "low" position in order to reach the desired power. Such initial control rod position is determined a priori. The limiting positions for the reg rod and shim blade should be also considered.

Ten transient substates have been defined: six in Configuration A and four in Configuration B. Transient substate TA1 is a condition where the power set point change is "small," given that the reg rod is located at a "low" position, and the reactivity information is valid. The "critical" position of the reg rod is determined a priori based on guidelines presented in Appendix E. The NLDC algorithm is used in this substate. Substate TA2 is similar to TA1 except that the reactivity information is not valid. For this substate, the fuzzy algorithm is used for power increase and the relay algorithm for power decrease.

Transient substates TA3 and TA4 are aggregations of two conditions. If the reg rod is located at a relatively "high" ("low") position during a power increase (decrease), then the power is adjusted by primarily using the shim blade. The other condition is when the demanded power change is "large," regardless of the initial reg rod position. The aggregation of these two conditions is referred to as a reshim condition. (Note: In practice, the MITR operating crew refers to "reshim" as a procedure where the power is regulated at a given level by using the shim blade while the reg rod is positioned to a desired operating height. For "small" power increase, given that the reg rod is initially located at a relatively "high" position, the operators normally adjust the shim blades and move the reg rod until it reaches its desired position. The power change is then initiated by using the reg rod.) The only feature that separates TA3 from TA4 is the validity of the reactivity information. The reg rod is adjusted to a desired position based on operating rules of thumb. The shim blade is adjusted by using the NLDC algorithm in TA3 and the relay algorithm in TA4. The details of the control logic are presented in Appendix E. A transition from TA3 or TA4 to TA1 or TA2 is permitted only if the reg rod is already located at the desired height, if both reg rod and shim blade reactivity constraints are satisfied, and if the power is already "close" to the set point. If the reactivity estimate is not valid, then the conservative reactivity constraints are imposed.

Transient substate TA5 is the "overshoot" or "undershoot" substate. The previous plant operating state is used to identify whether the transient is set point induced or an overshoot or undershoot substate. For example, if the plant is currently in the transient operating state, given that it was previously in steady state and given that there was no change in the set point, then such transient condition is considered as an overshoot/undershoot condition. During a power increase (decrease) maneuver, a transient substate where the power went over (under) the desired power by a specified amount is also considered as an overshoot/undershoot condition. Under this substate, the reg rod and shim blade are adjusted simultaneously based on the combination of relay control, heuristic logics, and Tech Specs requirements. The details are presented in Appendix E.

Transient substate TA6 and TB4 are substates where the shim blade reached its limiting position and the demanded control signal violates the limit. The limits on the shim blade position are based on the in/out limits and deviation from the shim bank height. In substate TA6, a procedure based on heuristics is used to adjust the reg rod if possible; otherwise, manual control is used. A similar type of logic is used in TB4 as discussed in Appendix E. A good person-machine interface is needed under these substates to inform the operators about the decision made by the reconfiguration logic. However, this is not addressed in the design.

Transient substates TB1, TB2, and TB3 are the analog of TA3, TA4, and TA5 respectively. The sets of control logic used are presented in Appendix E.

3.3.4.2 Performance Evaluation

The performance evaluation is an on-line rationality test to determine whether or not the chosen control law is bringing the plant to its desired power. For steady state operation, the control law that has been implemented in the previous time step is performing satisfactorily if the power is not deviating away from its desired set point

$$|e(t)| < |e(t-1)|$$

where $e(t)$ is the set point error = $P(t) - P_{set}$

$P(t)$ is the current power

$P(t-1)$ is the power at the previous time sample

P_{set} is the power set point.

A situation in which the above criterion is satisfied is said to be a reward condition; otherwise, it is said to be a penalty condition. A "hard bound" control (HBC) action is also introduced. For example, if $e(t)$ exceeds a certain positive value, a "hard bound" control to insert the control mechanism is recommended. If the control law that has been previously implemented does not agree with this recommendation, then the HBC criterion is said to be violated. In transient operating conditions, the same power trajectory criterion is used in order to verify that the power is proceeding in the right direction. In addition, constraints on the power and the rate of change of power are also imposed.

A sequential test is used to minimize the effects of noise in the signals. Heuristics based on the consecutive number of reward or penalty conditions are also used. The number of time steps the current control law is in effect is also considered in order to account for the delayed response of the plant. The details of the performance criterion used in the demonstration are presented in Appendix F.

As discussed earlier, the performance evaluation is only demonstrated in a selected number of POC's. For this design, the performance evaluation is primarily used in substates where the control actions are based on specific model-based control laws. POC's which utilize control procedures based on heuristics are not considered in the design and demonstration of the performance evaluator. The control law selected by the decision tree serves as a first guess in the control law reconfiguration process. If the performance conditions are satisfied then the control law originally mapped onto the current substate is used again. Otherwise, a performance adaptive or reinforcement algorithm is used to adapt the control law selection for such substate. The result of the performance evaluation is used by the reinforcement algorithm to update the probability associated with each admissible control law. For the MITR demonstration, a linear reward penalty scheme [Narendra et al., 1974] is used as a means of saving computer memory. The "standard" scheme has been slightly modified to account for how well the control law is meeting the performance criterion (see Appendix F). Other updating schemes can be used as mentioned in Chapter 2. No attempt, however, has been made to evaluate other algorithms.

For this design, the substates, where the performance evaluation applies, include steady substates SA1 and SB1 and transient substates TA1, TA2, TA3, TA4, TB1, and TB2. In steady substate SA1 and SB1 (reactivity is valid and the reactivity constraints are satisfied), a PID algorithm is initially used. The PID gains for SA1 and SB1 are different. The decision made by the decision tree is based on the assumption that the PID is properly tuned. If the PID is improperly tuned, which is very likely to happen in practical application, then the use of this control law could result in a power drift from the desired set point. The other admissible control laws for this substate are the relay and fuzzy (for power increase and reg rod only) algorithms. It should be noted that the fuzzy algorithm is designed for transient operation. However, it can also be used as a coarse means of control at steady state if the other options are not performing satisfactorily.

For transient substate TA1 (small transient and the reactivity is (valid) the NLDC is selected by the decision tree to adjust the reg rod. The backup control laws are the fuzzy (for power increase and reg rod only) and relay algorithms. The same set of control choices are implemented to adjust the shim blades for transient substates TA3 and TB1. For transient substates TA2, TA4, and TB2, the same set of control laws are used. However, the fuzzy (for power increase and reg rod only) or relay control is selected first by the decision tree because the reactivity is not valid.

3.3.4.3 Decision and Supervisory Logic

The decision and supervisory logic (DSL) orchestrates and supervises the operation of the plant operating condition (POC) identifier and performance evaluation (PE) modules of the reconfiguration logic in order to insure a safe operation of the controller. It overrides the control selection obtained from the POC identifier and PE if the reactor power is proceeding to an unsafe direction and if the limiting conditions on the control law specifications and drive motors are violated.

The DSL interfaces with a knowledge base to obtain the necessary heuristics for a given condition. The knowledge base is presented in terms of production rules (if-then rules) that have been derived from plant operating guidelines, Tech Specs requirements, operating rules of thumb, and physical constraints. It directly interprets the information supplied by the information vector.

The rules are specifically written for this particular application. Its completeness is not assured. However, the rules are written to insure that a rod insertion is achieved if there is a violation in the power, period, and shim blade and reg rod reactivity constraints. A limit on the amount of reactivity that is present in the reactor is also considered. These constraints depend on the plant configuration. As discussed earlier and in Appendix D, the reg rod and the shim blade reactivity constraint relationships are evaluated at all times, regardless of the validity of the reactivity estimates. The reactivity constraints are computed based on the most conservative reactivity estimate for the given power maneuver. The DSL uses the reg rod and shim blade reactivity constraint relationships that have been evaluated based on a higher power level, about 4500 kw. This set of constraints is referred to as the supervisory constraint to insure that there is sufficient rate of reactivity to prevent a power overshoot at 4500 kw. The supervisory constraint reviews the control action obtained from the POC identifier and the PE.

The rule-base consists of conditions regarding the power, period, control rod position, reactivity, control signals, and the validity of the model-based control algorithms. The rules are formulated so that:

- the power limit is not violated
- the period limit is not violated
- the reactivity limit is not violated
- the reactivity constraints are not violated for a specified power level
- the control rod position constraints are not violated (eg. in/out limits)
- the power trajectory is proceeding in the right direction
- there is no "large" power overshoot
- the power response is consistent with the control signal for the given control rod position
- the model-based control laws are operating in their designed range of operation.

3.4 Summary

The design guidelines for the MITR reconfigurable power controller has been discussed in this chapter. The plant operating conditions have been defined based on the reactivity information, status of the control drive mechanism, position of the reg rod and shim blades, and the nature of the power maneuver. A set of performance criterion are introduced based primarily on the power deviation from the desired set point and the rate of change of power. The decision and supervisory logic orchestrates and supervises the operation of the various modules of the reconfiguration logic in order to insure a safe operation of the controller. The results of the simulation and the on-line evaluation of the MITR reconfigurable power controller are presented in the next chapter.

CHAPTER 4. EVALUATION OF THE CONTROLLER DESIGN

The design of the MITR reconfigurable reactor power control, presented in Chapter 3, has been evaluated via computer simulations and on-line experiments. The control program has been coded in FORTRAN based on the guidelines presented in Chapter 3. Simulation tests have been conducted in order to test the control concept and the software prior to on-line evaluation. The purpose of the simulation studies is to determine if the control strategy is capable of performing its function by manipulating a computer-based model of the reactor. No direct comparison of the simulation and experimental results is made or implied.

4.1 Simulation Studies

4.1.1 Description of the Simulation Program

Simulation tests have been conducted in order to test the control concept and the software prior to on-line evaluation. The computer programs used in simulation studies consisted of the reactor model and the reactor power control program. The reactor power control program consists of the bank of control algorithms and procedures as well as the overall reconfiguration logic. The MITR model used is an adaptation of a point kinetics model with six delayed neutron groups [Bernard, 1984, Appendix B]. It also includes an empirical model which describes the heat transfer between the core and the primary coolant. The model simulates the changes in the reactor power in response to control rod and shim blade motions and changes in the primary coolant temperature. The reactor model interfaces with the control program which is capable of adjusting the shim blade and the reg rod in order to achieve the desired power level. The model supplies the control program with the simulated measurements of power, control rod positions, and coolant temperature. The simulated measurements include the effects of noise, bias and scale factor errors, time lag, and failure. It is assumed that there is no time lag in the actuators in adjusting the desired control mechanism.

4.1.2 Scope of the Simulation Studies

This section describes the scope of the simulation studies. For the simulations, the following assumptions are made:

1. The direct measurements (i.e., power, temperature and control rod positions) are valid at all times. The simulation program, therefore, is not linked to a signal validation routine [Ray, 1984].
2. Several conditions have been selected for the simulation studies. The control program does not include all the plant operating conditions and control procedures presented in Chapter 3 and Appendix E. Only those related to the simulation studies have been coded.
3. The concept of performance evaluation and control selection adaptation is demonstrated in selected substates in Configuration A (both reg rod and shim blade are available).

The control algorithm is simulated under a variety of operating conditions. Different types of maneuvers have been studied. The type of maneuvers depends upon the power demand and initial conditions. Small and large transients have been simulated. A control interval of 1 second has been chosen in order to be consistent with the on-line experimentation.

The case when the reactivity is not valid is also simulated. This is accomplished by modifying the effective delayed neutron fraction parameter in the reactor model, thus introducing an error in the reactivity balance. The threshold used in comparing the reactivity estimates obtained from the reactivity balance and inverse kinetics models is also reduced.

Control law anomaly during steady state and transient conditions is also studied. During steady state, the gains of the PID are detuned. This situation arises if some of the plant parameters for that condition changed due to plant disturbance, if the plant is incorrectly modeled in the first place, or if the gains are inadvertently changed. During a transient condition, an anomaly has been introduced in the fuzzy algorithm by deliberately changing the recommended control action at a given power level. Another way of doing this is to modify the rule base and the membership functions associated with the control algorithm.

In all the cases considered, noise has been modeled in the power, reg rod and shim blade positions, and temperature measurements. It is assumed that the noise is Gaussian with zero mean. A digital low pass filter has also been used in the power measurement before estimating the rate of change of power which is given in terms of the startup rate.

As discussed in Chapter 3, the plant operating state is defined by the deviation from the desired power and the rate of change of power. The steady state is met if both parameters are close to zero within their specified values respectively. For the simulation studies, the desired steady state power deviation, δP^* (where $\delta P^*=(P-P_{set})/P_{set}$), is set to 0.01 and the desired steady state start up rate criterion, SUR^*, is set to 26.06/300 (i.e. 300 second period) for the reg rod. The value of δP^* is set to 0.025 to prevent a switch over to a transient state as a result of a disturbance or control law anomaly at steady state. The values of δP^* and SUR^* have been chosen based on the results of earlier simulation studies and experimental trials.

A multiple consecutive occurence (MCO) test is used to determine the steady state condition, the violation of the reactivity constraint relationships, and the non-validity of the reactivity estimate. In the case of the steady state determination, the MCO is designed so that the counter is reset to zero each time the steady state criteria are violated. A similar test is used to determine the violation of the reactivity constraint relationship. The MCO test is implemented in this fashion because it is expected to yield a more conservative result, as observed in earlier simulation and experimental trials. In the case of the reactivity non-validity test, the counter is decremented if the reactivity is valid and incremented if it is not. This procedure minimizes the switch over from a valid to non-valid reactivity estimate condition, and thus from one control law to another. The counter threshold has been chosen as a trade off between time delay and false declaration.

The next section presents the description of each simulation run and the results associated with it.

4.1.3 Results of the Simulation Studies

A summary of the simulation studies is shown in Table 5. The results presented in this section are obtained from the "final" version of the control computer code. Modifications have been made to the original code in order to upgrade the multiple consecutive occurrence (MCO) test and the performance criteria used in the performance evaluator module. The modifications are based on the results of the earlier simulation and experimental trials. A typical set of results associated with a simulation run consists of several time plots:

1. "POWER" is the reactor power in kilowatts.
2. "SUR" is the startup rate in decades per minute.
3. "RR HEIGHT" is the reg rod height in inches.
4. "SB HEIGHT" is the shim blade height in inches.
5. "RR CONTROL" is the reg rod control signal where a value of 1 and -1 indicate a full-speed withdrawal and insertion respectively.
6. "SB CONTROL" is the shim blade control signal.
7. "SUBSTATE ID" is the substate identification tag as defined in Figure 12.
8. "ID CON LAW" is the control law identification tag. For the reg rod, the identification tag takes on the value of 1 for the PID,

Table 5. Summary of Simulation Runs

Case No.	Power Maneuver	Control Mechanism	Reactivity Anomaly	Control Anomaly
SR1	1-2 MW*	Reg Rod	No	No
SR2	1-2 MW	Reg Rod	Yes	No
SR3	1-2 MW	Reg Rod	Yes	Yes, during Steady State
SR4	1-2 MW	Reg Rod & Shim Blade	No	No
SR5	1-2 MW	Reg Rod	Yes	Yes, during Transient
SR6	1-4 MW	Reg Rod & Shim Blade	No	No
SR7	1-4 MW	Shim Blade	Yes	No
SR8	4-2 MW	Reg Rod & Shim Blade	No	Yes, during Steady State

* MW = Megawatts

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2 for NLDC, 3 for fuzzy control, 4 for relay control, and 5 for any heuristic-based control procedures. The corresponding identification tags for the shim blade control laws are 6, 7, 8, 9, and 10 respectively.

9. "REACT VALID" provides an indication of whether or not the reactivity information is valid based on a single time sample test. The reactivity validation procedure is discussed in Appendix D. "REACT VALID" is set to 0 if the reactivity is valid and to 1 otherwise.
10. "RR CONS MET" is the single point test result of the reg rod reactivity constraint evaluation based on the power set point. The test indicator is set to 0 if the constraint is met and to 1 otherwise.
11. "SB CONS MET" is the single point test result of the shim blade reactivity constraint evaluation based on the power set point. The test indicator is set to 0 if the constraint is met and to 1 otherwise.
12. "BALANCE" is the reactivity estimate based on the balance model.

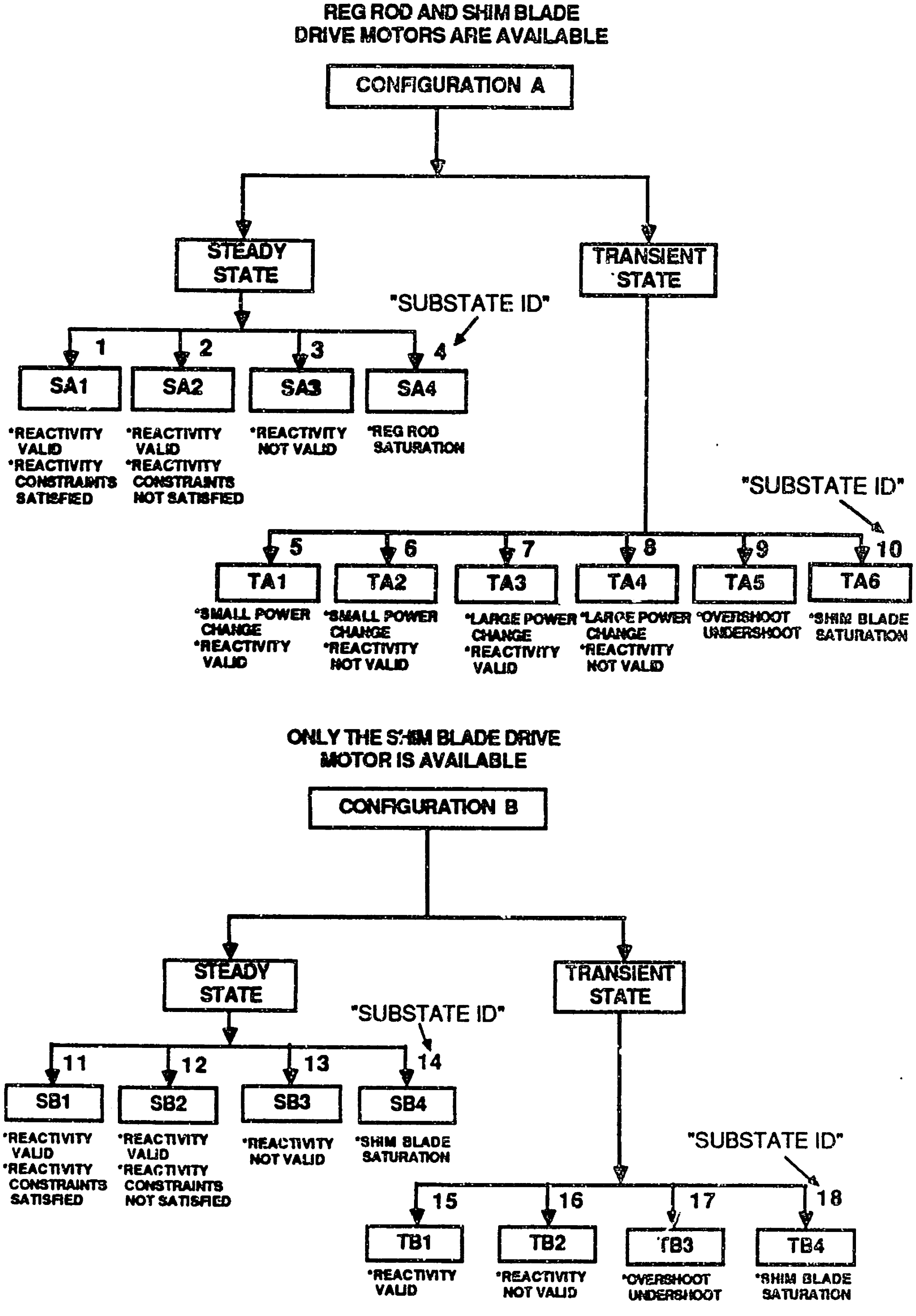

Figure 12. Substate Identification Tags

13. "INVERSE KIN" is the reactivity estimate based on a three group inverse kinetics model.
14. "BAL-INV KIN" is the difference between "BALANCE" and "INVERSE KIN."
15. "TEMPERATURE" is the reactor coolant outlet temperature.
16. "BAL RR CONT" is the recommended reg rod action based on the reactivity constraint obtained from the reactivity balance model.
17. "INV RR CONT" is the recommended reg rod action based on the reactivity constraint obtained from the inverse kinetics model.

Each section which describes a simulation run is designated by three alphanumeric characters, SRn, where SR stands for simulation run and n = 1, 2, 3, and so on to designate the case number. The figures which show the results are also designated in the same fashion. In some cases, the figures may have to be designated by four alphanumeric characters. The fourth character takes on the values of A, B, C, and so on to designate subcases. In all the cases presented below, the transient is initiated by changing the set point at time zero.

4.1.3.1 Case SR1: Reg Rod Control, No Reactivity or Control Law Anomaly

The objective of this run is to demonstrate the operation of the control law reconfiguration. No reactivity or control law anomaly has been introduced. The reactor power is raised from 1 to 2 MW with the reg rod initially located at about 3 inches. The transient is initiated by changing the power set point at time zero. Both reg rod and shim blade drive motors are available (Configuration A). This initial condition corresponds to a transient substate where the demanded power is small (see Appendix E) and the reg rod position is "low" (substate TA1 or "SUBSTATE ID"=5). Thus, the reg rod is used to change the power. Selected plots from the results of this simulation run are shown in Figure 13. The power is changed from 1 to 2 MW with little or no overshoot. The control laws are satisfactorily reconfigured during the power maneuver.

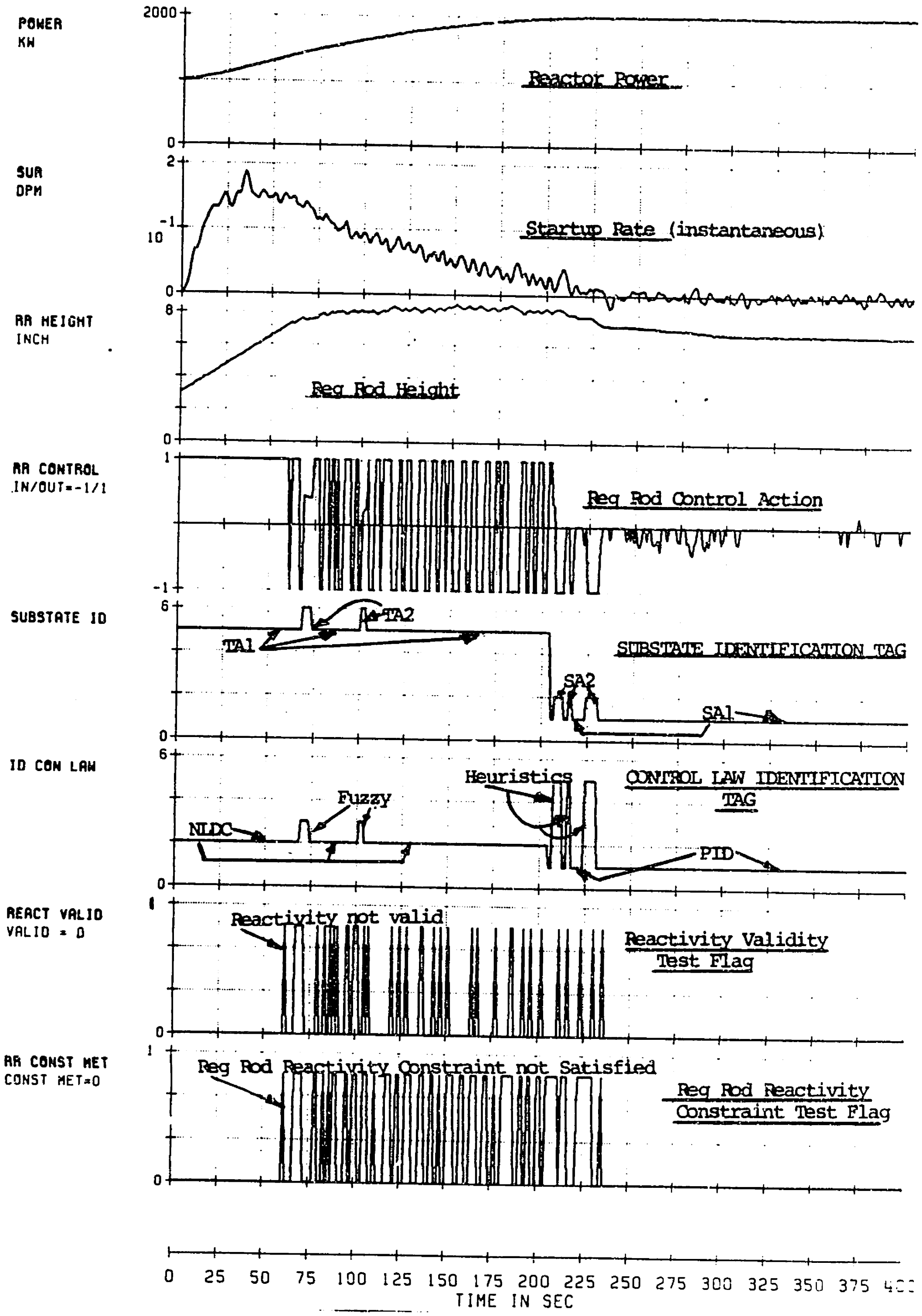

Figure 13. Case SR1 (Part 1 of 2): 1 to 2 MW power change using the reg rod, no reactivity or control law anomaly

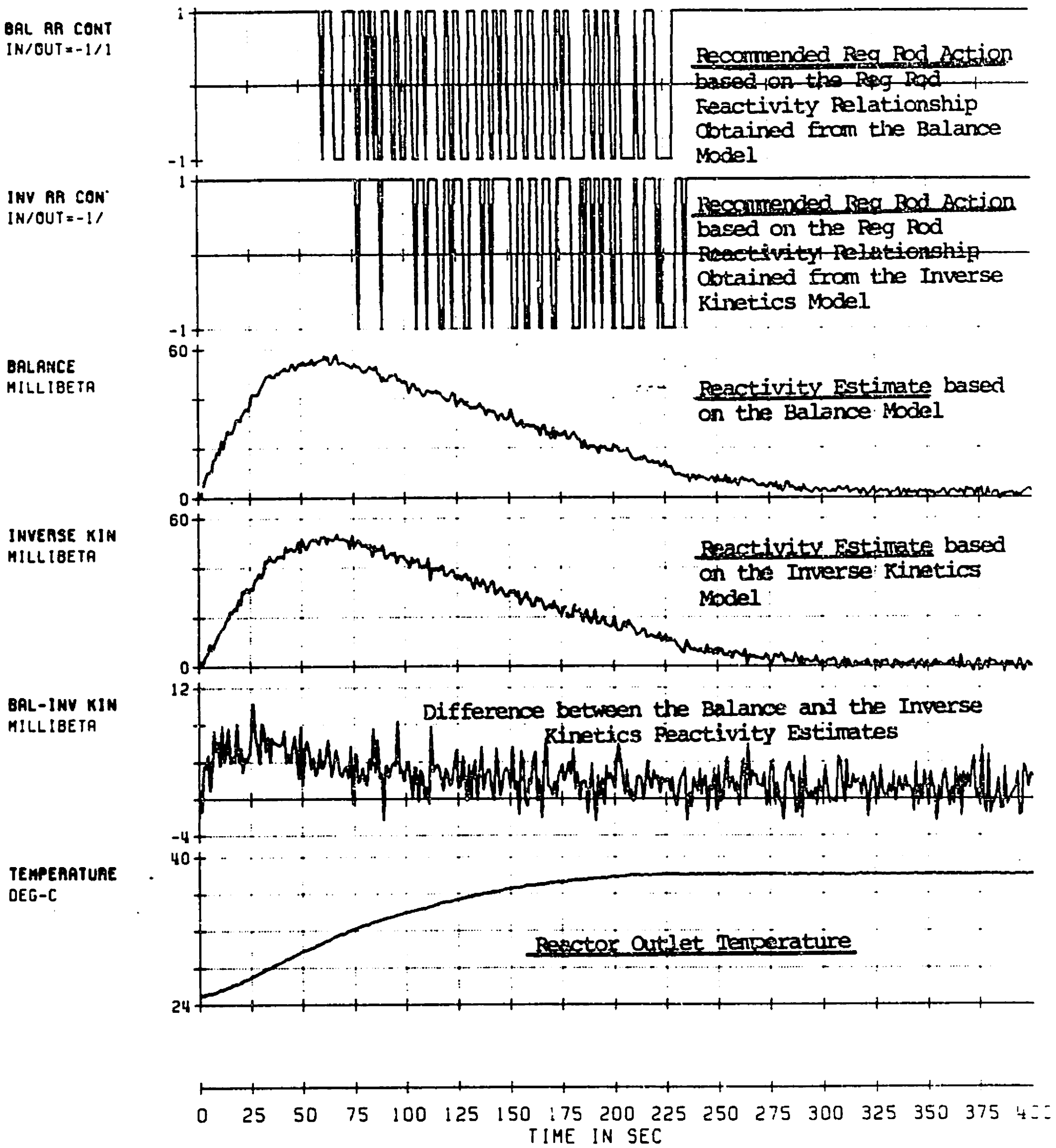

Figure 13. Case SR1 (Part 2 of 2): 1 to 2 MW power change using the reg rod, no reactivity or control law anomaly

During the transient part of the maneuver, the NLDC algorithm ("ID CON LAW"=2) is used as long as the reactivity estimate is valid (substate TA1 or "SUBSTATE ID"=5). The fuzzy algorithm ("ID CON LAW"=3) is used in a few instances when the reactivity has been declared invalid (substate TA2 or "SUBSTATE ID"=6). As discussed in Chapter 3 and Appendix C, the NLDC algorithm insures that the reactivity constraint, associated with the control mechanism in use, is always satisfied. For power increase, the control mechanism is withdrawn if the reactivity constraint is satisfied and inserted if the reactivity constraint is violated. In both cases, the control mechanism is moved at its full speed. The NLDC algorithm does not incorporate the multiple consecutive occurrence (MCO) criterion in making its decision. A "buffer" region (see Appendix C) or an "instruction" section [Bernard, 1984] is not used in this version of the NLDC, thus a lot of movement on the control mechanism can be observed. The fuzzy algorithm, on the other hand, is used whenever the reactivity is not valid, although it is also applicable regardless of the status of the reactivity information. However, it does not insure that the reactivity constraint is satisfied at all times. As opposed to the NLDC, the fuzzy algorithm can move the control drive mechanism at a fraction of full speed. Thus, its recommended control action, as shown in the control action plot, appears smoother as compared to that by the NLDC.

As discussed in Appendix D, the reactivity is declared valid if all three conditions are satisfied: 1) the difference between the reactivity estimate based on the balance model, ρ_{BAL}, and that of inverse kinetics, ρ_{INV}, is less than a specified threshold 2) the recommended reg rod control action based on the reg rod reactivity constraint (at the power set point) as derived from ρ_{BAL} is identical to that of ρ_{INV}, 3) the shim blade counterpart of the second condition is satisfied. As shown in the "BAL-INV KIN" plot (i.e., the difference between ρ_{BAL} and ρ_{INV}), the difference between the two estimates is within the threshold of 25 millibeta. This threshold has been chosen based on the results of previous simulation studies. However,as shown in "BAL RR CONT" and "INV RR CONT" plots, the recommended reg rod actions based on the reg rod reactivity constraint relationships, as obtained from ρ_{BAL} and ρ_{INV}, are not identical. Therefore, the reactivity is declared invalid. The "REACT VALID" plot shows the single point test result of the reactivity validation procedure. It set to zero if the single point test is declared valid and to 1 otherwise. A multiple consecutive occurence (MCO) test is used to declare an invalid reactivity condition. The use of the MCO test has minimized the switch over from one substate or control law to another as shown in "SUBSTATE ID" and "ID CON LAW" plots. A threshold of 3 has been chosen as a tradeoff between time delay and false declaration.

The plant operating condition has changed from transient to steady state after the steady state criteria are satisfied for several consecutive times as shown in the "SUBSTATE ID" plot. The MCO threshold has been set to 5 based on previous simulation and experimental trials. At the early part of "steady state" operation (around 205 to 230 seconds), the reg rod reactivity constraint has been violated. This corresponds to steady substate SA2 ("SUBSTATE ID"=2). The reg rod is inserted as recommended by a heuristic-based procedure as shown in reg rod action plot ("RR CONTROL"=-1) and control law identification tag plot ("ID CON LAW"=5). The plant operating condition (POC) has switched to SA1 ("SUBSTATE ID"=1) once the constraint is satisfied and the PID algorithm ("ID CON LAW"=1) is used. This phenomenon is again repeated for two more times. The plant operating substate eventually settled to SA1. Since the PID has satisfied the steady state performance criterion (i.e., the power has not drifted away from the desired setpoint), the reconfiguration logic continuously selects this control law throughout the end of the simulation.

Although the MCO criterion has been implemented, a frequent reconfiguration from NLDC to fuzzy algorithm and vice versa can still be observed especially during the transient portion of the maneuver. Despite the switch over described above, the power response is not affected, as observed from the results of a similar run where the NLDC is used all the time during the transient portion of the maneuver. One way to further minimize the switch over from the valid to invalid reactivity substate and vice versa is to increase the MCO threshold. This procedure, however, is expected to result in a longer time delay to reconfigure from one control law to another as a result of a change in the reactivity information. The resulting time delay is expected to change the behavior of the power response especially near the end of the transient part of the maneuver. For example, the use of the fuzzy algorithm does not insure that the reactivity constraint, associated with the control mechanism, is satisfied at all times. A large time delay to switch over from the fuzzy to the NLDC algorithm may lead to a slight overshoot in the power response, especially during on-line tests. A better approach to minimize the switch over, without introducing a large time delay, is to perhaps improve the reactivity validation scheme. As observed from the "BAL RR CONT" and "INV RR CONT" plots, the recommended control action is very sensitive to the reactivity estimate.

In summary, the multiple consecutive occurence (MCO) criterion has minimized the unnecessary switch over from one operating condition to another as shown by the single test reactivity validity ("REACT VALID") and reg rod reactivity constraint ("RR CONST MET") plots. However, the reactivity validation scheme may have to be upgraded to further minimize the switch over from TA1 (reactivity valid) to TA2 (reactivity invalid) and vice versa. A steady state switch over from SA1 to SA2 and vice versa, especially during the early part of steady state operation, may be also avoided if the MCO threshold for the steady state criteria is increased, as shown in previous simulation runs.

4.1.3.2 Case SR2: Reg Rod Control with Reactivity Anomaly

The objective of this simulation run is to demonstrate the operation of the reconfiguration controller in the presence of a reactivity anomaly. This case is similar to that in Case SR1 except that the reactivity estimate is forced to be invalid. Two approaches have been used. The first approach sets the threshold used in comparing the balance model and the inverse kinetics model to zero; thus, the reactivity is always declared invalid. The second approach involves the modification of a reactor model parameter; more specifically, the effective delayed neutron fraction, β, is set to a smaller value. This results in a faster reactor dynamics as compared to the nominal model. Therefore the reactivity coefficients assumed in the balance and the β assumed in the inverse kinetics model are all inaccurate. The two subcases, which correspond to these two approaches, are labelled subcase SR2A and subcase SR2B respectively.

Selected plots of the results are shown in Figure 14 and Figure 15 . In both cases, the power is successfully changed from 1 to 2 MW. The controller has satisfactorily reconfigured during the course of the maneuver. A slight overshoot has been observed as compared to that in Case SR1. This behavior is expected since the fuzzy algorithm does not insure that the reg rod reactivity constraint is satisfied at all times. As compared with the NLDC, the fuzzy algorithm, however, has minimized the reg rod motion as shown in the "RR CONTROL" plot.

During the transient part of the maneuver, the control law has switched from the NLDC to fuzzy algorithm once the reactivity has been declared invalid. The relay algorithm ("ID CON LAW"=4) is then used once the steady state criteria are satisfied (SA3, "SUBSTATE ID"=3). The plant operating substate has eventually switched to SA1 (reactivity is valid and the reactivity constraint relationships are satisfied), as designed, after a prolong steady state operation. The rationale for this switch is to achieve a smoother control. The PID algorithm takes over from hereon and successfully regulates the power at the desired power level.

In the case when the β of the reactor model is modified, the reactivity estimate is initially declared valid. The reactivity is eventually declared invalid when the recommended reg rod control actions based on reactivity constraint relationship, as derived from ρ_{BAL} and ρ_{INV}, are no longer identical. It should be noted that the difference between the balance and inverse kinetics estimates has also exceeded the threshold of 25 millibeta. A steady state behavior similar to that in Case SR2A can be observed.

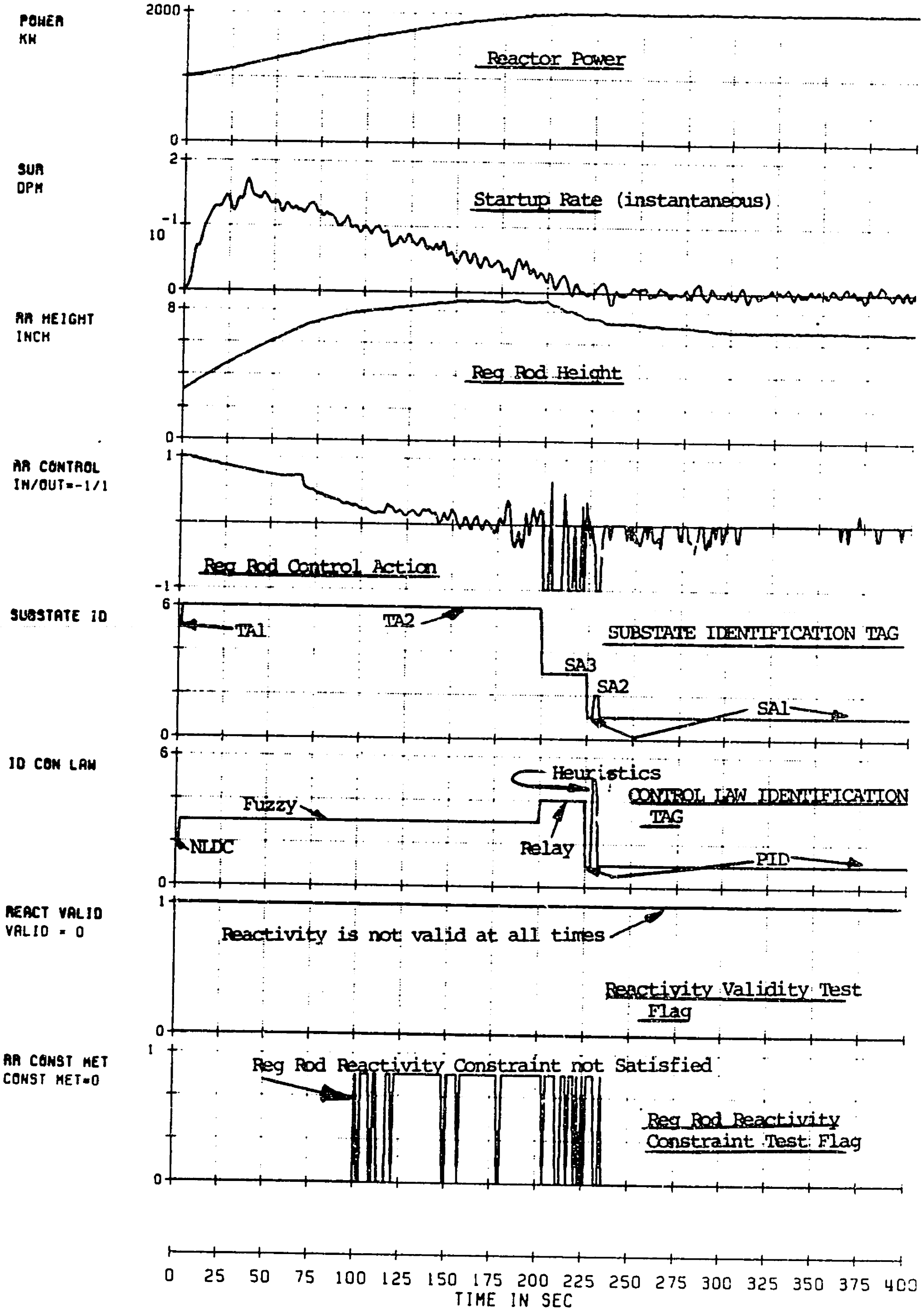

Figure 14. Case SR2A (Part 1 of 2): 1 to 2 MW power change using the reg rod, reactivity anomaly, reactivity deviation threshold is set to zero

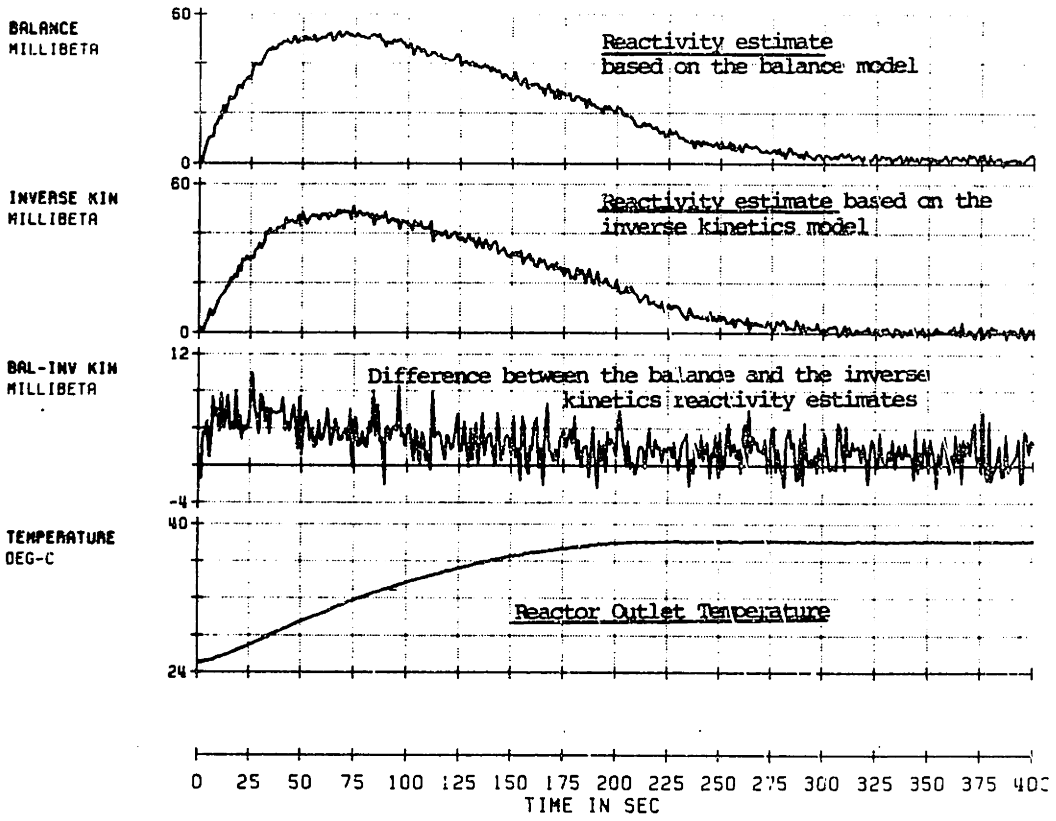

Figure 14. Case SR2A (Part 2 of 2): 1 to 2 MW power change using the reg rod, reactivity anomaly, reactivity deviation threshold is set to zero

4.1.3.3 Case SR3: Reg Rod Control with Control Anomaly at Steady State

The objective of this simulation run is to demonstrate the operation of the performance evaluator module of the reconfiguration logic at steady state, in particular steady substate SA1 (reactivity is valid and reactivity constraints are satisfied). The transient scenario is similar to that in the first two cases. However, control law anomalies have been introduced once steady substate SA1 is reached. The set of control

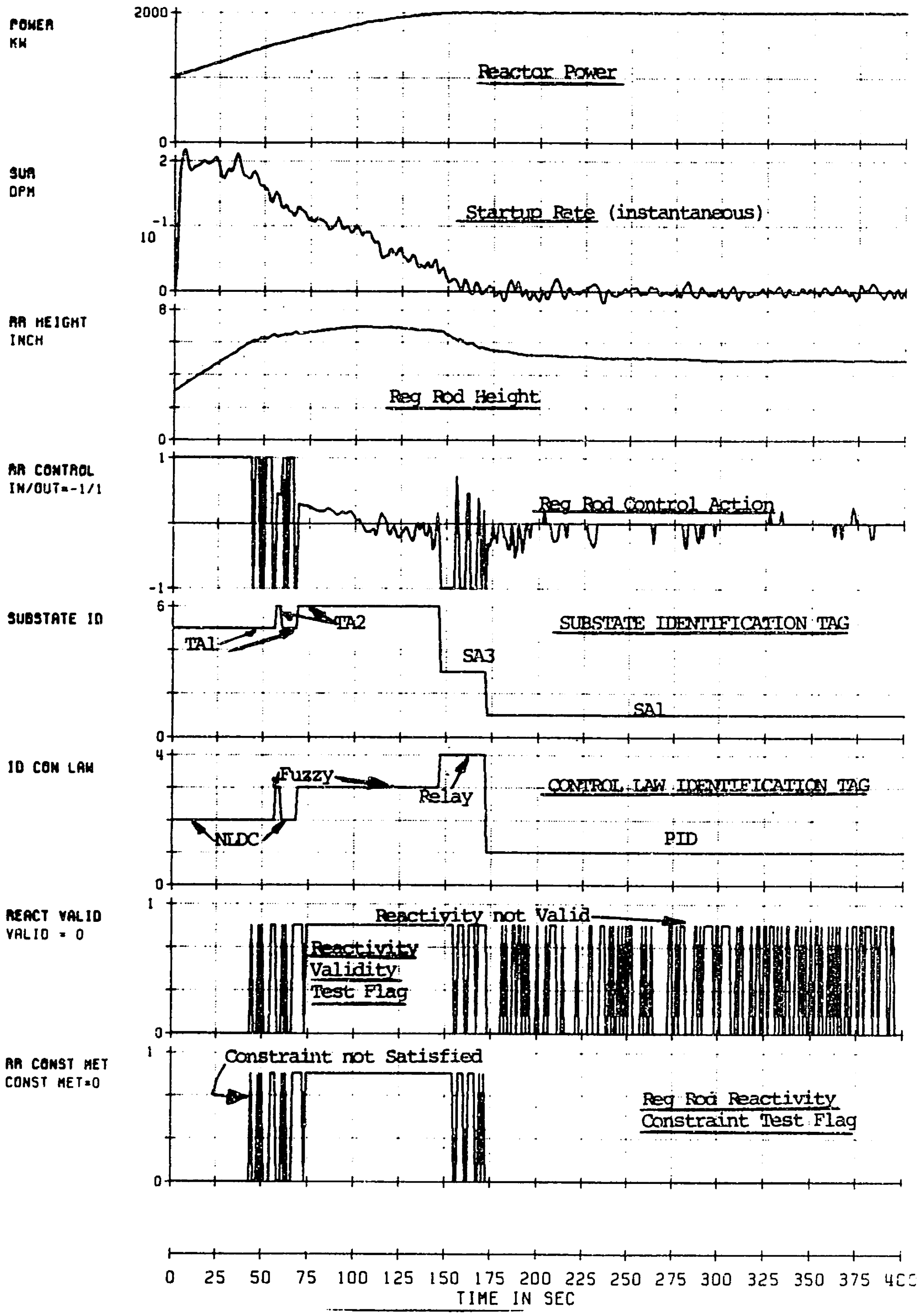

Figure 15. Case SR2B (Part 1 of 2): 1 to 2 MW power change using the reg rod, reactivity anomaly, β of the reactor model has been changed

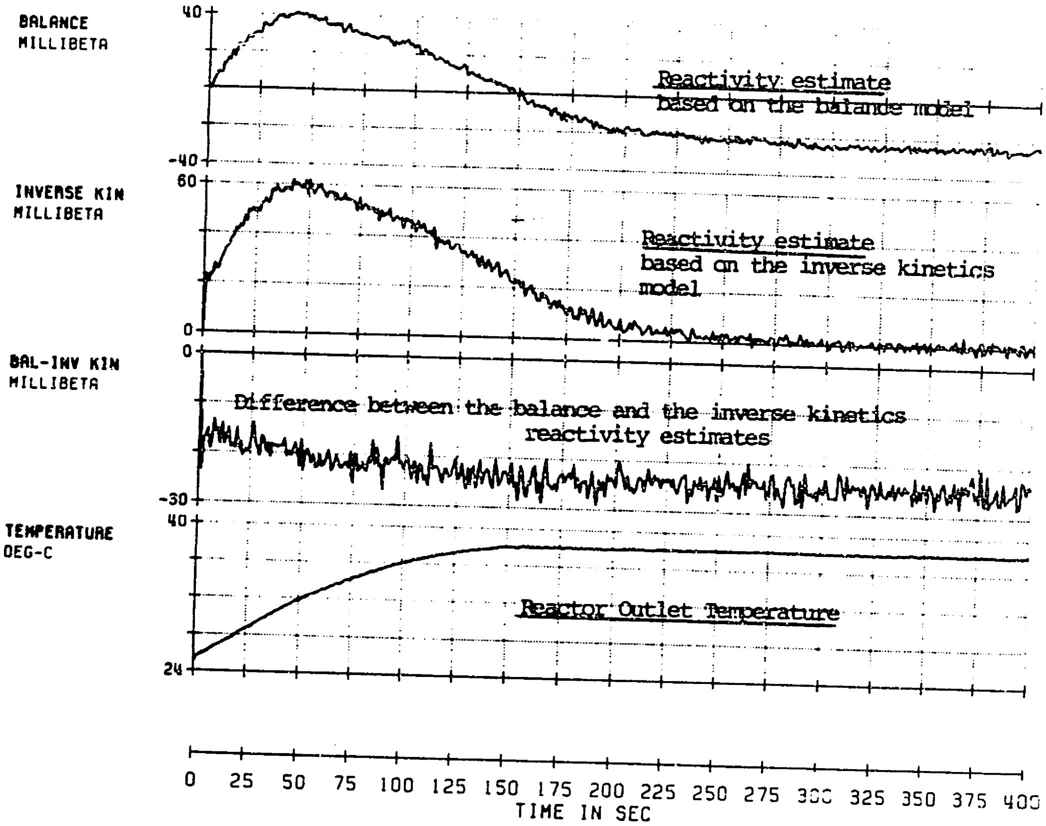

Figure 15. Case SR2B (Part 2 of 2): 1 to 2 MW power change using the reg rod, reactivity anomaly, β of the reactor model has been changed

options for SA1 includes the PID, fuzzy (for power increase only), and the relay algorithms. Three subcases have been considered:

1. Improperly tuned PID (large positive gain)
2. Improperly tuned PID (large negative gain)
3. Improperly tuned PID (large positive gain) and anomaly in the fuzzy algorithm.

An anomaly is introduced to the PID by deliberately changing the gain associated with the reactivity term (derivative) by a factor of 10^3. This situation corresponds to an improperly tuned PID. A large positive gain will result in full rod insertion (withdrawal) whenever the reactivity is positive (negative). The opposite situation is true for a large negative gain. An anomaly is also introduced in the fuzzy algorithm by deliberately commanding a full rod withdrawal to simulate incorrect formulation of the fuzzy subsets or rule base. The reward-penalty algorithm, as presented in Appendix E, is used. For this particular case, the learning coefficients, a and b, are both set to 0.4 based on earlier simulation and experimental trials.

Selected plots of the results for subcase SR3A are shown in Figure 16. The power has been successfully changed from 1 to 2 MW with little or no overshoot. The power has been properly regulated despite the presence of a control law anomaly. The transient behavior is very similar to that in case SR1. The reg rod reactivity constraint based on the power set point has been violated (substate SA2, "SUBSTATE ID"=2) at the early part of steady state operation (around 200 seconds), causing the reg rod to be inserted. Once the power dynamics settle down to substate SA1 ("SUBSTATE ID"=1), the PID ("ID CON LAW"=1) is selected based on the recommendation of the plant operating condition identifier (POCI) module. Because of the anomaly introduced in the PID, the reg rod is continuously inserted and the power drifts in the downward direction. The reward-penalty algorithm penalized the probability associated with the PID and incremented those of the fuzzy and the relay algorithms. Because of the way the maximum probability search routine has been coded, the fuzzy algorithm (the second element of the selection array) is eventually chosen ("ID CON LAW"=3). The fuzzy algorithm corrected the downward drift; thus, satisfying the performance criterion. However, the fuzzy algorithm also fails to maintain the power at the desired level within a given band (20 KW). An examination of the fuzzy algorithm rule base and membership functions indicates that the algorithm has a tendency to insert the rod for small positive startup rate near

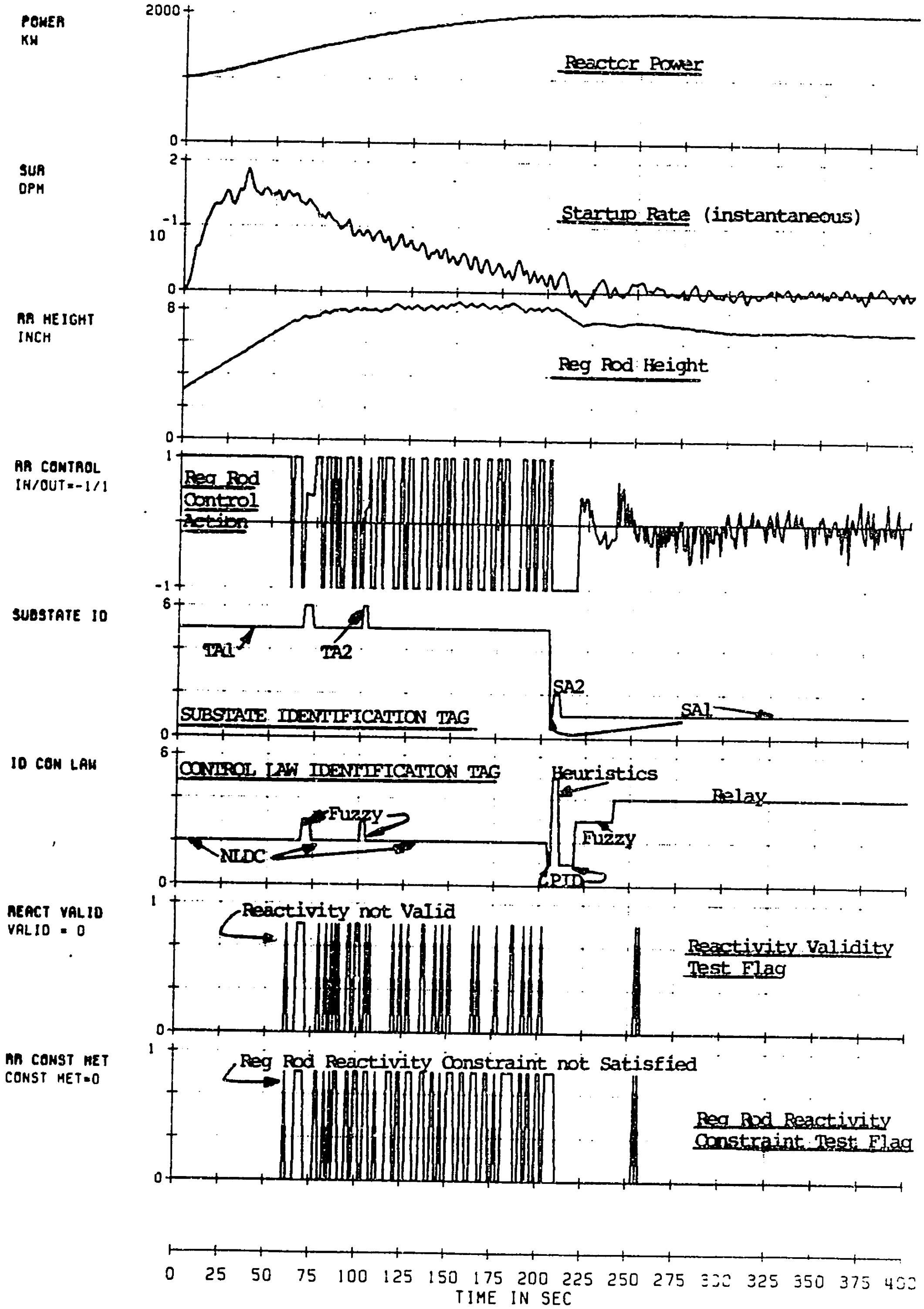

Figure 16. Case SR3A (Part 1 of 2): Control Anomaly at Steady State (large positive gain) at Steady State

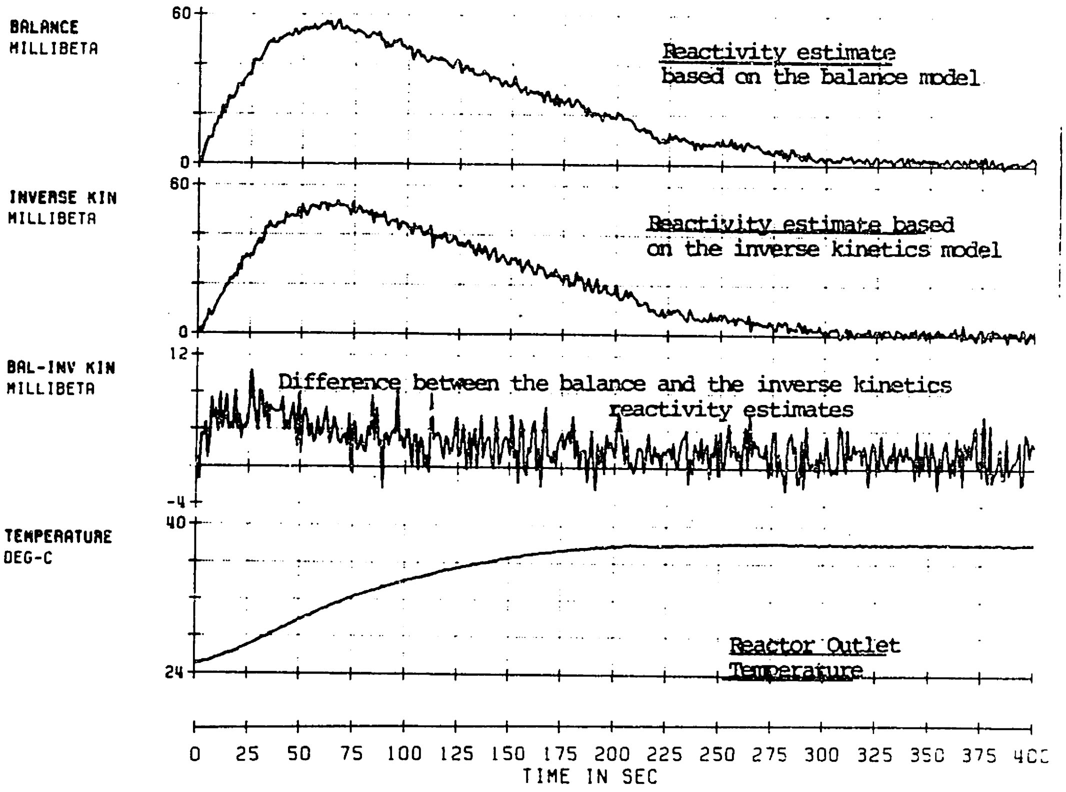

Figure 16. Case SR3A (Part 2 of 2): Control Anomaly at Steady State (large positive gain) at Steady State

the desired set point (see "RR CONTROL" plot at around 230 to 240 seconds). Furthermore, the power deviation needed to activate the rule to correct this action appears to be larger than the band specified by the performance criterion (20 KW). The relay algorithm eventually takes over and satisfactorily regulates the power within the specified band.

A sensitivity study on the learning coefficients has been conducted. The size of the learning coefficients determines the rate of convergence to the appropriate action. In all the cases considered, the control selection converges to the relay algorithm. The order of the backup control option has also been changed (i.e., the relay algorithm is set as the second element of the selection array instead of the fuzzy algorithm). In this case, the control selection converges to the second option for all values of the learning coefficients.

The set of results for case SR3B is shown in Figure 17. The power is properly regulated despite the presence of the control anomaly. It is very similar to that in SR3A. Because of the nature of the anomaly introduced in the PID, the reg rod is withdrawn. This action causes the reg rod constraint to be violated (substate SA2). The reg rod is inserted to satisfy the constraint, thus, maintaining a safe operation. A penalty is given to the PID each time an overriding control is implemented. The fuzzy algorithm takes over but fails to maintain the power within the desired band as in Case SR3A. The relay algorithm eventually takes over and satisfactorily regulates the power within the specified band.

In subcase SR3C, the anomaly has been introduced to both the PID and the fuzzy algorithms. Selected plots of the results are shown in Figure 18. The controller successfully reconfigured. The power has been regulated properly despite the control anomalies. A behavior similar to that in case SR3B can be observed. The relay algorithm is eventually chosen.

4.1.3.4 Case SR4: Reg Rod and Shim Blade Control, No Anomaly

The objective of this simulation run is to demonstrate the use of shim blade and reg rod concurrently. This situation corresponds to plant configuration A, as discussed in Chapter 3. No reactivity or control anomaly has been simulated. The power is changed from 1 to 2 MW with the reg rod initially at about 8 inches. As discussed in Chapter 3 and Appendix E, this situation corresponds to a "reshim" condition, substate TA3 ("SUBSTATE ID"=7). Selected plots of the results are shown in

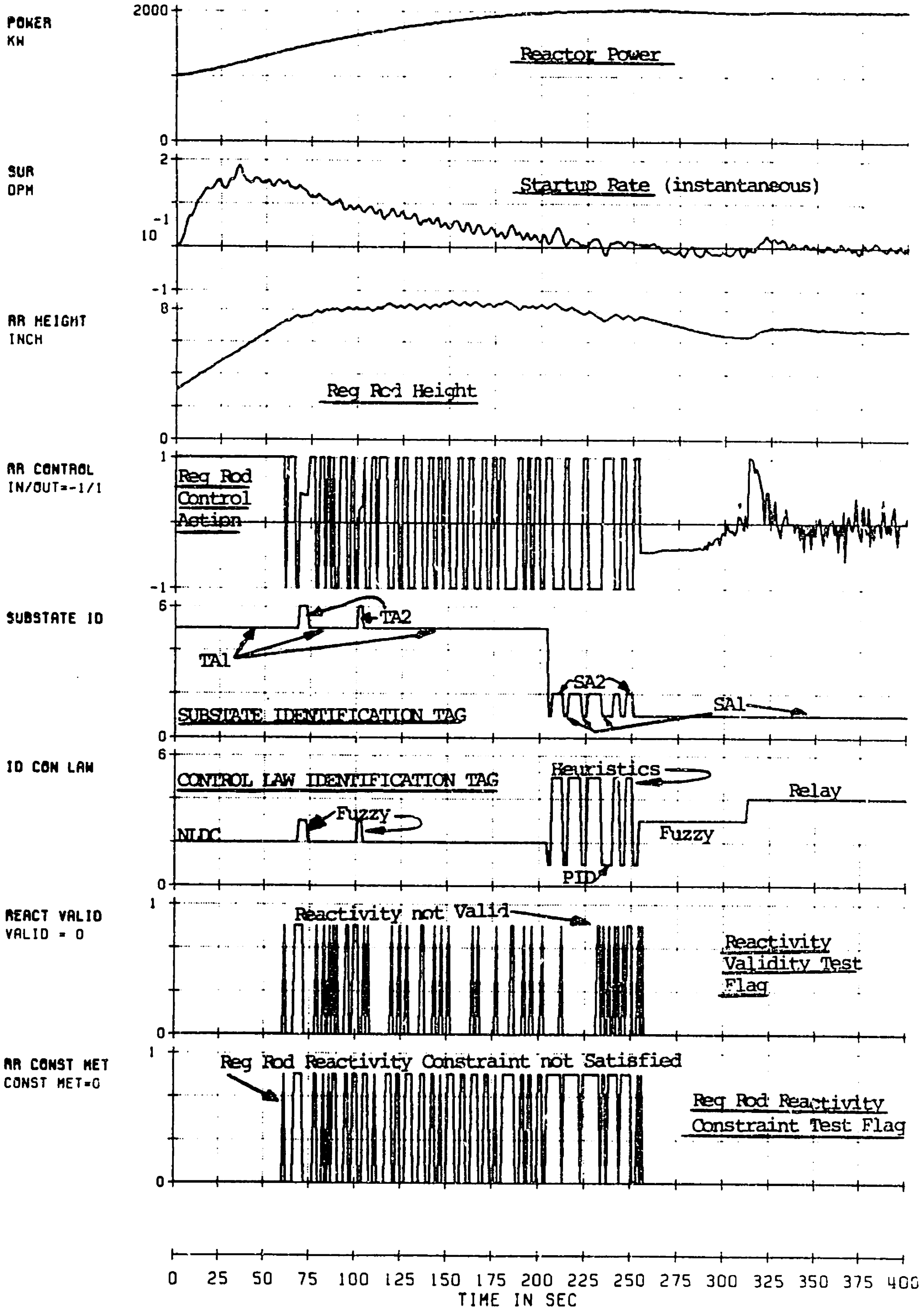

Figure 17. Case SR3B (Part 1 of 2): Reg Rod Control with Control Anomaly (large negative gain) at Steady State

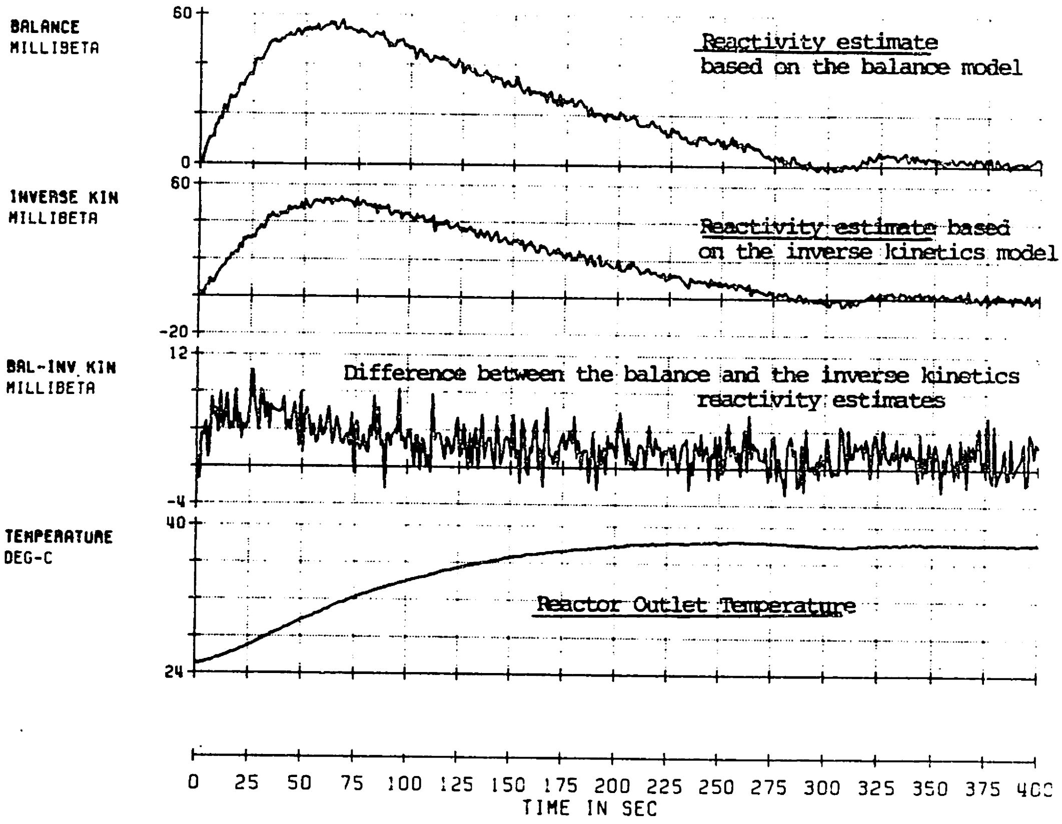

Figure 17. Case SR3B (Part 2 of 2): Reg Rod Control with Control Anomaly (large negative gain) at Steady State

Figure 19. The controller has successfully reconfigured and controlled the power during the course of the power maneuver. The shim blade is adjusted using the NLDC algorithm ("ID CON LAW"=7, shim blade). The reg rod is driven to its desired position as discussed in Appendix E. The reg rod eventually takes over the control once reactivity constraint relationships (based on the power set point) and the power and reg rod height conditions, as discussed in Appendix E, are all satisfied.

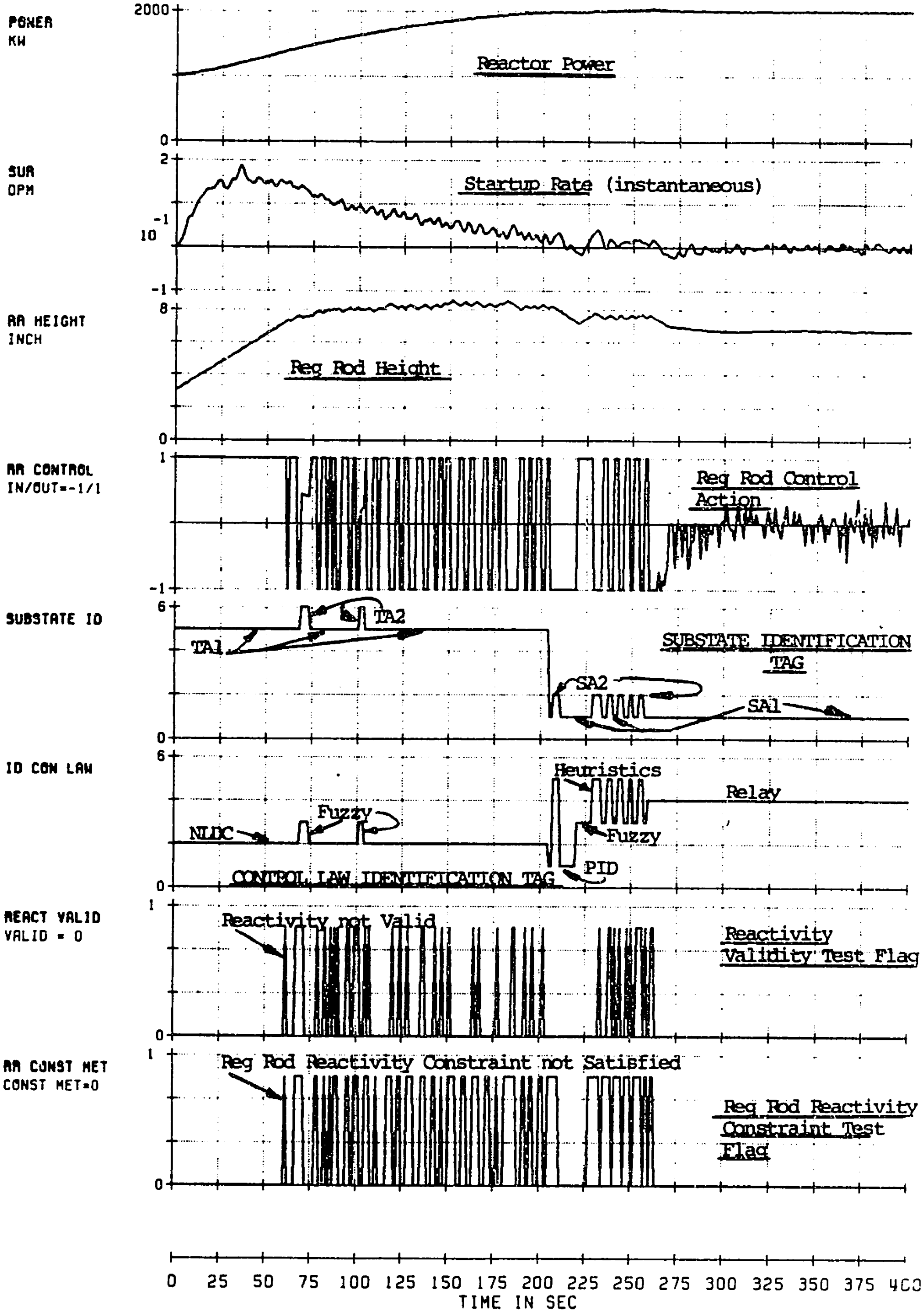

Figure 18. Case SR3C (Part 1 of 2): Reg Rod Control with Two Control Anomalies at Steady State

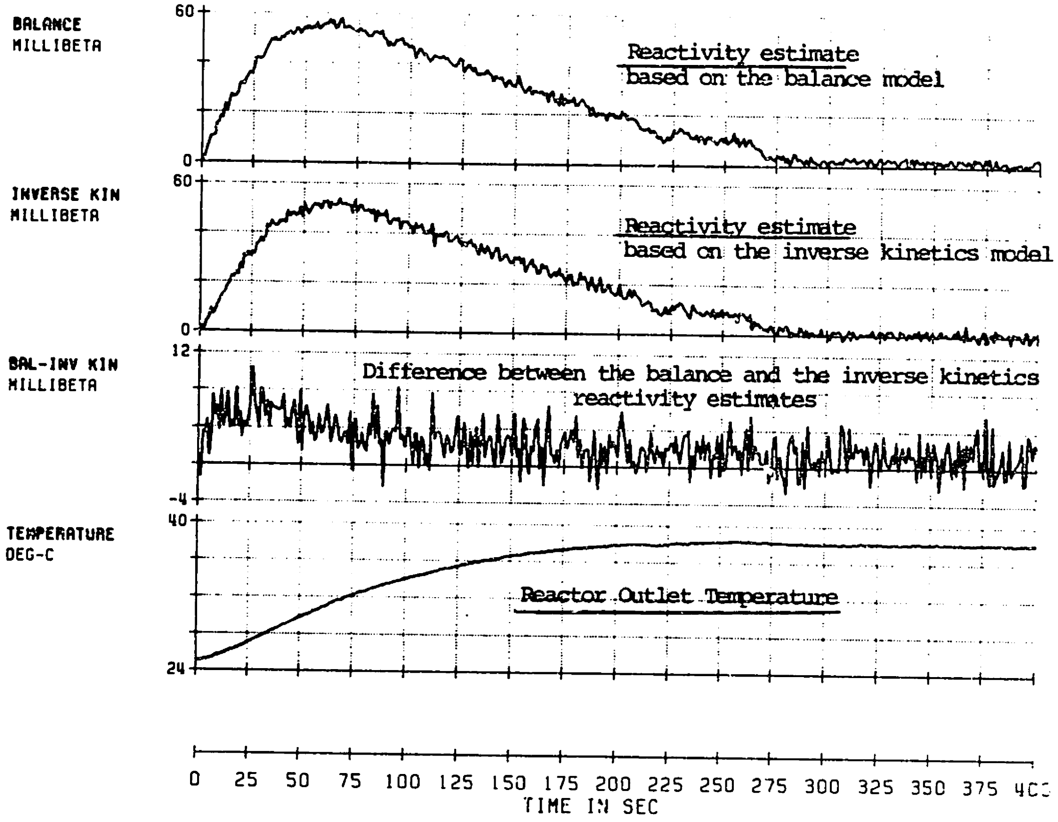

Figure 18. Case SR3C (Part 2 of 2): Reg Rod Control with Two Control Anomalies at Steady State

4.1.3.5 Case SR5: Reg Rod Control, Control Anomaly during a Transient State

The objective of this simulation run is to demonstrate the operation of the performance evaluator module of the reconfiguration logic during a transient condition. The power is changed from 1 to 2 MW using the reg rod. A reactivity anomaly is introduced so that the plant substate is classified as TA2 ("SUBSTATE ID"=6), small power change and the reactivity estimate is invalid. The threshold, that is used to compare the difference between the balance and the inverse kinetics estimates of

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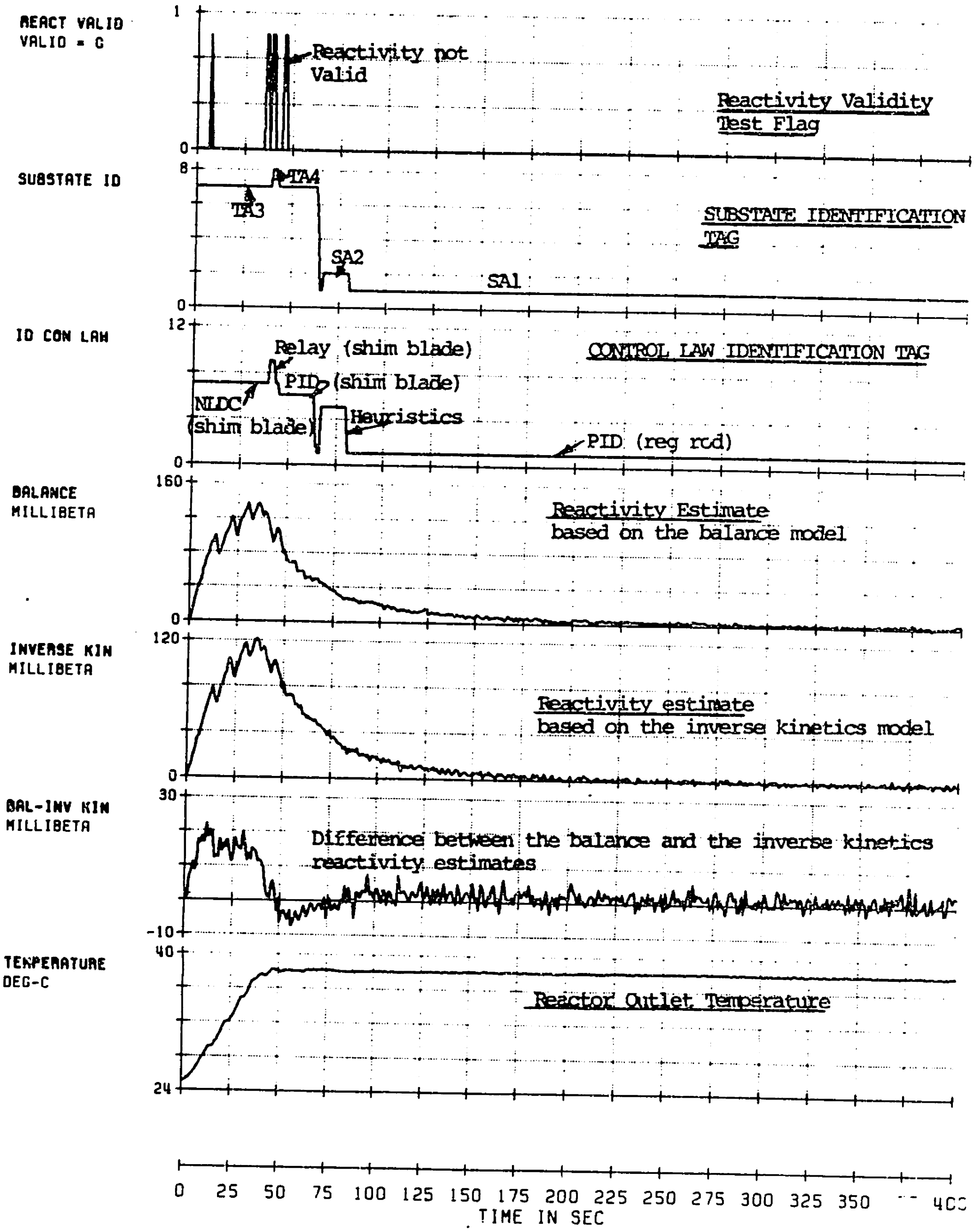

Figure 19. Case SR4 (Part 2 of 2): Reg Rod and Shim Blade Control, No Control Law or Reactivity Anomaly

reactivity, is set to zero. Furthermore, the effective delayed neutron fraction, β, for the reactor model has been changed from 0.00786 to 0.00766. For this substate, the viable control options include the fuzzy, relay, and the NLDC. The conservative constraint based on the power set point is used in the NLDC despite the fact the reactivity is declared invalid.

Selected plots of the results are shown in Figure 20. The controller properly reconfigures during the various stages of the maneuver and despite the presence of the control anomaly during the transient stage. Based on the recommendation of the plant operating condition identifier module, the fuzzy algorithm is implemented ("ID CON LAW=3") once the reactivity has been declared invalid (substate TA2). At about 1400 KW, an error in the fuzzy algorithm is introduced. The reg rod has been deliberately commanded to insert at full speed. This is a simple way to introduce an anomaly (Note: Another way of doing this is to update the rule base and the membership functions associated with the fuzzy subsets.). The anomalous control signal has caused the power to slowly level off prematurely. Such plant response indicates that the current control law is failing to meet the performance criterion, as discussed in Appendix F, and thus the control is penalized. The controller has eventually reconfigured to the relay algorithm ("ID CON LAW" has changed from 3 to 4) for the rest of the transient part of the maneuver. The 2 MW level is reached with little or no overshoot. The control action obtained from the relay algorithm is monitored by the conservative reg rod reactivity constraint relationship based on the power set point, thus preventing an overshoot.

4.1.3.6 Case SR6: Large Power Change, Reg Rod and Shim Blade Control

The objective of this simulation run is to demonstrate the control strategy during a large power change. No control or reactivity anomaly has been simulated. Both reg rod and shim blade are assumed available

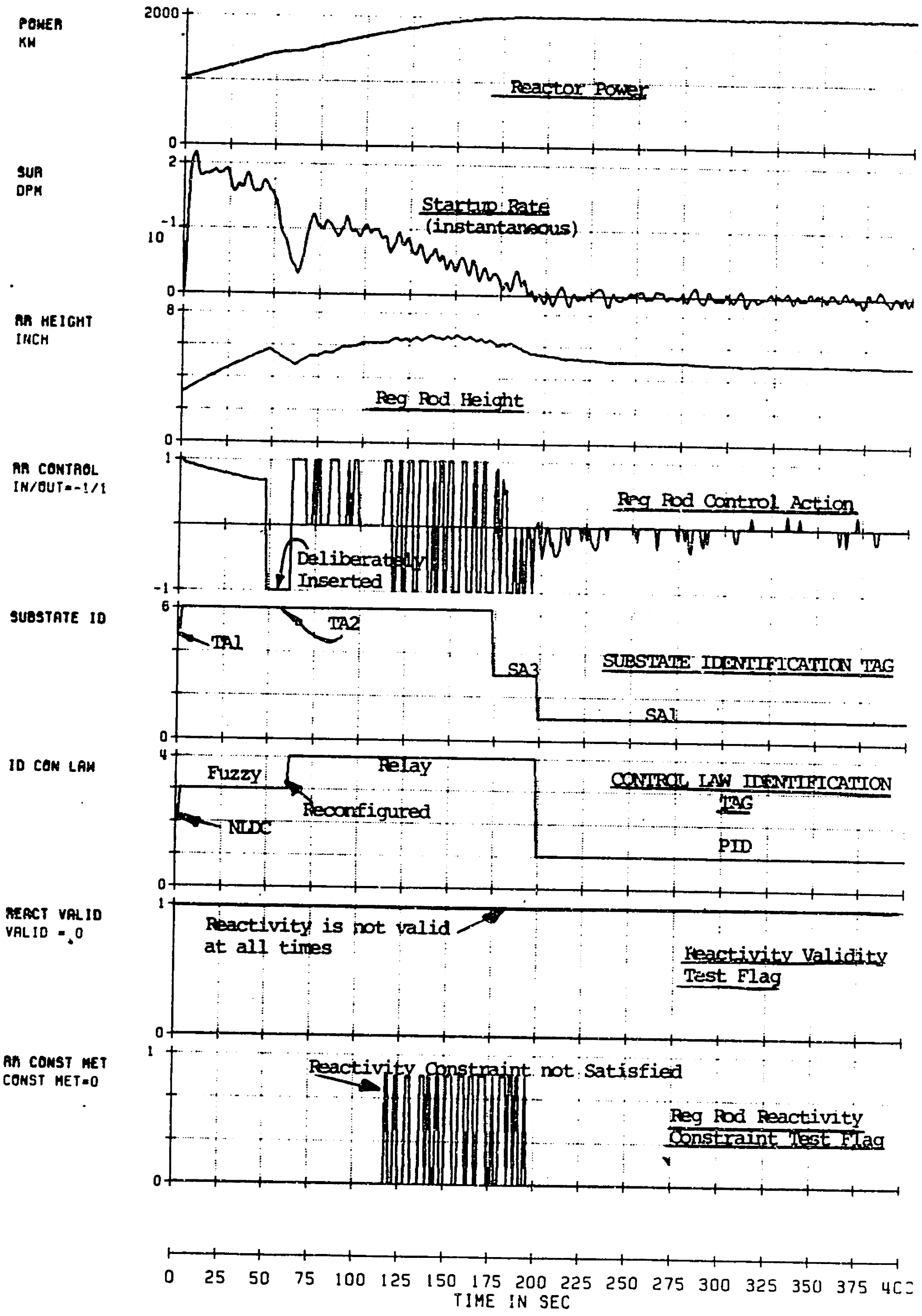

Figure 20. Case SR5 (Part 1 of 2): Reg Rod Control, Control Anomaly during a Transient State

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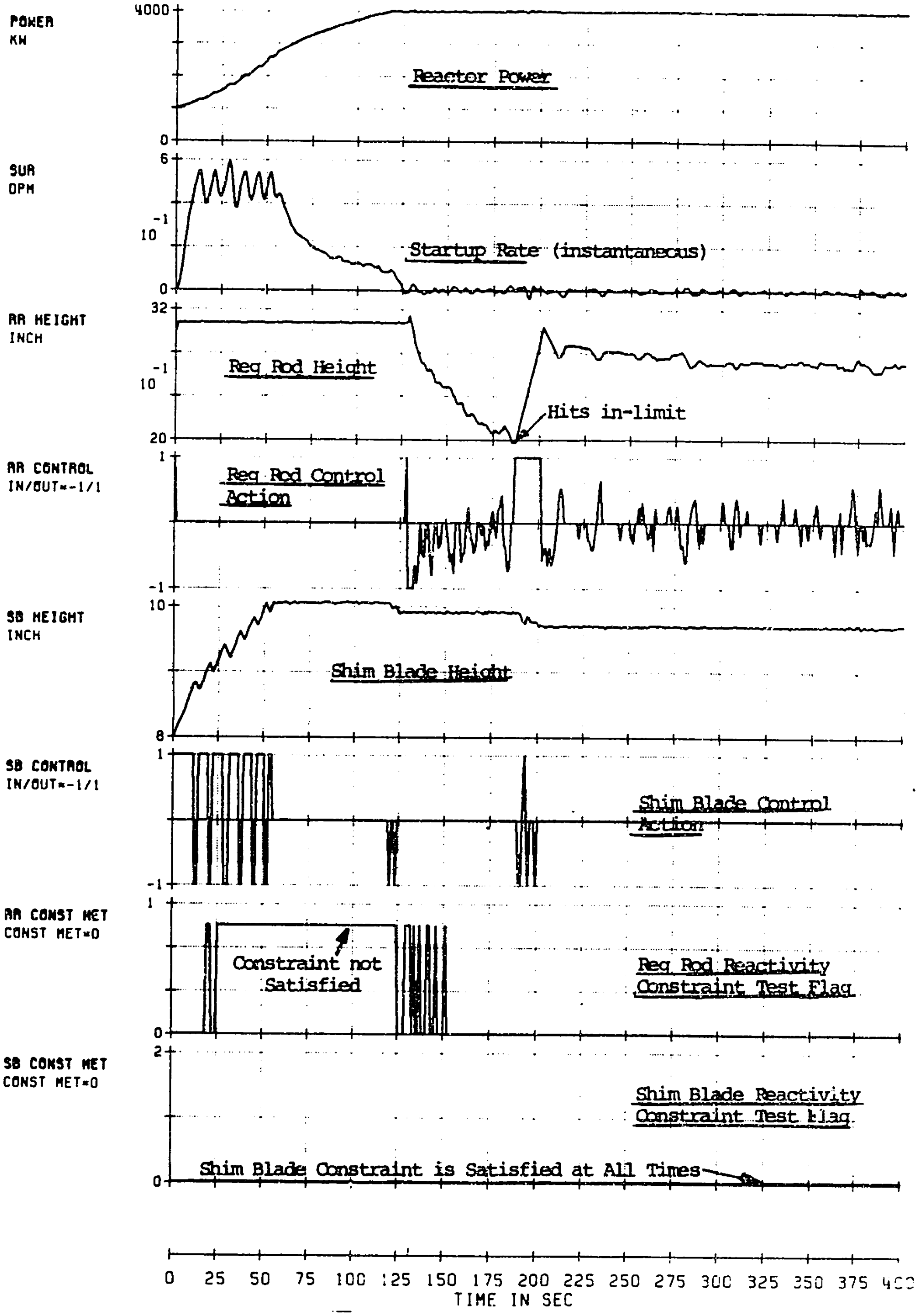

Figure 21. Case SR6 (Part 1 of 2): Large Power Change, Reg Rod and Shim Blade Control

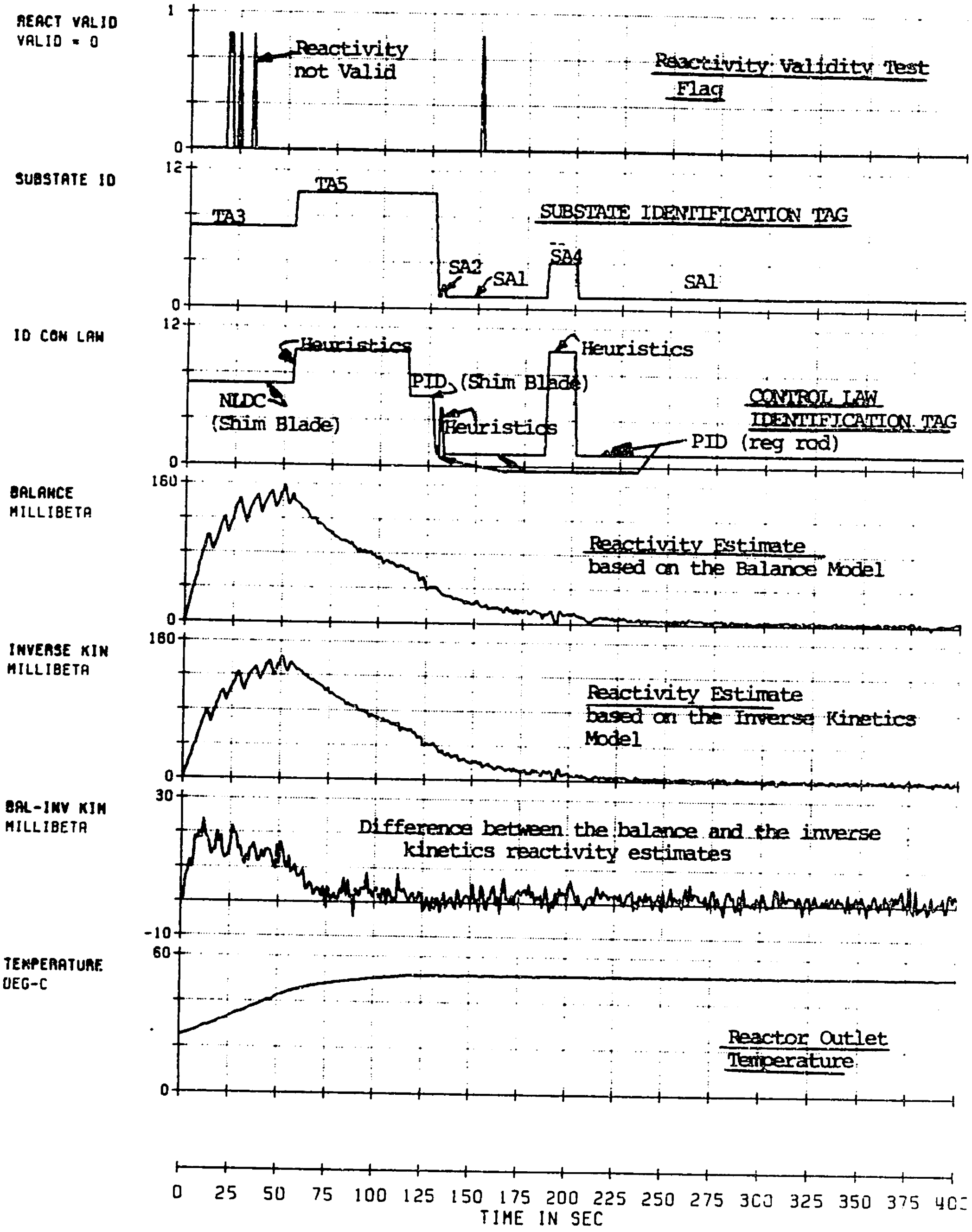

Figure 21. Case SR6 (Part 2 of 2): Large Power Change, Reg Rod and Shim Blade Control

desired set point, the shim blade is then adjusted by using the PID algorithm ("ID CON LAW"=6, shim blade). The control has eventually transfered from the shim blade to the reg rod once the specified reg rod position, power deviation conditions (see Appendix E), and the reactivity constraint relationships are satisfied. The steady state behavior is similar to that obtained from the previous runs. The PID algorithm ("ID CON LAW"=1, reg rod) is used to regulate the power. A rod insertion is commanded by the PID to compensate for the effects of the delayed neutrons. For this run, a reg rod saturation condition (substate SA4, "SUBSTATE ID"=4) has occurred. The reg rod hits the two inch in-limit at about 180 seconds as shown in the "RR HEIGHT" plot. A heuristic-based procedure is then used during this condition. The reg rod is withdrawn while the shim blade regulates the power. The resulting power response is coarser than that for conditions where the power is solely regulated by the reg rod. The reconfiguration logic then switched back to the PID algorithm once the desired reg rod position is reached.

4.1.3.7 Case SR7: Large Power Change, Shim Blade Control Only

The objective of this simulation run is to demonstrate the control strategy in situations when only the shim blade mechanism is available. This particular alignment is referred to as Configuration B. As mentioned in Chapter 3, the shim blade is driven by a fixed speed motor. An anomaly in the reactivity estimate is introduced by changing the effective delayed neutron fraction, β, used in the reactor model. In addition, the threshold used to compare the two reactivity estimates (i.e., reactivity balance and inverse kinetics) is set to zero. Selected plots of the results are shown in Figure 22. The power is successfully changed from 1 to 4 MW. The power response has not levelled off as smoothly as that in the case when the reg rod has been used. This is expected since the shim blade is worth much more than the reg rod and the drive motor used is a fixed speed rather than variable. The NLDC algorithm is initially used to adjust the power ("ID CON LAW"=7, shim blade). The control strategy reconfigures to the relay algorithm ("ID

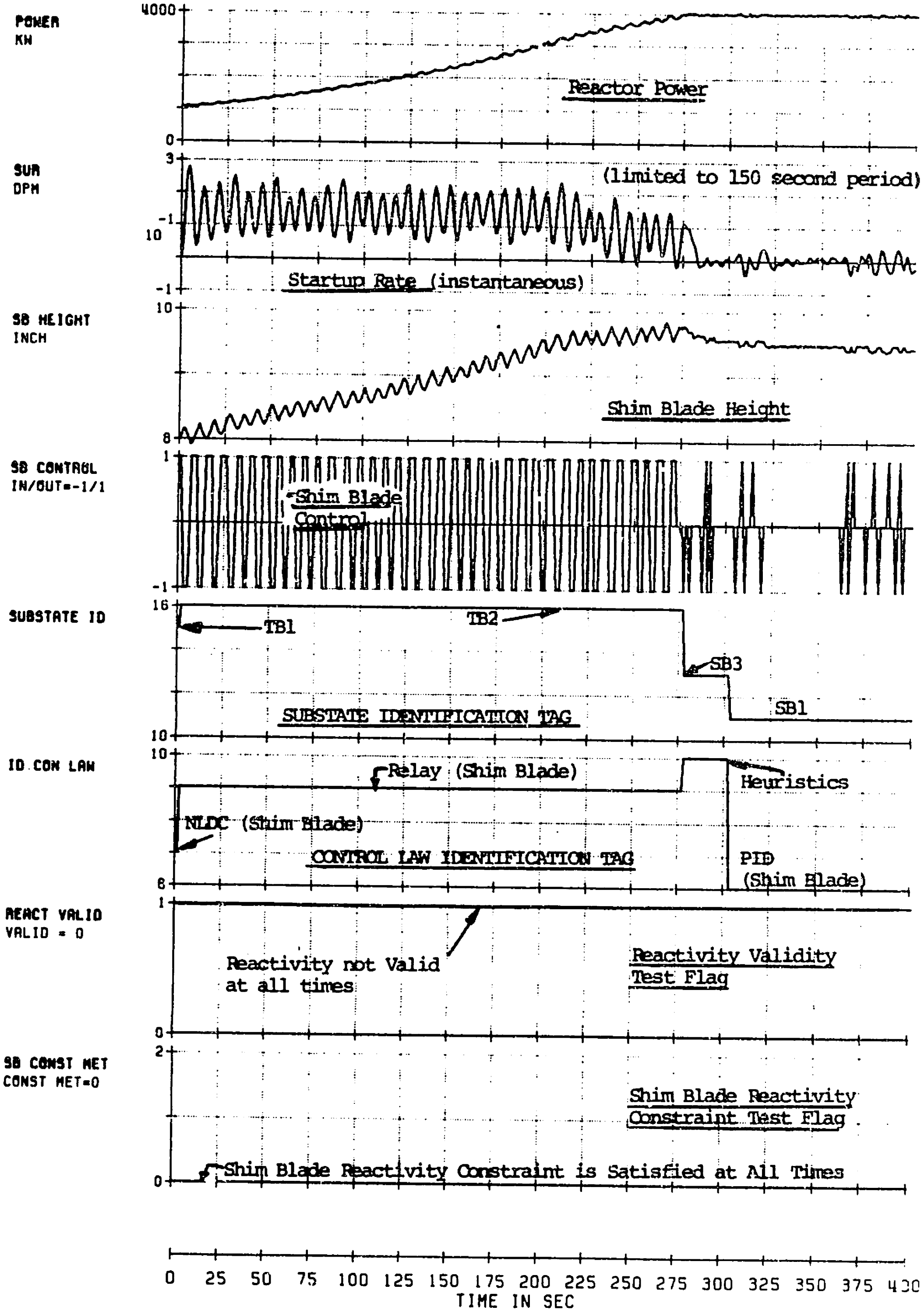

Figure 22. Case SR7 (Part 1 of 2): 1 to 4 MW Power Change, Shim Blade Control Only

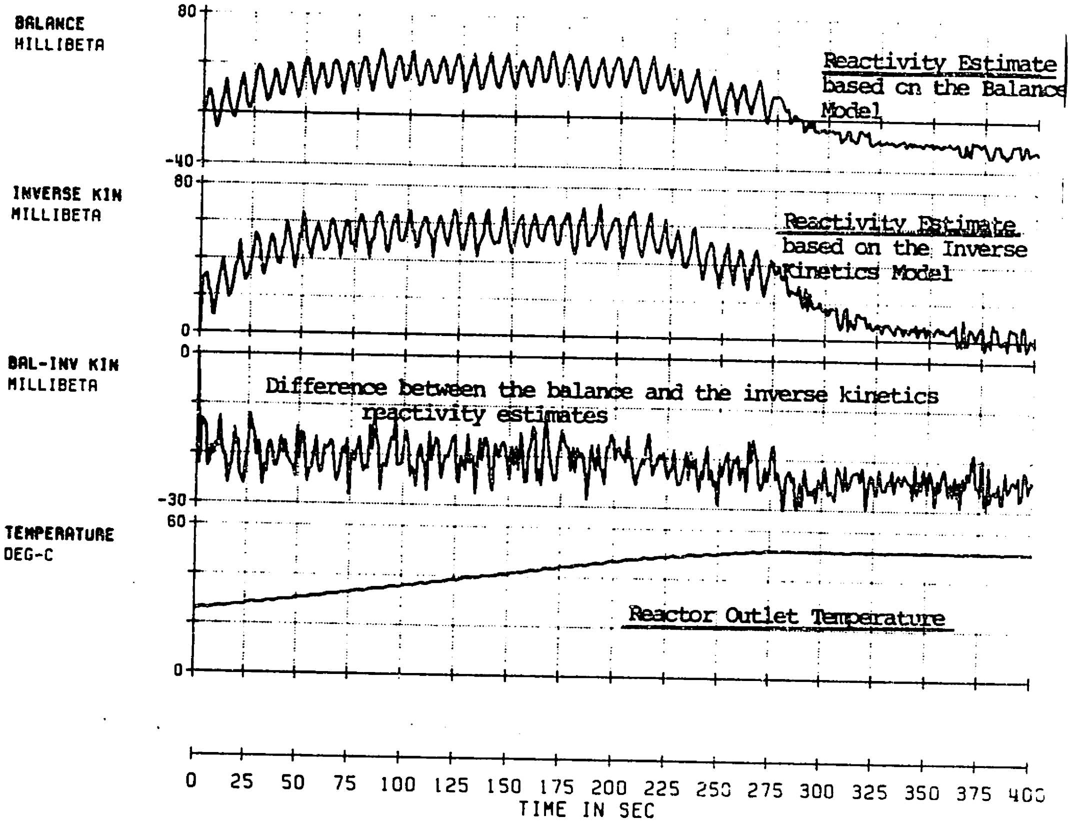

Figure 22. Case SR7 (Part 2 of 2): 1 to 4 MW Power Change, Shim Blade Control Only

CON LAW"=9, shim blade) after the reactivity is declared invalid. For this particular run, the relay algorithm limits the instantaneous period to 150 seconds. Furthermore, its operation is monitored by the "conservative" shim blade constraint which is based on the power set point. A shim blade withdrawal is not permitted if the reactivity constraint is violated. The desired power is eventually attained within the specified band. The PID algorithm ("ID CON LAW"=6, shim blade) is used to regulate th power after a prolong steady state operation.

4.1.3.8 Case SR8: Power Decrease, Reg Rod and Shim Blade Control

The objective of this simulation run is to demonstrate the operation of the reconfigurable control strategy during a power decrease maneuver. This demonstration shows a combination of the various scenarios presented in the earlier cases such as the simultaneous adjustment of the reg rod and shim blade and control law anomaly. Selected plots of the results are shown in Figure 23. The power is successfully decreased from 4 to 2 MW. The controller also properly reconfigures as a result of a change in demand, plant dynamics, and anomalous control law at steady state. The shim blade is used to decrease the power by implementing the NLDC algorithm ("ID CON LAW"=7, shim blade) while the reg rod is adjusted to its desired position. The shim blade implements the PID algorithm ("ID CON LAW"=6, shim blade) once the power becomes close to the desired set point. The control eventually transfers to the reg rod once the reactivity constraint relationships and the reg rod position and power deviation criteria are all satisfied. The PID algorithm ("ID CON LAW"=1, reg rod) then takes over once the steady substate SA1 (reactivity is valid and the reactivity constraints are satisfied) is reached. The PID, however, has been deliberately detuned (large negative reactivity gain), thus causing the power to drift away from the desired setpoint. The fuzzy algorithm ("ID CON LAW"=3, reg rod) is then selected, but it has also failed to meet the performance specifications. The relay algorithm ("ID CON LAW"=4, reg rod) eventually takes over and properly regulates the power at 2 MW. The learning coefficients used in the linear reward-penalty (LRP) algorithm are both set to 0.4. For this simulation run, the fuzzy algorithm has been included as one of the control options in substate SA1 despite the fact that such control law is not designed for power decrease.

The same case is considered but the learning coefficients have been set to 0.9. The converge to the "appropriate" control law is quicker for

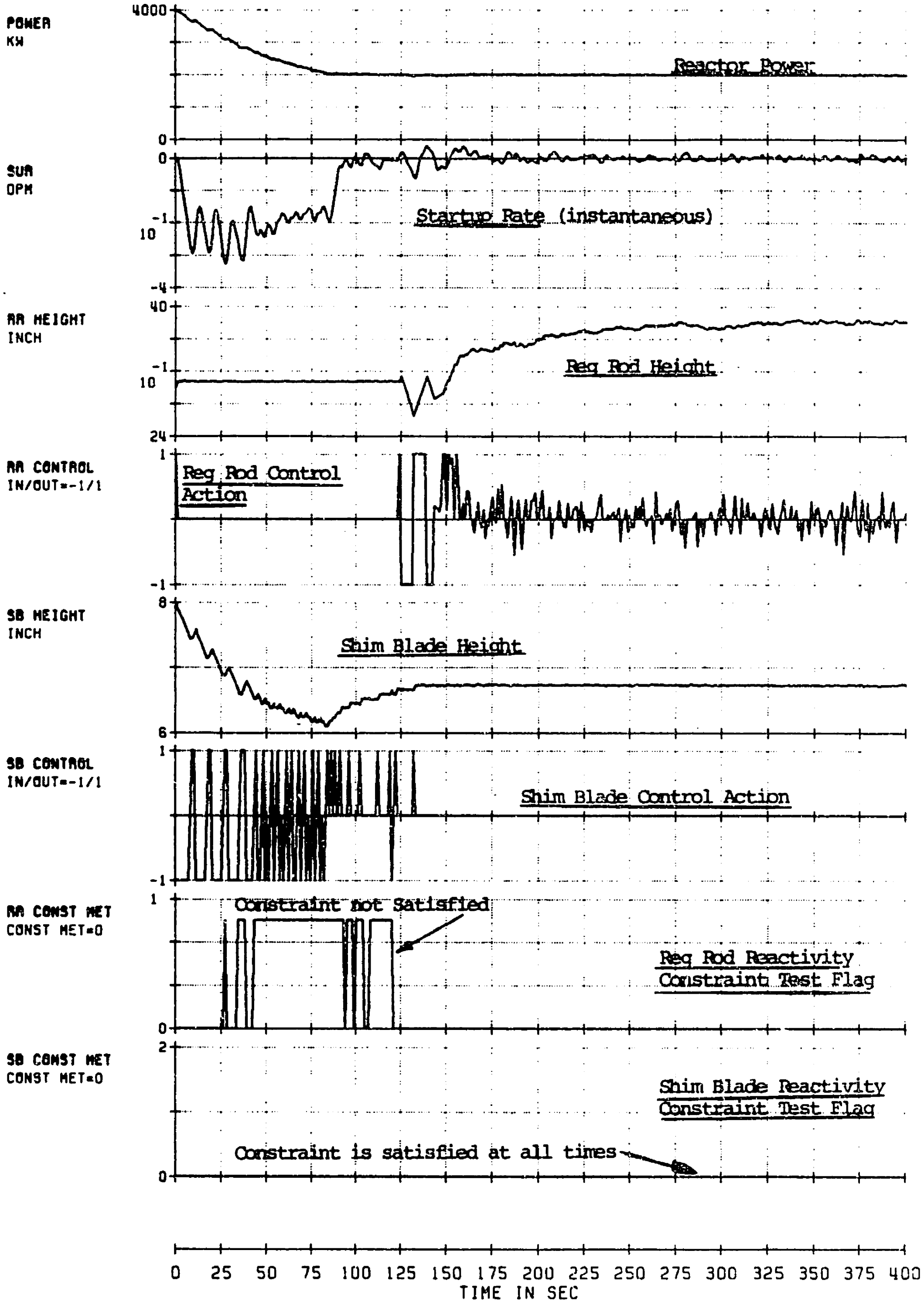

Figure 23. Case SR8A (Part 1 of 2): Power Decrease, Reg Rod and Shim Blade Control, With Control Law Anomaly at Steady State

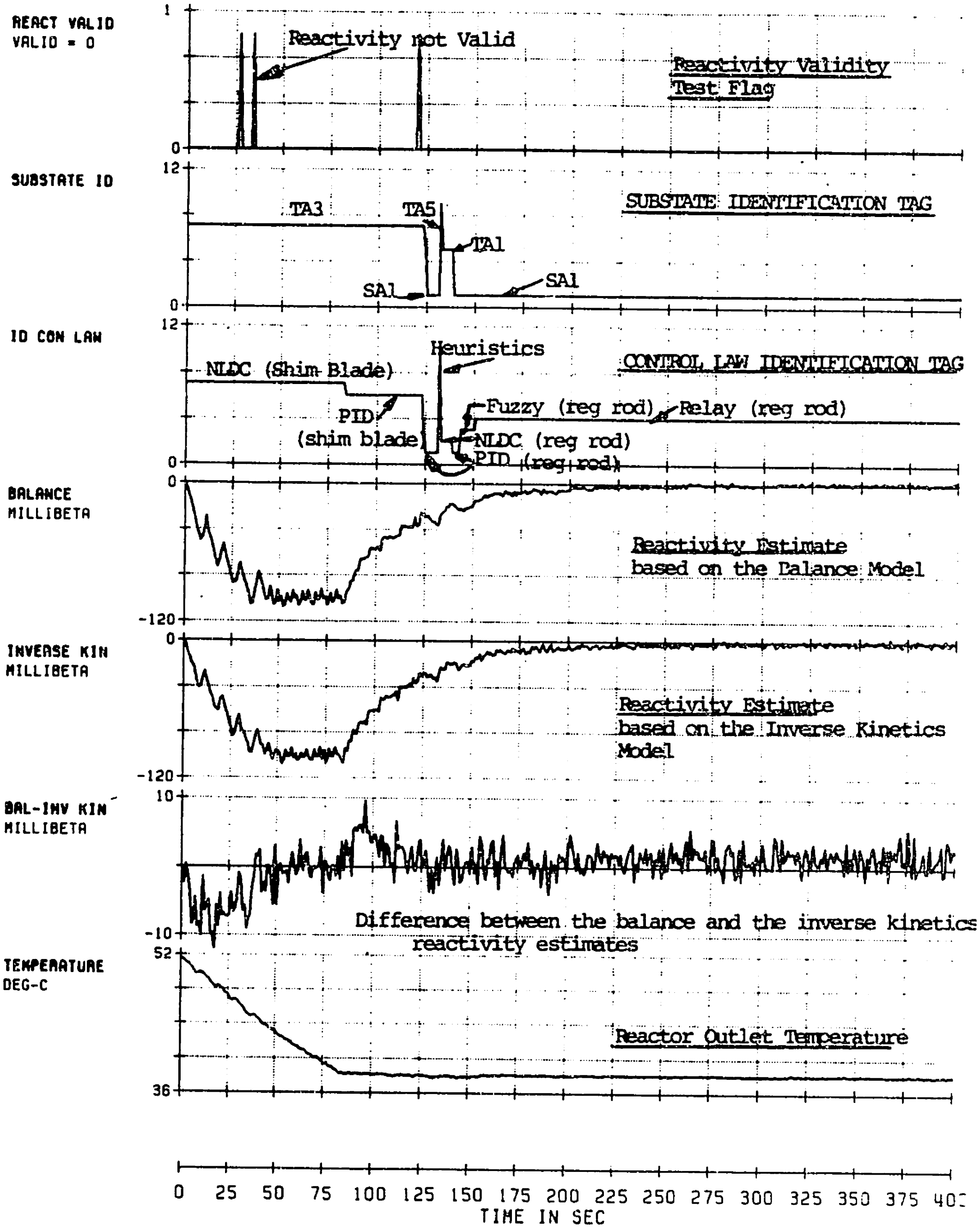

Figure 23. Case SR8A (Part 2 of 2): Power Decrease, Reg Rod and Shim Blade Control, With Control Law Anomaly at Steady State

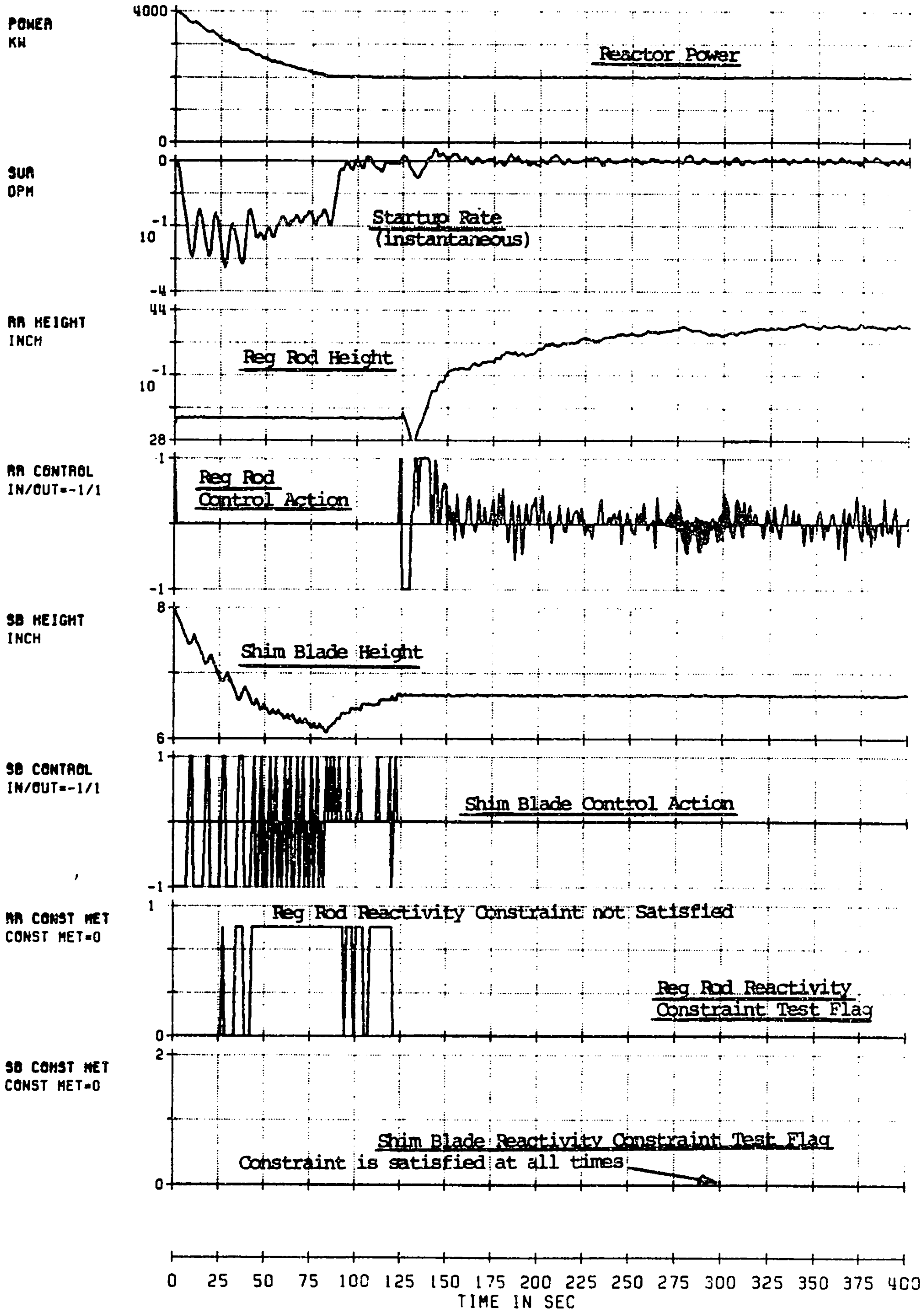

Figure 24. Case SR8B (Part 1 of 2): Power Decrease, Reg Rod and Shim Blade Control, With Control Law Anomaly at Steady State, Large Learning Coefficients

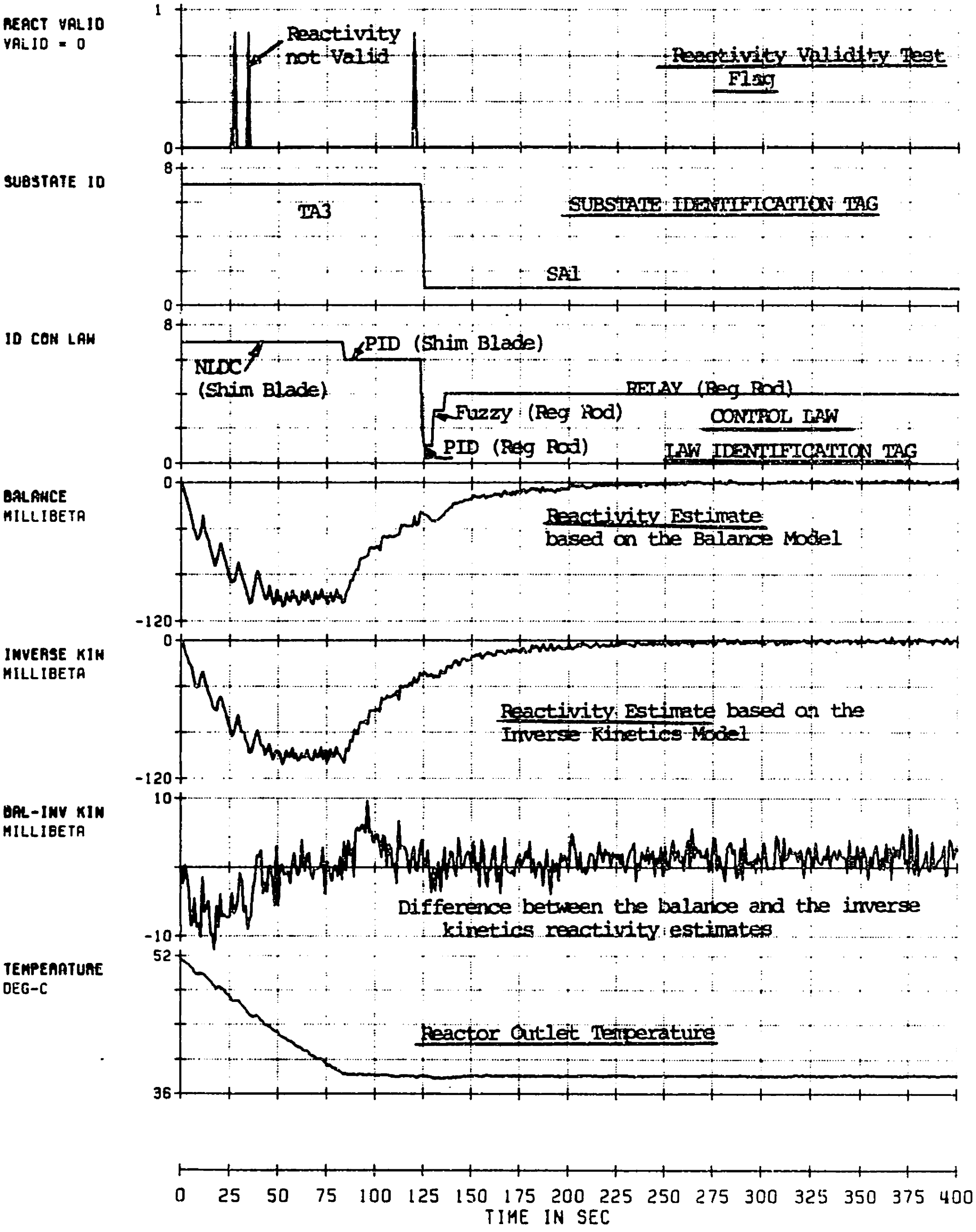

Figure 24. Case SR8B (Part 2 of 2): Power Decrease, Reg Rod and Shim Blade Control, With Control Law Anomaly at Steady State, Large Learning Coefficients

this subcase than that for the first subcase. Selected plots of the results for subcase SR8B are shown in Figure 24.

4.1.4 Summary of the Simulation Studies

The power has been successfully controlled in a variety of steady state and transient conditions. The reg rod provides a finer control than the shim blade as expected. The reconfiguration logic properly selected the "appropriate" control law as a result of changes in the plant demand, alignment, and dynamics as well anomalies in the control laws and changes in the plant dynamics that affect the validity of the control laws.

In cases where no control anomaly has been introduced, the plant operating condition identifier (POCI) module directly selects the control law or procedure via a decision tree approach. It should be noted that the MCO criterion has minimized the unnecessary switch over from one operating condition to another. However, it may be necessary to upgrade the reactivity validation procedure for the MITR to further minimize the switch over that is attributed to the status of the reactivity information especially during the transient part of the maneuver. At steady state, the switch over from substate SA1 to SA2 and vice versa, especially after the transient part of the maneuver, can be also avoided by increasing the MCO threshold for the steady state criteria as found in previous simulation runs.

In the presence of a control anomaly, the performance evaluator (PE) module successfully isolated the anomalous control option. A linear reward-penalty (LRP) algorithm has been used to update the probability associated with each option for a given condition (see Appendix F). The learning coefficients have been varied to show how the convergence rate to the "appropriate" control law (i.e., the one that consistently satisfies the performance criterion) is affected. As discussed in Appendix B and F, small values of the learning coefficients indicate small change in the probability distribution as a result of a penalty or reward condition, while large values of the learning coefficients indicate large change. As discussed in cases SR3 and SR8, the size of the learning coefficients is directly related to the convergence rate to the "appropriate" control law. Therefore, the larger the values of the learning coefficients are, the quicker it is for the PE to isolate the anomalous control option. Thus, the controller reconfigures more quickly.

4.2 On-line Evaluation of the Controller

4.2.1 Scope of the On-line Evaluation

A series of tests has been performed to evaluate the reconfigurable controller concept on the MIT Reactor (MITR). The control program used in the simulation studies is evaluated on-line over the range of 20 to 100% power. Because of the computer timing constraints and the unavailability of certain hardware/software interfaces, the implementation of the control program has been simplified. Along with the design assumptions presented in Chapter 3 and the assumptions made in the previous section (simulation studies), the following additional simplifications have been made:

1. The signal validation and the sensor calibration routines [Ray, 1984] are not linked with the control program. The controller inputs consist of a single sensor for power, hot leg temperature, reg rod position, shim blade #4 position, and shim blade #1 position. The power sensor that is used in the controller is chosen via keyboard input before commencing the experiment.
2. A number of plant operating conditions in configuration A (both shim blade and reg rod motors are available) has been selected for on-line demonstration of the reconfigurable controller because the reg rod and shim blade #4 cannot be controlled at the same time during the same experiment. The hardware/software interface needed to control both control mechanisms concurrently

is not presently available. The reg rod and shim blade #4 will be driven by a variable speed and a fixed speed motors respectively.

3. The sampling time is limited to 1.0 second. For this reason, an inverse kinetics model with three delayed neutron groups is used as one of the methods of estimating reactivity (see Appendix D).

The same steady state criteria that have been selected in the simulation studies are used in the experiments. A digital low pass filter on the power signal has been implemented before computing the startup rate (SUR, the rate of change of power). The unfiltered power measurement is used in other calculations.

4.2.2 Results of the On-line Evaluation

A summary of the experimental tests are shown in Table 6. In general, each case consists of several subcases. A typical set of results associated with an experimental run consists of a similar set of time plots whose label definitions are described in the section related to the simulation studies. An experimental run is designated by ERni where ER stands for experimental run, n takes on the values of 1, 2, and so on for the case number, and i takes on the values of A, B, and so on for the subcase label.

From the results of the simulation studies, the controller is expected to perform adequately. However, due to the simplified model used for the simulation, the experimental results will be different from those of the simulations. The results presented in this section are representative cases after tuning iterations of the thresholds used in the multiple consecutive occurrence tests. Furthermore, the experimental results presented here are obtained from the earlier as well as the "final" version of the control program as discussed in each case. Each version of the control program has been tested by simulation prior to re-trial. The experimental trials have been conducted over a period of

Table 6. Summary of Experimental Runs

Case No.	Power Maneuver	Control Mechanism	Reactivity Anomaly	Control Anomaly
ER1	1-2 MW	Reg Rod	No	No
ER2	1-2 MW	Reg Rod	No	Yes, at steady state
ER3	1-2 MW	Reg Rod	Yes	Yes, during a transient state

time in which there has been a major refueling. However, no modification has been made in the code because of this. In all the cases presented here, the transient is initiated by changing the power set point at time zero.

4.2.2.1 Case ER1: Base Case, No Control Law Anomaly

This case represents the "base" case for a power change from 1 to 2 megawatts (MW) with the reg rod initially at about 3.5 inches. The objective of this case is to demonstrate the operation of the reconfiguration logic under "normal" condition. No control law anomaly has been introduced. The transient is initiated by changing the power set point to 2 MW at time zero. The initial conditions for this case are similar to those for case SR1. The maneuver can be described as a "small" power change without the need to "reshim" since the reg rod position is "low" (see Appendix E for details).

Selected plots of the results are shown in Figure 25 and Figure 26. These two subcases are referred to as subcases ER1A and ER1B respectively. The data for the first subcase has been taken on a Monday (November 25, 1985) and the second on a Thursday (November 21,1985). The reactor dynamics are expected to be different for these two subcases because of the effects of xenon, shim bank position, and temperature. The power has been changed from 1 to 2 MW with no overshoot. The controller reconfigures properly during the course of the maneuver.

During the transient part of the maneuver, the NLDC algorithm ("ID CON LAW"=2) is used as long as the reactivity estimate is valid (substate TA1 or "SUBSTATE ID"=5). The fuzzy algorithm ("ID CON LAW"=3) is used in a few instances when the reactivity has been declared invalid (substate TA2 or "SUBSTATE ID"=6). As discussed in Chapter 3 and Appendix C, the NLDC algorithm insures that the reactivity constraint, associated with the control mechanism in use, is always satisfied. For power increase, the control mechanism is withdrawn if the reactivity constraint is satisfied and inserted if the reactivity constraint is violated. In both cases, the control mechanism is moved at its full speed. The NLDC algorithm does not incorporate the multiple consecutive occurrence (MCO) criterion in making its decision. A "buffer" region (see Appendix C) or an "instruction" section [Bernard, 1984] is not used in this version of the NLDC, thus a lot of movement on the control mechanism can be observed. The fuzzy algorithm, on the other hand, is used whenever the reactivity is not valid, although it is also applicable regardless of the status of the reactivity information. However, it does not insure that the reactivity constraint is satisfied at all times. As opposed to the NLDC, the fuzzy algorithm can move the control drive mechanism at a fraction of full speed. Thus, its recommended control action, as shown in the control action plot, appears smoother as compared to that by the NLDC.

As discussed in Appendix D, the reactivity is declared valid if all three conditions are satisfied: 1) the difference between the reactivity estimate based on the balance model, ρ_{BAL}, and that of inverse kinetics, ρ_{INV}, is less than a specified threshold 2) the recommended reg rod control action based on the reg rod reactivity constraint (at the power set point) as derived from ρ_{BAL} is identical to that of ρ_{INV}, 3) the shim blade counterpart of the second condition is satisfied. As shown in the "BAL-INV KIN" plot (i.e., the difference between ρ_{BAL} and ρ_{INV}), the dif-

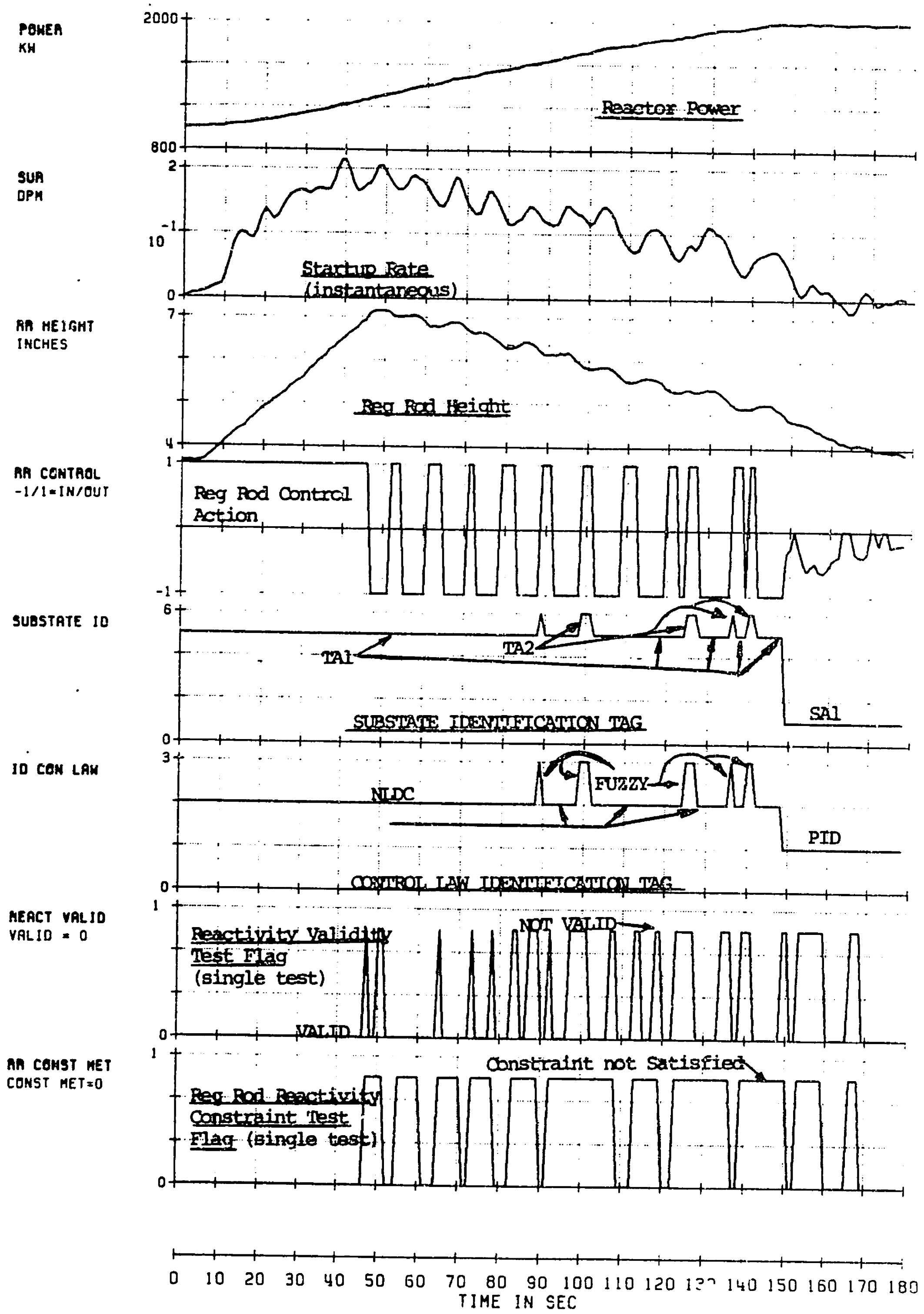

Figure 25. Case ER1A (Part 1 of 2): Base Case, No Control Law Anomaly, Mon-25-Nov-85

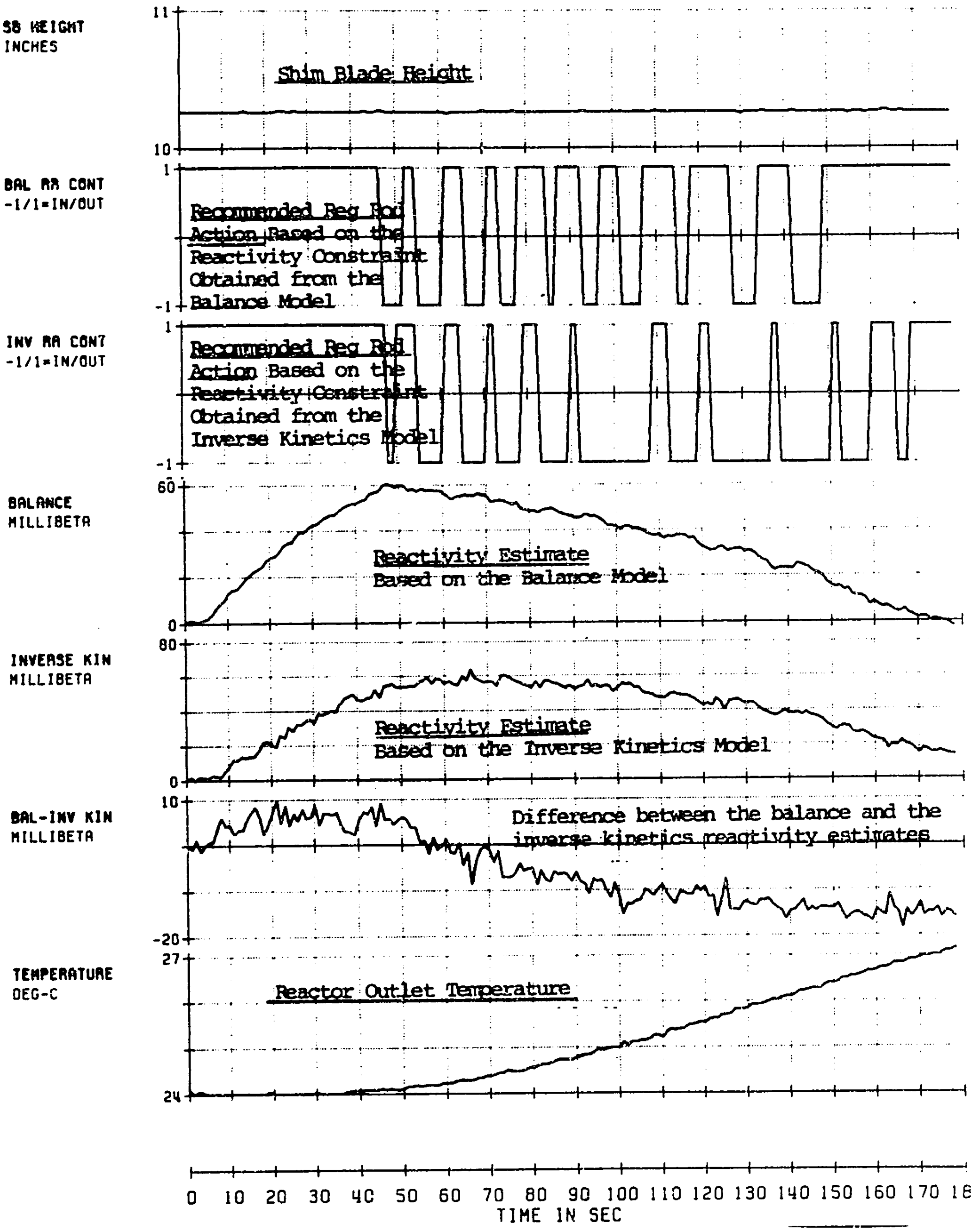

Figure 25. Case ER1A (Part 2 of 2): Base Case, No Control Law Anomaly, Mon-25-Nov-85

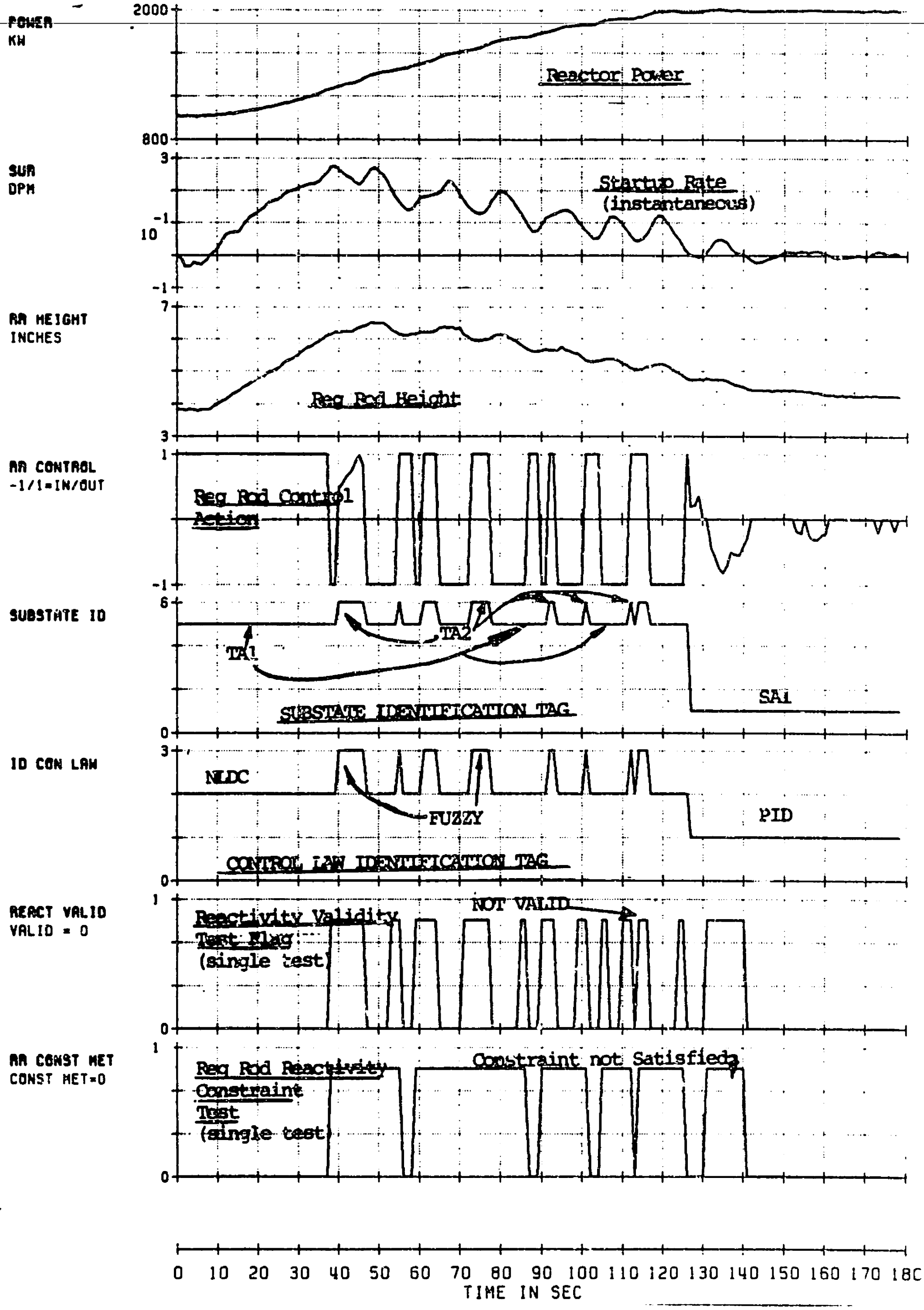

Figure 26. Case ER1B (Part 1 of 2): Base Case, No Control Law Anomaly, Thu-21-Nov-85

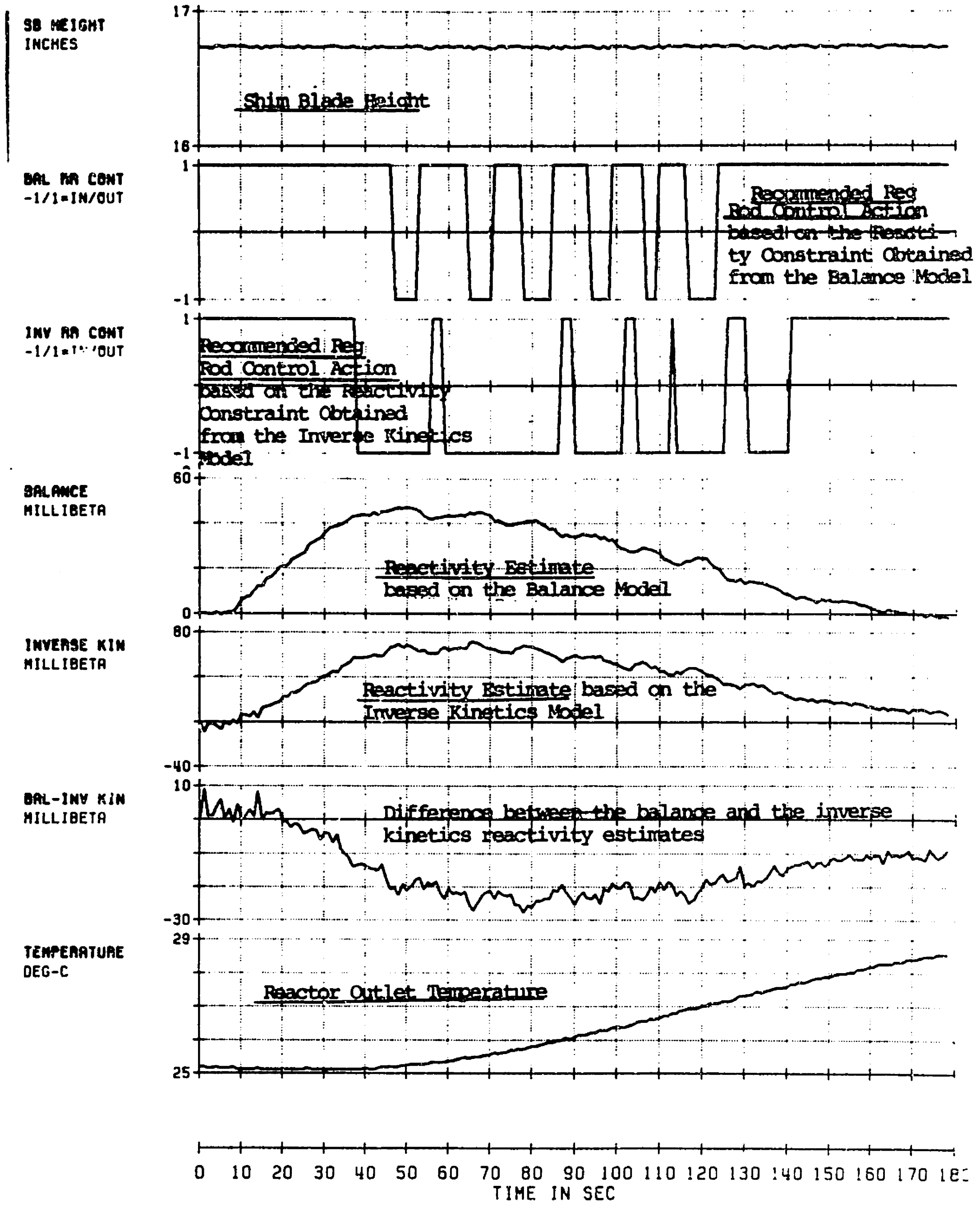

Figure 26. Case ER1B (Part 2 of 2): Base Case, No Control Law Anomaly, Thu-21-Nov-85

ference between the two estimates is within the threshold of 60 millibeta. This threshold has been chosen based on the results of previous reactivity studies (see Appendix D). However, as shown in "BAL RR CONT" and "INV RR CONT" plots, the recommended reg rod actions based on the reg rod reactivity constraint relationships, as obtained from ρ_{BAL} and ρ_{INV}, are not identical. Therefore, the reactivity is declared invalid. The "REACT VALID" plot shows the single point test result of the reactivity validation procedure. It set to zero if the single point test is declared valid and to 1 otherwise. A multiple consecutive occurence (MCO) test is used to declare an invalid reactivity condition. The use of the MCO test has minimized the switch over from one substate or control law to another as shown in "SUBSTATE ID" and "ID CON LAW" plots. A threshold of 3 has been chosen as a tradeoff between time delay and false declaration.

However, a frequent reconfiguration from NLDC to fuzzy algorithm and vice versa can still be observed especially during the transient portion of the maneuver. One of the reasons for this phenomenon can be attributed to how the MCO criterion has been implemented for the reactivity validity test. For both runs, a counter is incremented by one each time one of the three reactivity validity conditions is violated; otherwise, the counter is reset to zero. The reactivity is declared invalid once the counter reached the threshold of three. The counter is no longer incremented once it reached the threshold. On the other hand, the reactivity is declared valid whenever the counter is equal to zero; but, as mentioned above, the counter is reset to zero based on a single point test. Because of this procedure, a control law reconfiguration can be observed from fuzzy to NLDC and back to fuzzy as shown in the "ID CON LAW" plots. As a result of this phenomenon, the MCO test for the reactivity validity condition has been upgraded for runs conducted in the later dates. The counter is decremented by one each time the validity test is satisfied rather than immediately resetting it to zero. The counter is no longer decremented once it reached zero.

Despite the switch over described above, the power response is not affected, as observed from the results of a similar run where the NLDC is used all the time during the transient portion of the maneuver. One way to further minimize the switch over from the valid to invalid reactivity substate and vice versa is to increase the MCO threshold. This procedure, however, is expected to result in a longer time delay to reconfigure from one control law to another as a result of a change in the reactivity information. The resulting time delay is expected to change the behavior of the power response especially near the end of the transient part of the maneuver. For example, the use of the fuzzy algorithm does not insure that the reactivity constraint, associated with the control mechanism, is satisfied at all times. A large time delay to switch over from the fuzzy to the NLDC algorithm may lead to a slight overshoot in the power response. A better approach to minimize the switch over, without introducing a large time delay, is to perhaps improve the reactivity validation scheme. As observed from the experimental results, the recommended control action is very sensitive to the reactivity estimate especially during the later part of the transient.

The difference between the two reactivity estimates at the later part of the run can be attributed to the reactivity error in the balance as a result of the temperature dynamics (Note: The reactor coolant outlet temperature has not yet levelled off).

The control has reconfigured to the PID algorithm ("ID CON LAW"=1) once the steady state criteria are satisfied. This particular steady substate is referred to as SA1, ("SUBSTATE ID"=1) the reactivity is valid and the reactivity constraints are satisfied. The PID successfully regulated the power. No more control law reconfiguration has taken place since there has been no more changes in the plant substate and the PID has satisfied the performance criterion for the given substate.

Although both subcases started with very similar initial conditions, the Thursday run took less time to reach the 2 MW point. The reason for this is that the shim bank position is higher on Thursday than on Monday - the shim bank is raised as the week progresses to compensate for xenon. This means that the "shadowing" effect of the shim bank on the reg rod is less, and therefore the reg rod has more "effective reactivity worth."

The same experimental scenario is repeated after the refueling schedule. The results presented for this subcase are obtained from the upgraded version of the control code used in subcases ER1A and ER1B. Selected plots of the results are shown in Figure 27. The power has been successfully changed and the controller properly reconfigures during the course of the maneuver. The number of sudden transitions from fuzzy algorithm to NLDC has been slightly minimized as a result of the modification of the MCO criterion for the reactivity validity test. At steady state, a transition from SA1 to SA3 and back to SA1 took place with no observable effect on the power behavior. The reason for this switch over is due to the inconsistent between the results obtained from the "BAL RR CONT" and "INV RR CONT," as discussed earlier. But in general, no significant difference can be observed between the subcase ER1C results and those of the previous runs.

4.2.2.2 Case ER2: With Control Anomaly at Steady State

The objective of this experiment is to demonstrate the operation of the performance evalution component of the reconfiguration logic in the presence of a control anomaly during a steady state condition. This case is very similar to Case ER1 except for the control anomaly. The performance evaluation has been conducted only in substate SA1 (reactivity is valid and the reactivity constraints are satisfied). A reward-penalty scheme, as described in Appendix E, is implemented. The "learning coefficients," a and b, are set to 0.4 based on trade off analysis and previous simulation and experimental trials.

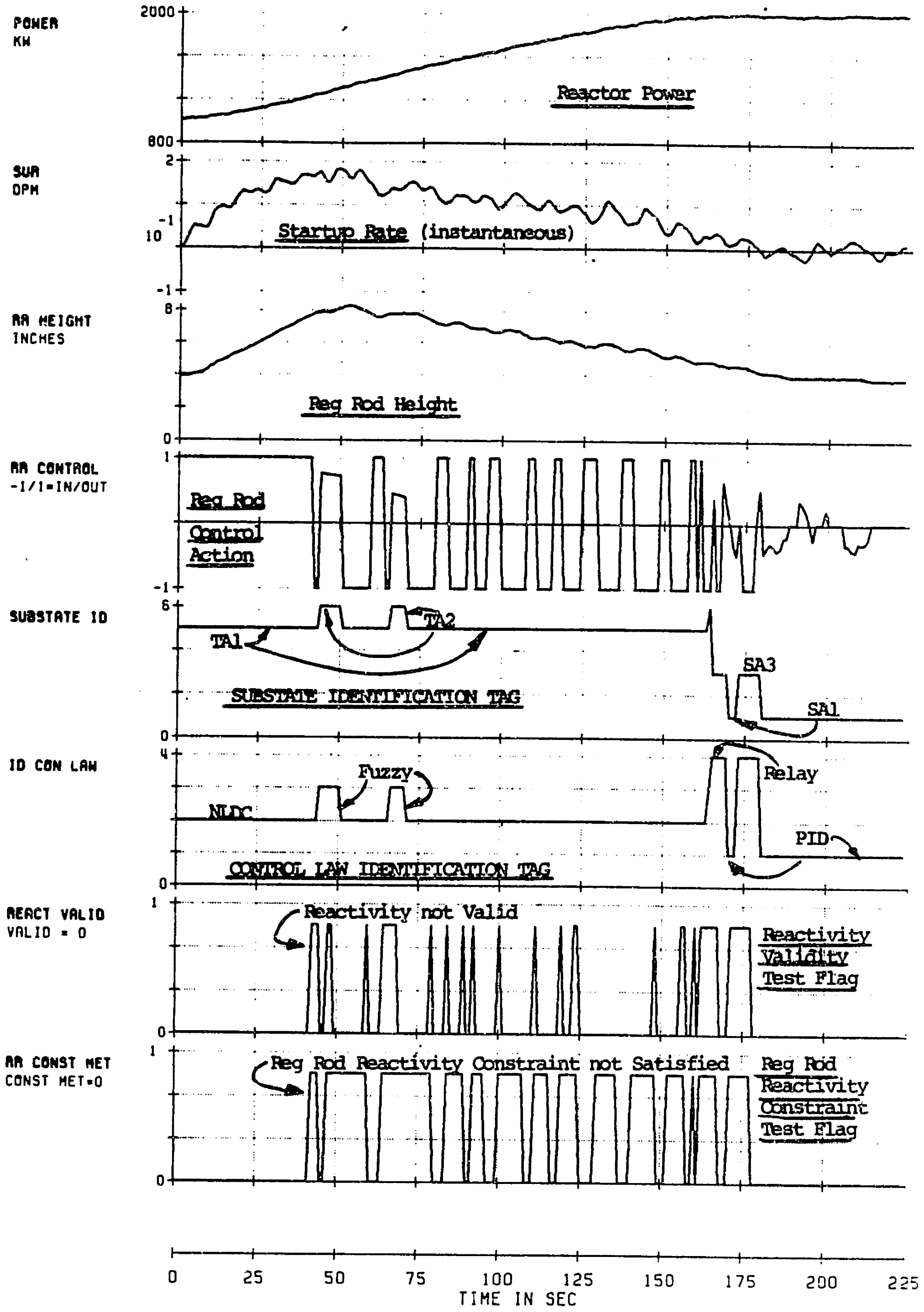

Figure 27. Case ER1C (Part 1 of 2): Base Case, No Control Law Anomaly, Tu-18-Feb-86 (after refueling)

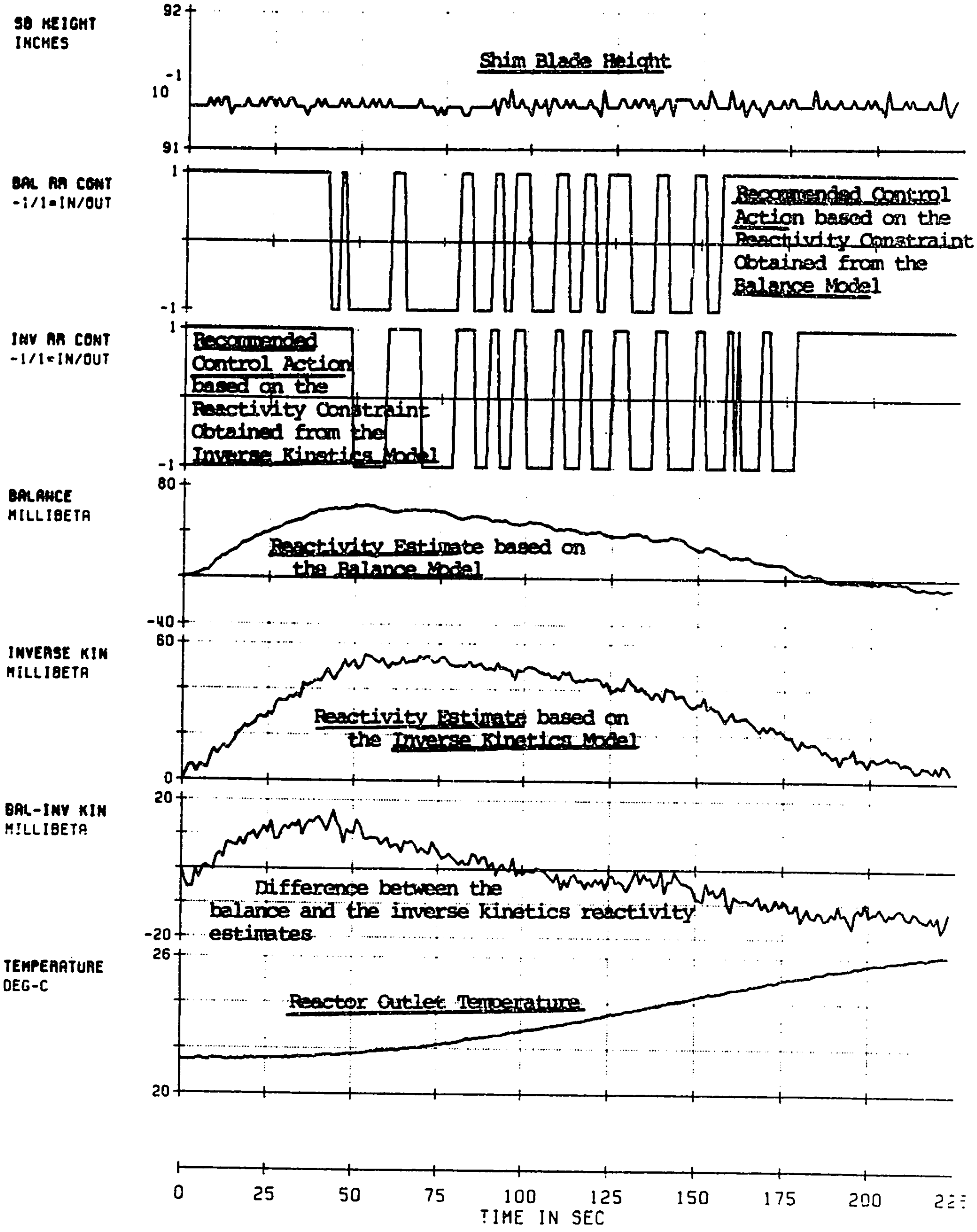

Figure 27. Case ER1C (Part 2 of 2): Base Case, No Control Law Anomaly, Tu-18-Feb-86 (after refueling)

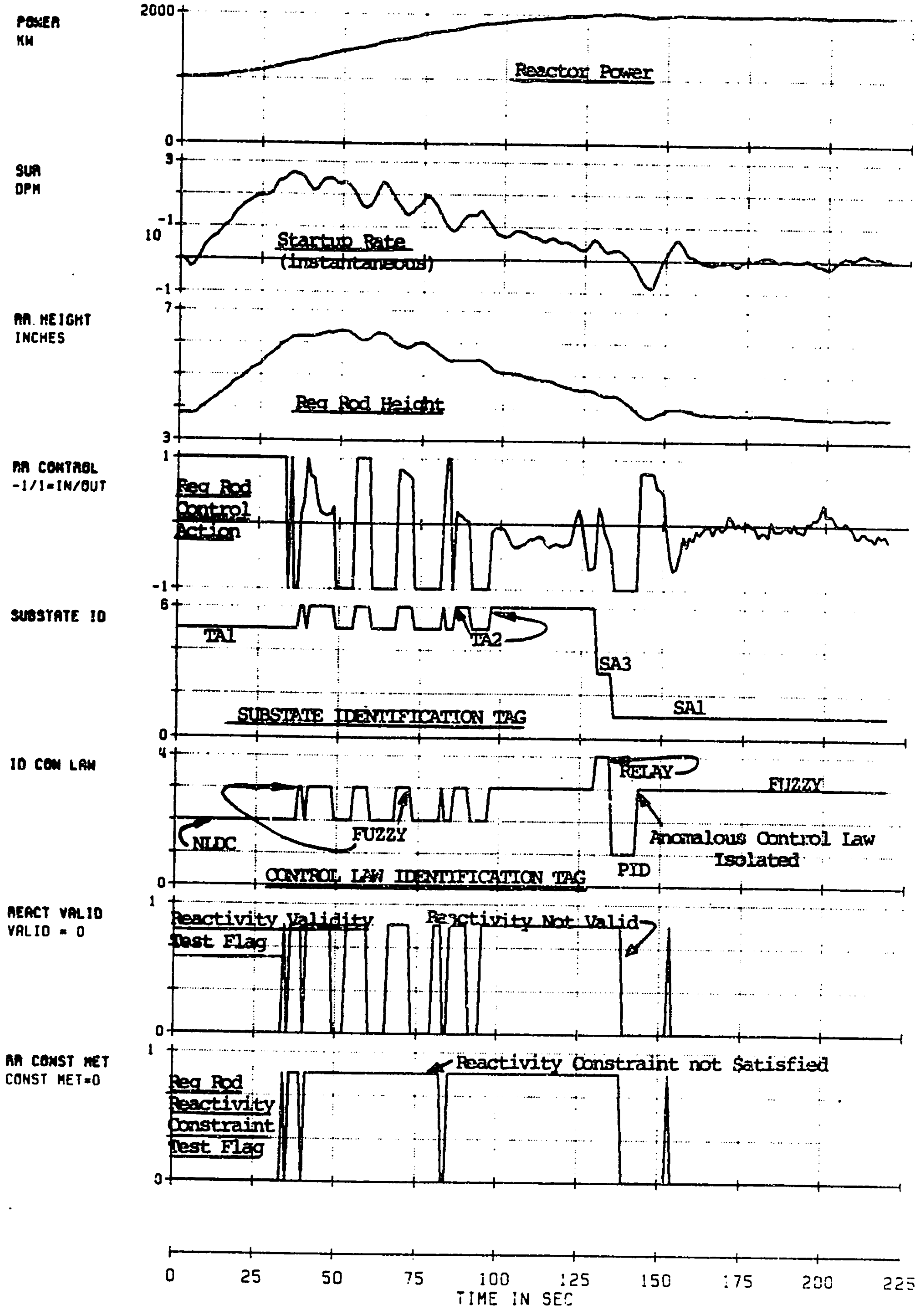

Figure 28. Case ER2A (Part 1 of 2): With Control Law Anomaly at Steady State, Tu-10-Dec-85

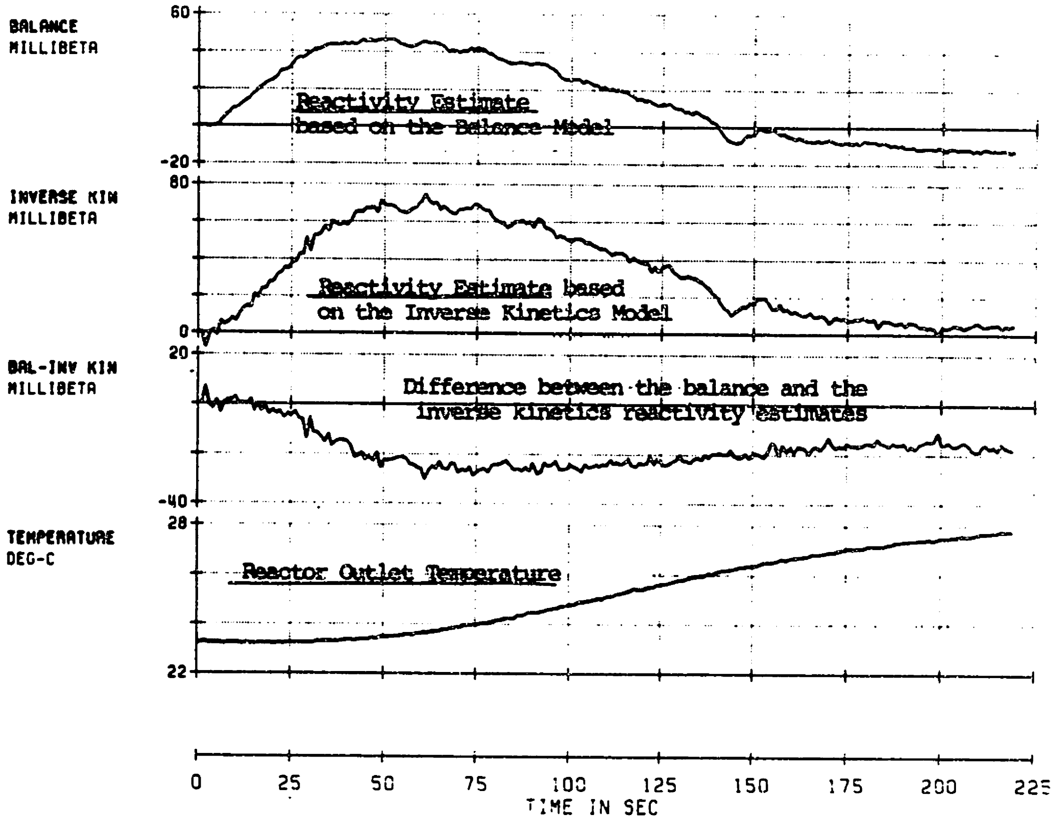

Figure 28. Case ER2A (Part 2 of 2): With Control Law Anomaly at Steady State, Tu-10-Dec-85

Case ER2 consists of five subcases. In subcases ER2A and ER2B, the PID algorithm is deliberately detuned by increasing the reactivity gain by a factor of a thousand, causing the control algorithm to be overly sensitive to the reactivity parameter. Therefore, the reg rod is moved at its maximum speed depending on the sign of the reactivity estimate. The runs have been conducted on a Tuesday and Friday respectively. Selected plots from the results of the two experiments are shown in Figure 28 and Figure 29. The power has been successfully changed from 1 to 2 MW with little or no overshoot. The controller reconfigured and the power is properly regulated despite the presence of the control law anomaly. The transient portion of the maneuver is very similar to that in subcase ER1A or ER1B. As in Case ER1, the frequent reconfiguration from NLDC to fuzzy algorithm and vice versa during the transient part is

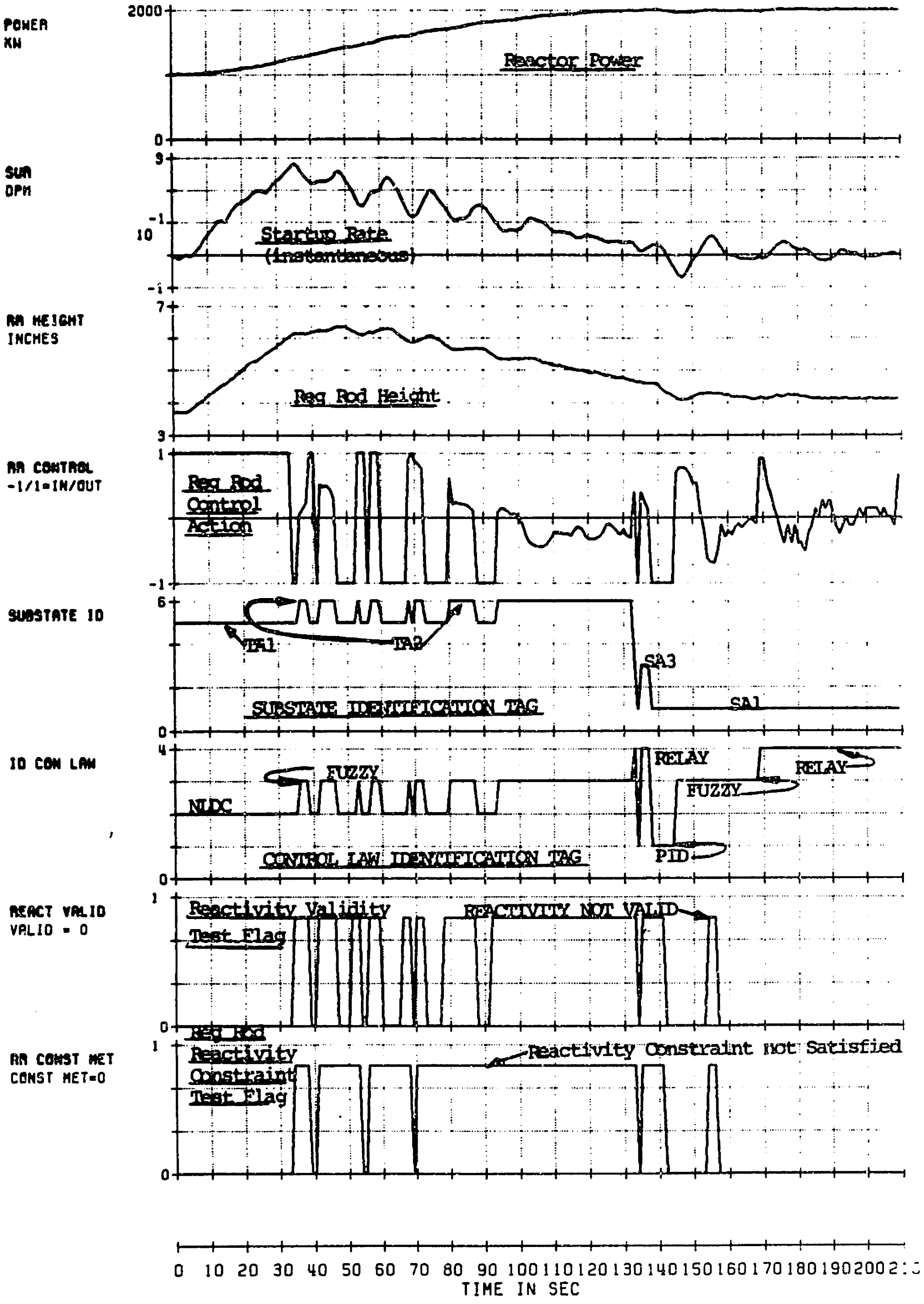

Figure 29. Case ER2B (Part 1 of 2): With Control Law Anomaly at Steady State, Fri-06-Dec-85

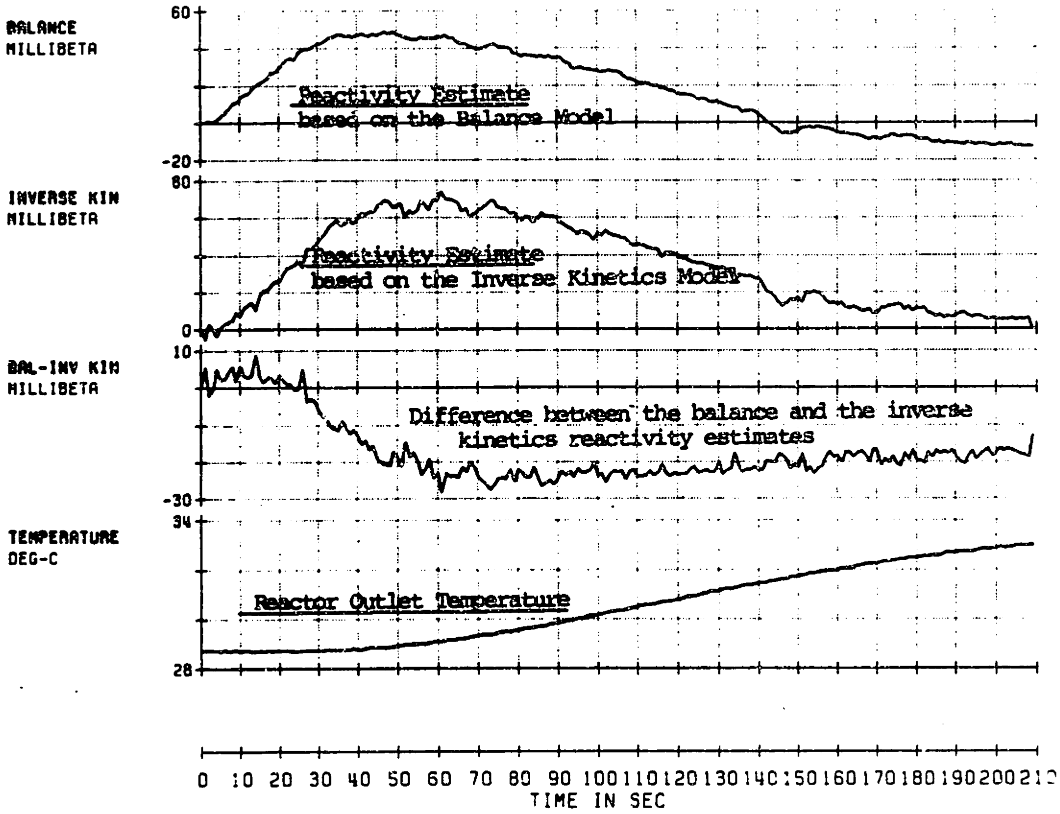

Figure 29. Case ER2B (Part 2 of 2): With Control Law Anomaly at Steady State, Fri-06-Dec-85

a result of how the MCO criterion used in the declaration of the reactivity validity condition has been implemented.

In case ER2A, the steady substate is initially declared as SA3 (steady state and the reactivity is not valid) and the relay algorithm is used. After the steady state criteria have been consecutively satisfied for a specified number of times, the reactivity validity condition is eventually disregarded. The reason for this is that the steady state control law for the MITR (PID) is no longer sensitive to the magnitude of the reactivity. Furthermore, a smoother control is expected from the PID algorithm. Steady substate SA1 is then declared (reactivity valid and reactivity constraints are satisfied) and the control reconfigured to the PID. The reg rod is inserted in a presence of small positive reactivity as a result of deliberately amplifying the PID reactivity gain. The power then slowly drifts away from the 2 MW setpoint. The reward-penalty algorithm penalized the probability associated with the PID and incremented those of the fuzzy and relay algorithms (the alternative control options). Because of the way the maximum probability search routine has been coded, the fuzzy algorithm (the second element of the selection array) is eventually chosen. This algorithm successfully regulated the power within the specified band. It also satisfied the performance criterion in SA1. Therefore, no more reconfiguration has taken place.

In case ER2B (Friday run), a similar scenario can be observed. However, the control selection eventually converged to the relay instead of the fuzzy algorithm. As discussed in the simulation studies, the fuzzy algorithm tends to command a small rod insertion near the power setpoint (see "RR CONT" plot). With the presence of xenon, such insertion command has led to a downward power drift; resulting in a penalty condition.

In case ER2C, an anomaly in the fuzzy algorithm has been introduced, in addition to that in the PID. The fuzzy algorithm has been modified so that a rod withdrawal is always in effect at steady state. The results are shown in Figure 30. The controller has successfully regulated the power despite the presence of an anomaly in two of the control options. The resulting steady state behavior is slightly different than that in subcase ER2A or ER2B. A "coarser" control can be also observed during the reconfiguration process. The PID is initially selected once substate SA1 (reactivity is valid and the reactivity constraints are satisfied) is reached. The PID has caused the power to drift in the downward direction. The control has eventually reconfigured to the fuzzy algorithm. The error that has been introduced by the PID has been corrected. But as the fuzzy algorithm continuously commands a rod withdrawal, it begins to cause the power to drift away in the upward direction. During the withdrawal, the reg rod reactivity constraint has been violated (substate SA2). A heuristic-based control action to insert

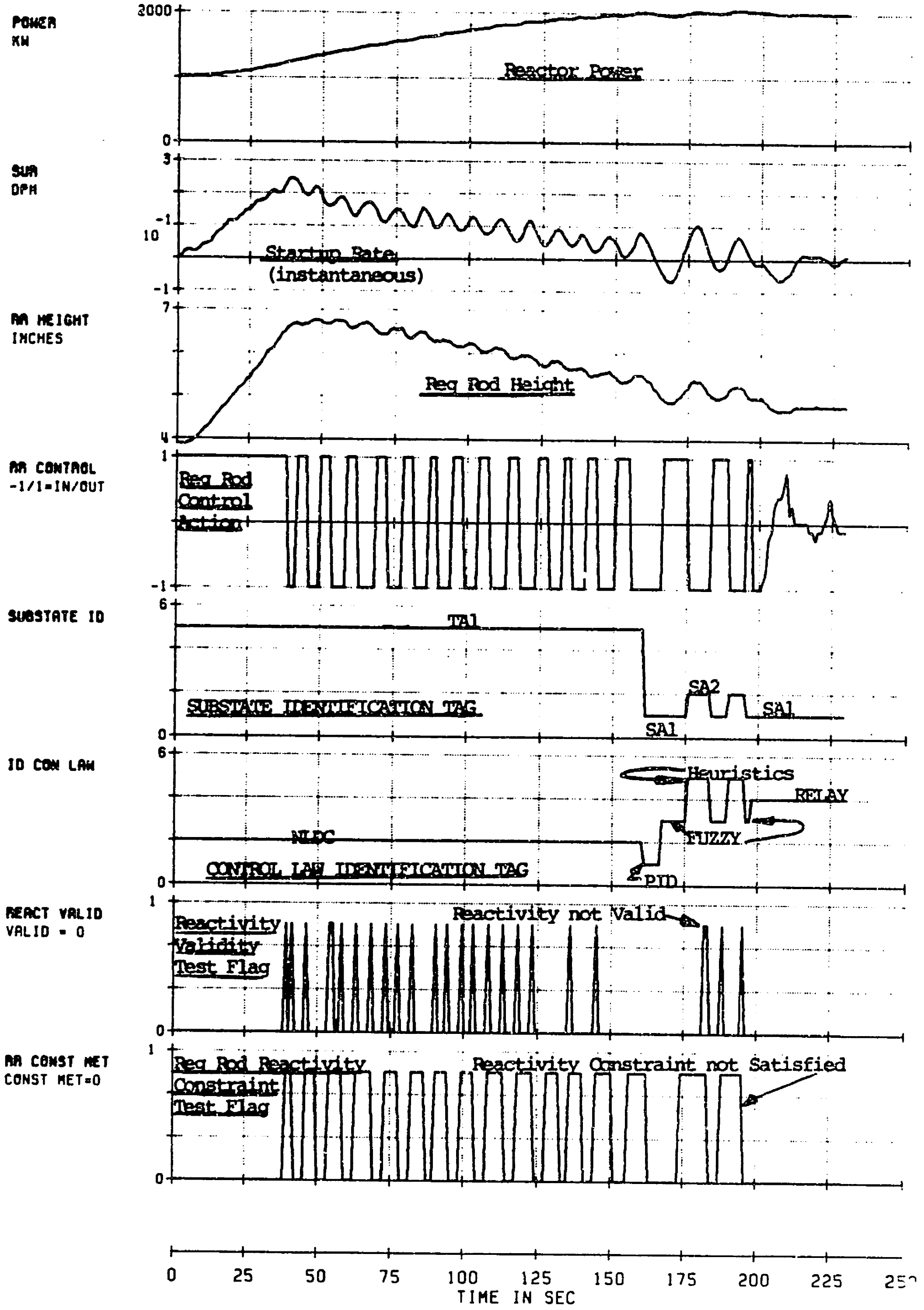

Figure 30. Case ER2C (Part 1 of 2): With Two Control Law Anomalies at Steady State, Fri-06-Dec-85

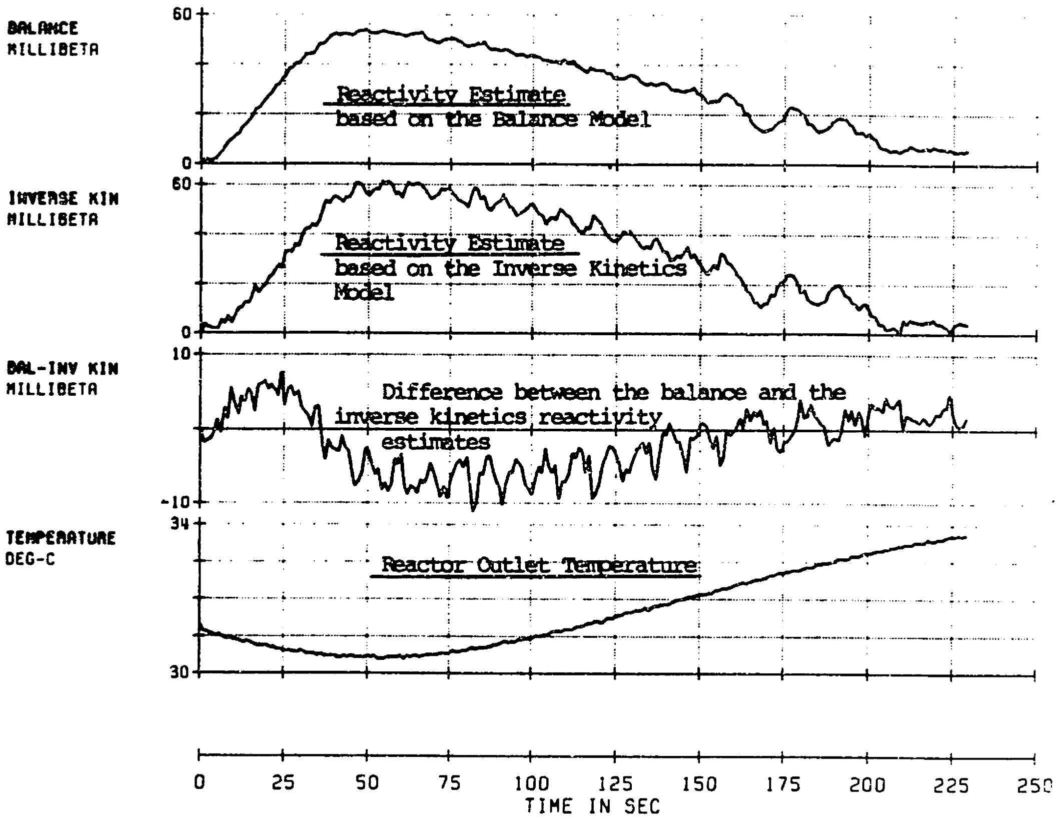

Figure 30. Case ER2C (Part 2 of 2): With Two Control Law Anomalies at Steady State, Fri-06-Dec-85

the reg rod is implemented until the condition returned back to SA1. The fuzzy algorithm has been placed back in operation because the probability distribution associated with the other options are not large enough to cause the control selection process to choose another option. The fuzzy algorithm has resumed withdrawing the rod - resulting in an upward power drift. It is then consistently penalized and the new probability distribution has eventually favored the relay algorithm. Throughout the rest of the experiment, no more control law reconfiguration has been made because the relay algorithm satisfied the criterion of maintaining the power at the desired set point within the specified bound.

It should be noted that the reward-penalty algorithm has not eliminated the PID and the fuzzy algorithms from the list of alternative control options. The probability associated with the PID has remained low in comparison to that of the relay action while the fuzzy algorithm is being penalized. For large values of learning coefficients, the convergence to the control law that satisfies the performance evaluation for the given condition may be quick or slow in some circumstances. Large values of learning coefficient can make the decision process very sensitive to noise. The controller may reconfigure from the relay algorithm back to PID because of noise and, thus, the selection process may repeat itself as observed in other trials. The reconfiguration logic accounts for this situation and overrides the recommendation made by the performance evaluator.

For all three runs, no penalty has been given as a result of a control override or large power drift. In subcase ER2C, the fuzzy algorithm, despite the presence of an anomaly that resulted in an upward drift, has operated within the reg rod reactivity constraint (based on the power setpoint). However, the resulting instantaneous power deviation for this run is about 40 kilowatts. A larger deviation is expected if the same experiment is conducted in the early part of the week when there is little or no xenon. Because of this phenomenon, the operation of the PE module has been upgraded by incorporating a control override due to large power drift in addition to the violation of the reactivity constraint relationships (see Appendix E). A control option whose recommended action has been overriden or resulted in an overriding condition is also penalized.

All three runs have been conducted prior to the refueling schedule. The results presented in subcases ER2A to ER2C have been obtained from the "original" version of the control code (no control override). The same set of experimental trials has been repeated after the refueling schedule. The upgraded version of the control program which incorporates the overriding conditions has been used.

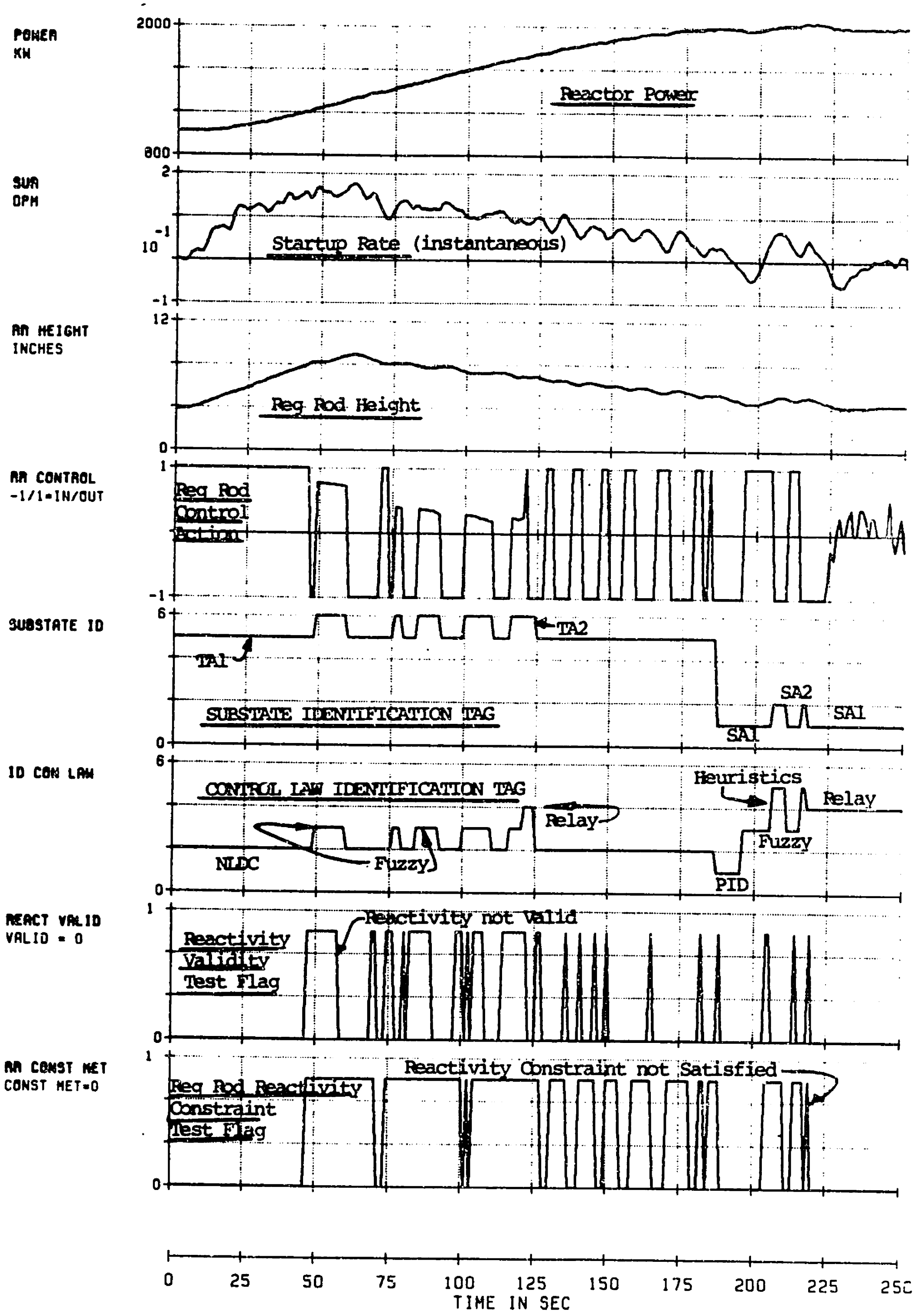

Figure 31. Case ER2D (Part 1 of 2): With Two Control Law Anomalies at Steady State, Mon-24-Feb-86, with control override, Learning Coefficients = 0.4

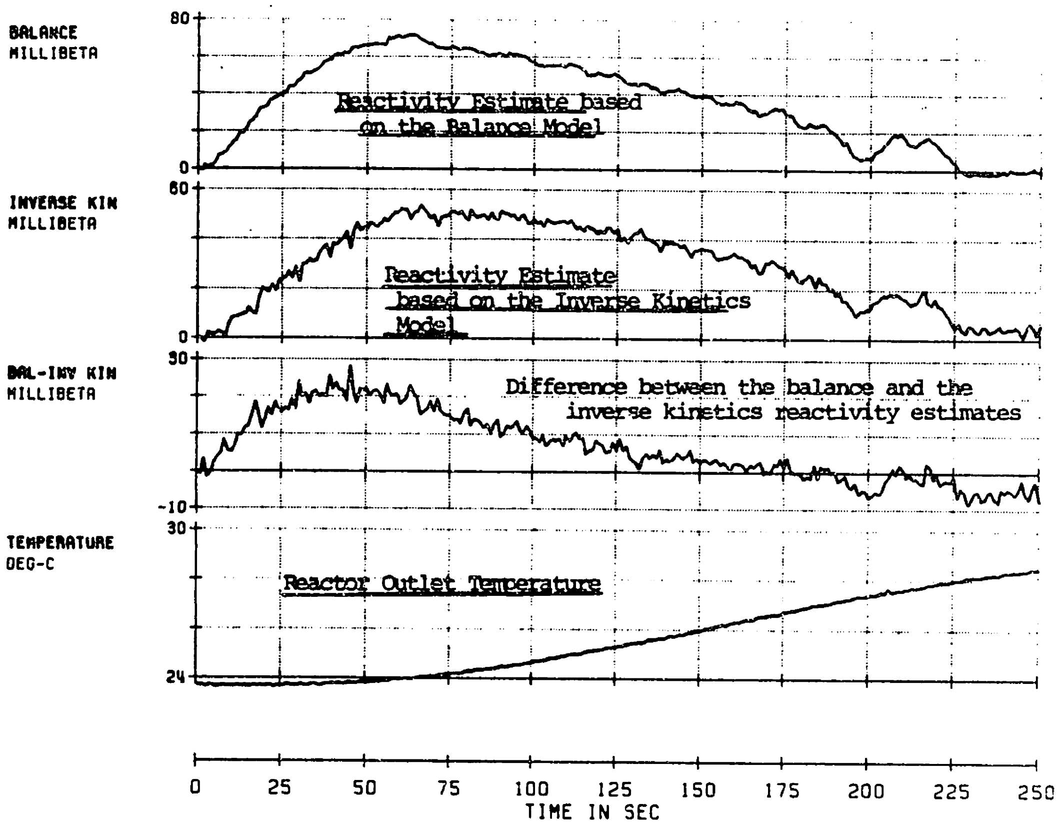

Figure 31. Case ER2D (Part 2 of 2): With Two Control Law Anomalies at Steady State, Mon-24-Feb-86, with control override, Learning Coefficients = 0.4

As shown in Figure 31, the incorporation of the control override at steady state has reduced the size of the power drift in the presence of the control anomaly. The experimental scenario for subcase ER2D is the same as that in ER2C except that ER2D has been conducted when there is no xenon in the reactor core. As in case ER2C, the PID is initially implemented in substate SA1. An anomaly in this control law has resulted in reg rod insertion. The power drifts in the downward direction, resulting in a penalty condition. A control override has been issued the moment the power deviation has exceeded a desired operating band. The PID is consistently penalized and the fuzzy algorithm eventually takes over. As shown in the "RR CONT" plot, the fuzzy algorithm generates a control withdrawal signal (around 195 seconds). The power then drifts in the upward direction, resulting in a control override (i.e. the reg rod is inserted at around 220 seconds as shown in the "RR plot") once the power deviation has exceeded a specified band. The fuzzy algorithm resumes withdrawing the reg rod when the overriding conditions (large power deviation and reactivity constraint) are not in effect. The controller has eventually reconfigured to the relay algorithm. The power has been kept within the steady state band despite the presence of a control anomaly in the PID and fuzzy algorithms. For subcase ER2D, the learning coefficients used in the LRP algorithm have been set to 0.4.

The same experiment has been repeated with the learning coefficients set to 0.6. Selected plots of the results for this subcase is shown in Figure 32. It should be noted that the control anomalies have been quickly isolated in this subcase than in subcase ER2D. As shown in the reactor power plots for these two subcases, the maximum steady state power deviation from the set point in subcase ER2E is slightly less than that in subcase ER2D. It should be noted that both experiments have been conducted when there is no xenon in the core.

4.2.2.3 Case ER3: Control Anomaly during a Transient

The objective of this experiment is to demonstrate the operation of the performance evaluation component of the reconfiguration logic in the presence of a control anomaly during a transient condition. The reactivity is forced to be invalid by setting the threshold used to compare the two reactivity estimates (i.e. reactivity balance and inverse kinetics) to zero. The experiment has been conducted after the refueling schedule. The "final" version of the code has been used. Selected plots of the results are shown in Figure 33. The power has been successfully changed from 1 to 2 MW by using the reg rod. The controller has also reconfigured properly in the presence of a control anomaly during the transient portion of the maneuver. The fuzzy algorithm has been implemented once the reactivity has been declared invalid. At about 55 seconds (1500 KW) into the run, an anomaly has been introduced in the

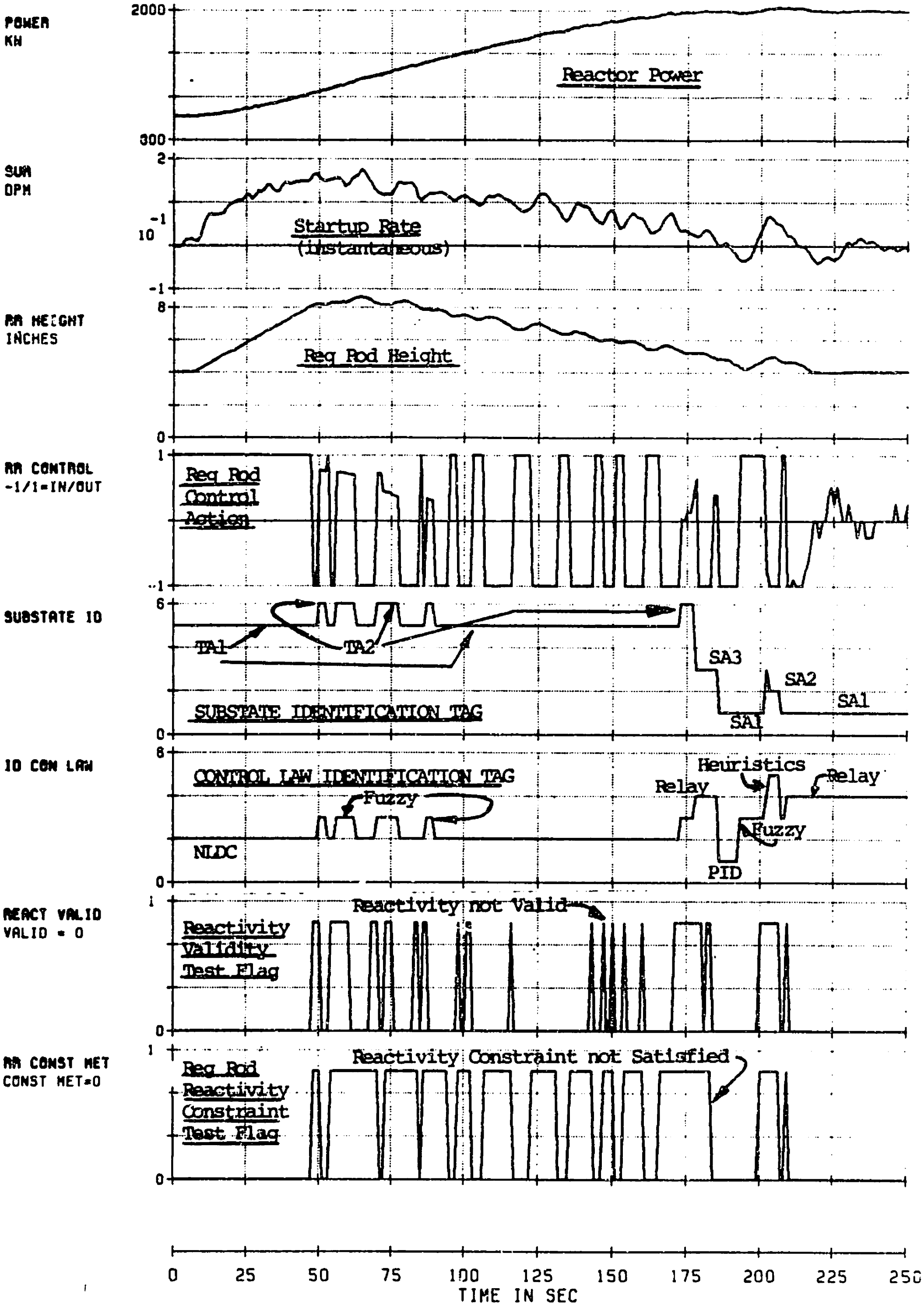

Figure 32. Case ER2E (Part 1 of 2): With Two Control Law Anomalies at Steady State, Mon-24-Feb-86, with control override, Learning Coefficients = 0.6

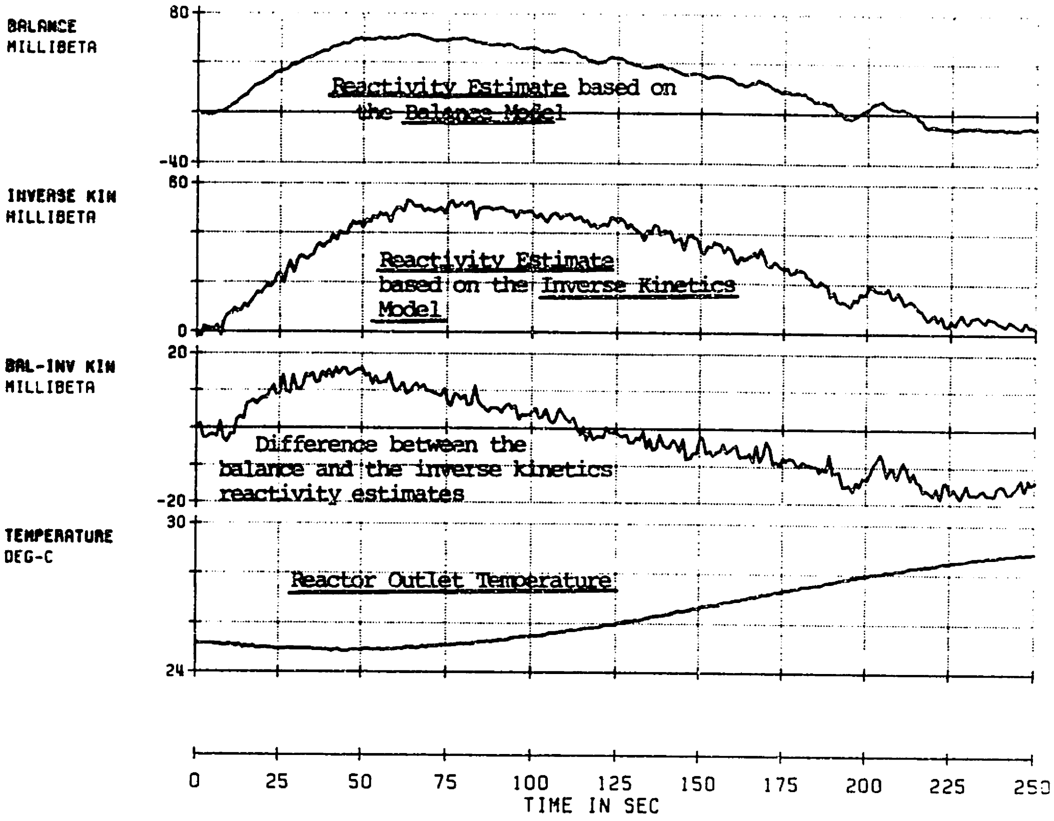

Figure 32. Case ER2E (Part 2 of 2): With Two Control Law Anomalies at Steady State, Mon-24-Feb-86, with control override, Learning Coefficients = 0.6

fuzzy algorithm by deliberately inserting the rod to simulate a possible incorrect rule base or membership function. Despite the insertion, the power continues to coast up. However, the rate of change of power has gradually decreased (see SUR plot), thus, resulting in a violation of the performance criterion based on the instantaneous period. The fuzzy algorithm has been penalized and the controller has eventually reconfigured to the relay algorithm (see "ID CON LAW" plot at about 70 seconds). For this experimental trial, the operation of the relay algorithm is supervised by the reg rod reactivity constraint based on the power set-point. It is also bounded by the supervisory reactivity constraint for the reg rod which is set at 4200 KW for this demonstration. The power set point is reached with little or no overshoot. The control strategy

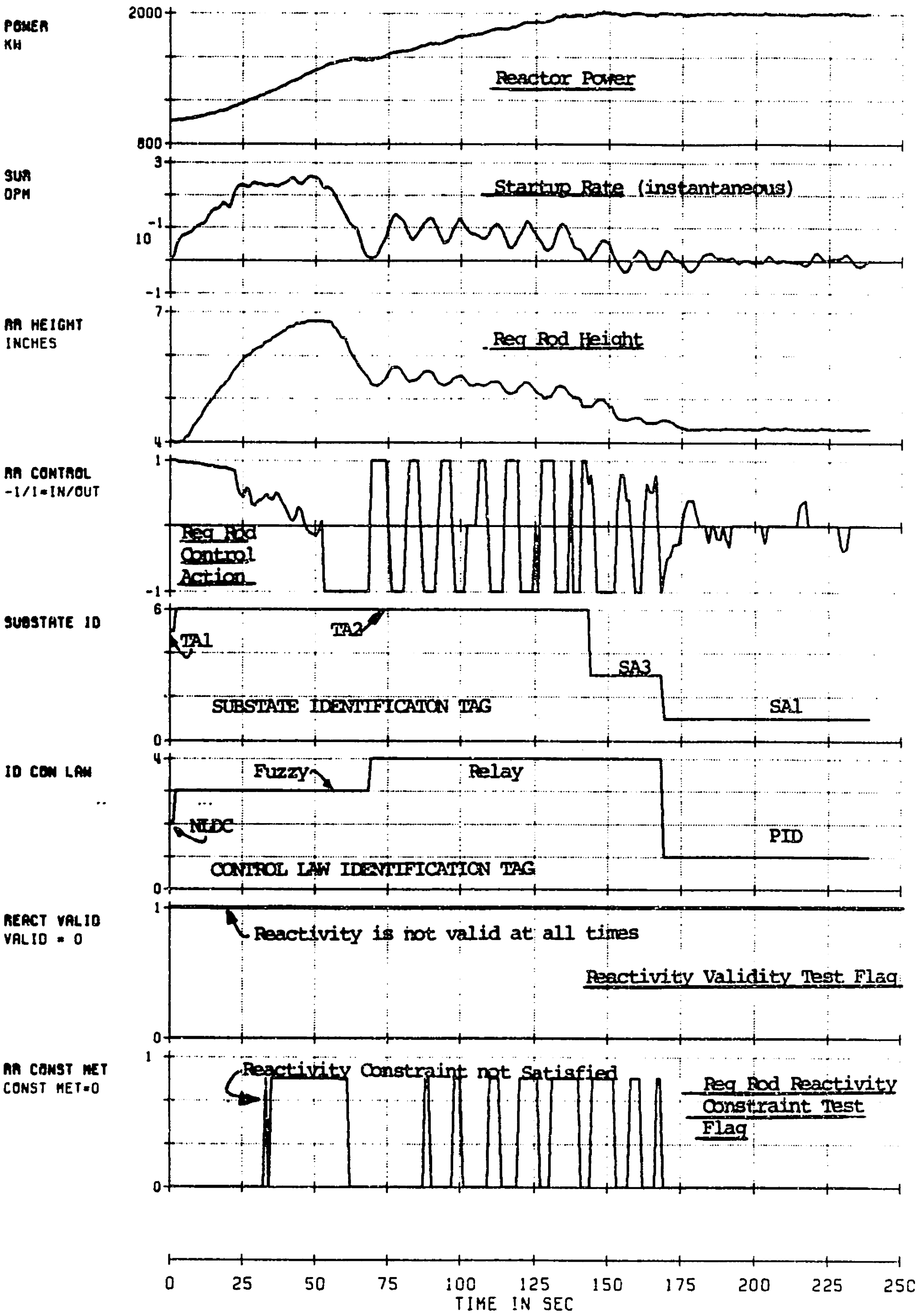

Figure 33. Case ER3 (Part 1 of 2): Control Anomaly during a Transient, MON-10-FEB-86

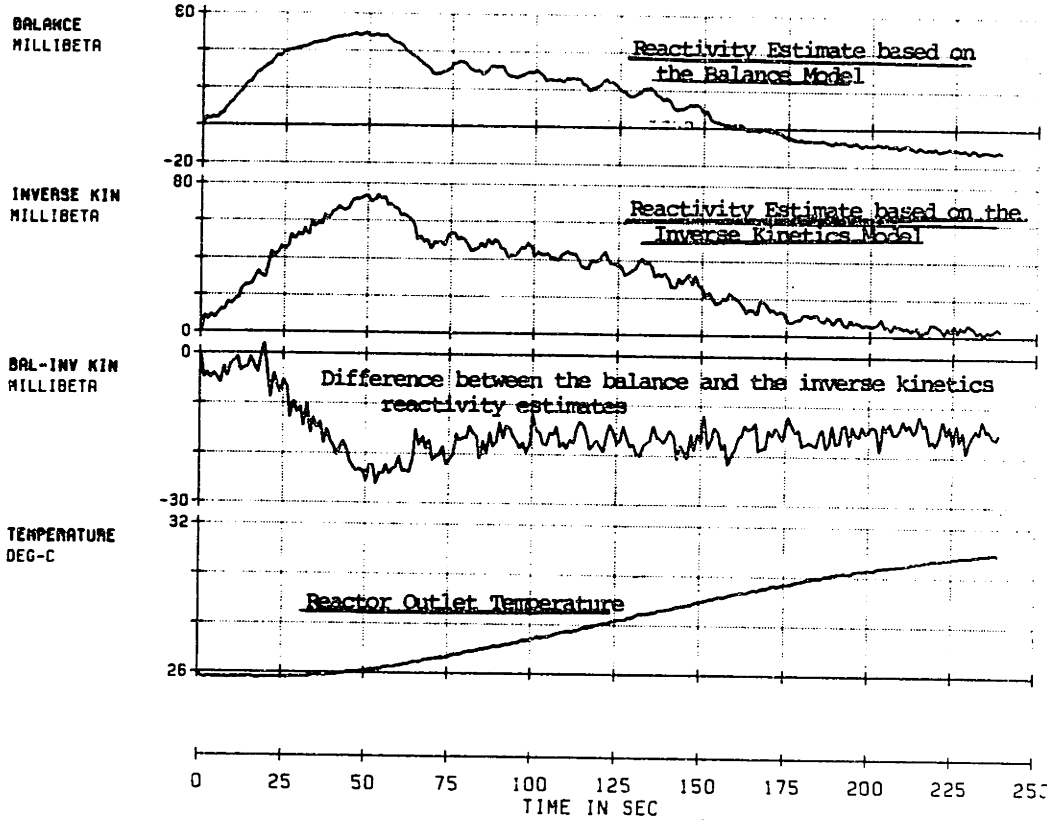

Figure 33. Case ER3 (Part 2 of 2): Control Anomaly during a Transient, MON-10-FEB-86

has reconfigured to the PID algorithm after the necessary steady state conditions have been satisfied. The power has been regulated smoothly from hereon.

Several points can be made regarding the results of this experiment. The control anomaly is not immediately manifested in the plant response in contrast to the results shown in the simulation run (Case SR5). The power continuously coast up despite the reg rod insertion. Because of the long delayed feedback, such anomaly may not be detected if it happens "near" the desired set point. An anomaly resulting in a reg rod withdrawal will be bounded by the decision and supervisory logic component of the reconfiguration logic. The associated control mechanism is inserted if the supervisory reactivity constraint relationship, set at

4200 KW, is violated and if the power exceeds the setpoint by a specified amount. In addition, a period criterion is incorporated in the performance evaluator. Therefore, a power overshoot that may result from an anomaly of this nature can be minimized.

4.2.3 Summary of Experimental Results

The experimental results presented in this section have been collected over a period of four months including a refueling schedule. Several cases have been tested and repeated during the early and later part of the week in order to account for the changes in the plant dynamics and characteristics.

The power has been successfully controlled in a variety of steady state and transient conditions without compromising the plant safety. The reg rod has been used in all of the trials. The power has been changed with little or no overshoot. The controller properly reconfigures during the course of the power maneuver. Despite the presence of a control law anomaly, the power has been regulated satisfactorily during steady state and transient conditions.

The frequent reconfiguration from substate TA1 (reactivity valid) to TA2 (reactivity invalid) and vice versa, especially during the transient part of the maneuver, has been minimized by incorporating the multiple consecutive occurence (MCO) criterion. The MCO threshold has been chosen as a tradeoff between time delay and false declaration. It appears, however, that the frequent reconfiguration during the transient, as a result of the reactivity information, can be further minimized by upgrading the reactivity validation procedure.

CHAPTER 5. SUMMARY

The objective of this research is to develop and demonstrate a digital, closed-loop, reconfigurable control concept that is based on fault tolerant systems technology. For this work, control reconfiguration refers to the reformulation of the control strategies or algorithms used in the system control, as a result of changes in the plant operating condition. A controller that implements this concept is called a reconfigurable controller. Although the concept is designed and demonstrated with special emphasis on applications to nuclear power plants, the general concept, however, is applicable to other process applications as well. Furthermore, the concept is applicable to the overall plant control, though it is specifically demonstrated here at the component and subsystem level.

In terms of nuclear plant control, the proposed reconfigurable controller is designed to be operational during non-emergency conditions. Its operation is under the envelope of the human operators and the plant protection systems. The objective of such a controller is to assist the human operators in controlling the plant in order to relieve them of the burden of being a major part of the control loop and therefore enhance their role in supervising the plant.

As part of the on-going work at the C.S. Draper Laboratory, Inc. and the MIT Nuclear Reactor Laboratory, the feasibility of the proposed control concept has been demonstrated via computer simulation studies and on-line implementation on the 5 megawatt (MW) MIT Reactor during various transient and steady state conditions.

Nuclear plant control systems have been receiving recent attention because of its possible safety and availability implications. The advancement in digital technology offers a great potential for new innovation and improvement in the plant control system. In addition, a fault tolerant design technique can be easily exploited in digital systems.

A control system is designed to control a plant or process. It consists of plant sensors, controllers, actuators, and demand or reference signal. As discussed in Chapter 1, the issues in designing a highly reliable and available control system based on digital technology are:

1. reliability of the hardware related to the controller, actuators, and sensors
2. reliability of the software related to the digitally-based controller
3. reliability of the information used in the controller
4. the controller's capability to accommodate a wide range of plant operating conditions.

In this thesis, the <u>fourth</u> issue has been addressed under non-emergency conditions. A conceptual design of a wide range controller is presented in this report. To implement this reconfigurable controller, the hardware and software related to the controller, along with the information supplied to the control algorithms, are to be provided so that they are reliable.

There are basically two approaches in addressing the problem of accommodating a wide range of plant operating conditions (POC's). One potential approach is to design a single control law which is based on a plant model that covers all the possible specified conditions. For power plant application, this approach will be difficult to implement because the plant dynamics are complex, nonlinear, time varying, and may not be well known. Furthermore, the governing model is expected to change during the course of operation. Thus, if such a model exists, the performance penalties during normal operation are expected to be excessive. Another approach involves the reconfiguration of various control algorithms for different POC's. This reconfiguration approach is the one taken in this thesis.

The design of the controller is based on a multi-stage reconfiguration logic to select the most "appropriate" control law from a bank of control laws. This bank of control laws consists of model-based algorithms and heuristic-based procedures as shown in Figure 4 on page 35. The reconfiguration logic utilizes three components: a plant operating condition identifier, control performance evaluator, and a decision and supervisory logic. A set of plant operating conditions is defined and identified by using a decision tree approach. This component represents the first stage of the reconfiguration logic. It organizes the available plant information by aggregating the plant information and classifying it into a hierarchial structure. The concepts of mode, configuration, state, and substate are introduced to represent the various levels of the decision tree. The POC's are defined by these four levels and they are represented by the end branches of the decision tree. Each of these end branches is then a priori mapped to a specific control algorithm. Control selection is made by searching the decision tree for the POC and, thus, the control law. This generalized framework can accommodate deterministic as well as statistical and fuzzy logic approaches. The next stage of the reconfigration logic involves the verification of whether or not the previously implemented control action is performing satisfactorily with respect to a given performance criterion. This stage of the reconfiguration logic is executed by the perfomance evaluator. If the control choice obtained from the decision tree performed satisfactorily for the given POC, then no changes in the control selection is made. Otherwise, the selection process is directed by the performance evaluator. If this situation occurs, the selection is made from a set of control laws that are expected to work suboptimally for the given POC. A probability is assigned to each control option. A selection is made based on the probability distribution. A maximum likelihood criterion is used. The probabilities are updated by using a performance adaptive or reinforcement algorithm which is driven by the results of the performance evaluator. Basically, the probability associated with the previous control choice is decremented if it fails to satisfy the performance criterion; otherwise, it is incremented. Various algorithms are available to perform such task. The update scheme for the probabilities associated with the control options, that are not selected, depends on the specific algorithm used. Finally, the decision and supervisory logic (DSL) orchestrates and supervises the operation of the plant operating condition identifier and the performance evaluator in order to insure the safety of the controller. It basically acts as a "safety jacket" for the controller. It can also override the control recommendation of the other two components if a specified bound in the controller is violated. The DSL interfaces with a knowledge base to derive the necessary control actions. The knowledge base includes information derived from plant operating guidelines, plant technical specification limits and requirements, operator experience, and qualitative knowledge about the plant dynamics and the control law limitations. It should be noted, however, that the operation of the reconfigurable controller is under the bound of an independent plant safety system.

The reconfigurable controller concept has been designed and successfully demonstrated on the MIT Reactor to control the reactor power within the instrumentation and processing hardware constraints. The design accounts for various operating conditions which have been defined based on reactivity information, status of the control drive mechanisms, and the nature of the power maneuver. Computer simulation studies were conducted to test the concept and the software prior to on-line evaluation. Several conditions have been selected for demonstration of on-line reconfiguration. The controller has successfully reconfigured and controlled the power during transient and steady state conditions within the required specifications.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following conclusions that can be made based on the results obtained from this thesis are:

1. The concept of reconfiguration of diverse control algorithms for different plant operating conditions has been developed and evaluated experimentally. It provides a viable means of accommodating a variety of plant operating conditions without relying on a single plant model that is valid for all the specified conditions. The utilization of a bank of model-based and heuristic-based control laws along with a reconfiguration logic can potentially extend the automatic control regime.

   The concept has been demonstrated on the MIT Research Reactor (MITR) to control its power. The power has been controlled satisfactorily under various steady state and transient conditions.

2. A multi-stage reconfiguration logic that has been incorporated in the controller provides a reliable means of selecting the appropriate control action without compromising the plant safety.
   - The use of a decision tree approach to implement a control based on the identified category of plant operating condition (POC) provides a simple and direct scheme to select the appropriate control law. The identification of the correct operating condition is important in making the appropriate control law selection. A systematic approach to define the POC's has been presented for easy identification. The implementation of techniques such as low pass filtering of the signals used in the controller as well as sequential testing of conditions is important in identifying the plant operating

condition as defined in the controller design. These techniques minimize the effects of noise and the unnecessary switch over from one control to another.

- The incorporation of a performance evaluator module for online verification of how well the previously implemented control law performs has been shown to be important. The evaluation is based on a given performance criterion and the plant response. A performance adaptive scheme has been used to direct the selection of the most "appropriate" control law, in case the a priori selection made by the decision tree fails to meet the performance specifications. The scheme has been demonstrated under steady and transient conditions. It works satisfactorily in the sense that the selection eventually converged to the control law that induces a plant response that meets the performance criterion. A linear reward-penalty scheme has been implemented. The formulation of the performance criterion as well as the selection of the learning coefficients is crucial in the operation of the adaptation scheme. Small values of the coefficients result in slow changes in the probability distribution associated with the control action. Large values of the coefficients, on the other hand, result in quicker response in the probability distribution. Noise in the signal can temporarily remove a "good" control law from operation; thus, causing a slower convergence rate to the appropriate control choice.
- Finally, the decision and supervisory logic insures that the selected control action will keep the plant operating within the bounds specified in the controller design - thus avoiding possible challenges of the plant safety systems. In the case of the MITR, limits on the reactor power, period, and reactivity constraints have been utilized.

3. Each control law is designed in such a way that it will provide stable operation in its regime of plant operating conditions (POC's). However, no formal proof of the overall controller sta-

bility has been presented. Nonetheless, the decision and supervisory logic provides a safety jacket by implementing an overriding control action to prevent the process from going to an unsafe condition in case the performance evaluation does not readily converge to an appropriate control law or the control strategy switches from one control law to another.

4. Based on the MITR power control experience, a real time program along with the data acquisition routines have been accommodated in a 64 kilobytes LSI 11/23 computer. A sampling time of 1.0 second has been used due to timing constraints. It should be noted, however, that all the conditions that have been defined in the design have not been included in the control program.
5. Simulation tests have been conducted in order to verify the control concept and software prior to on-line evaluation. But more importantly, the simulation studies have provided a preliminary indication of how well the controller will perform under controlled situations.
6. The importance of experimentation as part of the evaluation has been realized. Although the simulation studies have provided many insights in the operation of the reconfiguration control strategy, the evaluation of the concept is limited by the fidelity of the model. The simulation model cannot always capture the complex dynamics that occur in the process. Such consideration is important especially in closed-loop feedback control. For this particular work, the control strategy has been proven on-line under different initial conditions and in the presence of uncertainties in the reactivity estimates, modeling errors, and real plant instrumentation and process noise.
7. A major point to realize about this work is that the concept of control law reconfiguration does not imply fault tolerance in the control system. The design of a reconfigurable controller based on fault tolerant systems technology plays an important role in achieving a control system with high reliability and availability. The reconfigurable controller design requires a reliable set

of information regarding the sensors, actuators, and other plant components. Thus, the controller design also provides a guideline for specifying the minimum scope of a Fault Detection and Isolation (FDI) System. In general, the control concept presented in this thesis can be implemented in systems other than nuclear power plants.

8. The use of inverse kinetics and reactivity balance in validating the reactivity has been demonstrated on the MIT Reactor (MITR). In situations when the validation scheme declares an invalid reactivity condition, a conservative reactivity and reactivity constraint relationships can still be obtained. The use of the conservative information has been proven useful in supervising the decision made by the controller. For the particular demonstration, it was shown, however, that improvements may be needed on the MITR reactivity validation scheme. As discussed in the result section, the present scheme appears to be very sensitive to noise especially during the transient part of a power maneuver. Despite the implementation of multiple consecutive occurence criterion, the noise in the reactivity estimate has resulted in unnecessary reconfiguration from one control law to another. Nonetheless, such behavior has not compromised the operation of the controller.

6.2 Recommendations

Several areas for future work have been identified. They are related to the general implementation issues, general improvements in the modules used in the reconfiguration logic, and the specific enhancements on the MIT Reactor (MITR) reconfigurable control algorithm.

6.2.1 General Implementation Issues

1. Overall Control System Architecture: An architecture has been presented in Appendix H in order to show how the reconfigurable

control strategy discussed in this thesis relates to the other elements of the control system. The architecture treats each component of the system separately. For example, the actuator may be designed in a fault tolerant fashion regardless of the design architecture used in the controller and sensors, as long the overall system functional requirements are satisfied. A cost-benefit analysis can be conducted to determine the degree of fault tolerance needed in each components in order to achieve the reliability and availability requirements for the control system.

2. Reconfigurable Control Strategy: The entire MITR control program has been coded in FORTRAN. The multi-stage reconfiguration logic has been implemented in a serial fashion. As mentioned in the previous section, the control concept introduced in this thesis may be also applied in systems other than nuclear power plants. In general, the use of conventional computers to implement such control concept may not be an ideal way to meet the timing requirements. The elements of the reconfigurable control strategy can be potentially implemented by using parallel processing [Wu, 1985] to do the different tasks. For example, the plant operating condition identifier and performance evaluation modules may be implemented in one processor, the control laws in another processor, and the knowledge base in a processor that supports symbolic manipulation.

6.2.2 General Improvements in the Reconfiguration Modules

1. The use of a statistical approach or fuzzy logic might be used to identify the features that define a given plant operating condition.
2. An investigation of other reinforcement algorithms needs to be conducted especially for processes whose dynamics are extremely fast or slow. A more general scheme to account for the credit assignment problem (i.e., reward and penalty credit) associated with the control options needs to be addressed.

3. The determination of a more generalized performance criterion especially during transient conditions needs additional investigation.
4. The organization and implementation of the knowledge base also warrants additional examination. The knowledge base might be implemented in a symbolic fashion. The issue of automatically updating the knowledge base was not addressed, and therefore it requires further considerations. In the conceptual design of the reconfiguration logic, no explicit structure of the knowledge base has been assumed.

6.2.3 Specific Enhancements on the MITR Reconfigurable Controller

1. The determination of the features of the plant operating conditions might be upgraded by using fuzzy logic as opposed to a deterministic approach in order to better capture the operating rules of thumb and operator experience. For example, membership functions might be carefully formulated to account for large and small power change, low and high initial reg rod position, and other qualitative descriptions of the plant operating conditions.
2. The control procedures based on operating rules of thumb still have room for improvements. For example, the reshim procedure might be upgraded if desired.
3. The scope of the reconfigurable controller might be upgraded in order to account for all the conditions that have been considered in the design presented in Chapter 3.
4. Improved performance criterion during a transient should be investigated. A power trajectory and a test on the amount of control action that is used during a maneuver should be considered.
5. The information and decision generated by the controller should be made available to the operators. As designed, the control has to switch to manual control under certain circumstances such as

startup, shutdown, saturation of the control mechanism, and unavailability of the shim blade mechanism.

6. The expansion of the knowledge base is needed to account for other conditions that are not currently included in the present control program.
7. The design of other control laws to complement existing control laws are needed. For example, the fuzzy control algorithm might be extended during power decrease maneuvers.
8. The reactivity validation scheme should be upgraded to prevent the unnecessary switch over from a valid to an invalid reactivity condition and vice versa.
9. The control program might be restructured in order to make the architecture of the reconfiguration logic more transparent in the code.

All the above recommendations, that are specific to the MITR reconfigurable controller, depend on the availability and existence of the hardware interface, instrumentation, and the processors that are used to demonstrate the control concept. It should be noted that the present computer and instrumentation system cannot accommodate all these recommendations.

APPENDIX A. REVIEW OF VARIOUS CONTROL METHODOLOGIES

This appendix presents a brief review of several control methodologies that had been or could be potentially used for nuclear plant application. The general methodologies presented in this appendix are: 1) state variable feedback control, 2) adaptive control, and 3) "advanced" control schemes. These are only a few of the several approaches. There are a wide range of methods based on different aspects of a specific theory. The approaches noted above can still be broken down into several categories. An expanded view of the recent work in reactor control can be found in the bibliography compiled by Tylee [Tylee, 1985]. A survey of various methodologies is also presented in [Mc Morran, 1979].

The basic outline of the review includes 1) a general description, 2) advantages and limitations, and 3) experience with the methodology.

A.1 State Variable Feedback Control

A linearized model of the plant is often used in a state variable feedback (SVF) methodology [Kwakernaak and Sivan, 1972], [Bryson and Ho, 1975]. The scheme is presented in multivariable input and output formulation. The state equation is written in the state space form

$$\dot{\underline{x}} = A\underline{x} + B\underline{u}$$

where $\underline{x}$ represents the state vector, $\underline{u}$ is the control vector, A is the state matrix, and B is the control effectiveness matrix. The control signal is of the form

$$\underline{u} = -K\underline{x}$$

where K is the control gain matrix. It is often the case that not all the states defined by the plant model is measurable. An estimator or observer is used to provide an estimate of these unmeasured states.

There are different ways of selecting the gain matrix K. The two most common approaches are based on pole placement technique and linear quadratic regulator theory. In pole placement approach, K is chosen based on the desired eigenvalues or roots of the closed loop system characteristic equation. Physically, the eigenvalues of the closed loop system provide an indication of the controller behavior such as its speed of response and the resulting oscillation in the plant response after it has been subjected to a step input. In general, pole placement does not yield a unique gain. A good engineering judgement is often needed in choosing the desirable K

In linear quadratic regulator theory, the optimal control is one which minimizes the cost function

$$J = \int_{t=0}^{t=\infty} (\underline{x}^T Q \underline{x} + \underline{u}^T R \underline{u}) dt$$

where Q and R are weighting matrices. The optimal gain K is obtained by solving the steady state matrix Ricatti equation

$$PA + A^T P + Q - PBR^{-1}B^T P = 0.$$

where R is the solution to the matrix equation. The optimal gain is given by

$$K = -R^{-1}B^T P.$$

The optimal control drives the state variables toward zero (equilibrium) from any initial condition.

The SVF approach provides an analytical procedure for control design. It guarantees stability if there is no significant plant model change or input failures. It requires large computational burden if implemented for time varying case. The weighting matrices in the performance index do not directly provide an indication of the safety constraints. Fixed gain is often used. It requires an accurate plant model and it needs an estimator in cases when the states are not directly measured. Erroneous estimate can therefore lead to degraded control.

For nuclear power plant application, SVF has been used for temperature control [Godet et al, 1982], steam generator level control [Frogner et al., 1975], and other applications [Ebert, 1982], [Cooper, 1980], [Feeley et al., 1980].

A.2 Adaptive Control

This section is divided into two subsections. The first deals with the "conventional" [Astrom, 1983] adaptive technique and the second discusses the less conventional adaptive control.

An adaptive system is designed to control plants that have a wide range of operating conditions. A constant gain feedback control algorithm can work well in a limited operating range and difficulties can be encountered when the operating range change. This situation is expected in nuclear power plants and other process plants.

A.2.1 Conventional Adaptive Control

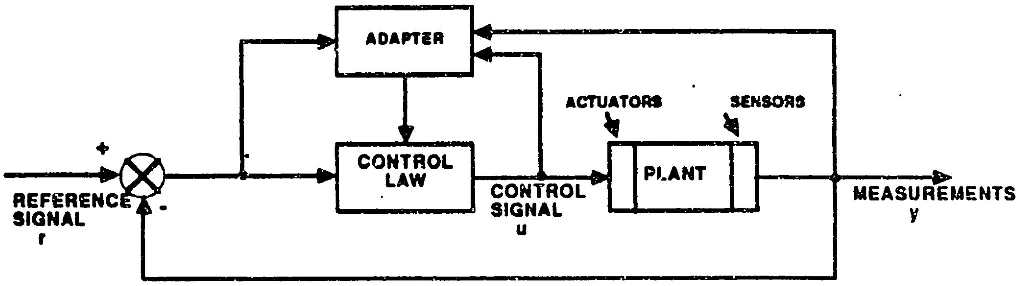

Figure 34. General Structure of a Parameter Adaptive System

The objective of an adaptive control system is to self adjust its parameters or gains during the course of plant operation. This description is consistent with the formally accepted description of an adaptive control [Saridis, 1977], [Astrom, 1983]. The general structure of an adaptive system is shown in Figure 34. Recent surveys and representative collection of papers on theory and applications of adaptive control can be found in [Astrom, 1983], [Narendra and Monopoli, 1980] and special issue of Automatica on adaptive control (September 1984, Vol 20, No. 5).

Adaptive control schemes offers several advantages. Optimal parameters can be adjusted using a well structured and systematic approach. State variable feedback can be incorporated in the adaptive scheme. The major drawback is that the underlying theory has several problems to resolve. The formulation of the adaptive schemes such as MRAC and STR (discussed below) are based on the assumption that may be too restrictive for real life engineering applications. These schemes have been shown to be inherently unstable in the presence of high frequency dynamics and unmeasured output disturbances [Rohrs, 1982]. However, several adjustment algorithms have been proposed to resolve the inherent problem. The success of adaptive control relies on the validity of the operating conditions under which the control law has been designed and the magnitude of the perturbation relative to a given reference condition.

There are three classes of parameter adaptive control schemes - gain scheduling, model reference, and self-tuning regulators. The design involves the determination of a systematic approach of changing the regulator parameters in response to changes in process and disturbance dynamics. The schemes are very similar and they differ only in the way the parameters of the regulator are adjusted.

A.2.1.1 Gain Scheduling

Gain scheduling is a table look up approach to change the control gain for different operating conditions. The choice of the process variables, which serve as the basis for the scheduling, is important. Extensive simulations or experimental studies are required to construct

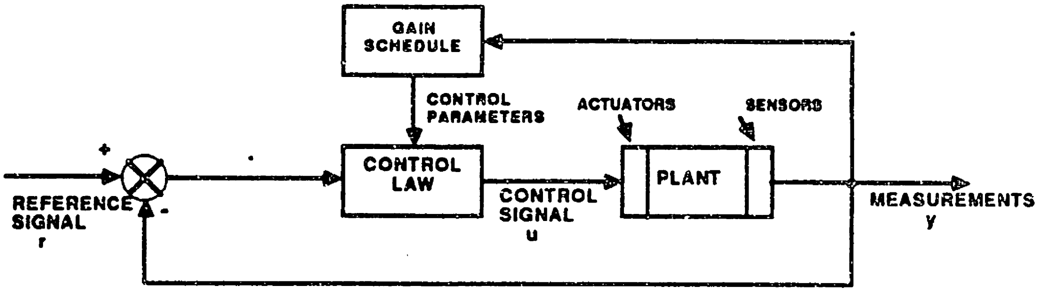

Figure 35. Gain Scheduling

such a table of control parameters. In terms of implementation, gain scheduling offers the advantage that the parameters can be changed very quickly in response to changes in the operating conditions. However, there is no feedback which compensates for an incorrect scheduling. This situation can result in a degraded control performance. A block diagram of the gain scheduling approach is shown in Figure 35.

The concept of gain scheduling has evolved during the early development of flight control systems. It is now dominantly used in process control. Its operation is strictly supervised by the operator to insure that the operating condition is valid for the scheduled gain.

Some examples of gain scheduling control systems are described in [Stein et al., 1977] for aircraft application, [Andreiev, 1977] for process control, and [Irving et al., 1980] for nuclear steam generator level control.

A.2.1.2 Model Reference Adaptive Control

A reference plant model is utilized to indicate how the actual plant should respond to a command signal [Landau, 1974]. The control gain in model reference adaptive control (MRAC) is adjusted by using the approach shown in Figure 36. It consists of two loops. The inner loop

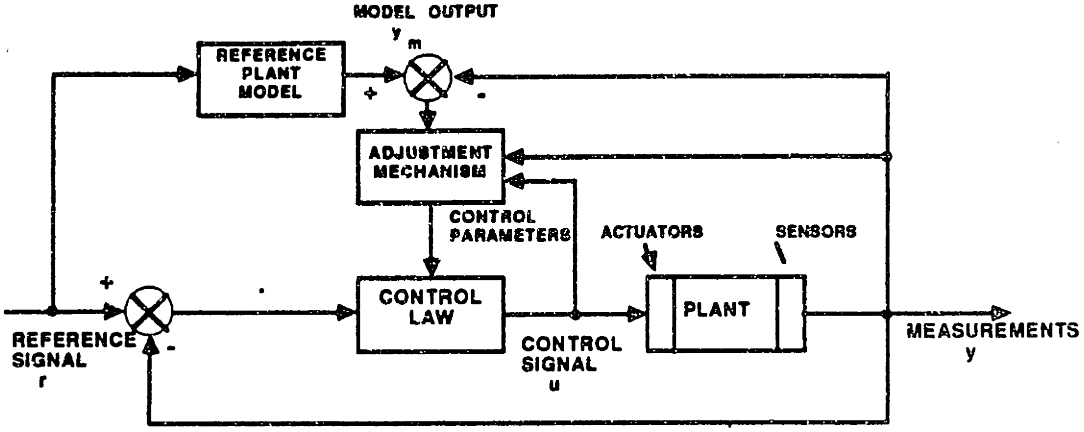

Figure 36. Model Reference Adaptive Control

is the standard control loop composed of the process and the control scheme. The outer loop consists of a reference model and a parameter adjustment scheme. The objective of the MRAC is to adjust the plant control parameters so that the error between the reference model and the actual process output goes to a small specified value without compromising the stability of the plant. There are various methods to adjust the control parameters. These methods involve the determination of the error sensitivity with respect to the adjustable parameters. A good plant model and a stable adjustment mechanism are important in order to utilize this control strategy. Physical constraints on the actuator can limit the capability of the MRAC.

The MRAC technique is widely used in aerospace as well as industrial applications [Landau, 1974]. It has also been proposed for power plant control [Mabius, 1981].

A.2.1.3 Self Tuning Regulator (STR)

Self tuning regulators are applied to control systems with unknown but constant parameters [Astrom et al., 1977]. They can also be used to

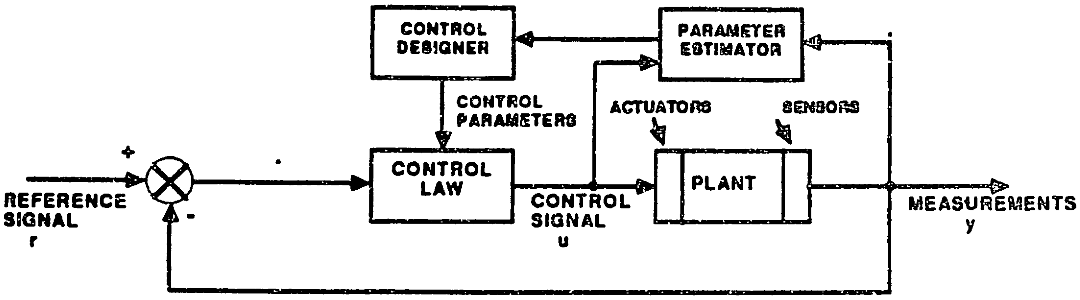

Figure 37. Self Tuning Regulator

system with slowly varying parameters. The structure of the STR is similar to that of the MRAC except for the outer loop. The outer loop of the STR consists of a recursive parameter estimator whose output is used to adjust the control gain as shown in Figure 37. In order to obtain good estimates, it is often necessary to introduce small perturbation signals. The examples of estimation schemes that are commonly used are [Astrom et al., 1977], [Astrom, 1983] least squares, extended Kalman filtering, and maximum likelihood methods. The success of STR relies on a good plant model and a stable parameter estimation scheme. STR's have been successfully applied to many different industrial processes [Astrom, 1977], [Kraus et al., 1984].

A.2.2 Other Adaptive Schemes

These are less conventional than those presented above in the sense that the overall controller structure is changed rather than just its parameters. Control algorithms of this type are also called self organizing controllers (SOC) [Saridis, 1977]. Probabilistic as well as learning algorithms are used to determined the control structure [Saridis, 1977], [Fu, 1970], and [Athans et al., 1977].

An example of a nonconventional adaptive scheme is the multiple model adaptive control (MMAC) [Athans et al., 1977] which had been earlier proposed for the F-8 flight control system. The design involved the use of a bank of Kalman filters and linear-quadratic SVF control laws for various operating conditions. The Kalman filter residuals are used to identify the operating state via a maximum likelihood test. Disregarding the hardware constraints and the complexity of implementation, the practical success of this approach relies on the accurate model of the process at different operating conditions, the validity of the probability density function used in the likelihood test, and its sensitivity to noise.

Numerous examples of SOC systems, which incorporate learning algorithm, have been reported [Saridis, 1977]. These systems assume little a priori knowledge or accuracy of the plant model. The major drawback of this approach is that it often requires a certain amount of time to converge to the appropriate control structure for a given condition. Basically, the resulting control structure is used to identify the plant operating condition. Furthermore, the search process allows for incorrect selection before the algorithm eventually "learns" the appropriate control structure. For time critical situations especially during transients or abnormal conditions, this approach may not be acceptable. However, the learning rate can be increased during this situation, but this could result in a wider control system bandwidth.

With the emergence of artificial intelligence, the utilization of an expert system technology in the organization of the control system has been proposed [Astrom, 1985].

A.3 Advanced Control Schemes

The advanced schemes presented in this section are: 1) model algorithmic control (MAC), 2) heuristics control, and 3) other miscellaneous control schemes.

A.3.1 Model Algorithmic Control (MAC)

The operation of MAC consists of the following features: internal model of the system, reference trajectory and output constraints, and control trajectory computation [Rouhani and Mehra, 1982].

The purpose of the internal model is to predict the future behavior of the system under different control inputs. It is used to compute the optimal control signal and to detect process changes, sensor failure, and component faults. Failure is detected if there is a large difference between the computed model outputs and the corresponding measured values. The internal model is obtained from off-line identification.

The desired response of the closed loop system is specified in the form of a reference trajectory and constraints. Typical specification requirements relate to overshoot, rise time, settling time, and maximum and minimum limits on the process variables. These requirements are difficult to specify in scalar performance index as in optimal or linear quadratic state variable feedback control.

The control trajectory is computed for a number of future time samples. An iterative optimization technique is used to minimize the distance between the desired reference trajectory and output trajectory predicted by the internal model.

MAC offers several advantages. It allows for on-line changes in the system model, and thus it is more flexible than state variable feedback approaches. The specification of the desired response and constraints is simplier than the specification of a scalar performance index. In practice, specification of scalar criterion function is difficult to do. Furthermore, scalar performance index does not absolutely guarantee that control and state constraints are satisfied on-line in the case of model uncertainties. Control requirements stated in terms of desired trajectories and constraints can be easily explained to the operators.

MAC suffers several limitations. It relies on an internal model of the system which is obtained via off-line identification. On-line identification is needed in cases where large random variations of system parameters are expected. The robustness and stability of MAC depends on the accuracy of the internal model. In addition, the desired trajectory may not always be satisfied due to physical constraints in the actuators and process variables.

MAC has been applied in several areas such as aircrafts [Mehra et al., 1978], power systems [Mehra and Eterno, 1980], and various industrial processes [Richalet et al. 1978].

A.3.2 Heuristic Control

Heuristic control schemes rely on rules of thumb used in plant operation. A qualitative rather than quantitative representation of the plant is used in determining the control strategy. Nonlinearity is easily accommodated. Boolean logic, pattern recognition [Fu, 1968], and fuzzy set logic [Zadeh, 1984], [King and Mamdani, 1977] have been used to determine the control action based on the available plant measurements.

Heuristic control scheme is not very well structured as compared to the more conventional control approaches. The robustness and the stability properties of this control scheme depends on the conditions assumed in the model. The major drawback of heuristic control is the possible erroneous control implementation due to incomplete conditions incorporated in the model, conflicts between the operating rules, and misclassification or misidentification of the operating conditions due to noise.

A.3.3 Other Control Schemes

Set theoretic control is another state variable feedback approach for linear time invariant systems. It is assumed that the limits on controls and process state variables are known in advance. The objective of the design is to ensure that all system variables remain within the specified bounds under all plant conditions. The system disturbance is assumed unknown but bounded. The goal is to find the maximum bound on the disturbance such that all the system variables are bounded. This constraint optimization problem is solved by using a "brute force" or the Lagrangian approach. Set theoretic control has been proposed as an advanced concept in electric generating plant control [Gould et al., 1981]. The objective is to improve the response characteristics of the plant - being able to increase and decrease the power output at required rates without violating the imposed plant constraints by using only the available control.

For nonlinear control problems, a variable structure system (VSS) or sliding mode control has been proposed [Itkis, 1976]. It is different from traditional control schemes in the sense that its structure is changed in jump-wise fashion during a transient proccess depending on the current value of the error signal and its derivative. The VSS design problem is to select parameters for each of the structures and to define the swithing logic. This approach offers the advantages of high speed of response and insensitivity to variations in plant parameters and external disturbances. A good model of the plant is needed.

APPENDIX B. PERFORMANCE ADAPTIVE OR LEARNING ALGORITHM

A performance adaptive or learning algorithm [Mendel and Fu, 1970], [Narendra et al., 1974] is used as a mechanism to direct the control selection process if several options are available for a given category of plant operating condition. This procedure is useful in selecting a option in cases when the plant and its environment are not known or poorly known. The objective of the learning algorithm is to adapt the control system action during these situations by monitoring the performance of the previously selected control option based on the plant response relative to a desired performance condition. The scheme can be also thought of as an adaptive scheme based on performance. The space, which defines the operating conditions, is divided into several regions. Each region is assigned a set of candidate control options. Each control option for that particular region is assigned a probability. This probability provides a measure of how well such control option will perform based on its previous performance for that given region. With this scheme, the system "learns" in the sense that the probability associated with the "most appropriate" control option will eventually dominate. This scheme does not make an assumption regarding the nature of the probability density functions for the options, unlike in classical statistical decision schemes.

In general, given that there are r(i) control options for condition i, the probabilities associated with the allowable control actions in operating condition i is described by the distribution

$$P_i(t) = (P_{i1}(t), P_{i2}(t), \ldots\ldots, P_{ir(i)}(t))$$

where i = operating condition, $i = 1, 2, \ldots, m$
j = control option, $j = 1, 2, \ldots, r(i)$

where $0 < P_{ij}(t) < 1$

$$\sum_{j=1}^{r(i)} P_{ij}(t) = 1.$$

The "best" possible control action for a given type of operating condition is the control action with the maximum $P_{ij}(t)$ associated with it.

The learning algorithm update is based on the concept of reinforcement. Let $H(t)$ be the reinforcement function. This function indicates whether or not the previous control action performed satisfactorily. A satisfactory performance is a nonpenalty condition while an unsatisfactory performance is a penalty condition. The probability associated with a given control action is incremented (rewarded) or decremented (penalized) based on the value of $H(t)$.

There are various types of reinforcement or learning algorithms that have been reported [Barto, et al., 1981], [Fu, 1970], [Glorioso, et al., 1980], [Jones and Fu, 1969], [Narendara et al., 1974], [Narendara et al., 1980], [Saridis, 1977]. The concept has been studied and applied in many different applications. There are algorithms which are well structured and there are also those which are too ad hoc.

Consider a linear reinforcement model. The basic idea behind it is rather simple. Let t designates the current time sample. If the system selected an action U_k at time t-1, given that the system was in operating condition i, and a nonpenalty condition occurs, then the value of $P_{ik}(t)$ is increased and all the other components of $P_i(t)$ are decreased. For a penalty condition, $P_{ik}(t)$ is decreased and the other components are increased. This type of algorithm is called reward-penalty. In some algorithms, the probability distribution is unchanged when a penalty condition occurs. Such algorithms are called reward-inaction.

A linear reinforcement algorithm for updating the distribution function for a given operating condition is as follows:

If action U_k was selected at time t-1 given that
the system was in operating condition i then

For nonpenalty condition

$$P_{ik}(t) = P_{ik}(t-1) + \sum_{j \neq k}^{r(i)} F_{ij}(t-1)$$

$$P_{ij}(t) = P_{ij}(t-1) - F_{ij}(t-1) \qquad (j \neq k)$$

For penalty condition

$$P_{ik}(t) = P_{ik}(t-1) - \sum_{j \neq k}^{r(i)} G_{ij}(t-1)$$

$$P_{ij}(t) = P_{ij}(t-1) + G_{ij}(t-1) \qquad (j \neq k)$$

where $F_{ij}(t)$ = reward function
$G_{ij}(t)$ = penalty function.

The two common algorithms are based on the linear reward-penalty (LRP) and linear reward-inaction (LRI) models. For these models, the reward and penalty functions are linear functions of the probability distribution as shown below:

For LRP

$$F_{ij}(t) = a_i P_{ij}(t)$$

$$G_{ij}(t) = b_i (1/(r(i)-1) - P_{ij}(t))$$

For LRI

$$F_{ij}(t) = a_i(t) P_{ij}(t)$$

$$G_{ij}(t) = 0$$

where a_i, b_i are called the "learning coefficients" for operating condition i. In general, a_i and b_i are assumed time invariant.

The learning coefficients dictate the sensitivity of the distribution function with respect to a change in the performance measure of the selected action. High sensitivity can be attained by using large values of a and b and vice versa. The values of the learning coefficients have to be selected such that $0 < a, b < 1$.

The distribution function can be initialized based on an a priori knowledge of the plant behavior. The probability associated with the control action that is believed to be the "best" for the given operating condition is set to one and the rest are set to zero. If there is no a priori knowledge about the "best" option, then the control actions are weighted equally.

APPENDIX C. MITR CONTROL ALGORITHMS

This appendix presents the control algorithms that are incorporated in the MIT Reactor (MITR) reconfigurable reactor power controller. The objective, basis, and limitations of each algorithm are discussed.

C.1 Proportional-Integral-Derivative (PID) Control Law

This control law is primarily used for steady state operation. It can be used to control the reg rod. Shim blade control using this control law is also possible. This is an upgraded version of the work reported by Ray [Ray et al. 1983C].

The power estimate derived from the signal validation system is fedback to the control law in order to produce a control signal that is proportional to the set point error (the difference between the current power and the desired power). The controller also computes the reactivity deviation and uses it as an additional feedback signal. An inverse kinetics approach is used for on-line estimation of reactivity [Ray et al., 1983C]. The power level and its history are used in the estimation procedure. The reactivity signal provides an anticipatory response to compensate for the disturbance. This signal produces a correction that is independent of the steady state estimate of the reactor power. The reactivity feedback corresponds to the derivative signal in a more conventional proportional-integral-derivative (PID) control algorithm. This algorithm also incorporates reset or integral action to eliminate steady state error. The control law is given by

$$u = K_p (P_{set} - P) - K_\rho \rho + K_I \int (P_{set} - P)\, dt$$

where K_p is the proportional gain, K_I is the intergral gain, K_ρ is the reactivity gain, and P_{set} is the power set point. The error integral is reinitialized to zero each time this control law is switched back in operation. The integral is also set to zero if the power deviation exceeds a specified level. The control gains are fixed and chosen off-line. For small step change in power the PID algorithm may also be used but its gains may have to be adjusted or scheduled for different power levels via off-line selection or a more sophisticated on-line adaptation.

C.2 Non-Linear Digital Controller

This control algorithm is designed for transient control [Bernard et al., 1984], more specifically for load maneuver. It can also be used during steady state condition without compromising the safety of the plant but its performance is not expected to be as good as that of a steady state control algorithm. The NLDC can be used to adjust either the reg rod or the shim blades.

The NLDC prevents unacceptable power overshoot during power increase maneuver or undershoot during a power decrease. It relates the reactor power, period, and reactivity that exists during the transient. The algorithm insures that the control mechanism being used has "sufficient" reactivity so that it is always possible to change the direction of the power trajectory at the desired termination point of the transient by reversing the direction of the control mechanism signal. For example, during a power increase, the power could still increase while the rod is being inserted. This situation occurs if the control rod has no sufficient reactivity - especially if it has been withdrawn too high - to compensate for the existing positive reactivity that is present. The algorithm limits the reactivity in order to insure that control is always feasible with the specific control mechanism. The relationship to determine this limit is called the reactivity constraint. For the NLDC algorithm, the power set point has been chosen as the termination point for the transient. For power increase, a withdrawal of the control mechanism is permitted as long as:

$$(\rho - \rho_{max}/\lambda_{eff})/\rho_{max} < \tau \log(P_{set}/P)$$

and for power decrease, an insertion is allowed as long as:

$$(\rho + \rho_{max}/\lambda_{eff})/\rho_{max} \geq \tau \log(P/P_{set})$$

where

ρ is the total reactivity estimate

ρ_{max} is the absolute value of the maximum possible <u>rate</u> of reactivity change that can be obtained if the selected control mechanism is moved

λ_{eff} is the time dependent effective one-group decay constant

P is the current reactor power

P_{set} is the power set point

τ is the reactor period.

The left hand side of the inequality is referred to as the required time, T_R, to eliminate the excess reactivity present beyond the amount that can be negated by a reversal of the rod motion. The right hand side of the inequality is called the available time, T_A, to attain the desired power. The control logic is to withdraw the rod if $T_A > T_R$ and to insert if $T_A < T_R$ as shown in Figure 38.

The performance of the NLDC relies on the accurate prediction of the reactivity and the effective one-group decay constant. For the MITR, the decay is fitted as an exponential function of reactivity. An on-line estimate of the reactivity is obtained by using the shim blade and reg rod nonlinear reactivity worth curves and the coolant temperature reactivity feedback. The current algorithm uses the temperature coefficient which is based on equilibrium conditions. An inverse kinetics model is also used to determine the reactivity, as discussed in Appendix D.

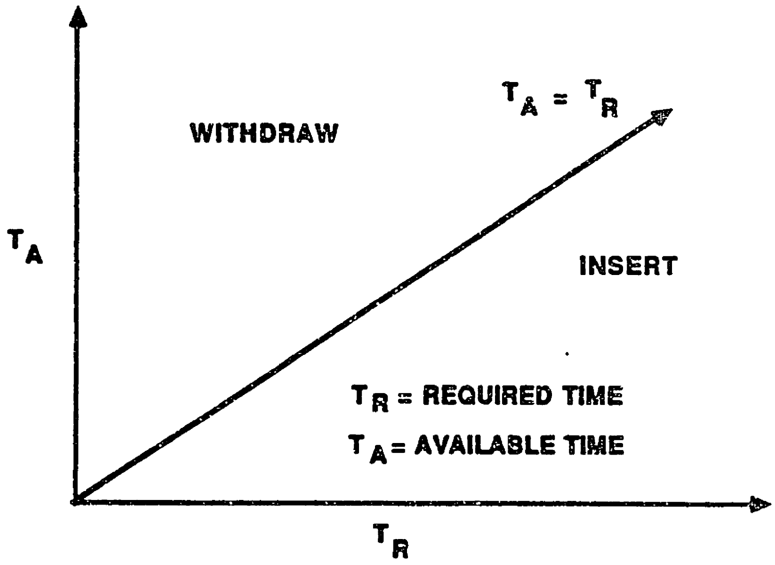

Figure 38. NLDC Control Logic: This is valid for both power increase and decrease maneuvers.

The required inputs for the NLDC are reactor power, control rod positions (shim blades and reg rod), and the average reactor coolant temperature. Unmodelled reactivity contributions such as the effects of xenon and temperature transients can lead to erroneous reactivity estimate. The reactivity constraint relationship assumes a perfect knowledge of the maximum possible rate of reactivity change that can be obtained if the selected mechanism is moved. This quantity corresponds to the speed of the drive motor. The NLDC provides a viable means of control if all its inputs are valid.

In the presence of noise and disturbance, the NLDC control logic presented above can cause chattering in the control action and, thus, more wear and tear in the drive motor. More specifically, the control logic is given below

For power increase :

```
        If ( $T_R < T_A$ ) SIGNAL = OUT
        If ( $T_R \ge T_A$ ) SIGNAL = IN
  For power decrease
        If ( $T_R \ge T_A$ ) SIGNAL = IN
        If ( $T_R < T_A$ ) SIGNAL = OUT.
```

It should be noted that the inherent structure of the control logic can lead to a control oscillation. For example, during a power increase, the rod is normally withdrawn whenever the constraint is satisfied ($T_A > T_R$). The moment $T_A \le T_R$ the rod is immediately inserted. This action will cause T_A to be greater than T_R again after a few control intervals and the cycle will repeat itself.

This behavior can be minimized by adding a "buffer" zone in the control logic. Two sets of user specified parameters are introduced for each type of maneuver. The modified logic is shown below:

```
For power increase
   If ( $T_R < T_A$ ) then
      If ( $T_R > ( T_A - T_1 )$ then
      SIGNAL = HOLD
      ELSE SIGNAL = OUT
   If ( $T_R \ge T_A$ ) then
      If ( ( $T_R - T_A$ ) < $T_2$  and
      If ( current ( $T_R - T_A$ ) < previous ( $T_R - T_A$ ) ) then
           SIGNAL = HOLD
      ELSE SIGNAL = IN.

For power decrease
   If ( $T_R \ge T_A$ ) then
      If ( $T_R < ( T_A - T_3 )$ then SIGNAL = HOLD
      ELSE SIGNAL = IN
   If ( $T_R < T_A$ ) then
      If ( ( $T_A - T_R$ ) < $T_4$  and
```

```
If ( current ( $T_A$ - $T_R$ ) < previous ( $T_A$ - $T_R$ ) ) then
    SIGNAL = HOLD
ELSE SIGNAL = OUT.
```

where T_1, T_2, T_3, and T_4 specify the "HOLD" boundary. A sketch of the modified logic is shown in Figure 39.

Table 7. Description of the NLDC Experiments

Run #	Logic	Low Pass filter
1	Modified	YES
2	Modified	NO
3	Original	NO
4	Original	YES

Four experiments were conducted on Monday June 17, 1985 to test the modified logic. The power was raised from 1 to 1.5 megawatts-thermal (MWt) in each case. A first order low pass filter with time constant of 2 seconds was used in some of the runs to smooth out the estimated reactor period. The parameters T_1 and T_2 have been set to 10 and 5 seconds respectively. The description of the four runs are summarized in Table 7. The fixed speed drive motor has been used in all of the experiments presented here. Hence the motor is always given time to come to a complete stop before it is issued a signal to reverse direction [Bernard, 1984].

The results are shown in Figure 40 to Figure 43 for experiments #1, #2, #3, and #4 respectively. There are 5 time plots associated with each experiment. These plots include the reactor power (POWER) in kilowatt (kw), the reactor startup rate(SUR) in decades per minute (DPM), the reg rod height (RR HEIGHT) in inches, the reactor outlet temperature

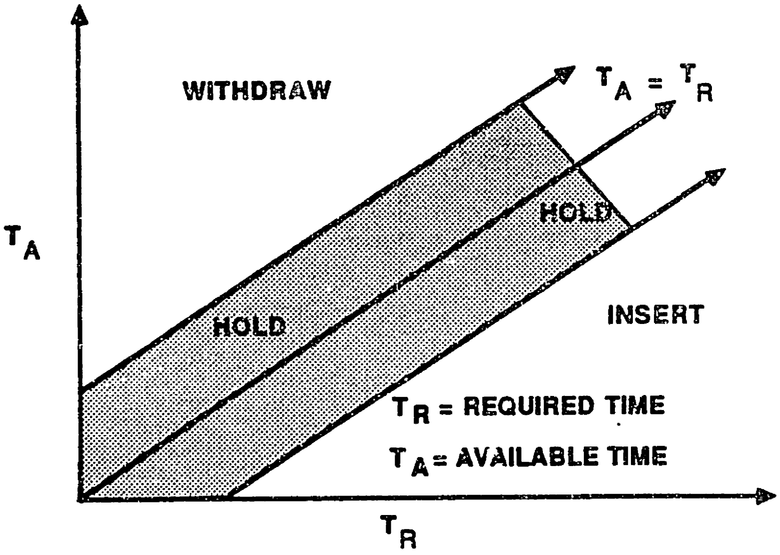

Figure 39. Modified NLDC Control Logic

(TEMPERATURE) in degrees-C, and the reg rod control signal (CONTROL). The "original" scheme is represented by case #3 - no low pass filter. The results indicate that the modified logic complemented by a low pass filter (case #1) minimized the oscillations, but it takes slightly longer (about 15 seconds) to bring the power to the desired level as compared to case #3. The modified logic without the low pass filter (case #2) exhibits a behavior that is similar to that in case #3. The use of low pass filter enhances the time trace of the rate of change of power (SUR). However, it results in low frequency oscillation in the reg rod motion as shown in case #4 (original logic with low pass filter).

C.3 Fuzzy Control Law

This control law is primarily designed to adjust the reg rod during transients [Bernard et al., 1985]. Such transients could be operator induced set point change or a plant disturbance. The present algorithm only accounts for power increase.

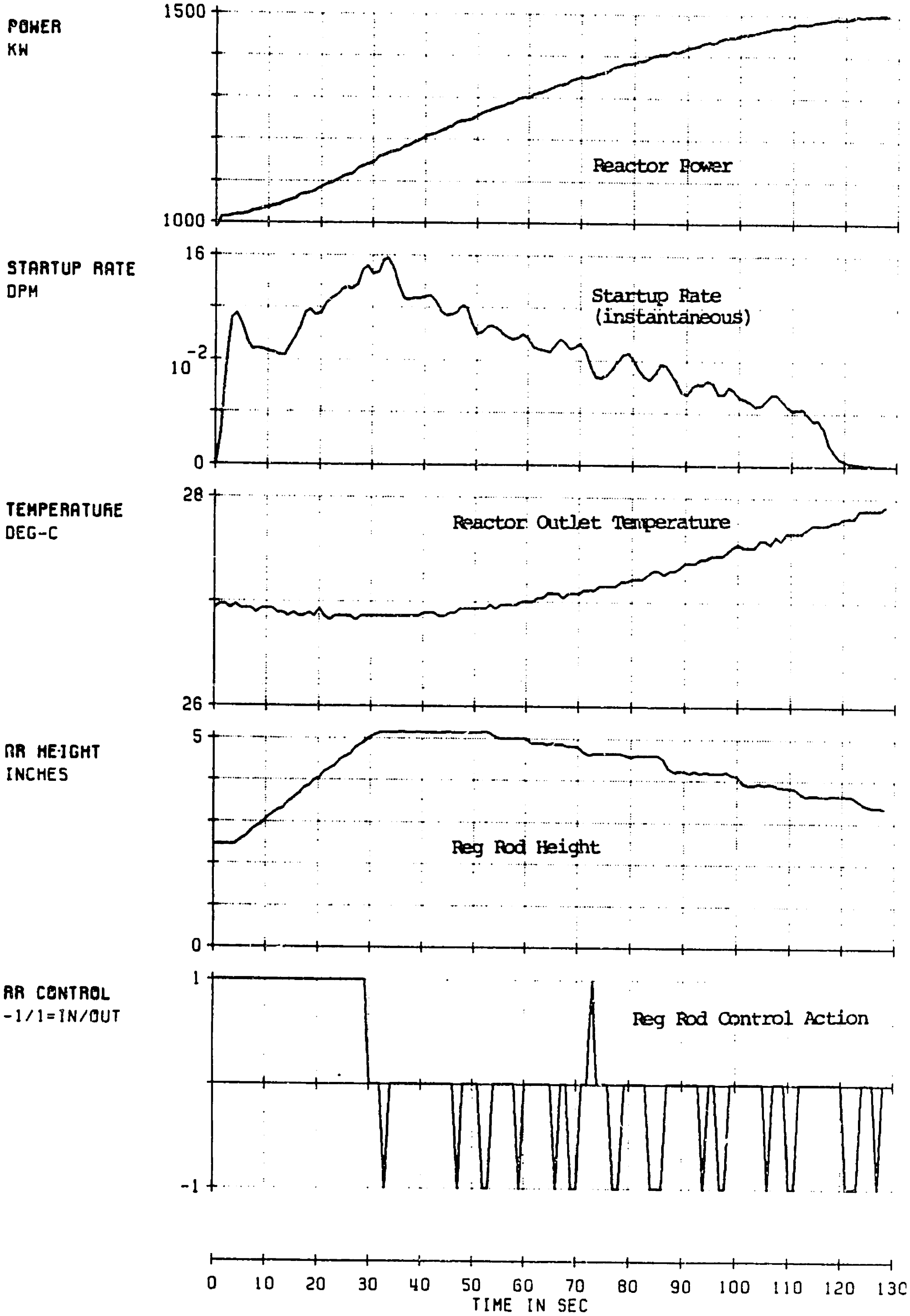

Figure 40. Modified NLDC Logic with Filter

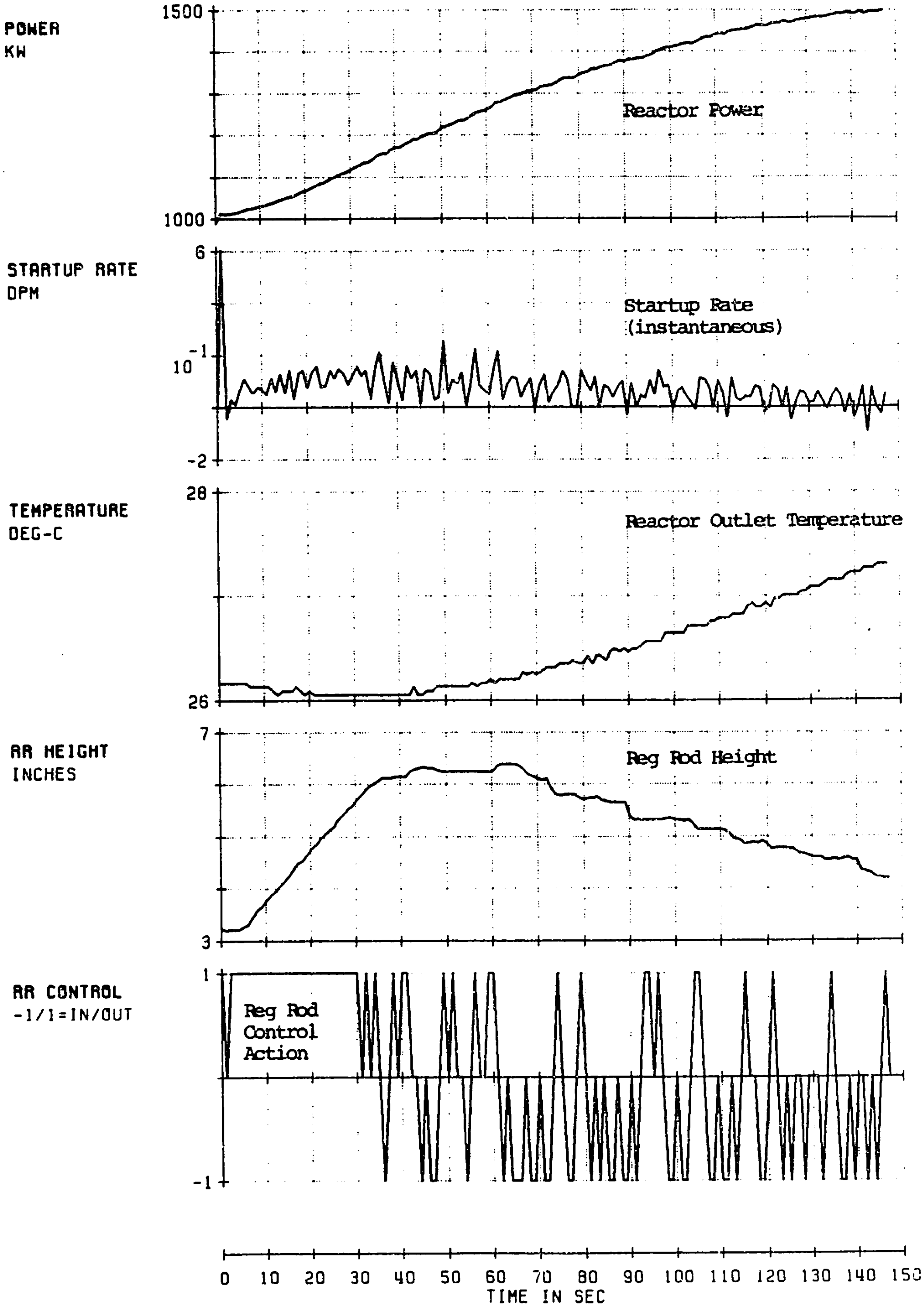

Figure 41. Modified NLDC Logic without Filter

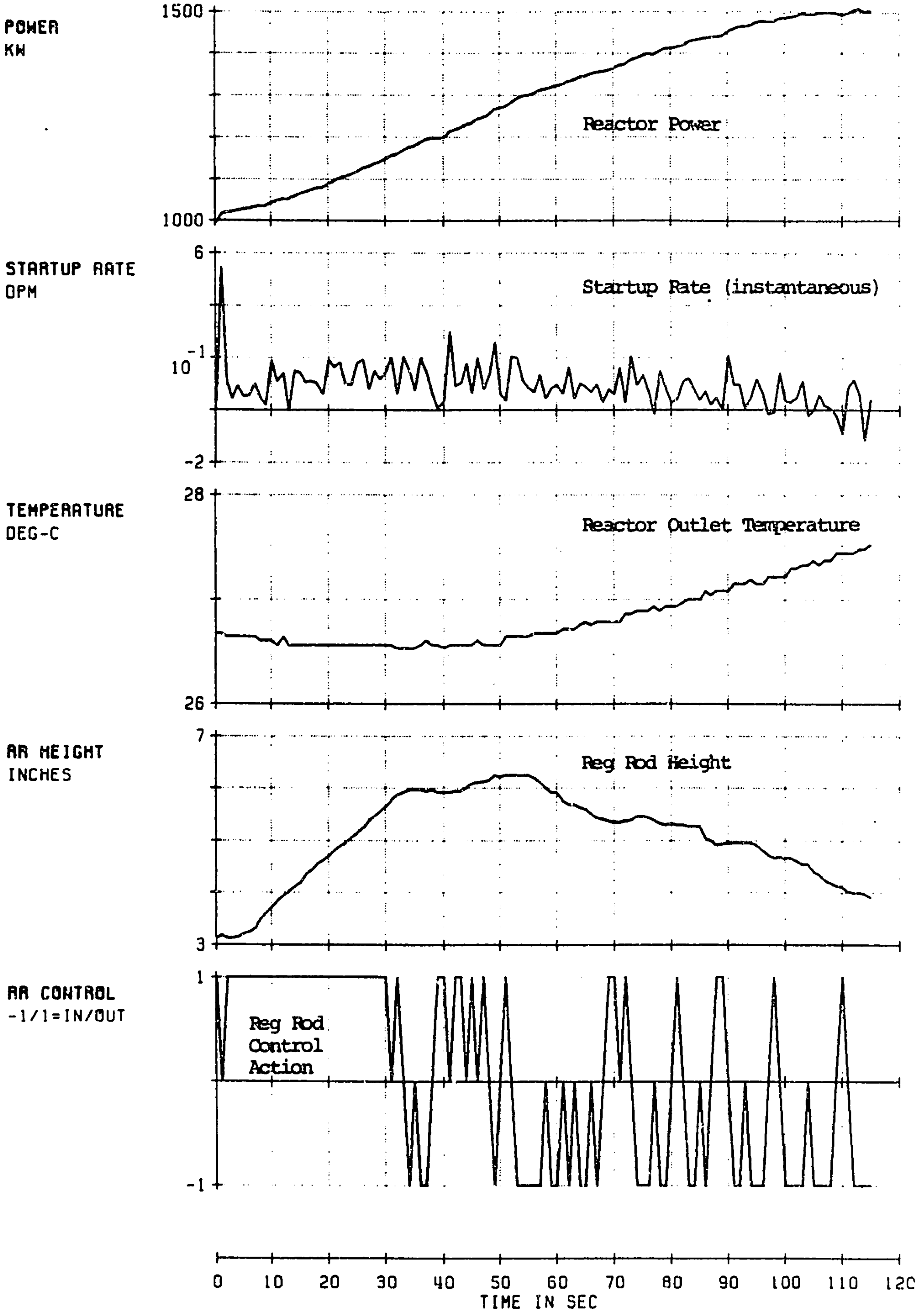

Figure 42. Original NLDC Logic without Filter

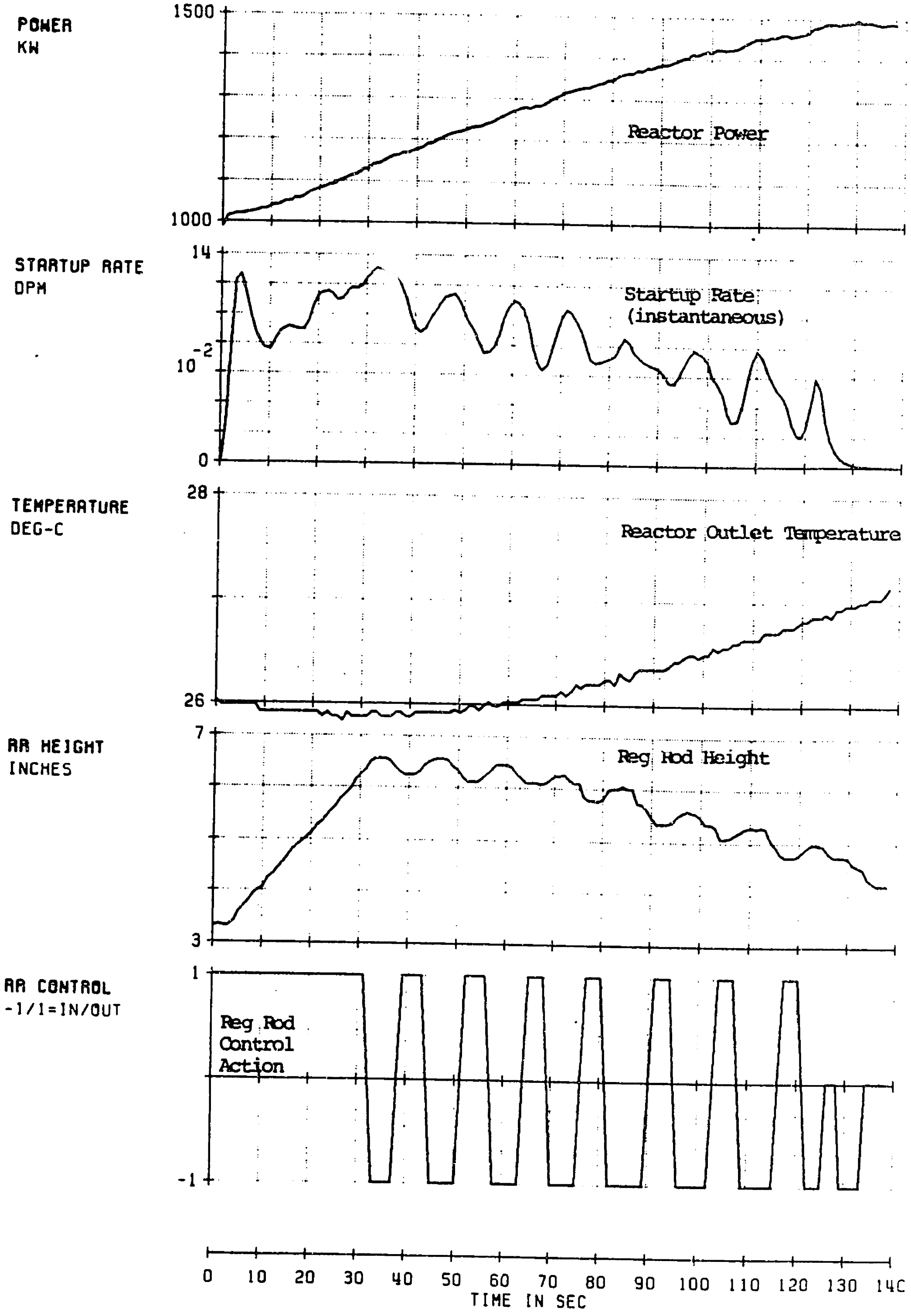

Figure 43. Original NLDC Logic with Filter

Fuzzy logic had been developed to provide a model for human reasoning. It is a technique used to describe systems that are too complex and whose state measurements are not well known [Zadeh, 1984]. Such systems cannot be fully quantified. They are characterized by a non-linear, time varying behavior, poor quality of available measurements, wide range of operating conditions, and unknown disturbances.

In fuzzy set theory, transition between set membership and nonmembership is gradual rather than sharp. Fuzzy logic uses statements that are graded or qualified as opposed to ones that are strictly true or false. The use of fuzzy logic allows one to describe the system in terms of linguistic rather than numerical variables. For example, the reactor power can be described as long, too long, short or too short. Conditional relationship between variables are easily accommodated by the rules of fuzzy logic. Comprehensive surveys of the work on this area are presented in [Tong, 1977] and [Maiers et al., 1985]. Fuzzy rule-based technique is used to emulate the actions taken by the licensed operators. It provides a means of determining the appropriate action when several conditional rules are applicable to a given situation. The present design for the MITR incorporates 20 conditional rules which are based on 14 fuzzy subsets of the plant states. The reactor states consist of the fractional change in power, period, rod height, and the rod withdrawal beyond a "critical" position. The control action is selected by first determining the states of the plant and their membership grades in the appropriate fuzzy subsets. Then the rules of fuzzy logic is used to the subsets associated with a given rule to determine the relative weight of the rule. The resulting weight associated with a given rule is referred to as the "degree of fulfillment" (DOF). The net action is found by weighting each rule by its DOF.

The fuzzy rule based controller does not rely on the exact plant model of the reactor or its parameters. However, the plant states in which this control algorithm are based on have to be accurate enough (i.e., as long as they are not grossly in error) to identify the relevant rules that apply to the given condition.

This controller offers several advantages [Bernard et al., 1985]. The information obtained from the operators' experience are incorporated in the decision process. The operational procedure can be explicitly included in the fuzzy model to indicate the basis sequence of action in advance and the timing of their implementation over longer intervals. The algorithm presents the control decision is such a way the operators can easily relate to. It also provides the operators the ability to evaluate and modify the decision rules if appropriate. As demonstrated, the algorithm is less sensitive to noise and it uses less movement of the control mechanism.

The major drawback of this technique is that its rule-base may not be complete and, therefore, it may not be capable of determining the appropriate action under all conditions. As in the case of the present design, the rules for power decrease are not included. Furthermore, steady state control is not very satisfactory because it lacks certain rules to eliminate steady state off set. In addition, it does not guarantee that the reactivity constraint is always satisfied (see NLDC). Nonetheless, only the reactor power, period, and control rod positions are the required inputs for this algorithm. Therefore, the algorithm is valid as long as all of its inputs are valid for the intended operating range.

In general, fuzzy controllers have been successfully used in a variety of practical applications. However, the design relies on ad hoc techniques. The design is also plant specific. The membership grades, states, and the conditional rules have to be adapted to control other reactors or processes.

C.4 Relay Control

The "relay" control algorithm is used to adjust either the reg rod or the shim blade during steady state or transient condition. The design is based on a set of logic that is derived from the deviation from the desired power and the rate of change of power. Its performance is not expected to be as "good" as that of the NLDC or Fuzzy control algorithm during transients. The PID is also expected to perform better than the relay control during "ideal steady state" conditions. The main advantage of the relay control is that it only requires two pieces of information about the plant current condition. Since little knowledge is assumed about the plant, the parameters of this control law are chosen so that the resulting control action is "conservative." This control law will be primarily used when the other transient or steady state control strategies are not performing satisfactorily.

The plant states used by the controller are defined by the error from the desired operating power and the rate of change of power. They can also be defined in terms of monotonically increasing functions of those two original variables. The diagram shown in Figure 44 represents how the control law states are defined into various regions. The objective is to bring the plant states to the origin. For this application, the deviation from the desired power is represented by a monotonically increasing function, $f(P-P_{set})$, where P is the current power and P_{set} is the desired power or the power set point. The rate of change of power is defined in terms of the startup rate, SUR. Also shown in the state diagram are the switching curves and the control action for each region. Away from the origin, the possible control actions are control rod insertion, withdrawal, and hold. The control mechanism is withdrawn or inserted at the maximum possible rate allowed by the drive motor. The switching curves are obtained either empirically or based on operating guidelines. For this application, the curve S_1 is of the form:

$$|S_1| = \begin{cases} 1/\tau_{LIM} & |f(P-P_{set})| \geq f_{lim} \\ (\tau_{LIM} + S_\tau(f_{lim} - f))^{-1} & f_{ss} < |f(P-P_{set})| < f_{lim} \end{cases}$$

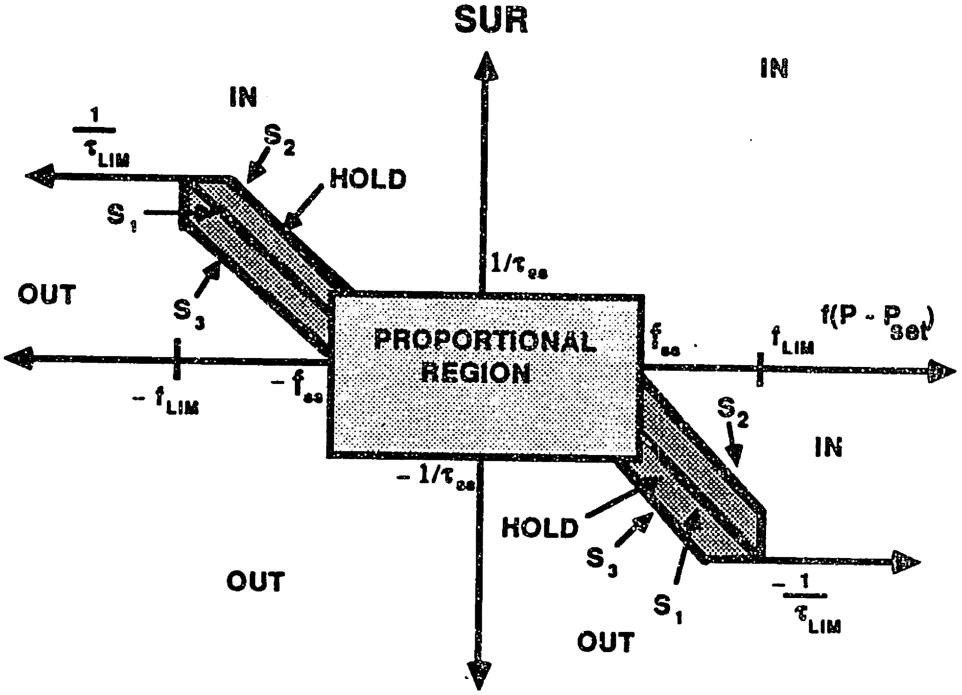

Figure 44. Relay Control State Diagram

$$1/\tau_{SS} \quad , \quad |f(P-P_{set})| \leq f_{ss}$$

where

$S_\tau = K(\tau_{SS} - \tau_{LIM})/(f_{lim} - f_{ss})$,

$f(P-P_{set})$, τ_{LIM}, τ_{SS}, f_{lim}, $K > 1$, and $f_{ss} > 0$.

The two curves that forms the boundary for the "HOLD" region is given by

$$|S_2| = (| 1/S_1| + \delta_s)^{-1}.$$

$$|S_3| = (| 1/S_1| - \delta_s)^{-1}.$$

The parameters that define S_1 are control mechanism dependent.

The region near the origin is referred to as the "proportional" region. The control signal in this region is proportional to the power error. For the MITR, the control signal, u, is given by

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APPENDIX D. REACTIVITY ESTIMATION AND VALIDATION

This appendix presents the techniques used to estimate and validate the reactivity on the MIT Reactor (MITR). The reactivity is one of the variables needed to identify a specific plant operating condition on the MITR reconfigurable reactor power controller. As mentioned in Appendix B, the NLDC algorithm uses reactivity as one of its inputs. A misestimation of this variable can lead to an erroneous control recommendation by the NLDC. Further dicussions on reactivity estimation on the MITR are given in the recent efforts by J. Bernard [Bernard, 1984, pp 276-285] and V. George [George, 1985].

D.1 Reactivity Estimation

For this particular research, the two approaches used to estimate the reactivity on the MITR are the reactivity balance and the inverse kinetics models.

The reactivity balance model consists of the measured regulating rod (reg rod) and shim blade reactivity worth curves and the temperature coefficient of reactivity. Figure 45, Figure 46 , and Figure 47 show the reactivity associated with the reg rod, shim blade, and primary coolant temperature [Bernard, 1984]. The contribution of xenon in the balance is not included for this particular application although work has been recently presented on the estimation of xenon on the MITR [George, 1985]. The reactivity balance equation is given by

$$\rho(t) = \rho_{RR}(H_{RR}(t)) + \sum_{i=1}^{N_{SB}} \rho_{SBi}(H_{SBi}(t)) + \rho_T(T(t)) - \rho_o$$

$$\rho_o = \rho_{RR}(H_{RR}(t_o)) + \sum_{i=1}^{N_{SB}} \rho_{SBi}(H_{SBi}(t_o)) + \rho_T(T(t_o))$$

where ρ is the reactivity, H_{RR} is the reg rod position, H_{SB} is the shim blade position, T is the reactor outlet (hot leg) temperature, t is

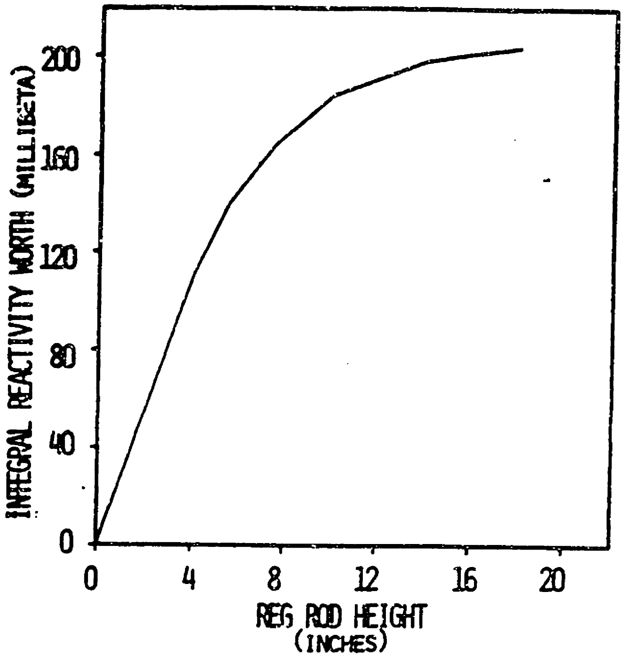

Figure 45. Integral Regulating Rod Worth

time, N_{SB} is the number of shim blades, ρ_0 is the initial reactivity, and t_0 is the initial time. The inputs used in the balance are the reg rod position, shim blade position, and the hot leg temperature. The balance assumes that the reactor is initially at rest or steady condition. (i.e., the reactor power is not changing rapidly). In addition, the contribution of the temperature coefficient of reactivity has been included in the balance under the assumption that the reactor is in thermal equilibrium. Disregarding the effects of xenon, the errors in the balance can be attributed to the reactivity worth curves, which are core life cycle dependent, and to the error and assumptions made regarding the temperature coefficient of reactivity.

The inverse kinetics model is another approach used to estimate the reactivity on the MITR [Bernard, 1984]. It accounts for the combined

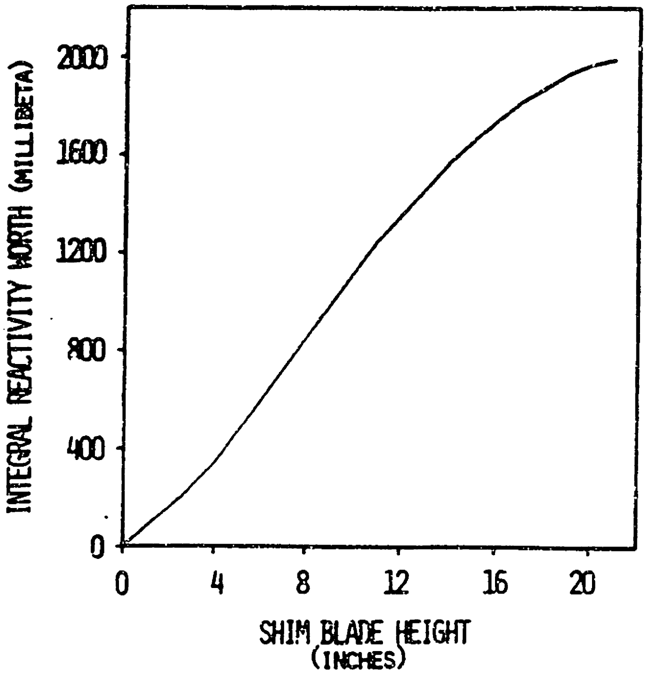

Figure 46. Integral Shim Blade Worth

effects of changes in the control mechanism positions, temperature, and xenon. The reactor point kinetics equation is written so that the reactivity is determined in terms of the measured power and estimated precursor concentrations. The reactor kinetics equation can be written as

$$dP/dt = (\rho - \beta) P/\Lambda + \sum_{i=1}^{N} \lambda_i C_i$$

$$dC_i/dt = \beta_i P/\Lambda - \lambda_i C_i \qquad i = 1, N$$

$$\text{where } \beta = \sum_{i=1}^{N} \beta_i$$

or

$$\rho = (\Lambda/P)\,(dP/dt + \beta - \sum_{i=1}^{N} dC_i/dt \qquad i = 1, N$$

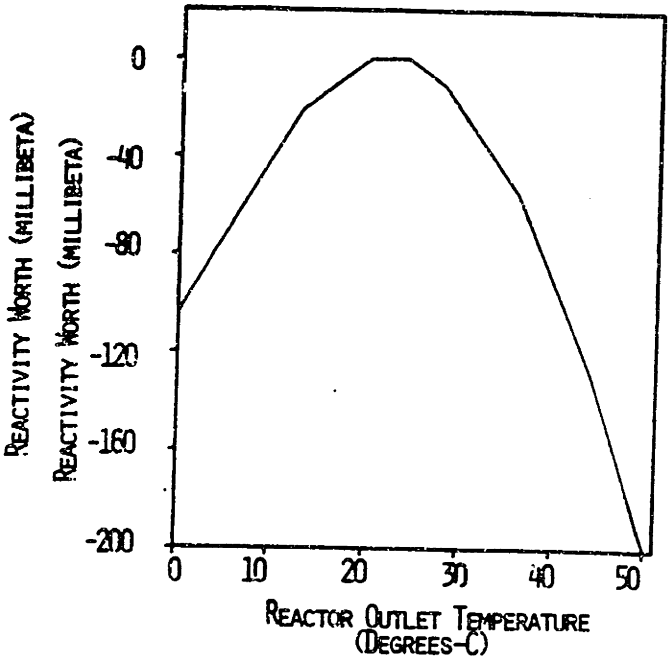

Figure 47. Reactivity Associated with the Primary Coolant Temperature

where ρ is the reactivity, P is the reactor power, β_i is delayed neutron fraction for the ith group, Λ is prompt neutron lifetime, C_i is the precursor concentration for the ith group, λ_i is the precursor decay constant for the ith group, and N is the number of groups of delayed neutrons. This model is valid for $|\rho| < \beta$. The six and three delayed neutron group constants for the MITR are given in Table 8. The three delayed neutron group constants are obtained by collapsing those of the six delayed neutron groups by using the method presented by Skinner and Cohen [Skinner and Cohen, 1959].

The precursor concentration equations can be solved in a discrete time fashion with the measured power as the forcing function. The dis-

Table 8. MITR Delayed Neutron Group Constants

$\beta = 0.00786$
$\Lambda = 0.00010$

Six Groups Approximation

	λ_i (sec^{-1})	β_i
1	0.0124	0.00026
2	0.0305	0.00172
3	0.1110	0.00154
4	0.3010	0.00311
5	1.1400	0.00090
6	3.0100	0.00033

Three Groups Approximation

	λ_i (sec^{-1})	β_i
1	0.0124	0.00026
2	0.0369	0.00268
3	0.6320	0.00491

---

crete-time solutions can be obtained as recursive relations at each sampling time k

$$C_i(k+1) = \Phi_i C_i(k) + [1-\Phi_i]\beta_i P/\Lambda\lambda_i.$$

where $\Phi_i = \exp(-\lambda_i T_s)$

T_s = is the sampling or update time.

The rate of change of power can be determined by differentiating the power history. Low pass filtering of the power signal before differentiating is needed to minimize the effects of noise. However, the derivative term is small and it does not significantly affect the reactivity estimate as found during the simulations and as reported earlier [Bernard, 1984]. By ignoring this term, one makes the assumption that is commonly referred to as the "prompt-jump" approximation [Waltar and Reynolds, 1981].

D.2 Reactivity Validation

The reactivity is said to be valid if the estimates based on the reactivity balance, ρ_B, and inverse kinetics, ρ_I, satisfy all the conditions below:

- $| \rho_B - \rho_I | < \rho^*$ where ρ^* is a given threshold
- The results of the reg rod reactivity constraints are consistent for both ρ_B and ρ_I (i.e., the recommended reg rod control action based on the reg rod reactivity constraint relationship as derived from ρ_B is identical to that of ρ_I - also see the description of NLDC in Appendix C) The reactivity constraint has been evaluated based on the power set point.
- The results of the shim blade reactivity constraints are consistent for both ρ_B and ρ_I.

To prevent false declaration of invalid reactivity condition because of noise, a multiple consecutive occurence (MCO) test [Fisher et al.,1983] is used.

The logic diagram for reactivity validation is shown in Figure 48. A TRUE/FALSE flag is used to indicate the result of each reactivity validity test. A flag is set to TRUE if the associated test is satisfied; otherwise, the flag is set to FALSE. The outputs of the reg rod and shim blade reactivity constraints are given by $C_{RR}(\rho)$ and $C_{SB}(\rho)$ respectively. In terms of the "available/required" time conditions for reactivity constraint (see Appendix C), the values of C_{RR} and C_{SB} represent either rod insertion, withdrawal, or hold. The results of the three tests are compared using Boolean logic. The reactivity is said to be valid if all three tests yield TRUE outputs.

Furthermore, as shown in this logic diagram, the "conservative" values of C_{RR} and C_{SB} are chosen all the time, regardless of the validity of the reactivity estimate. For example, during a power increase maneu-

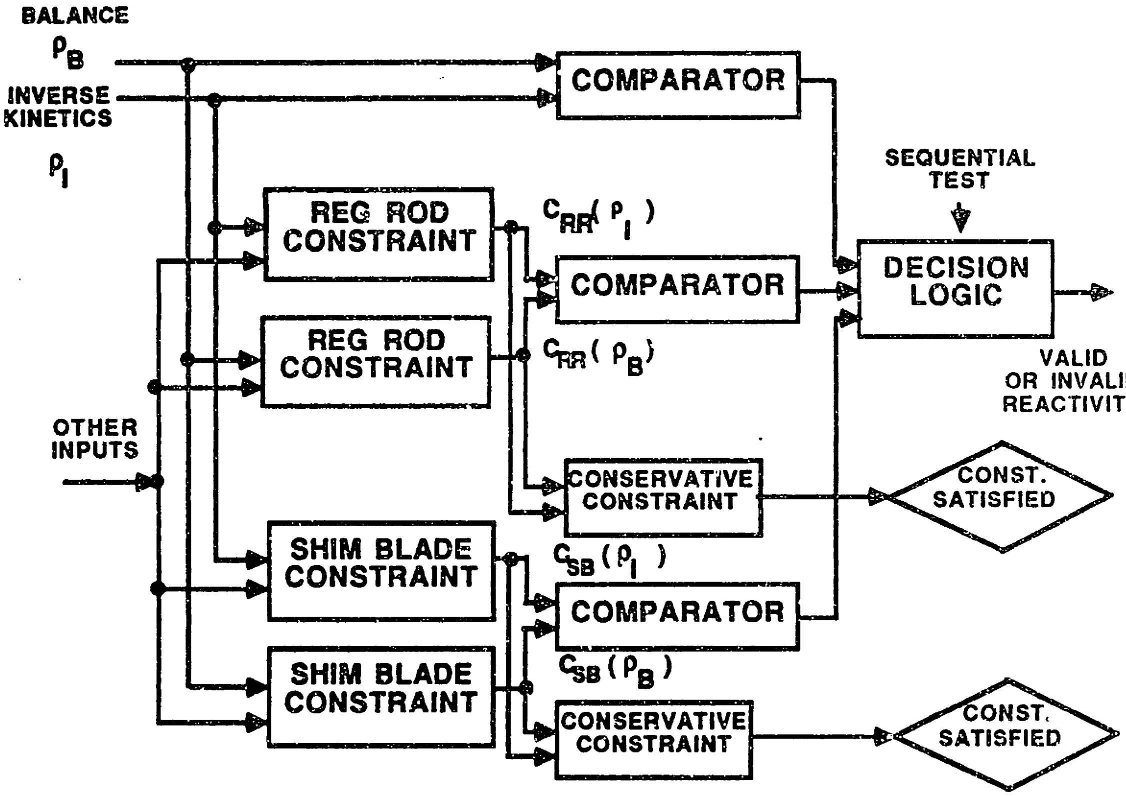

Figure 48. Logic Diagram for Reactivity Validation

ver, the "conservative" value of C_{RR} or C_{SB} corresponds to an insertion action.

D.3 Evaluation

The two approaches have been evaluated via simulations and on-line experimentations. Similar evaluation procedure has been used by John Bernard in his earlier work [Bernard, 1984]. The evaluation procedures and results are presented below.

D.3.1 Computer Simulation

In the computer simulation tests, a point kinetics model with six delayed neutron groups has been used [Bernard, 1984, Appendix B] to simulate the MITR dynamics. The reactor model is updated every 0.01 seconds. This model simulates the reactor power that is used to drive the inverse kinetics model. The sensitivity of the inverse kinetics reactivity model, based on three and six delayed neutron groups, with respect to the update time (or sampling time, T_s) of precursor concentration and noise level in the power measurement has also been investigated. No modeling error has been introduced in the reactivity balance model. The difference between the balance and inverse kinetics has been examined. In all these runs, the reactor power has been adjusted from 1 to 4 MW by controlling the shim blade with the NLDC algorithm. It should be noted that the initial position of the shim blade is not consistent with that in real operation. The simulation study is conducted solely to understand which variables or parameters affect the difference between the reactivity balance and inverse kinetics model under "ideal" conditions. The simulation results can only be compared with the experimental results in the qualitative rather than in the absolute sense because of the simplicity of the model. The effects of low pass filtering the power signal have also been considered. A filter time constant of 2 seconds has been used.

The results are shown in Figure 49 to Figure 56. There are 8 plots associated with each run. These plots include the following:

1. POWER: the reactor power in kilowatts (KW)
2. SUR: the reactor startup rate in decades per minute (DPM)
3. HEIGHT SB: shim blade height in inches
4. BALANCE: reactivity estimate (millibeta) based on a reactivity balance model
5. INVERSE KIN3: reactivity estimate (millibeta) based on a 3 delayed neutron group model
6. BAL - INV KIN3: the difference between BALANCE and INVERSE KIN3
7. INVERSE KIN6: reactivity estimate (millibeta) based on a 6 delayed neutron group model
8. BAL - INV KIN6: the difference between BALANCE and INVERSE KIN6

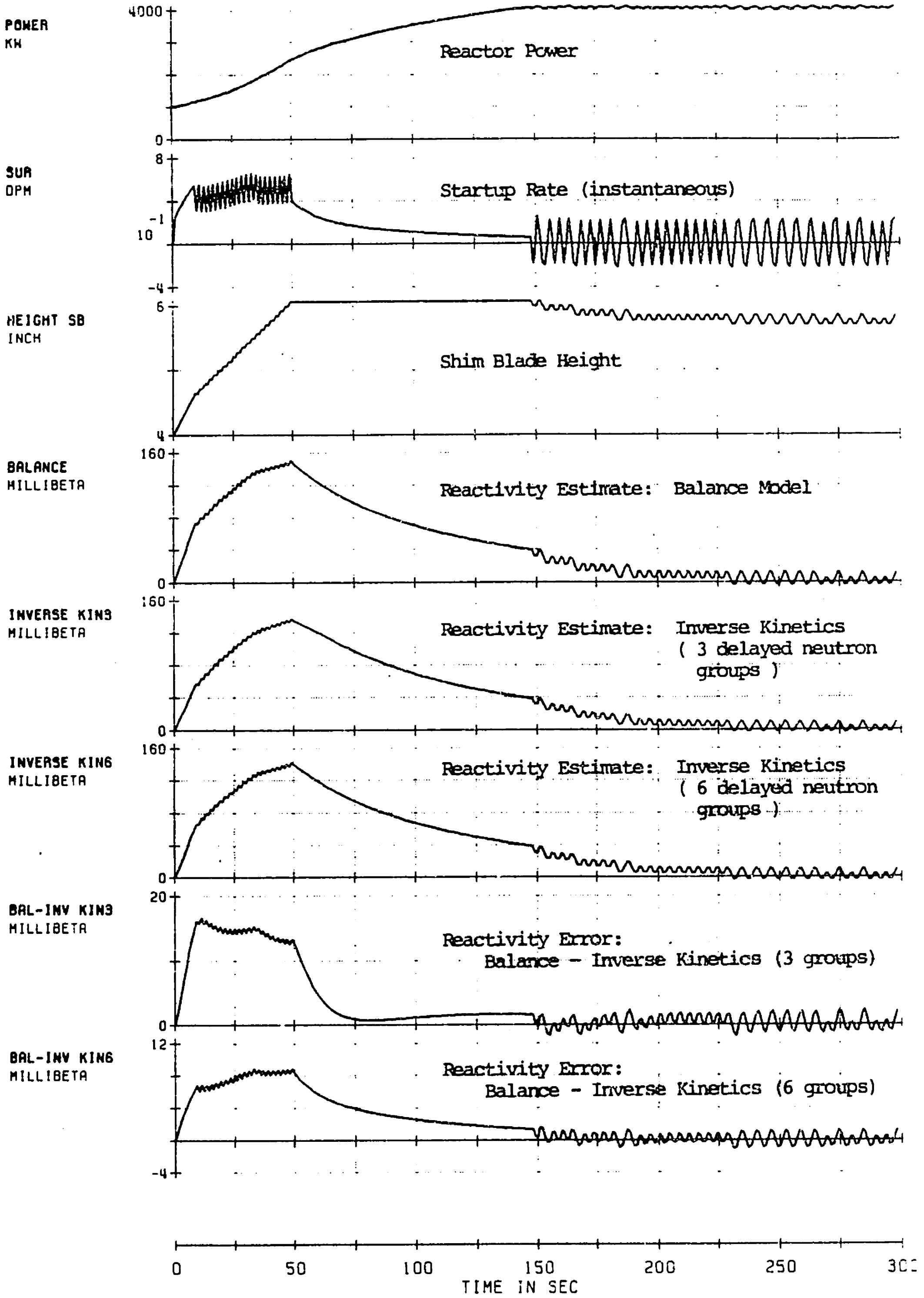

Figure 49. Simulation Results: No Noise, T_s = 1.0 sec

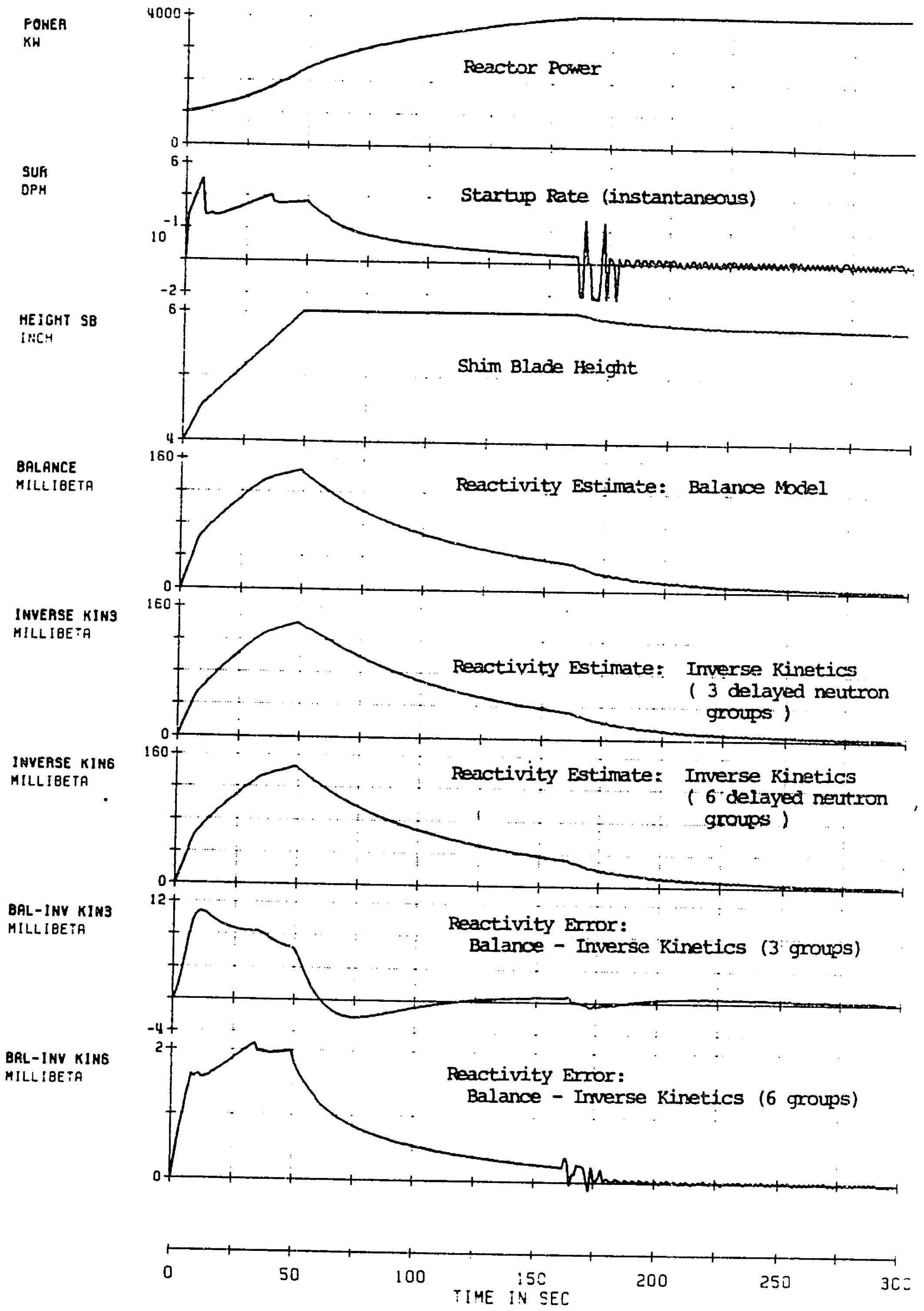

Figure 50. Simulation Results: No Noise, T_s = 0.1 sec

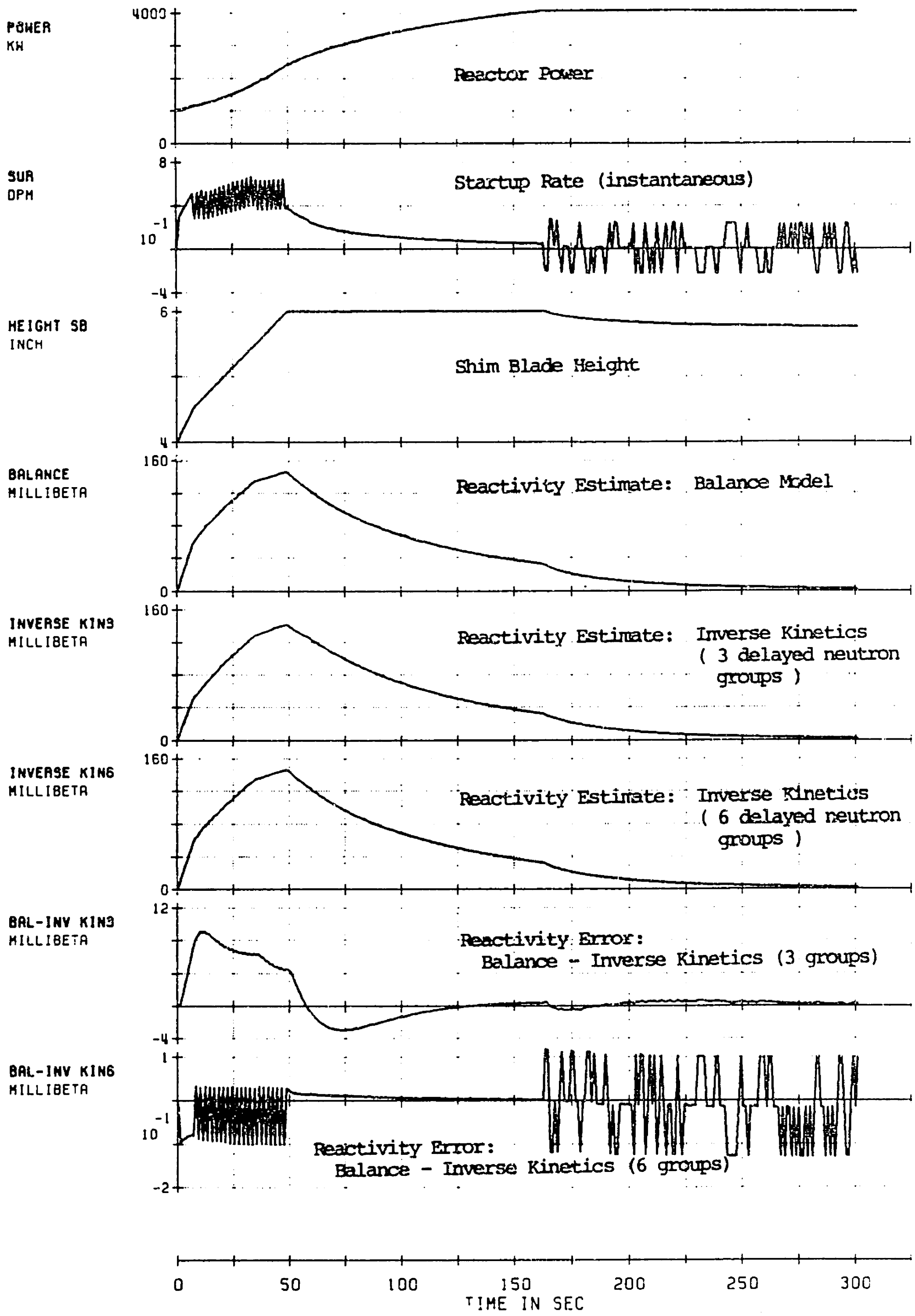

Figure 51. Simulation Results: No Noise, T_s = 0.01 sec

The effects of the update time (or sampling time, T_s) on the inverse kinetics model is illustrated in Figure 49 to Figure 51. These simulation runs do not include noise. The results indicate that for large update time (T_s) of the precursor concentration equation, relative to the simulation integration time (0.01 seconds), the inverse kinetics model, independent of the number of delayed neutron groups, tends to lag the reactivity balance (Figure 49 and Figure 50). The difference between the balance and the inverse kinetics prediction becomes negligible as the dynamic effects associated with the control rod movement diminishes. However, as the update time decreases, the error associated with the six delayed neutron group model also decreases despite the presence of the dynamics of the control rod motion. Such behavior is not observed in the three delayed neutron group model. There appears to be a transient error in this model no matter how small the update time. This error illustrates the limitations of the three delayed neutron group formulation. Since noise is not included in the first three cases, the results appear to be piecewise continuous. This behavior can be observed because the control rod reactivity worth curve is not smooth.

The next sets of results demonstrate the effects of a low pass filter, noise level, and prompt jump approximation on the reactivity estimate for a fixed update time of 0.1 seconds. The results shown in Figure 52 to Figure 56 indicate that the power derivative term does not significantly affect ρ_I independent of the low pass filter configuration. Based on a simple calculation, a startup rate, SUR, of 0.8 DPM corresponds to a 0.4 millibeta correction in ρ_I. The plots also show that the difference between ρ_B and ρ_I becomes more apparent when the power signal is low pass filtered.

D.3.2 On-line Experimentation

During the on-line tests, the reactor power was changed from 1 to 2 MW by using either the reg rod or the shim blade. The NLDC algorithm without the low pass filter on the power measurement was used. The use

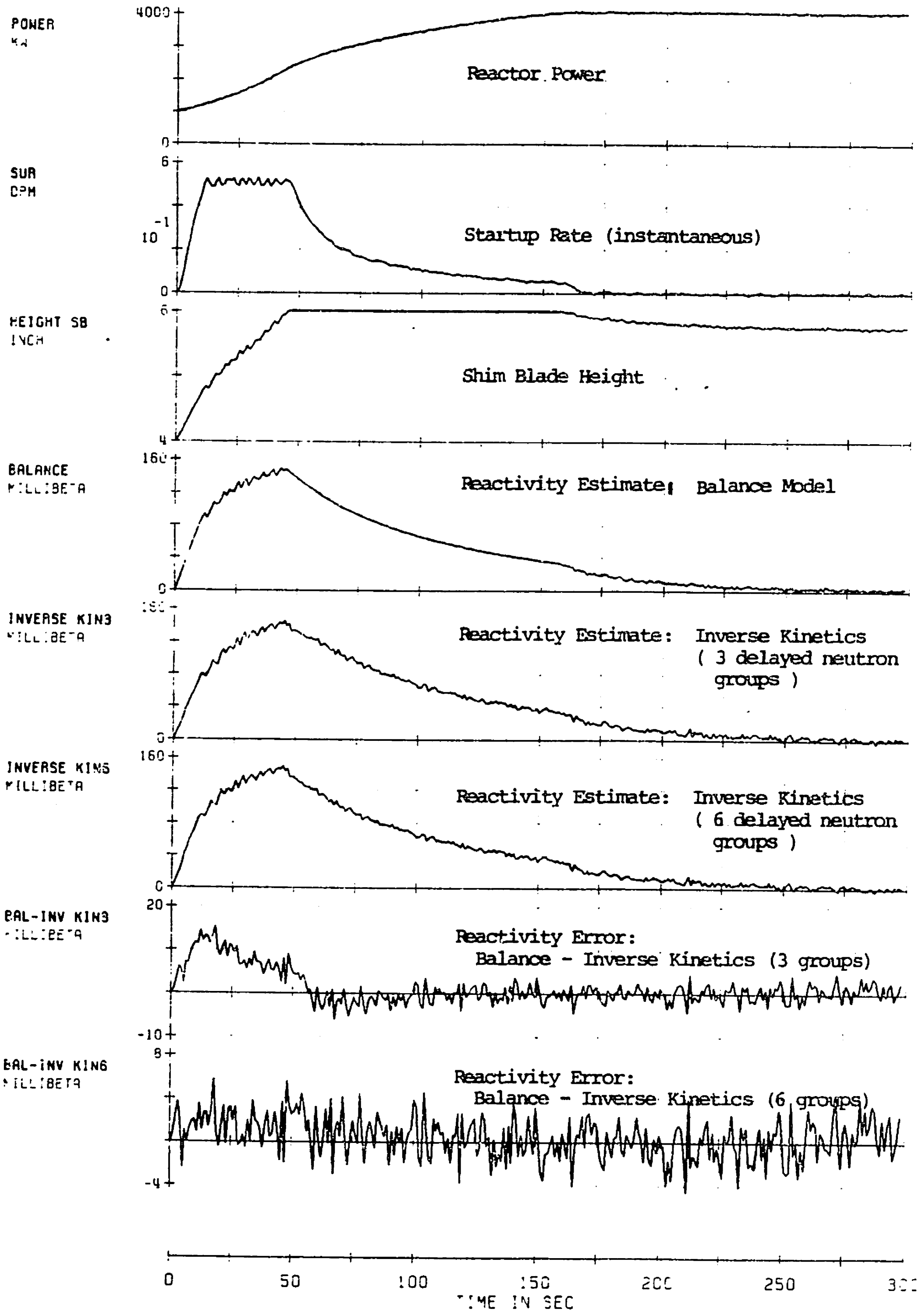

Figure 52. Simulation Results: 2% Noise, T_s = 0.1 sec, with Low Pass Filter

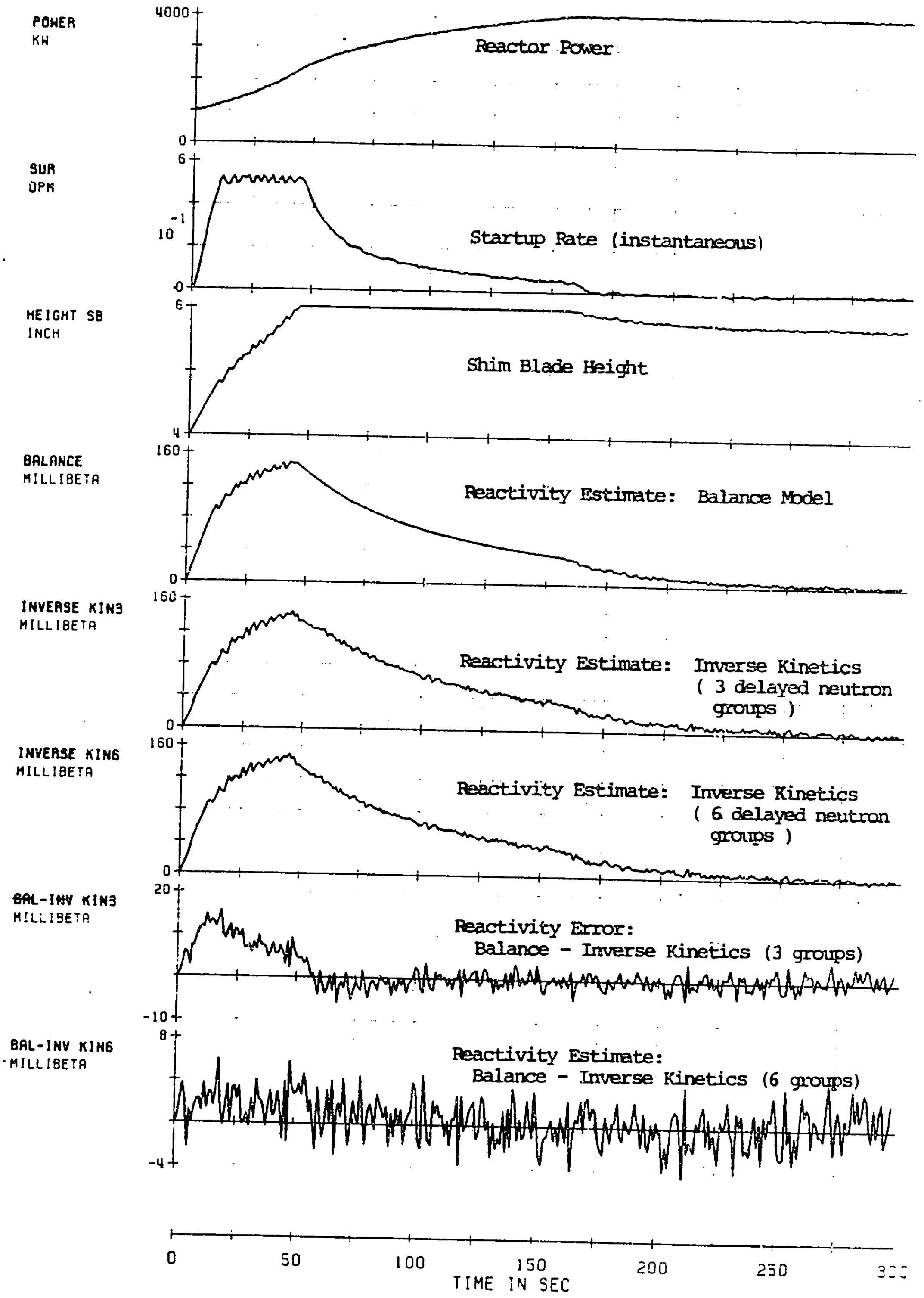

Figure 53. Simulation Results: 2% Noise, T_s = 0.1 sec, with Low Pass Filter, Prompt Jump Approximation

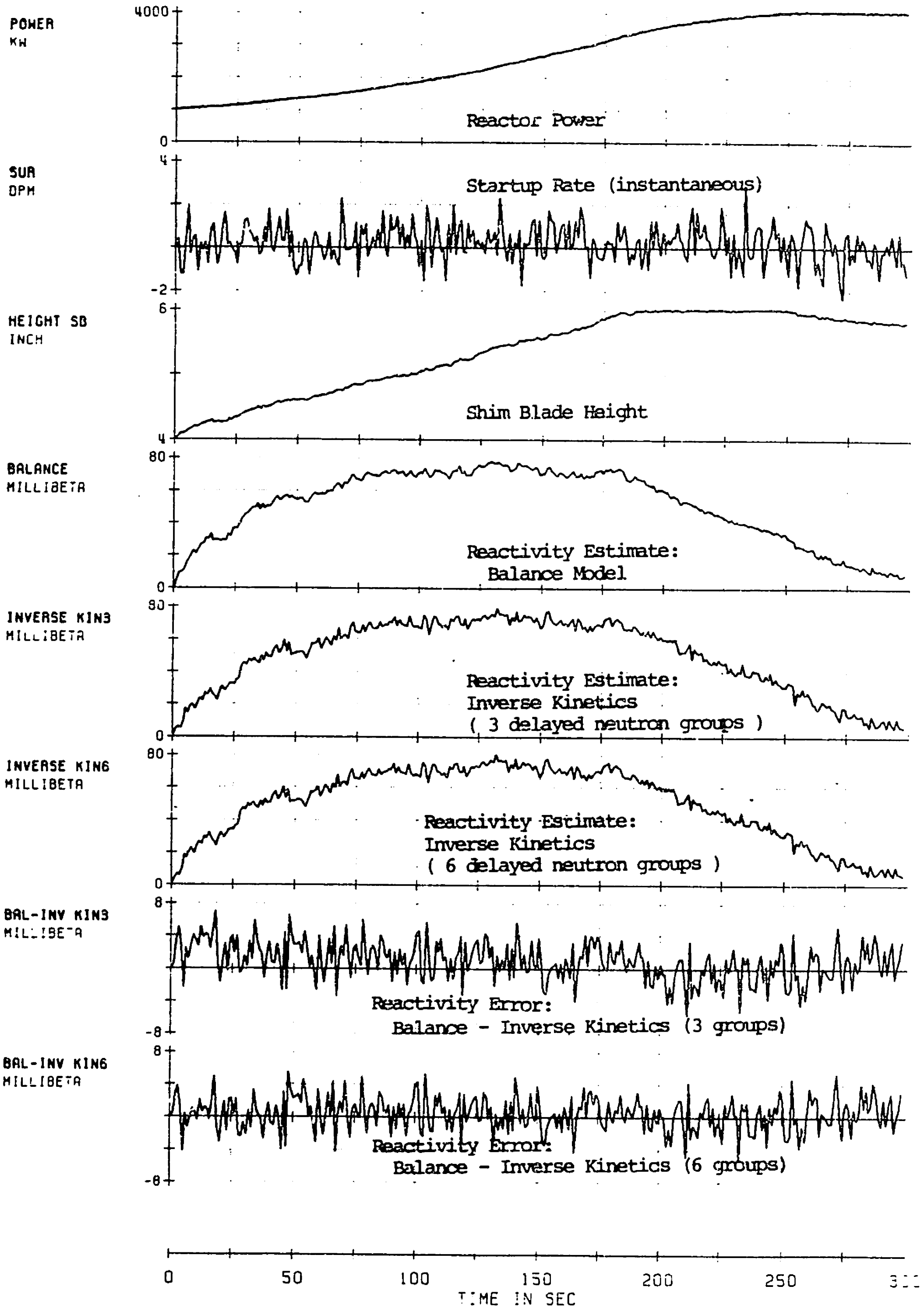

Figure 54. Simulation Results: 2% Noise, $T_s = 0.1$ sec, no Low Pass Filter

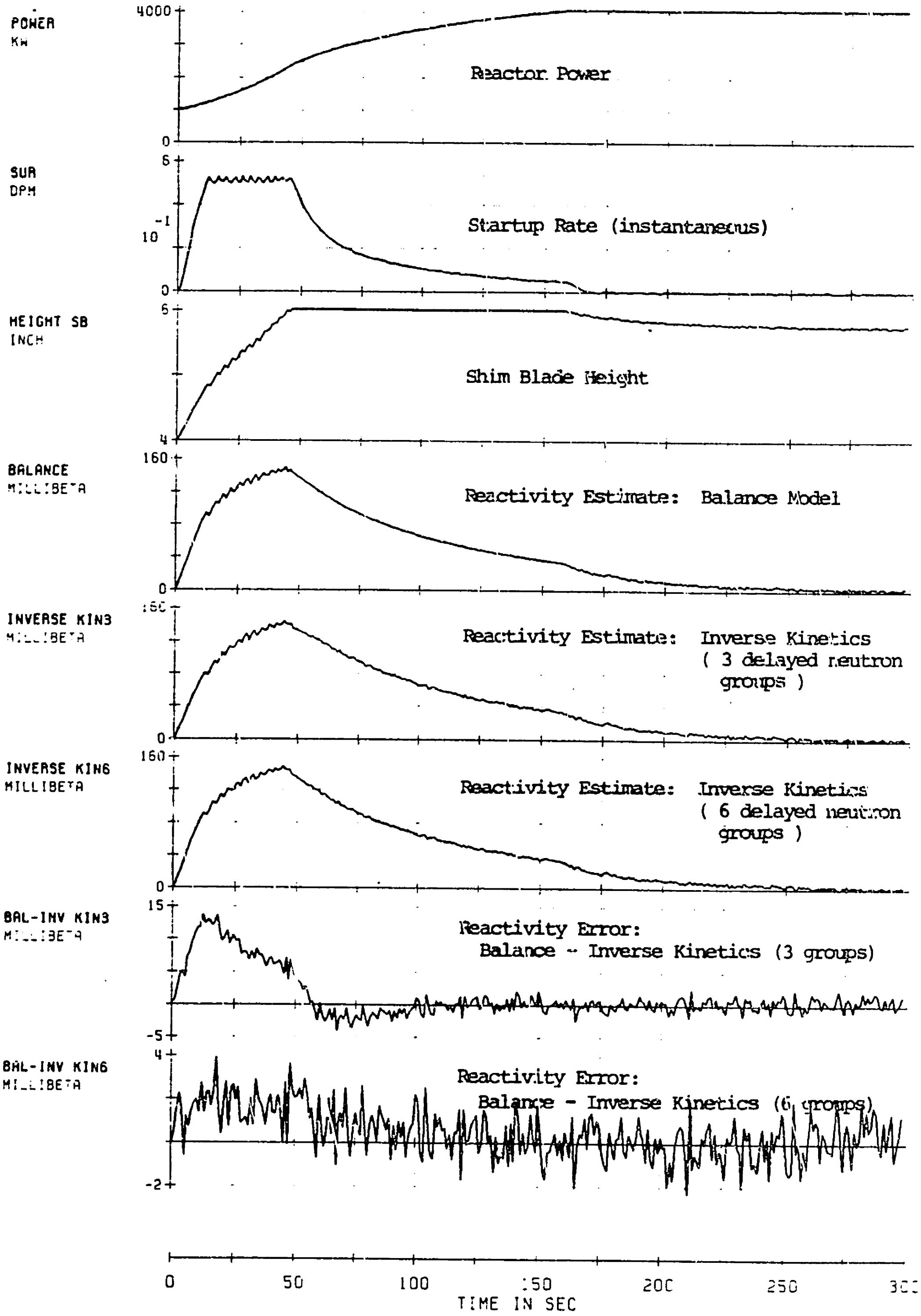

Figure 55. Simulation Results: 1% Noise, T_s = 0.1 sec, with Low Pass Filter

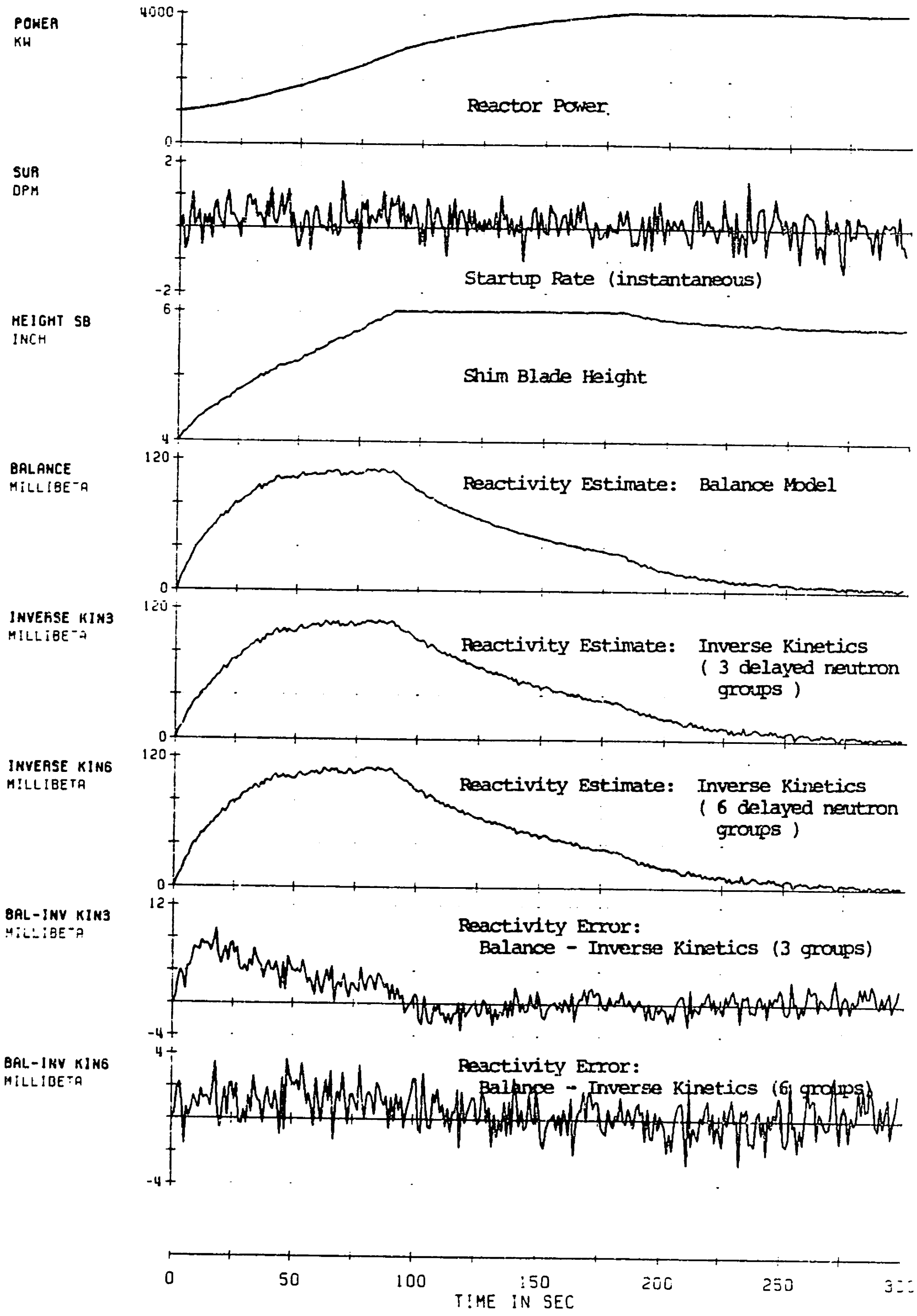

Figure 56. Simulation Results: 1% Noise, T_s = 0.1 sec, no Low Pass Filter

of ρ_B and ρ_I as input to the NLDC was also investigated. Some of the tests were conducted with and without xenon. Because of timing limitations in the processing system (LSI 11/23), an update time of 1.0 second has been chosen. The integration time of the delayed neutron precursor concentration has to satisfy the condition that $\lambda_i T_s < 1$ in order to maintain numerical stability, where T_s is the update time or sampling time. For this reason, only the 3 delayed neutron group model has been evaluated on-line.

The experimental results are presented in Figure 57 to Figure 66. Each run is characterized by the type of control mechanism used (i.e. reg rod or shim blade), the presence of xenon, and the reactivity estimate used in the NLDC (i.e. ρ_B or ρ_I). Unless indicated, each experiment was started with a "steady state" initial condition on power. There are 7 plots associated with each run. These plots include the following:

1. POWER: the reactor power in kilowatts (kw)
2. SUR: the reactor startup rate in decades per minute (DPM)
3. HEIGHT SB or HRR: shim blade or reg rod height in inches
4. TEMPERATURE: reactor coolant outlet temperature in degrees-C
5. BALANCE: reactivity estimate (millibeta) based on the reactivity balance model
6. INVERSE KIN: reactivity estimate (millibeta) based on the 3 delayed neutron group model
7. BAL - INVK or BAL - INV KIN: the difference between BALANCE and INVERSE KIN

As expected from the simulation evaluations, ρ_I lags ρ_B whenever the dynamic effects associated with the control rod motion is present as shown in Figure 57 to Figure 66 . The difference between ρ_B and ρ_I is more apparent in the shim blade runs. For this case, the difference between ρ_B and ρ_I can be attributed to the error in modeling the long-lived precursor groups, update time, and errors associated with the balance (control rod worth curves, temperature coefficient, and xenon). The negative difference between ρ_B and ρ_I that can be observed at the later part of some of the runs can be attributed to the dynamic effects of temperature on ρ_B. The use of ρ_I or ρ_B in the NLDC algorithm has produced no significant difference in the overshoot behavior as observed from the power histories for the reg rod and shim blade runs.

The effects of xenon is not very apparent from the plots because the time frame shown is not long enough. Its influence on the initial conditions for the next experimental run is quite difficult to observe from the plots. It appears that the effects of xenon has been cancelled out by the temperature effects. The plots indicate that the temperature has not yet levelled off when the experiments were started. Furthermore, the initial temperature and its dynamics are not the same for all the experiments. The same initial condition on temperature is difficult to achieve in a series of experiments because the reactor thermal dynamics is slow and it is time and power history dependent.

Figure 65 shows that the inverse kinetics approach can provide a "reasonable" estimate of reactivity as an input to the NLDC algorithm under nonsteady initial conditions. This is one of the limitations of the reactivity balance as shown in Figure 66. An erroneous estimate of reactivity results in a degraded NLDC performance (large power overshoot).

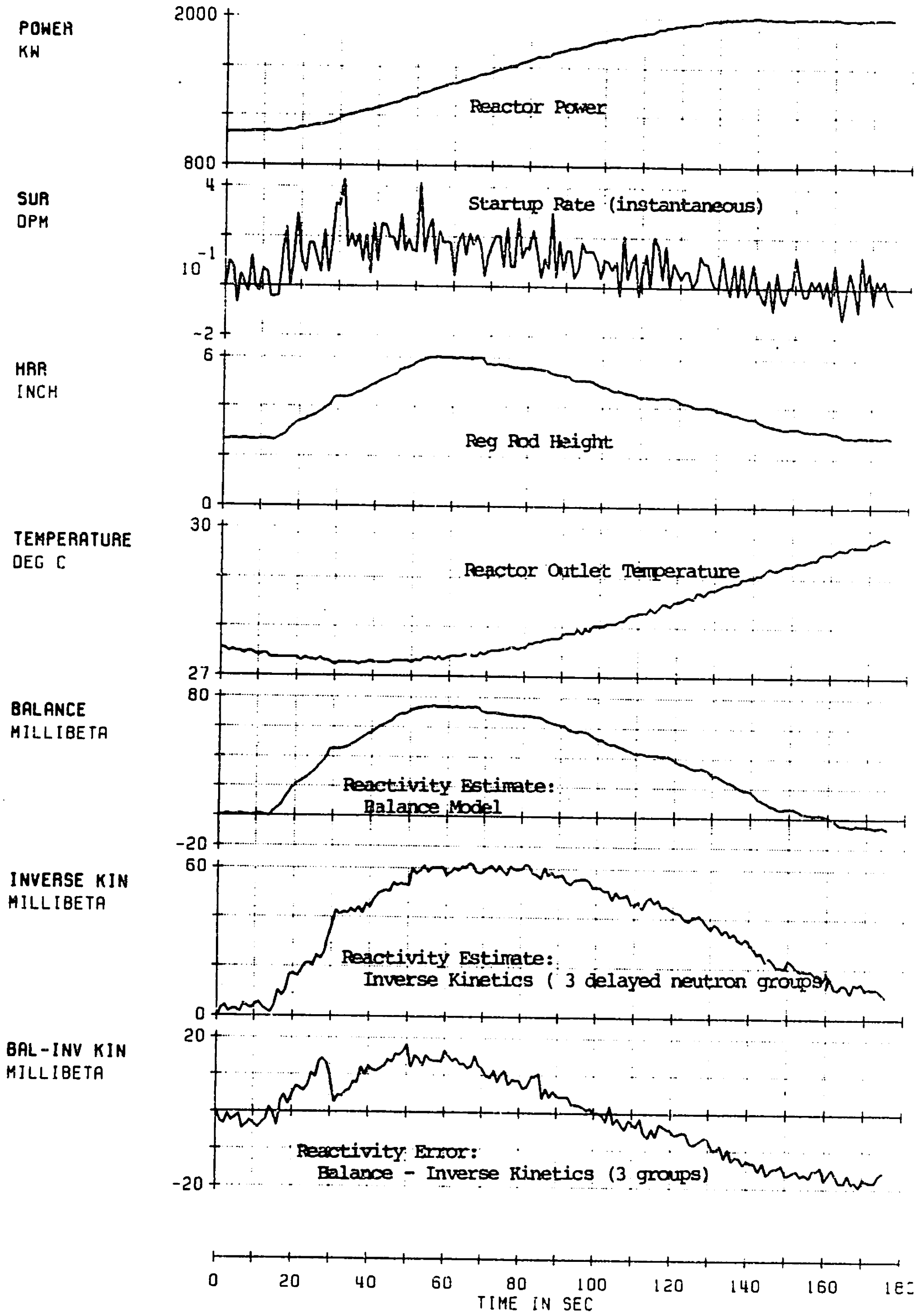

Figure 57. Experimental Results: Reg Rod Control, Inverse Kinetics, No Xenon

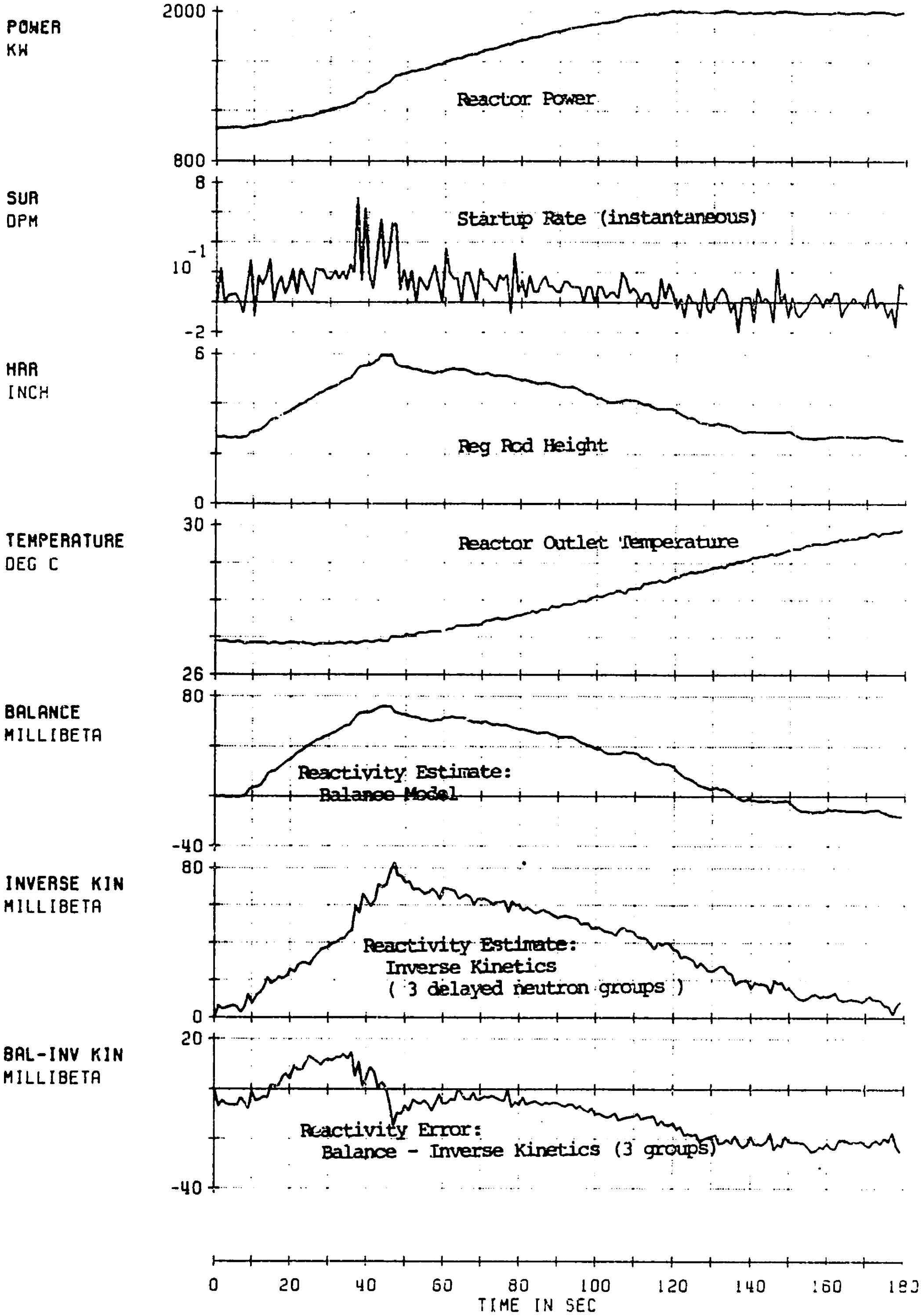

Figure 58. Experimental Results: Reg Rod Control, Reactivity Balance, No Xenon

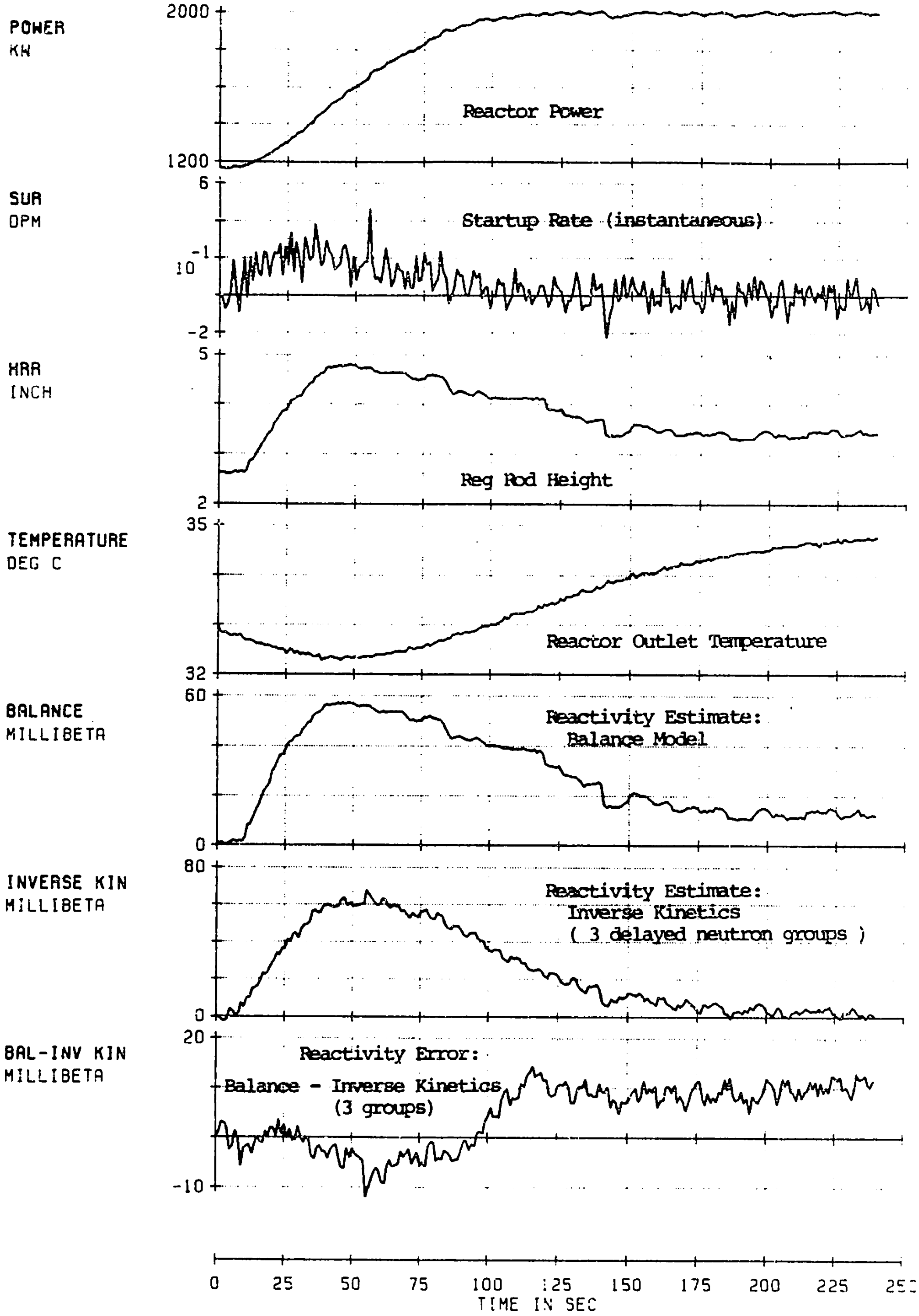

Figure 59. Experimental Results: Reg Rod Control, Inverse Kinetics, With Xenon

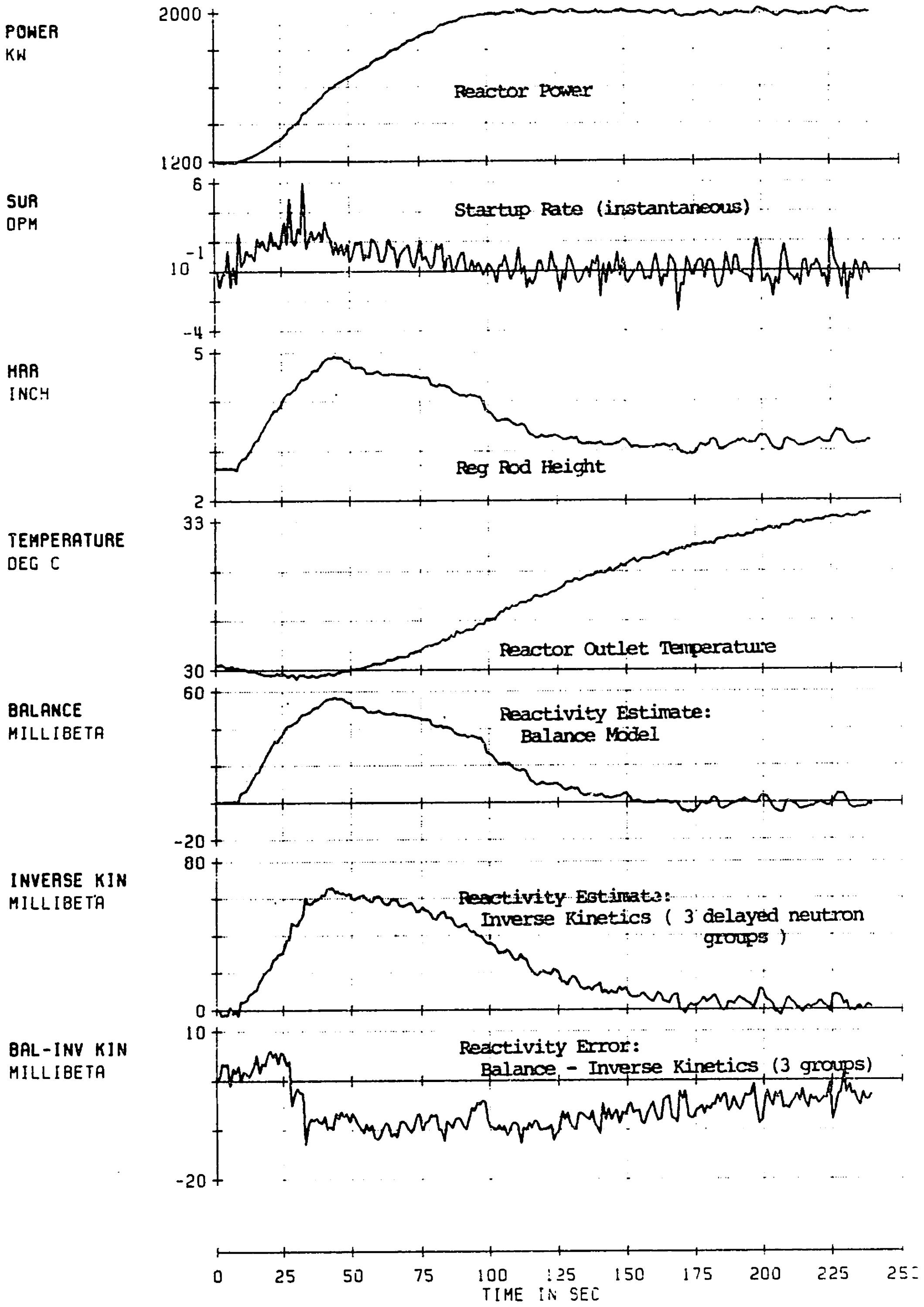

Figure 60. Experimental Results: Reg Rod Control, Reactivity Balance, With Xenon

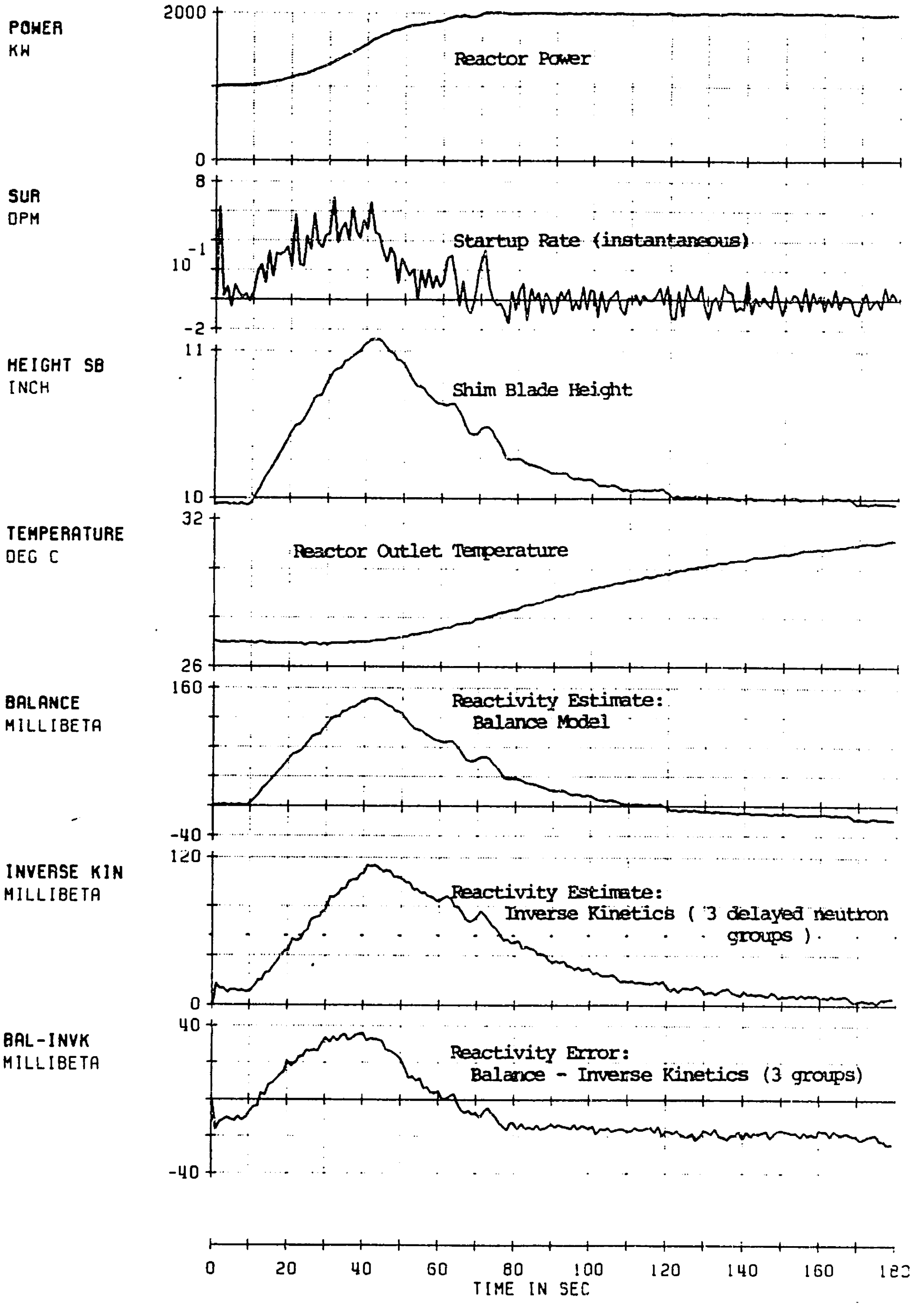

Figure 61. Experimental Results: Shim Blade Control, Inverse Kinetics, No Xenon

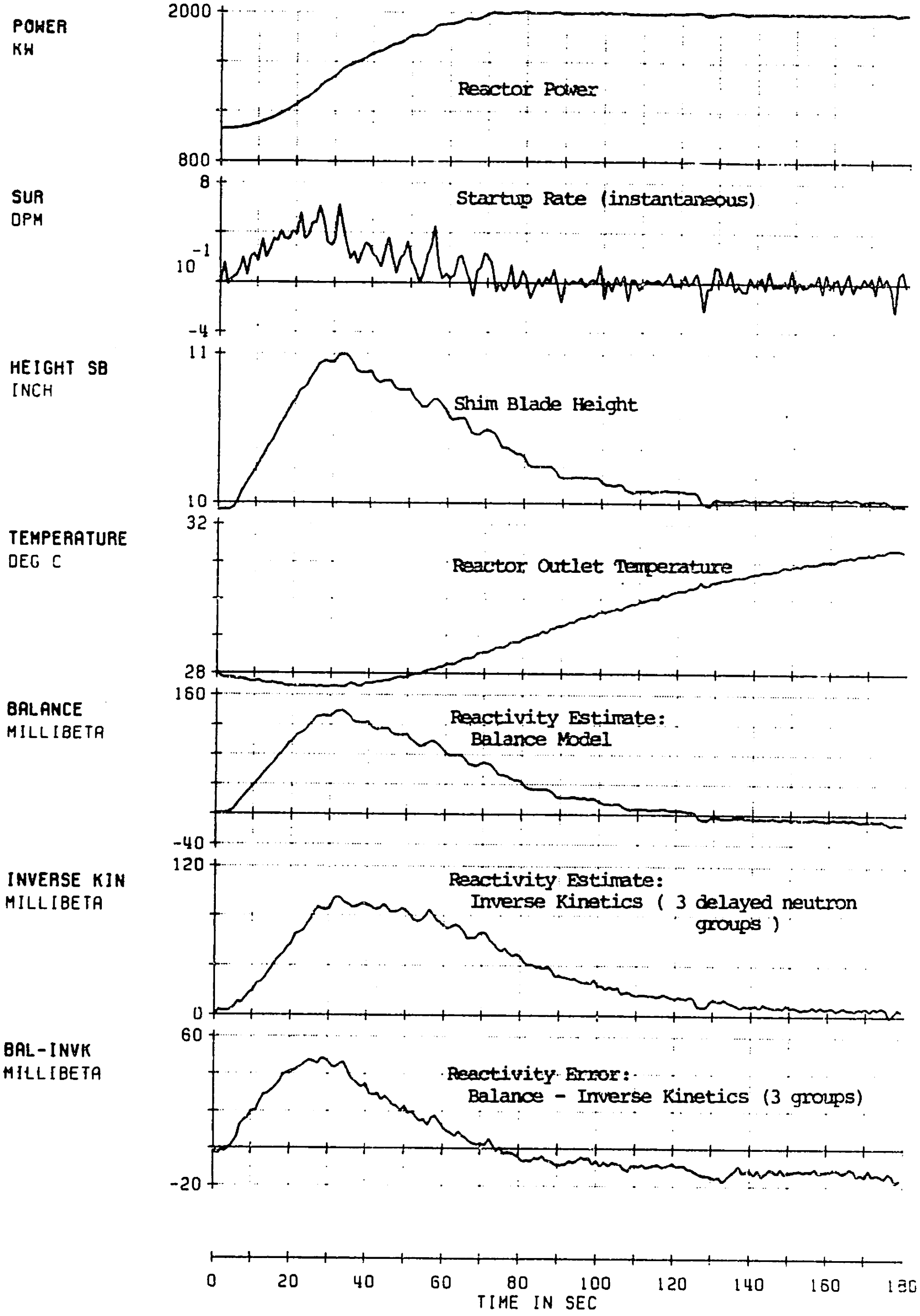

Figure 62. Experimental Results: Shim Blade Control, Reactivity Balance, No Xenon

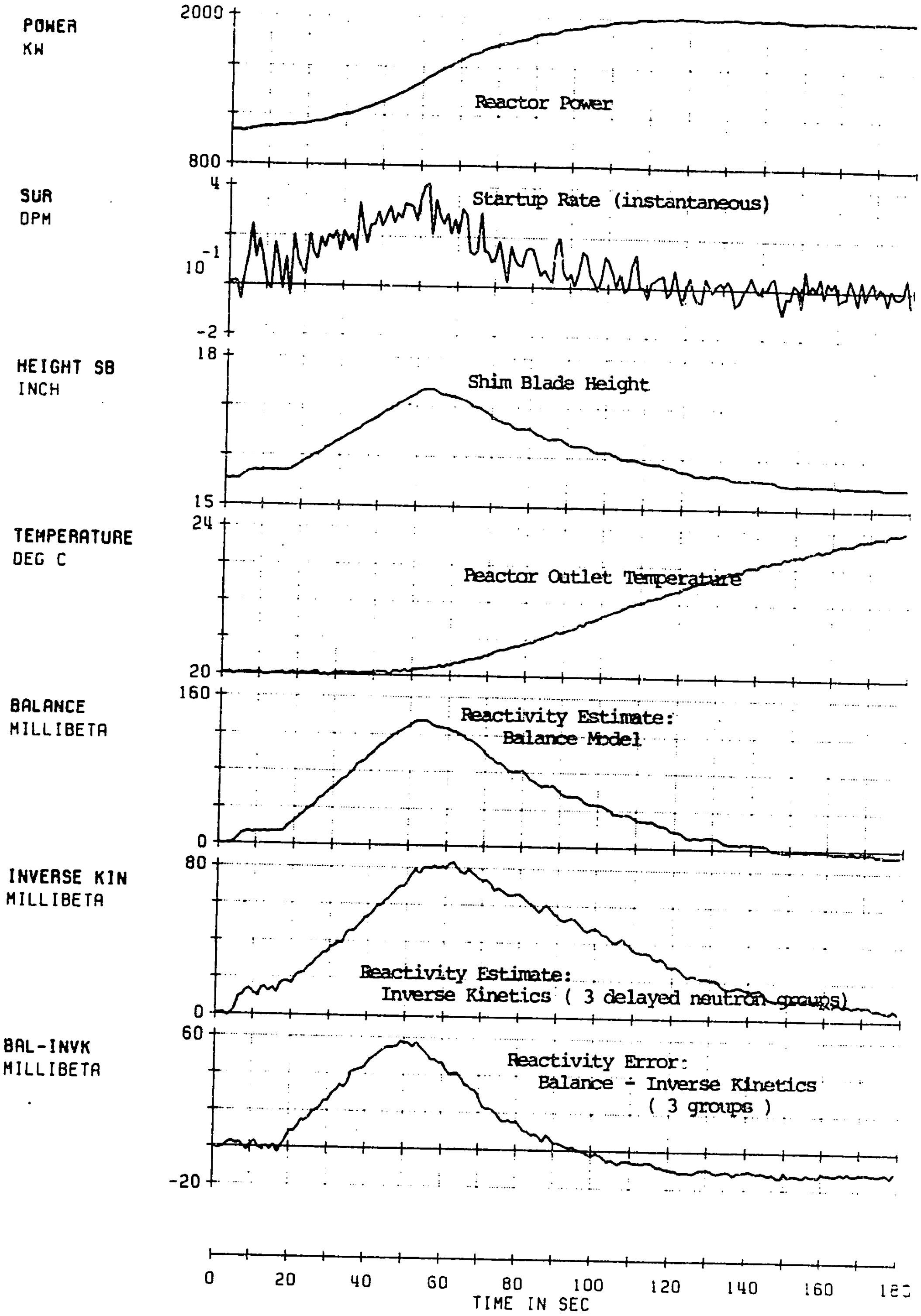

Figure 63. Experimental Results: Shim Blade Control, Inverse Kinetics, With Xenon

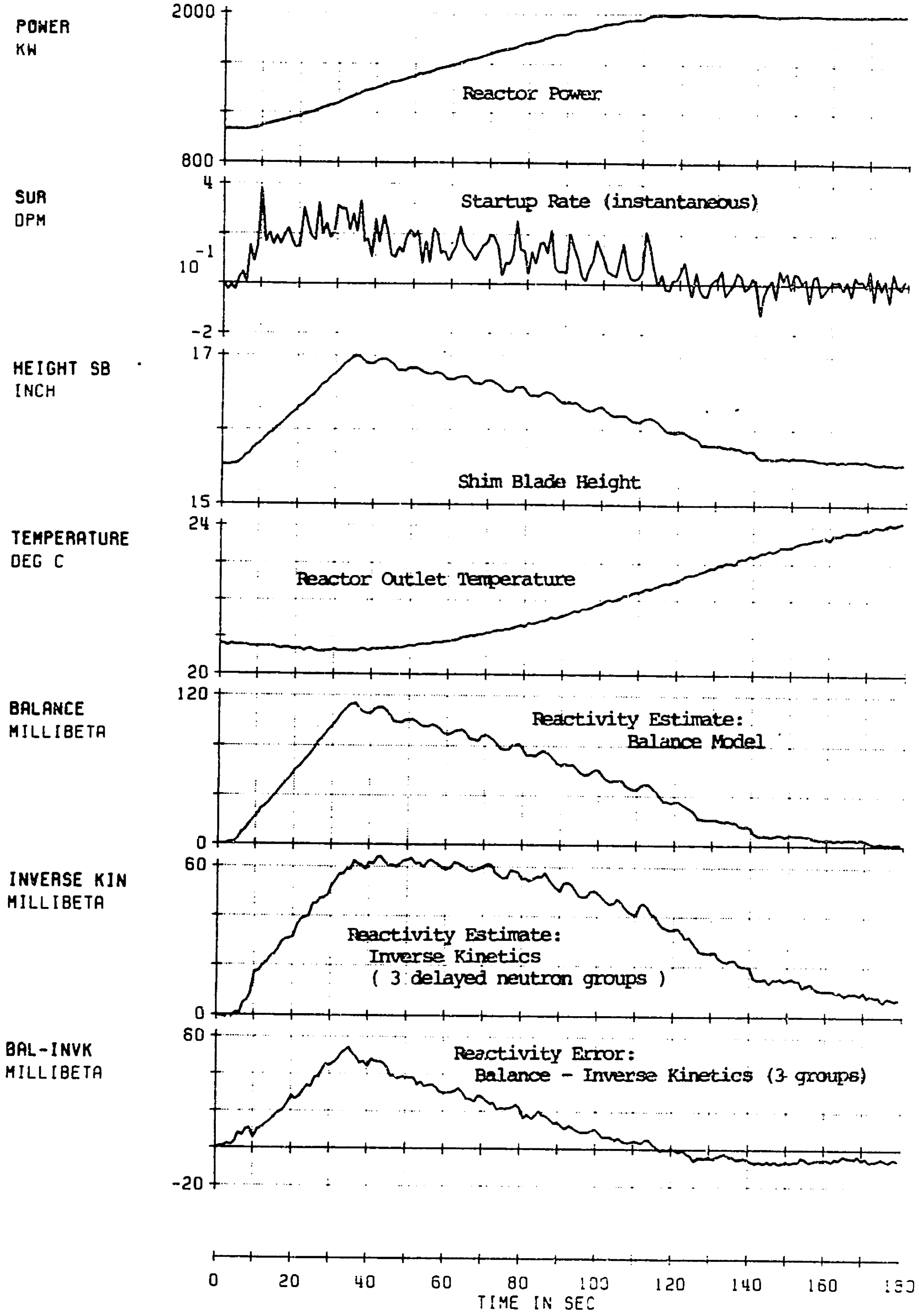

Figure 64. Experimental Results: Shim Blade Control, Reactivity Balance, With Xenon

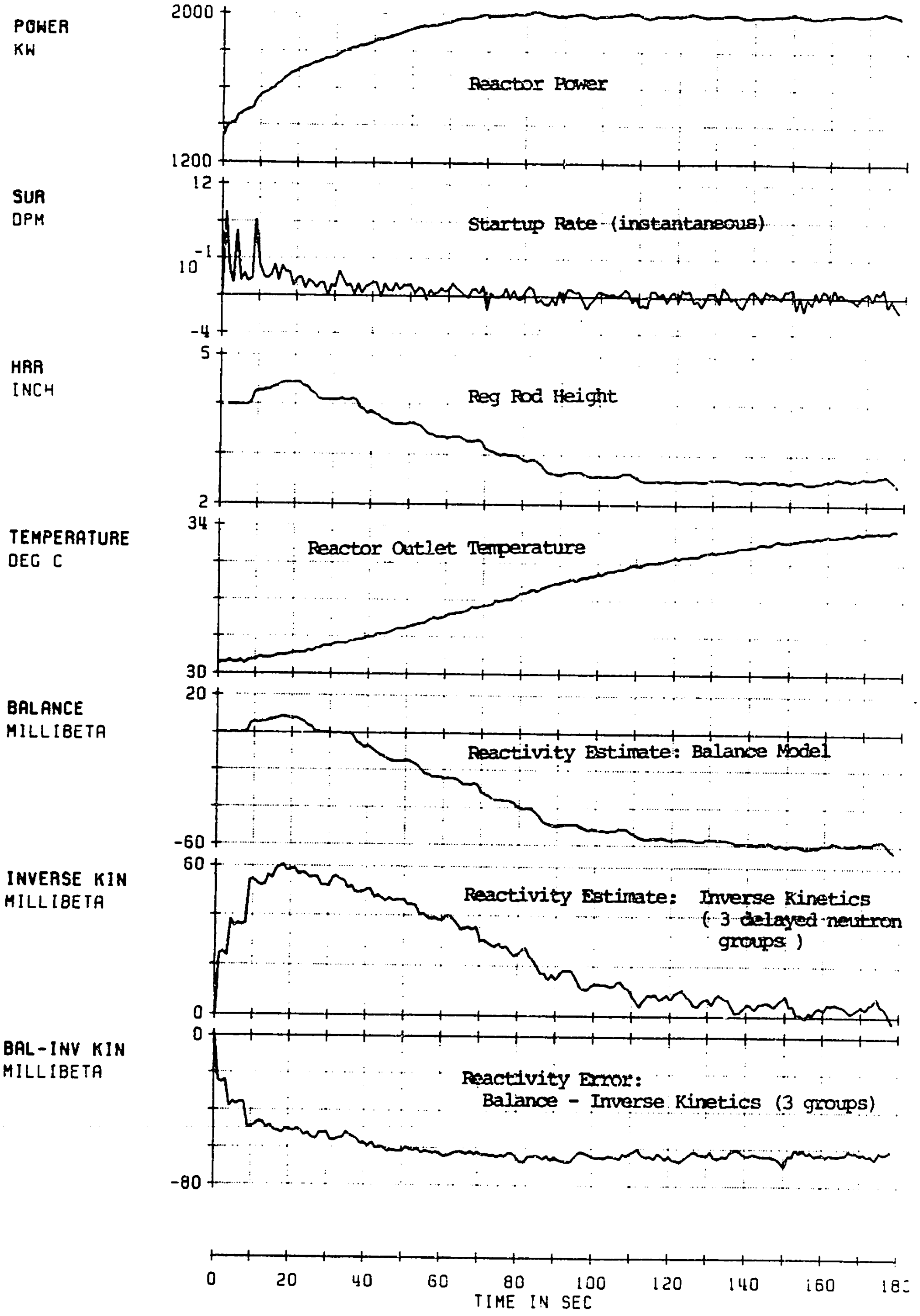

Figure 65. Experimental Results: Reg Rod Control, Inverse Kinetics, With Xenon, Transient Initial Conditions

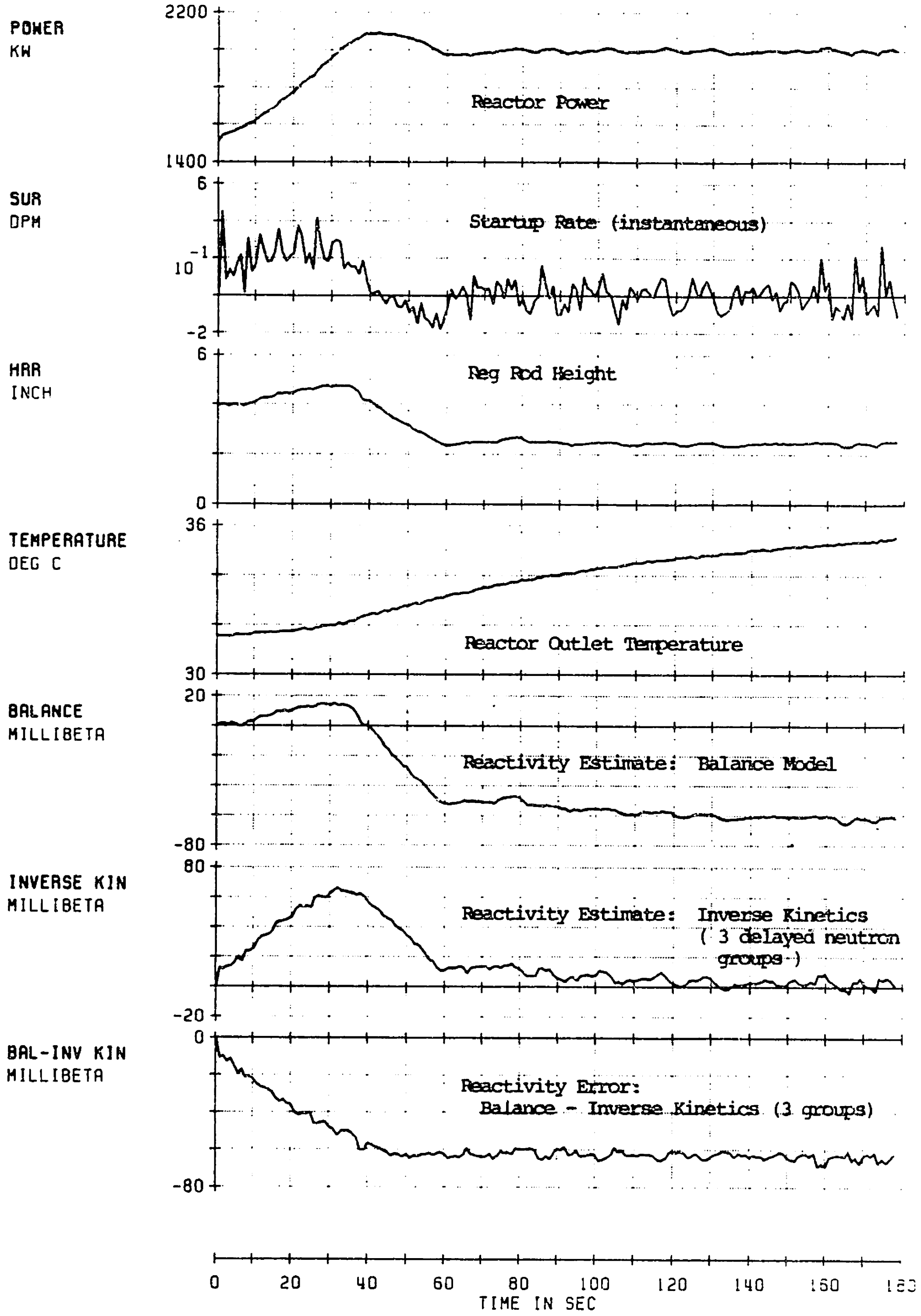

Figure 66. Experimental Results: Reg Rod Control, Reactivity Balance, With Xenon, Transient Initial Conditions

APPENDIX E. MITR SUBSTATES AND CONTROL ACTIONS

This appendix is divided into two sections. First, it describes the details of how the MIT Reactor (MITR) plant operating conditions that have been incorporated in the controller design are defined. In addition, the details of the control procedures, mentioned in Chapter 3, are also discussed.

The plant operating conditions have been defined so that the control laws that have been previously evaluated on the MITR can be used. Heuristics based on operating rules of thumb and operator experience [Bernard, 1986] have been used to define the features of some of the plant operating conditions (POC's). Simplifications have been made so that the control program can be accommodated in the plant computer for the demonstration. A general technique, however, is presented on how to determine the features that are needed to define a specific plant operating condition in case there is a desire to upgrade the definitions.

The model-based control laws are discussed in Appendix C. The control procedures introduced in this appendix are based on heuristics which capture the operating rules of thumb, plant operating guidelines, and operator experience.

E.1 MITR Substate Definition

E.1.1 Valid Reactivity

A valid reactivity estimate is one of the conditions needed to define a specific plant operating condition on the MITR reconfigurable controller design. The reactivity, ρ, is obtained from a balance, ρ_B, and inverse kinetics, ρ_I, models. As discussed in Appendix D, ρ is valid if all the following conditions are satisfied: 1) the difference between ρ_B and ρ_I is within a specified value, 2) the recommended reg rod control actions as derived from the reg rod reactivity constraint relationship (the power setpoint as the the termination point) using ρ_B and ρ_I are the same, and 3) The recommended shim blade control actions as derived from the shim blade reactivity constraint relationship using ρ_B and ρ_I are the same. A multiple consecutive occurrence (MCO) criterion, as discussed in Chapter 2, is used to minimize the effects of noise.

E.1.2 Reactivity Constraint Criteria

Regardless of the validity status of the reactivity, the reg rod and shim blade reactivity constraints are evaluated based on the power setpoint. The more conservative of the two reactivity estimates (i.e, ρ_B or ρ_I) is used in the evaluation. For example, for power increase, the larger of the two reactivity estimates is used to compute the reg rod and shim blade reactivity constraints. For power increase, the reactivity constraint for a given control mechanism is satisfied if a control mechanism withdrawal is recommended. In the case of power decrease, the reactivity constraint is satisfied if a control mechanism insertion is recommended. A multiple consecutive occurrence criterion is used to minimize the fluctuations in the results of the single test reactivity constraint evaluation.

E.1.3 Magnitude of the Power Change

An assessment of the magnitude of the power change is needed in order to determine whether or not the power change will be executed using the reg rod or the shim blade. The reference power, P_{ref}, and the difference between the set point, P_{set}, and P_{ref} are two important variables to consider. For example, an increase of 1 megawatt (MW) from 3 to 4 MW requires less time than a 1 MW change from 1 to 2 MW. The reason for this is that the reactor power and period are exponentially related. Hence, a power increase at high power level can be easily accommodated by the reg rod, given that it has sufficient reactivity.

(Note: There is a "strong" negative temperature feedback at high power level on the MITR, but it is not enough to overcome the effect of the power-period relationship.)

For this application, the magnitude of the power change is classified into "small" and "large" power changes. The concept of fuzzy logic [Zadeh, 1984] is used in the classification. A "small" power change (SPC) is defined by a "small" difference between P_{set} and P_{ref} and low P_{ref}. A membership function, μ_{SPC}, is defined in each of the power conditions. In general, a different set of membership functions applies to a power increase and decrease maneuvers. Based on the rules of fuzzy logic (see Appendix G), the degree of fulfillment (DOF) of the small power change (SPC) condition is given by

$$DOF_{SPC} = \min\ (\ \mu_{SPC}(\Delta P)\ ,\ \mu_{SPC}(P_{ref})\ )$$
where $\Delta P = |P_{set} - P_{ref}|$.

The DOF for large power change, DOF_{LPC}, is given by

$$DOF_{LPC} = 1 - DOF_{SPC}.$$

For the simulation and experimental demonstrations, $\mu_{SPC}(\Delta P)$ and $\mu_{SPC}(P_{ref})$ have been represented by step functions as a means of conserving the available computer storage. For power increase and decrease, $\mu_{SPC}(\Delta P)$ is set to 1 for $|\Delta P| \leq 1000$ KW and zero otherwise. For simplicity, $\mu_{SPC}(P_{ref})$ has been set to 1 for all values of P_{ref}.

E.1.4 "Reshim" Condition

This is a condition when the power has to be adjusted using the shim blade while the reg rod is positioned to a desired position. It is defined by the magnitude of the power change and the initial reg rod position. The word "reshim" is used by the MITR operating crew to describe a control procedure where the power is regulated by the shim blade at a given power level while the reg rod is adjusted to its desired operating position. A "reshim" is conducted to compensate for xenon and to bring the reg rod to a desired position prior to a small power change. For small power change, given that the reg rod is located away from its desired position, a "reshim" procedure is first conducted before the power is changed to the new set point. Once the reg rod has reached its desired operating position, the power is then changed using this control mechanism rather than the shim blade, thus, achieving a smoother control.

For the simulation studies, a criterion for reshim is implemented based on the simplified version of the actual operating criterion used by the MITR operating crew. A "reshim" is needed if

1. The power change is large regardless of the initial reg rod position and the direction of the power change.
2. The power change is small but the reg rod is initially "high" ("low") during a power increase (decrease).

Given that the magnitude of the power change has already been classified, as discussed previously, the initial reg rod position is also assessed by using the concept of fuzzy logic. For the simulation studies, step functions are used for the same reason as discussed in the power change classification. For power increase, the reg rod is declared "high" if it is initially located above 5 inches. For power decrease, the reg rod is declared "low" if it is initially located below 7 inches. The desired reg rod operating band has been specified to be within 3 to 5 inches. A better approach to determine whether or not the reg rod, at its initial height, has enough reactivity to accomplish the power change without violating a limiting position is to develop a model that can predict how much reactivity is needed to change the power to a specified level and then determine from the reg rod reactivity worth curve whether or not it is possible. This technique, however, presents an additional computational burden.

A reshim condition can be also declared in the middle of a transient. Given that the reg rod is used to adjust the power, a reshim condition is declared if the reg rod hits a specified position and the current power deviation from the desired level is still "large." The same technique, as discussed above, is used. Based on simulation studies, the critical position and power deviation have been chosen as 9 inches and 0 kw respectively for power increase and 4 inches and 500 kw respectively for power decrease.

During the course of a power maneuver, the control can be switched from the shim blade to the reg rod only if: 1) the reg rod has reached its desired position (about 3 to 5 inches), given that the power is within the desired level, and 2) both reg rod and shim blade reactivity constraint conditions are satisfied.

E.1.5 Overshoot/Undershoot Condition

An overshoot condition is declared if the desired power setpoint is exceeded by a specified amount during a power increase. An undershoot condition, on the other hand, occurs if the power goes below the set point by a specified amount during a power decrease. An oveshoot/undershoot condition is also declared if the plant operating state switched from steady to transient state given that the set point has not been changed.

E.1.6 Reg Rod and Shim Blade Saturation

A control mechanism is said to be saturated if it hits its specified limiting position. For the reg rod, the in/out limit is the criterion used for saturation. For the shim blade, the in/out limit and the position deviation from the shim bank height are the two conditions used to declare a saturation condition.

E.2 Control Procedures for the MITR Substates

This section presents the details of the control procedures for the MITR substates as discussed in Chapter 3. Some of the procedures are formulated from heuristic rules which are based on operating guidelines and operator experience. The formulation is MITR specific. The substates are defined in Chapter 3 and they are also shown in Figure 67.

1. Substate SA1: The PID algorithm is selected based on the recommendation of the plant operating condition identifier (POCI) module of the reconfiguration logic. The performance evaluator (PE) module makes a selection from an alternative set of control laws. This set includes the fuzzy (for power increase only) and the relay algorithms.
2. Substate SA2: The control action that is recommended by the reg rod reactivity constraint relationship (based on the power set point, P_{set}) is implemented whenever such constraint is violated. The shim blade is adjusted if the corresponding reactivity constraint relationship is violated. It is also adjusted, along with the reg rod, if the power is drifting away from a desired band.
3. Substate SA3: The reg rod is adjusted using the relay algorithm. The number of times when the magnitude of e(t) (i.e., the difference between the current power and P_{set}) exceeds a specified amount is also considered. If this number exceeds a specified threshold, the shim blade is adjusted using the relay algorithm.
4. Substate SA4: The reg rod is moved in the direction away from the in/out limit while the shim blade is adjusted by using the relay algorithm.
5. Substate SB1: The shim blade is adjusted using the PID algorithm. Since only the fixed speed motor is assumed available, the shim blade is not moved if the magnitude of the command signal is less than 0.5 of the maximum possible speed.

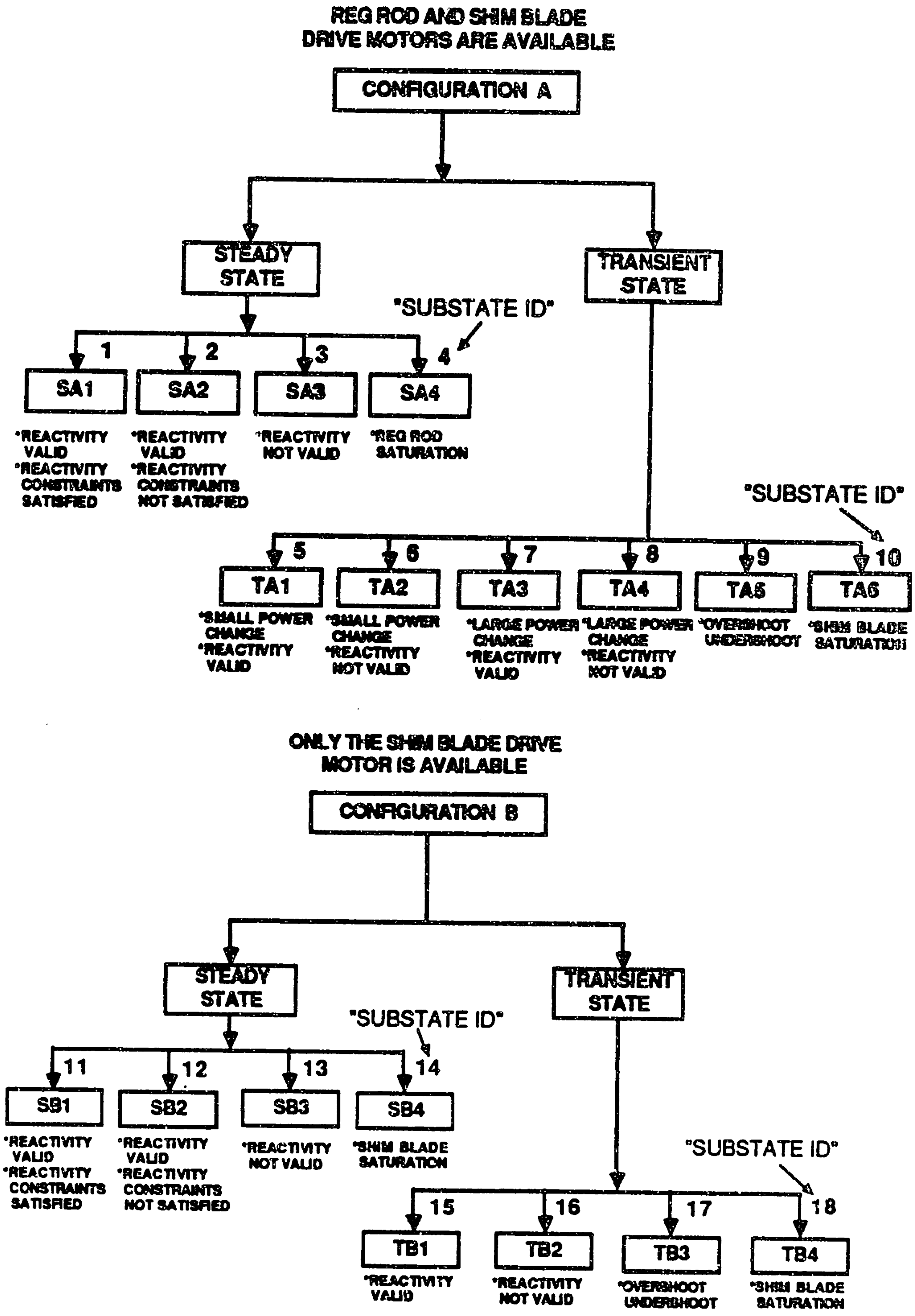

Figure 67. MITR Substates

6. Substate SB2: The shim blade is adjusted based on the recommended action obtained from the shim blade reactivity constraint relationship.
7. Substate SB3: The shim blade is adjusted using the relay algorithm.
8. Substate SB4: The control is switched to manual operation.
9. Substate TA1: The reg rod is adjusted using the NLDC algorithm.
10. Substate TA2: The reg rod is adjusted using the fuzzy algorithm during a power increase and the relay algorithm during a power decrease. The operation of the PE module is demonstrated in this substate during a power increase maneuver. The alternative set of control laws includes the relay and the NLDC algorithms.
11. Substate TA3: The shim blade is adjusted using the NLDC algorithm if the power is away from the setpoint; otherwise, the PID is used. The reg rod is incrementally adjusted at full speed towards a desired height. The reg rod control is set to zero once the desired height is reached. (NOTE: The MITR operators do not normally initiate a "small" power change with the shim blades. This procedure is only conducted if the demanded power change is "large." For "small" power change (less than 1000 KW), the power maneuver is normally conducted by first regulating the power at P_{ref} by using the shim blades while the reg rod is moved to its desired position. Once this position is reached, the power is changed to the demanded power by using the reg rod.)
12. Substate TA4: The shim blade is adjusted using the relay algorithm. The control action is reviewed by the shim blade reactivity constraint relationship which is evaluated at P_{set} (Note: the more conservative of the two reactivity estimates is used to evaluate the constraint.) The reg rod is adjusted in the same fashion as in TA3.
13. Substate TA5: The reg rod is adjusted at full speed in the direction opposite that of $e(t)$, where $e(t) = P(t) - P_{set}$, (i.e., proportional law).

14. Substate TA6: The control is set to zero if 1) during a power increase, the reactor period is positive given that the high position limit is reached (let the power coast up), 2) during a power decrease, reactor power is negative given that the low position limit is reached (let the power coast down). Otherwise, the control is switched to manual.
15. Substate TB1: The shim blade is adjusted using the NLDC algorithm.
16. Substate TB2: The shim blade is adjusted using the relay algorithm. The recommended control signal is reviewed by the shim blade reactivity constraint relationship which is evaluated at P_{set}.
17. Substate TB3: The shim blade is adjusted using a proportional law.
18. Substate TB4: The same procedure used in TA6 is implemented.

APPENDIX F. MITR PERFORMANCE EVALUATOR MODULE

The objective of this appendix is to describe the details of the performance evaluator module used on the MITR reconfigurable controller which is presented in Chapter 3. This appendix is divided into two sections. The first section describes the performance criterion that has been used in the demonstration. The second section presents the adaptive or reinforcement scheme which updates the probabilities associated with the control options for a given condition.

F.1 Performance Criterion

This section describes the performance criterion used in the demonstration of the reconfigurable controller on the MITR. It is divided into two subsections to describe the two conditions that have been considered. The first condition is steady substate SA1. This is a substate where the reactivity is valid and the reg rod and shim blade reactivity constraints based on the power set point are both satisfied. The second is transient substate TA2, where the reactivity is declared invalid given that power maneuver is "small." In both conditions, the reg rod is used to adjust the power.

F.1.1 Steady State Performance Criterion

For substate SA1, the performance criterion is based on three tests

1. the magnitude and direction of the power error e(t) which is defined as the difference between the current power, P, and the power set point, P_{set}. This test will be referred to as the "e-test."
2. the comparison between the previously selected control action, $U^{*}(t-1)$, and the "hard bound" control (HBC), U_{HBC}, which is based on heuristics presented in Figure 68. The HBC takes on the value

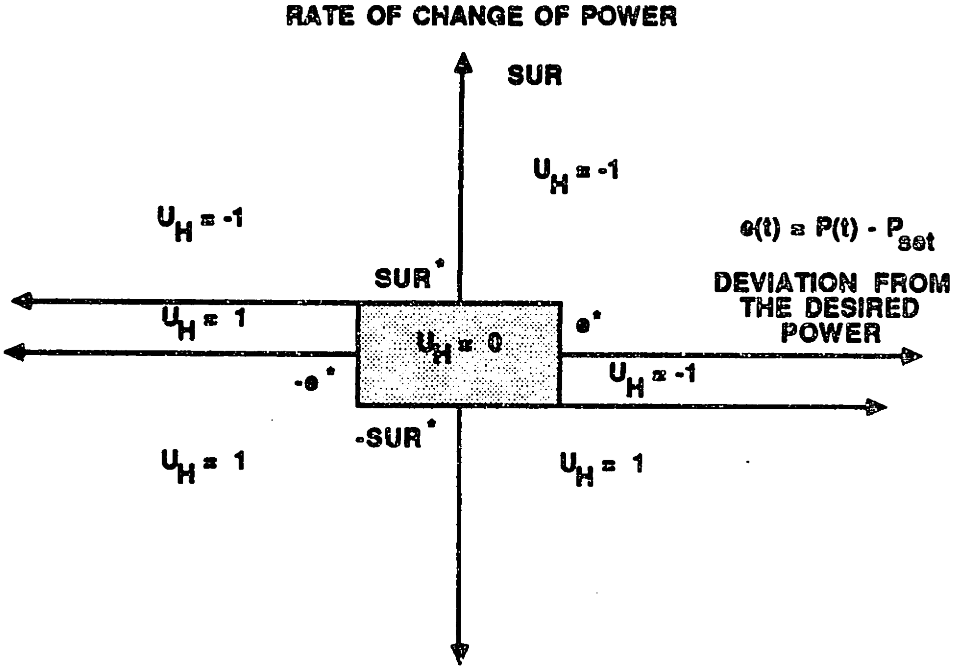

Figure 68. "Hard-bound" Control

of 1 for withdrawal, 0 for hold, and -1 for insertion. The value of e^*, as defined in Figure 68, lies within the bound of the steady state criterion. This test will be referred to as the "HBC-test."

3. overriding conditions to be discussed later in this section.

In addition, heuristics are used based on the number of times a control option has been used consecutively, given that there is no change in the plant operating substate.

The previous control action has satisfied the performance criterion if

1) the magnitude of the power error is decreasing, $|e(t)| < |e(t-1)|$,
2) $U^*(t-1)$ agrees with U_{HBC},

$|U_{HBC}(t) - U^*(t-1)| \leq 1$,

and 3) there is no control override.

The second test can override the result of the first test and the third test can override the first two tests. A reward condition is declared if all the tests are satisfied and a penalty condition if at least one is violated. An inaction condition is introduced in case when the "e-test" seems to be inconclusive, that is, if the error is smaller than a specified amount, ϵ_1, and if the control option has not operated long enough. The condition regarding ϵ_1 serves as a dead band condition. The rationale for the second inaction condition is to minimize the effects of delayed feedback associated with the previous control actions; thus, giving the newly selected option a chance.

Two overriding conditions are introduced to declare a penalty condition. The "e-test" and the "HBC-test" are bypassed if either overriding condition is in effect. The first overriding condition is declared if the previous control action has caused the substate to change from SA1 to SA2 (control based on the reactivity constraint takes over), given that the selected control law has been consecutively used for a specified number of times and given that the HBC test has not been violated prior to the violation of the reactivity constraint. The above heuristics are important in preventing the unselection of a given control option due to delayed feedback effects associated with the delayed neutrons especially immediately after the termination of the transient part of the maneuver. The other overriding condition occurs if

$|U_{HBC}(t-1)| - U^*(t-1)| > U_\epsilon$

given that 1) $e > \epsilon_2$, where $\epsilon_2 > e^*$,
as defined in Figure 68 on page 230,
(Note: $U_{HBC} = 0$, if $|e| < e^*$)

and 2) the control threshold, $U_\epsilon < 1$.

Under this condition, the HBC is implemented at time t-1 and the corresponding control law that has been selected by the performance evaluator module is penalized at time step t (i.e., the next time step). The rationale for this override is to prevent the power from going to an unsafe condition and to avoid a switch over to another substate. Delayed feedback effects are accounted for by declaring an inaction condition, if the currently selected control option has not yet continuously operated for a specified number of time steps.

As discussed later in this appendix, the implementation of the linear reward-penalty (LRP) algorithm [Narendra, et al., 1974], has been modified to account for the varying degree of reward and penalty conditions. A reward, inaction, or penalty condition is indicated by a reinforcement function, $H(t)$. As opposed to the "standard" implementation, $H(t)$ is allowed to take on a value between -1 to 1, rather than 1, 0, or -1,

$$H(t) \begin{array}{ll} < & 0 \text{ for a penalty condition} \\ = & 0 \text{ for an inaction condition} \\ > & 0 \text{ for a non-penalty condition.} \end{array}$$

The magnitude of $H(t)$ accounts for the severity of the penalty and any possible delayed feedback associated with the previous control actions.

For this application , $H(t)$ is based on the magnitude of the error, the number of times a penalty or reward condition occurs, the number of times a control action has been used, and the type of overriding condition. Based on the "e-test," two counters are introduced to count the the number of times a penalty, N_{PEN}, and reward, N_{REW}, conditions occur. N_{PEN} and N_{REW} are allowed to have values between 0 and a specified upper bound. N_{PEN} is incremented whenever N_{REW} is decremented and vice versa. A counter to indicate the number of times a control law has been in effect, N^*, is also introduced. All three counters are reset to zero each time there is a change in the control selection and a change in the substate. N_{PEN} and N_{REW} are not updated if $|e(t)|$ is less than ϵ_1, the "inaction" dead band, in order to minimize the effects of noise in evaluating the value of $H(t)$.

For a penalty condition, $H(t)$ is defined so that it takes on the value of:

Based on the "e-test:" $H(t) = H_e(t) H_{NPEN}(t)$

where $H_e(t) = -|e(t)|/e^*$ $\quad \epsilon_1 \le |e(t)| \le e^*$

$\qquad -1.0 \quad |e(t)| > e^*$

and $H_{NPEN}(t) = 0.5 \quad N_{PEN} \le N_{P1}$

$\qquad 1.0 \quad N_{PEN} > N_{P1}$

where N_{P1} is a specified threshold.

Based on the "HBC-test:" $H(t) = -1.0$ if $|U_{HBC}(t) - U^*(t-1)| > 1.0$

Based on the Override conditions:

$H(t) = -0.5$ if the substate has changed from SA1 to SA2, given that N^* is greater than a specified number; otherwise, $H(t) = 0$

$H(t) = -0.5$ if the HBC overrides the control action from the previous time step, given than N^* is greater than a specified number; otherwise, $H(t)=0$.

For a reward condition, H(t) takes on the value of:

Based on the "e-test:" $H(t) = 0.0 \quad N_{REW} < 2$

$\qquad 0.1 \quad N_{REW} = 2$

$\qquad 0.5 \quad N_{REW} = 3$

$\qquad 1.0 \quad N_{REW} \ge 4$

Based on the "HBC-test:" $H(t) = 1.0$ if $U_{HBC}(t) = U^*(t-1)$.

For an inaction condition, H(t) takes on the value of zero.

F.1.2 Transient Performance Criterion

This performance criterion is specifically formulated for substate TA2, the reactivity is invalid and the power change is "small." The reg rod is used to adjust the power. For this substate, the plant operating condition identifier module of the reconfiguration logic recommends the use of the fuzzy algorithm for a power increase. The backup control laws that are considered by the performance evaluator, in case the fuzzy algorithm fails to satisfy the performance criterion, include the relay and the NLDC algorithms. During a power decrease, the relay algorithm is recommended with the NLDC algorithm as the backup. It should be noted that the fuzzy algorithm is only designed for power increase. For this reason, the performance evaluation is only demonstrated during this type of maneuver.

Several tests are introduced as a means of determining the performance criterion. The first test checks whether or not the power is proceeding towards the desired set point. The control law is performing satisfactorily if $|e(t)| < |e(t-1)|$ where $e(t) = P(t) - P_{set}$. A reward or penalty condition is declared depending on whether or not the above criterion is satisfied. Since $e(t)$ is a noisy signal, two counters are introduced to account for the number of times a penalty, N_{PEN}, and reward, N_{REW}, conditions occur. Both counters are reset and updated in a similar fashion as their steady state counterparts. The reinforcement function, $H(t)$, is dictated by the values of N_{PEN} and N_{REW}. For this application, N_{PEN} and N_{REW} are bounded between 0 and 5. $H(t)$ takes on the value of:

For a penalty condition: $H(t) = 0.00$ for $N_{PEN} \leq 2$
-0.50 for $N_{PEN} = 3$
-0.75 for $N_{PEN} = 4$
-1.00 for $N_{PEN} > 5$
For a reward condition: $H(t) = 0.00$ for $N_{REW} \leq 2$
0.50 for $N_{REW} = 3$
0.75 for $N_{REW} = 4$
1.00 for $N_{REW} > 5$

A penalty condition is also declared based on the rate of change of power. A control law is penalized if it is changing the power so "fast" or "slow." For simplicity, a criterion based on heuristics is introduced. A desired trajectory may be formulated on-line or off-line. However, this may be difficult to formulate and implement since there are too many variables and conditions to consider in determining such a trajectory. Furthermore, each alternative control law has different characteristics, and, therefore, the evaluation of the trajectory becomes more complicated if the performance evaluator recommends a change in the selection of the control law. Any error in the trajectory can lead to unnecessary changes in the control selection. For this application (power increase), two rules have been formulated in a deterministic fashion in order to assess the rate of change of power resulting from the previously implemented control action. A full penalty condition is declared ($H(t) = -1$) if the instantaneous period is less than 100 seconds. The rate of change of power is declared "too slow" if the period and the magnitude of the power error, $|e(t)|$, are greater than their respective specified values. The specified period and power error are determined empirically. The second rule is not considered if the relay algorithm is in operation. The reason for this is that the relay algorithm is designed to be very conservative with respect to the allowable instantaneous period. A counter is introduced to track the number of times the second rule is satisfied. The penalty given to the control law is proportional to the value of this counter.

F.2 Implementation of Reinforcement Algorithm

The objective of this section is to present the modification made in the implementation of the linear reward-penalty (LRP) algorithm [Narendra et al., 1974]. The modification accounts for the varying degree of how well the performance criterion is satisfied. As presented in Appendix B, the probabilities associated with the control options for condition i is given by

$$P_i(t) = (P_{i1}(t), P_{i2}(t), \ldots\ldots\ldots, P_{ir(i)}(t))$$

where $r(i)$ is the number of options for condition i

$$0 < P_{ij}(t) < 1$$

$$\sum_{j=1}^{r(i)} P_{ij}(t) = 1.$$

The update procedure is as follows:

If action U_k has been selected at time t-1, given that the system is in operating condition i then:

For nonpenalty condition

$$P_{ik}(t) = P_{ik}(t-1) + \sum_{j \neq k}^{r(i)} F_{ij}(t-1)$$

$$P_{ij}(t) = P_{ij}(t-1) - F_{ij}(t-1) \qquad (j \neq k)$$

For penalty condition

$$P_{ik}(t) = P_{ik}(t-1) - \sum_{j \neq k}^{r(i)} G_{ij}(t-1)$$

$$P_{ij}(t) = P_{ij}(t-1) + G_{ij}(t-1) \qquad (j \neq k)$$

For inaction condition

$$P_{ij}(t) = P_{ij}(t-1)$$

where $F_{ij}(t)$ = reward function

$G_{ij}(t)$ = penalty function.

The reward and penalty functions are given by

$$F_{ij}(t) = a_i P_{ij}(t)$$

$$G_{ij}(t) = b_i/(r(i)-1) - b_i P_{ij}(t)$$

where a_i, b_i are called the learning coefficients. These coefficients are normally assumed time invariant.

A non-penalty or reward condition is declared if the performance criterion is satisfied; otherwise, a penalty condition is declared. An inaction condition is declared if the performance criterion cannot be evaluated conclusively. The reinforcement function is introduced to indicate whether or not the condition is a reward, penalty or inaction. More explicitly, the reward and penalty functions can be written in terms of the reinforcement function, H(t)

$$F_{ij}(t) = H(t)a_iP_{ij}(t)$$
$$G_{ij}(t) = H(t)b_i(1/(r(i)-1) - P_{ij}(t))$$

Based on this explicit formulation, it can be observed that the reinforcement function directly determines the amount of change in the probability distribution. In the "standard" implementation, H(t) can only take on the value of -1, 0, or 1 to indicate penalty, inaction, or reward respectively. This implies that the control options are always "fully" rewarded or penalized. A change in the implementation is introduced so that the magnitude of H(t) provides a subjective measure of how well the control action is satisfying the performance criterion. Therefore, H(t) is redefined as follows

$$H(t) \begin{array}{ll} < & 0 \text{ for a penalty condition} \\ = & 0 \text{ for an inaction condition} \\ > & 0 \text{ for a non-penalty condition} \end{array}$$

With the upgraded definition of H(t), a control action can be rewarded or penalized slightly or up to the maximum possible amount, thus, changing the "learning" rate (i.e. effectively changing a_i and b_i).

APPENDIX G. BASIC ELEMENTS OF FUZZY SET THEORY

The concept of a fuzzy set allows for imprecise and qualitative information to be expressed quantitatively [Zadeh, 1984]. It is a generalization of the ordinary notion of a set.

The ordinary set is precise in its meaning. It has a definite transition from membership to non-membership. The fuzzy set, on the other hand, allows the qualitativeness of the measure to be reflected in a gradual membership transition. Let S be a set, and let μ be a function which assigns to each element e in S a number $\mu(e)$. The number $\mu(e)$, which describes the grade of membership of the element e in S, is called the membership function. For ordinary set, $\mu(e)$ can take values of either 0 or 1. A fuzzy set has a membership function which takes all values between 0 and 1. By definition, e does not belong to S if $\mu(e) = 0$.

Fuzzy sets can be combined based on simple definitions. The union of two sets, A+B, is defined by the membership function

$$\mu_{A+B}(e) = \max(\mu_A(e), \mu_B(e)).$$

The intersection of two sets, A*B, is defined by

$$\mu_{A*B}(e) = \min(\mu_A(e), \mu_B(e)).$$

Negation is defined by $(1 - \mu_A(e))$.
A more detailed discussion of this subject can be found in [Zadeh, 1973] and [Zadeh, 1984].

APPENDIX H. PROPOSED CONTROL SYSTEM ARCHITECTURE

The objective of this appendix is to discuss the role of the reconfigurable controller in a fault tolerant control system design. A proposed architecture of such control system is presented. This control system is under the bound of the plant protection and safety systems.

A control system is designed to control a plant or process. It consists of sensors, actuators, and controllers. A proposed architecture on how to incoporate fault tolerance in each element of the the control system is shown in Figure 69. Fault tolerant concepts can be applied in the sensors, actuators, and controllers. For a digital controller, the processor hardware and software, in addition to the control strategy being implemented, have to be considered. One possible approach to achieve fault tolerance in the sensors is to utilize direct and analytic redundancy [Ray et al., 1983A] along with a sensor fault detection and isolation (FDI) algorithm. In the case of the actuating system, direct redundancy may be incorporated. The information obtained from the actuator and sensor FDI systems are fedback to the controller. Fault tolerance in the sensor and actuators have been demonstrated on the MIT Reactor (MITR) [Lanning et al., 1985].

For a digital controller, fault tolerance can be incorporated in the processor hardware and software. In the processor hardware, fault tolerance can be achieved through direct redundancy. As shown in Figure 69, each processor receives a common set of validated inputs from the sensor and actuating systems. Each processor runs the same set of software. The outputs of the processors are then compared for consistency. A technique such as the one described in [Lala, 1985] may be used. The software architecture may be designed by incorporating N-version programming technique [Avizienis and Chen, 1977], for example, in order to achieve software fault tolerance. As shown in Figure 69, three ver-

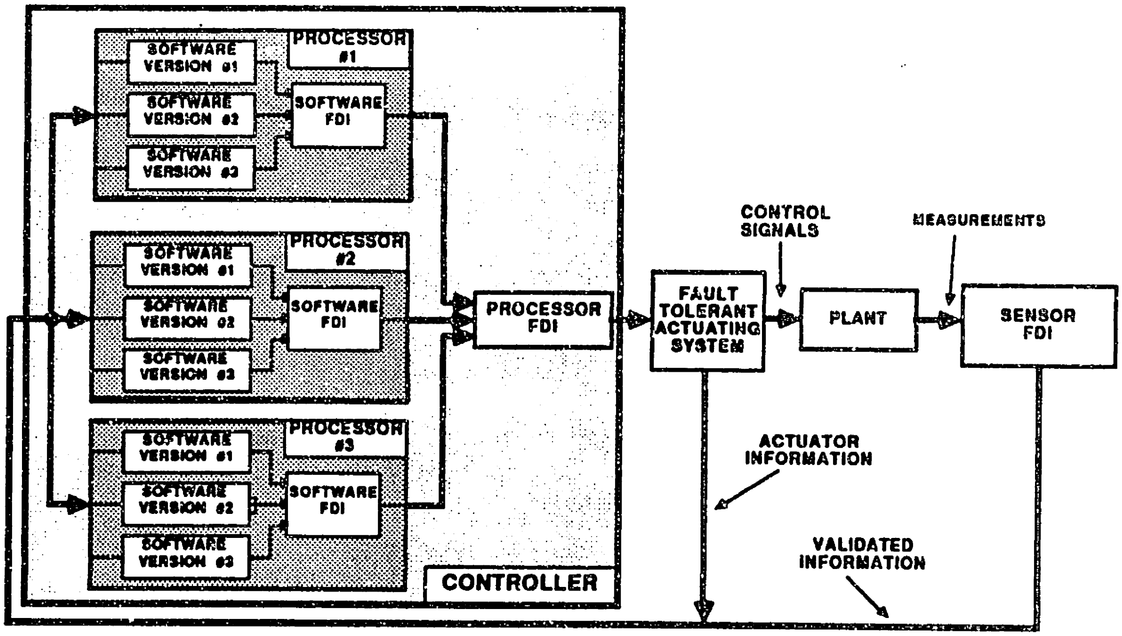

Figure 69. Proposed Fault Tolerant Control System Architecture

sions of the software are implemented in each processor. The outputs are compared for consistency.

The reconfiguration control scheme, such as the one presented in this thesis, resides in each version of the software. The control scheme is designed to accommodate various operating conditions which include anticipated changes in the plant dynamics, component alignment and status, and demand. These conditions also include failures in the actuators, sensors, and plant components that can be detected but cannot be isolated or directly be replaced by an identical element. The controller requires that the information it needs to synthesize the appropriate control action is reliable. It should be noted that a failure in the sensor or actuating system that does not alter the information supplied to the controller is treated as a "normal condition" in the point view of the controller.

Based on this proposed architecture, the reliability or availability of the control system is determined by the degree of fault tolerance in each of its elements. The weakest link in the control system dictates its overall reliability. With this architecture, one can design and analyze each of its elements independently in order to optimize the cost of the control system based on its reliability requirement. It is important that each element is designed so that the functional and interfacing requirements are satisfied.

APPENDIX I. SENSITIVITY OF THE CONTROL MECHANISM DRIVE MOTORS

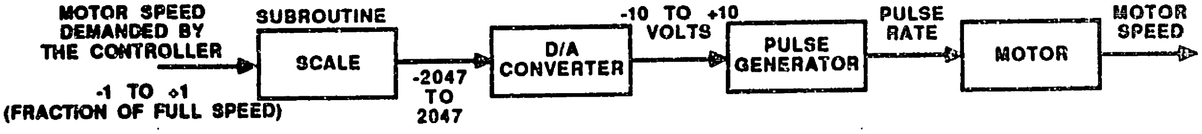

Figure 70. Signal Conversion for the MITR Variable Speed Drive Motor

This appendix discusses some of the details regarding the operation of the variable speed drive motor used on the MITR reg rod. The full speed of this motor corresponds to a reg rod movement of 4.25 inches/min (108 mm/min). The block diagram presented in Figure 70 shows the conversion of the drive motor command signal, generated by the control program, to the actual drive motor speed. The controller generates a command signal between -1 and +1 to represent a full speed insertion and withdrawal of the control element respectively. This signal is then scaled before it is sent to the digital-to-analog (D/A) converter.

The D/A converter has a 12 bit resolution. This implies that the allowable range of values of the digital signal can be divided into 2^{12} (4096) discrete levels where each level represents 1 bit. The sign of the digital signal is accounted for in the conversion. The digital signal is passed through a D/A converter to produce a voltage signal. For the MITR drive motor system, 10 volts is equivalent to 2047 bits or 1 bit = 4.885×10^{-3} volts. The voltage signal is then passed through a pulse generator. The voltage to pulse rate signal conversion is given in Figure 71. The conversion from pulse rate to drive motor speed is shown in Figure 72. It should be noted that the drive motor does not move if the magnitude of the voltage signal is less than 0.25 volts. This corresponds to a controller-generated command signal of about 0.025 of the drive motor's full speed.

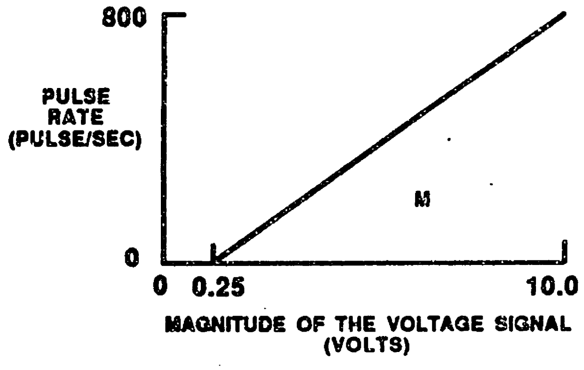

Figure 71. Voltage to Pulse Rate Signal Conversion

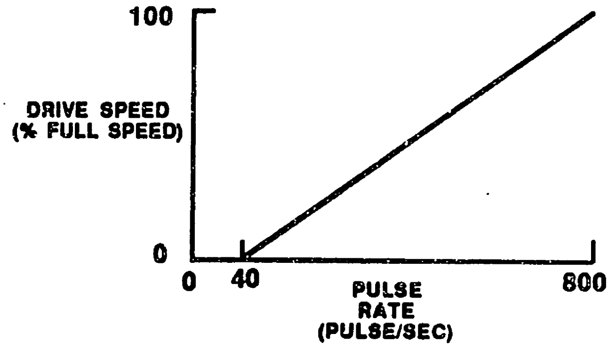

Figure 72. Pulse Rate to Drive Motor Speed Conversion

APPENDIX J. CODE LISTING

Attached is a listing of the FORTRAN computer program used in the simulation studies and on-line demonstration. The MIT Reactor (MITR) simulation program is a modification of the code written by John A. Bernard [Bernard, 1984, Appendix B]. The main program, MITDSP, for the on-line demonstration and the interfacing subprograms (FDITST, DISPLY, INPUTC) for data acquisition and information display are simplified versions of the programs written by Asok Ray. RTS, SETR, and IDAC are subprograms that are included in the the Data Translation Real-Time Library Package. HALT, LLCHAR, LWAIT, TTINIT, TTRSET, and XWAIT are subprograms that were also written by Asok Ray. The sensor signal validation and calibration routines are not included during the on-line demonstration because of computer memory limitations. It should be noted that there are two different listings of the BLOCK DATA, CPARAM, OUTPUT, and RCON - one for simulation and one for on-line demonstration. Some of the subroutines used in the simulation studies and on-line demonstration (e.g., SS1, TPERF) are similar except for minor changes in some the parameters and therefore a different set of listings is not attached. The sequence of subroutine call is documented within the code. The definition of the variables that are included in the common blocks can be found in the beginning of the main routine used in the simulation studies.

J.1 Simulation Code Listing

```
C==================================================================
C  RECONFIGURABLE CONTROLLER PROGRAM: SIMULATION AND ON-LINE DEMO
C                                     ON THE MITR
C  AUTHOR: RENATO S. ORNEDO
C
C===================================================================
C THIS PROGRAM SIMULATES THE MITR
C CONTROL MECHANISM: 1 REG ROD  & 6 SHIM BLADES
C
C ADAPTATION OF J.A. BERNARD'S MODEL
C   REFERENCE J.A.BERNARD'S PH.D. THESIS APPENDIX B
C====================================================================
C
C  PROGRAM STRUCTURE
C
C---------------------------------------------------
C  ON-LINE PROGRAM
C
C    MITDSP I---> CPARAM
C           I
C           I---> INPUTC
C           I
C           I---> DISPLY
C           I
C           I---> FDITST ---> RCON
C
C  MITDSP = MAIN PROGRAM, COLLECTS SENSOR DATA
C  CPARAM = READS CONTROLLER PARAMETERS
C  INPUTC = READS INPUT FROM THE CRT
C  DISPLY = WRITES RESULT ON THE CRT
C  FDITST = INTERFACE BETWEEN MAIN PROGRAM AND CONTROL PROGRAM
C  RCON   = DRIVER ROUTINE FOR CONTROL PROGRAM
C---------------------------------------------------
C  SIMULATION PROGRAM
C
C    MAIN   ----> INTER I---> PARAMS
C                       I
C                       I---> CPARAM
C                       I
C                       I---> SENSOR
C                       I
C                       I---> RCON
C                       I
C                       I---> PLOT
C
C
C  MAIN   = SIMULATION PROGRAM (POINT KINETICS, 6 DELAYED NEUTRON GROUP)
C  INTER  = INTERFACE ROUTINE (INCLUDES SENSOR MODEL)
C  PARAMS = READS SENSOR MODEL PARAMETERS
C  CPARAM = READS CONTROLLER PARAMETERS
C  SENSOR = SENSOR MODEL
C  RCON   = DRIVER ROUTINE FOR CONTROL PROGRAM
C  PLOT   = WRITES VARIABLES TO BE PLOTTED
C----------------------------------------------------
C  CONTROLLER PROGRAM
```

```
C
C    RCON ---> I---> STATE ---> PSTATE
C              I
C              I---> RHOVAL
C              I
C              I---> SAFETY
C              I
C              I---> MODE ---> I---> SS -----I---> SS1 I-> PID
C              I               I             I         I
C              I               I             I         I-> FUZZY
C              I               I             I         I
C              I               I             I         I-> RELAY
C              I               I             I
C              I               I             I---> SS2
C              I               I             I
C              I               I             I---> SS3 --> SRELAY
C              I               I             I
C              I               I             I---> SS4 --> SRELAY
C              I               I
C              I               I---> TRANS --I---> CMOTOR
C              I               I             I
C              I               I             I---> POSTRA ---> POSSHIM
C              I               I             I
C              I               I             I---> TRANNO I--> NLDC
C              I               I             I            I
C              I               I             I            I--> TPERF
C              I               I             I            I
C              I               I             I            I--> RELAY
C              I               I             I
C              I               I             I---> RSHIM  I--> NLDC
C              I               I             I            I
C              I               I             I            I--> RELAY
C              I               I             I            I
C              I               I             I            I--> PID
C              I               I             I
C              I               I             I---> INITSE
C              I               I             I
C              I               I             I---> KBOVER ---> SRELAY
C              I               I
C              I               I---> SATUR
C              I
C              I---> USEL ---> I---> CONST
C              I               I
C              I               I---> CHECK
C              I
C              I---> OUTPUT
C              I
C              I---> IDAC
C              I
C              I---> TSAVE
C
C  RCON   = DRIVER ROUTINE FOR CONTROL PROGRAM
C  STATE  = ESTIMATES PLANT VARIABLES
C           PSTATE = IDENTIFIES STATES BASED ON POWER & SUR
C  RHOVAL = REACTIVITY VALIDATION
C  SAFETY = CHECKS FOR SAFETY LIMITS
C  MODE   = "DRIVER" ROUTINE IN THE "STATE" LEVEL
C           SS    = "DRIVER" FOR "STEADY STATE" ROUTINES
C           TRANS = "DRIVER" FOR "TRANSIENT STATE" ROUTINES
C  USEL   = "DRIVER" FOR SUPERVISORY ROUTINES
C           CONST = COMPUTES SUPERVISORY REACTIVITY
C                   CONSTRAINT RELATIONSHIP
C           CHECK= CHECKS FOR LIMITS ON THE REG ROD OR
C                   SHIM BLADE POSITION
C  OUTPUT = WRITES SELECTED RESULTS
C  IDAC   = GENERATES ACTUATOR SIGNAL
C  TSAVE  = SAVES OLD VALUES OF SELECTED VARIABLES
C
C=====================================================================
C  DEFINE VARIABLE NAMES
C=====================================================================
C  COMMON /A / RL, BETA, RD(6), B(6), DN(6), DECAY
C     RL   = PROMPT NEUTRON LIFETIME
C     BETA = EFFECTIVE DELAYED NEUTRON FRACTION
```

```
C     RD    = DELAYED NEUTRON CONCENTRATION FOR GROUP I
C     B     = BETA FOR DELAYED GROUP I
C     DN    = DECAY CONSTANT FOR DELAYED GROUP I
C     DECAY= EFFECTIVE DECAY CONSTANT
C  COMMON /BSAFE / QSAFE(5)
C     QSAFE   = SAFETY FLAG
C  COMMON /CCON  / U1(2), U2(2), U3(2), U4(2)
C     U1    = PID   CONTROL SIGNAL    (1/2 = REG ROD/SHIM BLADE)
C     U2    = NLDC  CONTROL SIGNAL    (1/2 = REG ROD/SHIM BLADE)
C     U3    = FUZZY CONTROL SIGNAL    (1/2 = REG ROD/SHIM BLADE)
C     U4    = RELAY CONTROL SIGNAL    (1/2 = REG ROD/SHIM BLADE)
C  COMMON /CCONF / ICONF(2), ISTATE, JDEV, JSUR, KFLAGS, ISCOM
C     ICONF  = LABEL    ( SEE SUBROUTINE PSTATE )
C     ISTATE = LABEL    ( SEE SUBROUTINE PSTATE )
C     JDEV   = LABEL    ( SEE SUBROUTINE PSTATE )
C     JSUR   = LABEL    ( SEE SUBROUTINE PSTATE )
C     KFLAGS = STEADY STATE FLAG
C     ISCOM  = "HARD-BOUND" CONTROL
C  COMMON /CDESP/ STEADY
C     STEADY = STEADY STATE BAND
C  COMMON /CFILT / TFILTP, TFILTS
C     TFILTP, TFILTS = LOW PASS FILTER TIME CONSTANT FOR POWER & SUR
C  COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
C     FPOW   = POWER SIGNAL   (1/2 = OLD/NEW)
C     FTPC   = REACTOR OUTLET TEMPERATURE
C     FHRR   = REG ROD HEIGHT
C     FHSB   = SHIM BLADE HEIGHT (1/2 = SHIM BLADE #4/#1)
C     CONT   = CONTROL SIGNAL   (1/2 = REG ROD/SHIM BLADE)
C  COMMON /CFUZ  / IFUZ1, IFUZ2
C     IFUZ1 = CONTROL ANOMALY FLAG   (SEE SUBROUTINE SS1)
C     IFUZ2 = CONTROL ANOMALY FLAG   (SEE SUBROUTINE TPERF)
C  COMMON /CIOCON/ IINP, IOUT, KPRIN
C     IINP  = READ DEVICE
C     IOUT  = WRITE DEVICE
C     KPRIN = PRINT FLAG
C  COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
C     IRSHIM= "RESHIM" FLAG
C     IPOS  = SUBSTATE IDENTIFICATION TAG
C     NFLAGS= NO. OF TIMES IN "STEADY" STATE
C     ITRAN = SIZE OF POWER MANEUVER (1 = SMALL POWER CHANGE)
C  COMMON /CNFLAG/ NJRHO, IPOSO
C     NJRHO = MCO COUNTER FOR REACTIVITY VALIDITY TEST
C     IPOSO = PREVIOUS VALUE OF IPOS (SUBSTATE I.D. TAG)
C  COMMON /CPLANE/ DTAUS(2), PS, DBUF1, DBUF2
C     DTAUS = LIMITING PERIOD FOR THE RELAY ALGORITHM (1/2=RR/SB)
C     PS, DBUF1, DBUF2 = RELAY ALGORITHM PARAMETER
C  COMMON /CREF  / PREF, HRRREF, HSBREF, TPCREF
C     PREF   = REFERENCE POWER
C     HRRREF= REFERENCE REG ROD HEIGHT
C     HSBREF= REFERENCE SHIM BLADE #4 HEIGHT
C     TPCREF= REFERENCE TEMPERATURE
C  COMMON /CREV  / IREV
C     IREV = 0 ----> VARIABLE SPEED DRIVE MOTOR, FIXED SPEED OTHERWISE
C  COMMON /CRHO  / DKRR, DKSB, DKT, DELK, DELKRF, DC
C     DKRR   = REACTIVITY CONTRIBUTION FROM THE REG ROD
C     DKSB   = REACTIVITY CONTRIBUTION FROM SHIM BLADE #4
C     DKT    = REACTIVITY CONTRIBUTION FROM TEMPERATURE FEEDBACK
C     DELK   = TOTAL REACTIVITY (BALANCE MODEL)
C     DELKRF= REFERENCE REACTIVITY
C     DC     = DECAY CONSTANT
C  COMMON /CSAV  / CONSAV(2)
C     CONSAV= PREVIOUS CONTROL SIGNAL (1/2=REG ROD/SHIM BLADE)
C  COMMON /CSEL  / IDCON(2), IDROD(2)
C     IDCON = CONTROL LAW ID LABEL   (1/2 = OLD/NEW)
C     IDROD = CONTROL ROD ID LABEL   (1/2 = OLD/NEW)
C  COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
C     PSET   = POWER SETPOINT
C     DESDP = DESIRED STEADY STATE POWER DEVIATION
C     DESSUR= DESIRED STEADY STATE SUR
C     DESTAU= DESIRED STEADY STATE PERIOD
C  COMMON /CSROD / SVRR, SVSB
C     SVRR   = MAXIMUM SPEED OF THE REG ROD DRIVE MOTOR
C     SVSB   = MAXIMUM SPEED OF THE SHIM BLADE DRIVE MOTOR
C  COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
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C 1                 ,ADEVP(2), FASUR, FATAU, HDEL(2)
C     DEVP  = FRACTIONAL POWER DEVIATION  (1/2 = OLD/NEW)
C     FSUR  = STARTUP RATE                (1/2 = OLD/NEW)
C     FTAU  = REACTOR PERIOD              (1/2 = OLD/NEW)
C     PFAC  = POWER FRACTION RELATIVE TO THE SETPOINT
C     KFLAG = POWER MANEUVER FLAG
C     ADEVP = ABSOLUTE VALUE OF DEVP
C     FASUR = ABSOLUTE VALUE OF FSUR
C     FATAU = ABSOLUTE VALUE OF FTAU
C     HDEL  = REG ROD POSITON DEVIATION FROM REFERENCE POINT (1/2 = OLD/NEW
C  COMMON /CTIME / TIME, TSAM
C     TIME  = TIME STEP INDICATOR
C     TSAM  = SAMPLING TIME
C  COMMON /CUSENS/ RNX, TPCX, HRRX, HSBX(2)
C     RNX   = POWER SIGNAL (UNFILTERED OR FROM SIMULATION MODEL)
C     TPCX  = TEMPERATURE SIGNAL (UNFILTERED OR FROM SIMULATION MODEL)
C     HRRX  = REG ROD POSITION SIGNAL (UNFILTERED OR FROM SIMULATION MODEL)
C     HSBX  = SHIM BLADE POSITION SIGNAL (UNFILTERED OR FROM SIMULATION MODEL
C  COMMON /ERHOV / ERHO
C     ERHO  = THRESHOLD FOR ERROR BETWEEN THE BALANCE & INVERSE KINETICS
C             REACTIVITY ESTIMATES
C  COMMON /JLIMIT/ TLIM, SIGX(2)
C     TLIM  = AVAILABLE TIME BASED ON A SUPERVISORY POWER LEVEL
C             (SUPERVISORY REACTIVITY CONSTRAINT)
C     SIGX  = RECOMMEND SIGNAL BASED ON THE SUPERVISORY
C             REACTIVITY CONSTRAINT (1/2=REG ROD/SHIM BLADE)
C  COMMON /JPARA1/ VALB(2),  VALK(2), IRHOB(2), IRHOK(2),
C 1                 QVRHO(4), QCONS(2), IRHO(2)
C     VALB = REQUIRED TIME BASED ON REACTIVITY BALANCE  (RR/SHIM BLADE)
C     VALK = REQUIRED TIME BASED ON INVERSE KINETICS    (RR/SHIM BLADE)
C     IRHOB= RECOMMENDED CONTROL ACTION BASED ON THE REACTIVITY
C            CONSTRAINT RELATIONSHIP (BALANCE) RR/SHIM BLADE
C     IRHOK= RECOMMENDED CONTROL ACTION BASED ON THE REACTIVITY
C            CONSTRAINT RELATIONSHIP (INV KIN) RR/SHIM BLADE
C     QVRHO= REACTIVITY VALIDITY TEST FLAG
C     QCONS= REACTIVITY CONSTRAINT TEST FLAG
C     IRHO = CONSERVATIVE CONTROL ACTION BASED ON THE REACTIVITY
C            CONSTRAINT RELATIONSHIP  RR/SHIM BLADE
C  COMMON /JPARAM/ RX(2), VAL1(2), VAL2
C     RX   = MAXIMUM RATE OF CHANGE OF REACTIVITY AVAILABLE
C            (1/2 = REG ROD/SHIM BLADE)
C     VAL  = CONSERVATIVE REQUIRED TIME (REACTIVITY CONSTRAINT)
C            FOR 1/2 = REG ROD/SHIM BLADE
C     VAL2 = AVAILABLE TIME BASED ON THE POWER SETPOINT
C  COMMON /LPARAM/ ARP, BRP
C     ARP, BRP = LEARNING COEFFICIENTS
C  COMMON /RESET / QCSET, QPSET, QRSET
C     QCSET = CHANGE IN CONTROL LAW INDICATOR (NOT USED)
C     QPSET = CHANGE IN SETPOINT POWER INDICATOR
C     QRSET = CHANGE INDICATOR (NOT USED)
C  COMMON /RPARAM/ BAND(2,2), GAIN(4,2), TRHO, BETT(3), DEL(3)
C     BAND  = BAND FOR PID
C     GAIN  = PID GAIN PARAMETERS
C     TRHO  = FILTER TIME CONSTANT (PID)
C     BETT  = DELAYED NEUTRON FRACTION (3 GROUPS)
C     DEL   = DECAY CONSTANT (3 GROUPS)
C  COMMON /RTEMP / RHOKIN, AD(3), BD(3)
C     RHOKIN= REACTIVITY ESTIMATE BASED ON INVERSE KINETICS
C     AD,BD = PARAMETERS FOR INVERSE KINETICS MODEL
C  COMMON /SMOTOR/ IMOTOR
C     IMOTOR = 0 --> CONFIGURATION "B"
C            = 1 --> CONFIGURATION "A"
C  COMMON /SPARAM/ XBIAS(9), XNOISE(9), XSCALE(9), XTAU(9)
C     XBIAS = BIAS  PARAMETER FOR SENSOR MODEL
C     XNOISE= NOISE PARAMETER FOR SENSOR MODEL
C     XSCALE= SCALE FACTOR ERROR PARAMETER FOR SENSOR MODEL
C     XTAU  = TIME LAG PARAMETER FOR SENSOR MODEL
C  COMMON /SSENS / RN, HRR, HSB(6), TPC, SIGRR, SIGSB(6)
C     RN    = "PERFECT" SIMULATED POWER SIGNAL
C     HRR   = "PERFECT" SIMULATED REG ROD POSITION SIGNAL
C     HSB   = "PERFECT" SIMULATED SHIM BLADE POSITION SIGNAL
C     TPC   = "PERFECT" SIMULATED REACTOR OUTLET TEMPERATURE SIGNAL
C     SIGRR = SIMULATED CONTROL SIGNAL FROM THE REG ROD ACTUATOR
C     SIGSB = SIMULATED CONTROL SIGNAL FROM THE SHIM BLADE ACTUATOR
```

```
C
C========================================================================
C======================================================================
      DIMENSION DND(6), DKSB(6), HSBREF(6)
      COMMON/A/RL,BETA,RD(6),B(6),DN(6),DECAY
      COMMON /CTIME/ TIME, TSAM
      COMMON /CIOCON/ IINP, IOUT, KPRIN
      COMMON /CSET /  PSET, DESDP, DESSUR, DESTAU
      COMMON /SSENS/  RN, HRR, HSB(6), TPC, SIGRR, SIGSB(6)
      COMMON /CFUZ/   IFUZ1, IFUZ2
      DATA RRMS, SBMS / 2*0.070833 /
C------------------------------------------------------------------------
      IINP = 5
      IOUT = 6
      CALL VERS
      TSAM  = 1.0
      TINT  = 0.0
      TIME  = 0.0
      SIGRR     = 0.00
      DO 10 I = 1, 6
      SIGSB(I) = 0.0
   10 CONTINUE
C----------------------------------------------------------
      READ(IINP,*) TFINAL,TSTEP,KPRIN,IFUZ1,IFUZ2
      READ(IINP,*) PSET
      READ(IINP,*) RNREF,HRRREF,TPCREF,HSBREF
      READ(IINP,*) BETA
C----------------------------------------------------------
      RN     = RNREF                    | REFERENCE CONDITIONS
      HRR    = HRRREF
      TPC    = TPCREF
      TPCX   = TPC
      DKRR   = RHORR(HRR)
      DKT    = RHOTC(TPC)
      DKSBS  = 0.0
      DO 102 I = 1,6
      HSB(I)= HSBREF(I)
      DKSB(I)=RHOSB(HSB(I))
  102 DKSBS   =DKSB(I) + DKSBS
      DELKRF= DKRR + DKT + DKSBS
      DO 105 I=1,6
  105 DN(I)=RNREF*B(I)/(RD(I)*RL)
      CALL LAMDA
C========================================
C CALL INTERFACE ROUTINE:
C INTER CALLS SENSOR, CONTROLLER EXEC, AND IDAC
110   CONTINUE
      CALL INTER
C===============================================================
120   CONTINUE                          | REACTIVITY BALANCE
      HRR    = HRR + SIGRR*RRMS*TSTEP      | REG ROD
      DKRR   = RHORR(HRR)
      DKT    = RHOTC(TPC)                  | TEMPERATURE
      DKSBS  = 0.0                         | SHIM BLADE
      DO 125 I = 1, 6
      HSB(I)     = HSB(I) + SBMS*SIGSB(I)*TSTEP
      DKSB(I)    = RHOSB(HSB(I))
      DKSB(I)    = DKSB(I)
  125 DKSBS      = DKSBS + DKSB(I)
      DELK   = DKRR + DKT + DKSBS - DELKRF  | TOTAL REACTIVITY
  130 CONTINUE
      DO 160 I=1,6
  160 DND(I)=B(I)*RN/RL-RD(I)*DN(I)
C-----------------------------------------------
C     RND=BETA*(DELK/1000-1.)*RN/RL + RND
      RND=0.0
      DO 165 I=1,6        | USE "PROMPT JUMP" APPROXIMATION
  165 RND=DN(I)*RD(I)+RND         | TO SAVE TIME
      OBETA=BETA*(DELK/1000-1.)/RL
      RN =-RND/OBETA
C-----------------------------------------------
      DO 170 I=1,6
  170 DN(I)=DN(I)+DND(I)*TSTEP
C   TEMPERATURE EFFECTS USING NEWTON'S LAW OF COOLING.
```

```
      A     = (2.45*(RN-1000.)/3900.)+2.
      TPCD  = 0.05*RN - A*TPC
      TPC   = TPC + TPCD*TSTEP
      TINT  = TINT + TSTEP
      IF(TINT .GE. TSAM) GO TO 200
      GO TO 120
C=============================================================
  200 CONTINUE
      TINT = 0.0
      TIME = TIME + TSAM
      SUR  = 26.06*(RND/RN)
      CALL LAMDA
      IF(TIME  .GE. TFINAL) GO TO 300
      GO TO 110
  300 CONTINUE
      STOP
      END
      BLOCK DATA    ! SIMULATION ROUTINE
C================================================================
      COMMON /CTIME / TIME, TSAM
      DATA TIME, TSAM / 0.0, 1.0 /
C--------------------------------------------------------------
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      DATA PSET, DESDP, DESTAU / 1000., 0.3, 300. /
C--------------------------------------------------------------
      COMMON /CFILT / TFILTP, TFILTS
      DATA TFILTP, TFILTS / 2* 1.0 /
C--------------------------------------------------------------
      COMMON /RPARAM/ BAND(2,2), GAIN(4,2), TRHO, BETA(3), DEL(3)
      DATA BAND, TRHO / 2*20., 2*10., 1. /
      DATA GAIN  / 1.0, 0.0, 0.0, 500., 1.0, 0.0, 0.0, 500. /
      DATA BETA, DEL /0.0333, 0.3416, 0.6251,  0.0124, 0.0369, 0.632/
C--------------------------------------------------------------
      COMMON /LPARAM/ ARP, BRP
      DATA ARP, BRP / 2*0.5 /
C--------------------------------------------------------------
      COMMON/A/RL,BETT,RD(6),B(6),DN(6),DECAY
      DATA RL/0.0001/
      DATA RD/0.0124,0.0305,0.111,0.301,1.14,3.01/
      DATA BETT/0.00786/
      DATA B/0.00026,0.00172,0.00154,0.00311,0.00090,0.00033/
C--------------------------------------------------------------
      END
      SUBROUTINE CHECK(SIGNAL,SIGSAV, ID)
C===================================================================
C CHECK: ROD REVERSAL, IN/OUT LIMITS, DEVIATION LIMITS, NORMALIZATION
C===================================================================
      COMMON /CREF  / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2),CONT(2)
C-------------------------------------------------------
      IF ( ID .EQ. 1 ) GO TO 100     ! SIGNAL REVERSAL CHECK: ONLY FOR
      IF ( SIGSAV*SIGNAL .LT.0.0 ) SIGNAL=0.0 ! FIXED SPEED MOTOR
  100 CONTINUE
C-------------------------------------------------------
      IF ( ID .GT. 1) GO TO 510
      IF ( FHRR .LT.  2.0 .AND. SIGNAL .LT. 0. ) SIGNAL = 0.0
      IF ( FHRR .GT. 16.0 .AND. SIGNAL .GT. 0. ) SIGNAL = 0.0
      GO TO 900
  510 CONTINUE
C-------------------------------------------------------
      IF ( FHSB(1).LT.  1.0 .AND. SIGNAL .LT. 0.) SIGNAL = 0.0
      IF ( FHSB(1).GT. 20.0 .AND. SIGNAL .GT. 0.) SIGNAL = 0.0
      IF((FHSB(1)-HSBREF ).GE.2.0  .AND. SIGNAL.GT.0.0) SIGNAL=0.0
      IF((HSBREF -FHSB(1)).GE.2.0  .AND. SIGNAL.LT.0.0) SIGNAL=0.0
C-------------------------------------------------------
  900 CONTINUE
      IF ( SIGNAL.LT. -1.0  ) SIGNAL =-1.0
      IF ( SIGNAL.GT.  1.0  ) SIGNAL = 1.0
C-------------------------------------------------------
      RETURN
      END
      SUBROUTINE CMOTOR ! SIMULATION ROUTINE
C============================================
C SETS DRIVE MOTOR STATUS
```

```
C  QMOTOR = TRUE -------> CONFIGURATION A
C  QMOTOR = FALSE ------> CONFIGURATION B
C============================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /SMOTOR/IMOTOR
      QMOTOR = .TRUE.
      IF ( IMOTOR .EQ. 0 ) QMOTOR = .FALSE.
      RETURN
      END
      SUBROUTINE CONST ( X1, VAL1, VAL2, SIGX, IDR )
C FOR ON-LINE DEMO AND SIMULATION
C===========================================================
C DETERMINES RECOMMENDED ACTION BASED ON THE
C SUPERVISORY REACTIVITY CONSTRAINT:   1000, 4200 KW LIMITS
C===========================================================
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CIOCON/ IINP,IOUT, KPRIN
      COMMON /CSET   / PSET, DESDP, DESSUR, DESTAU
      COMMON /CREF   / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CRHO   / DKRR, DKSB, DKT, DELK, DELREF, DC
      COMMON /CSAV / CONSAV(2)
      COMMON /CCONF/  ICONF(2), ISTATE, JDEV, JSUR, KFLAGS, ISCOM
C--------------------------------------------------
      IF ( KFLAGS ) 200, 400, 400
  200 CONTINUE                        ! LOWER POWER
      SIGX = -1.0
      IF(-100. .LE. FTAU(2). AND. FTAU(2) .LT. 0.0) GO TO 255
      IF(DELK .LT. -100.)                          GO TO 255
      VAL2  = FTAU(2)*ALOG(FPOW(2)/1000.)
      IF(FPOW(2).LT. 1000.) VAL2=0.0
      IF(VAL2 .GT.  0.0) GO TO 258
      IF(VAL1 .LT. VAL2) GO TO 255
      GO TO 258
  255 CONTINUE
      SIGX = 1.0
  258 CONTINUE
      IF ( CONT(IDR) .LT. SIGX ) CONT(IDR) = SIGX
      GO TO 990
C-------------------------------------------------------
  400 CONTINUE                            ! RAISE POWER
      SIGX = 1.0
      VAL2  = FTAU(2)*ALOG(4200./FPOW(2))
      IF(FPOW(2).GT. 4200.) VAL2=0.0
      IF(VAL2 .LT.  0.0) GO TO 408
      IF(VAL1 .GE. VAL2) GO TO 405
      GO TO 408
  405 CONTINUE
      SIGX = -1.0
      IF ( CONT(IDR) .GT. SIGX ) CONT(IDR) = SIGX
  408 CONTINUE
C-------------------------------------------------------
  990 CONTINUE
      RETURN
      END
      SUBROUTINE CPARAM       ! SIMULATION ROUTINE
C==================================================================
C READS AND WRITES INPUT PARAMETERS
C==================================================================
      COMMON / CSET / PSET, DESDP, DESSUR, DESTAU
      COMMON / CIOCON/ IINP, IOUT, KPRIN
      COMMON / CSROD/ SVRR, SVSB
      COMMON / CFILT/ TFILTP, TFILTS
      COMMON / RPARAM/ BAND(2,2), GAIN(4,2), TRHO, BETA(3), DEL(3)
      COMMON / LPARAM/ ARP, BRP
      COMMON / CPLANE/ DTAUS(2), PS, DBUF(2)
      COMMON / ERHOV / ERHO
      COMMON / SMOTOR/ IMOTOR
      READ ( IINP, * ) DESDP, DESTAU
      READ ( IINP, * ) TFILTP, TFILTS
      READ ( IINP, * ) SVRR, SVSB
      READ ( IINP, * ) ARP, BRP
```

```
      READ ( IINP, * )  (BAND(I,1),I=1,2),(GAIN(I,1), I = 1, 4 ), TRHO
      READ ( IINP, * )  (BAND(I,2),I=1,2),(GAIN(I,2), I = 1, 4 )
      READ ( IINP, * )  (DTAUS(I),I=1,2),PS,(DBUF(I),I=1,2)
      READ ( IINP, * ) ERHO
      READ ( IINP, * ) IMOTOR
      IF ( DESDP  .LE. 0.0 ) DESDP  =   1.0
      IF ( DESTAU .LE. 0.0 ) DESTAU = 300.0
      DESSUR = 26.06/DESTAU
      IF ( BAND(2,1) .LE. 0.0 ) BAND(2,1) = 20.0
      IF ( BAND(2,2) .LE. 0.0 ) BAND(2,2) = 20.0
C-----------------------------------------------------------------
C  NOMINAL DRIVE MOTOR SPEED  0.070833
      SVRR = 0.070833*SVRR
      SVSB = 0.070833*SVSB
      IF ( KPRIN .EQ. 0 ) GO TO 900
      WRITE ( IOUT, 100 )
  100 FORMAT ( 1X, 'CONTROLLER PARAMETERS' )
      WRITE (IOUT, 110) PSET, DESDP, DESTAU, DESSUR
      WRITE (IOUT, 120) TFILTP, TFILTS
      WRITE (IOUT, 130) SVRR, SVSB
      WRITE (IOUT, 140)  (BAND(I,1),I=1,2),(GAIN(I,1), I=1,4),TRHO
      WRITE (IOUT, 140)  (BAND(I,2),I=1,2),(GAIN(I,2), I=1,4),TRHO
  110 FORMAT(' PSET, DESDP, DESTAU, DESSUR: ', 1P,4(E9.2,1X))
  120 FORMAT(' FILTER TAUS- TFILTP, TFILTS: ', 1P,2(E9.2,X))
  130 FORMAT(' MOTOR SPEED- SVRR  , SVSB  : ', 1P,2(E9.2,1X))
  140 FORMAT(' BAND,BANDIN,GAIN-PIDR, TRHO: ', 1P,7(E9.2,1X))
C-----------------------------------------------------------------
  900 RETURN
      END
      SUBROUTINE FILTER ( X, XO, Y, TAU, A, B )
C=====================================================================
C   FIRST ORDER FILTER             X --->|       | ---> Y
C   H(S) =  1/(TAU*S+1)                   ------
C   Y(N+1)=A*(X(N+1)+X(N)) + B*Y(N)
C   A = DT/(2*TAU+DT)           B =  (2*TAU-DT)/(2*TAU+DT)
C=====================================================================
      COMMON /CTIME/ TIME, DT
      DIMENSION Y(2)
      IF  (TAU.GT.0) GO TO 100
      Y(2)=X
      GO TO 999
  100 CONTINUE
      IF  (TIME.GT.0.0) GO TO 200
      A=DT/(2.*TAU+DT)
      B=(2.*TAU-DT)/(2.*TAU+DT)
      Y(2)=X
      GO TO 900
  200 CONTINUE
      Y(2)= A*(X+XO)  + B*Y(1)
  900 CONTINUE
      XO = X
  999 CONTINUE
      RETURN
      END
      SUBROUTINE FUZZY    ! ON-LINE DEMO AND SIMULATION ROUTINE
C=====================================================================
C FUZZY CONTROLLER: SEE JAB'S PAPER
C=====================================================================
      DIMENSION FX(10), UX(20), R(20)
      DIMENSION FP(6), FT(6), FD(2), FH(2)
      COMMON /CIOCON/ IINP, IOUT, KPRIN
      COMMON /CREF  / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PF,   KFLAG,
     1                ADEVP(2), FASUR, FATAU, HDELX(2)
      COMMON /CSEL / IDCON(2), IDROD(2)
      COMMON /CCON / U1(2), U2(2), U3(2), U4(2)
C-------------------------------------------------------------------
      DATA UX / -1.0,  0.0, -1.0, -1.0,  1.0,
     1           0.0, -1.0, -1.0,  1.0,  0.0,
     2          -1.0, -1.0,  1.0,  0.5,  0.0,
     3          -1.0,  1.0,  0.5, -1.0, -1.0 /
C-------------------------------------------------------------------
      HDEL = HDELX(IDROD(2))
```

```
      DO 100 I = 1, 6            ! REINITIALIZE MEMBERSHIP FUNCTIONS
      FP(I)=0.0
  100 FT(I)=0.0
      DO 110 I = 1, 2
      FD(I)=0.0
  110 FH(I)=0.0
C-----------------------------------------------------------------
      DO 120 I=1,10              ! CLASSIFICATION OF PERIOD
  120 FX(I)=0.0
      T = FTAU(2)
      IF (     0.0 .LE. T .AND. T .LE.   50.0)  FX(1)=1.0
      IF (    50.0 .LT. T .AND. T .LE.  100.0)  FX(2)=1.0
      IF (   100.0 .LT. T .AND. T .LE.  120.0)  FX(3)=1.0
      IF (   120.0 .LT. T .AND. T .LE.  500.0)  FX(4)=1.0
      IF (   500.0 .LT. T .AND. T .LE. 1000.0)  FX(5)=1.0
      IF (  1000.0 .LT. T )                     FX(6)=1.0
      IF (T .LE. -1000.0)                       FX(7)=1.0
      IF (-1000.0 .LT. T .AND. T .LE. -500.0)   FX(8)=1.0
      IF ( -500.0 .LT. T .AND. T .LT.    0.0)   FX(9)=1.0
C TOO SHORT
      FT(1)=FX(1)  + FX(2)*(2.0-0.02*T)
C SHORT
      FT(2)=FX(2)  + FX(3)*(6.0-0.05*T)
      FT(2)=FT(2)  + FX(1)*(0.0+0.02*T)
C POSITIVE
      FT(3)=FX(3)  + FX(4)*(1.314-0.00262*T)
      FT(3)=FT(3)  + FX(2)*(-1.000+0.02*T)
C LONG
      FT(4)=FX(4)  + FX(5)*(2.0-0.002*T)
      FT(4)=FT(4)  + FX(3)*(-5.0+0.05*T)
C TOO LONG
      FT(5)=FX(5)  + FX(6)  + FX(7)*0.8 + FX(8)*(-0.8-0.0016*T)
      FT(5)=FT(5)  + FX(4)*(-0.314+0.00262*T)
C NEGATIVE
      FT(6)=FX(7)  + FX(8)  + FX(9)
      FT(6)=FT(6)  + FX(5)*(-1.0+0.002*T)  + FX(6)*0.8
C-----------------------------------------------------------------
      DO 220 I=1,10   ! CLASSIFICATION OF POWER FACTOR
  220 FX(I)=0.0
      IF (    PF  .LE. 0.4)  FX(1)=1.0
      IF ( 0.4  .LT. PF .AND. PF .LE. 0.8 )  FX(2)=1.0
      IF ( 0.8  .LT. PF .AND. PF .LE. 0.90)  FX(3)=1.0
      IF ( 0.90 .LT. PF .AND. PF .LE. 0.98)  FX(4)=1.0
      IF ( 0.98 .LT. PF .AND. PF .LE. 1.00)  FX(5)=1.0
      IF ( 1.00 .LT. PF )  FX(6)=1.0
C VERY LOW
      FP(1)=FX(1)+FX(2)*(2.0-2.5*PF)
C LOW
      FP(2)=FX(2)  + FX(1)*(2.5*PF)
      FP(2)=FP(2)  + FX(3)*(9.0-10.*PF)
C CLOSE
      FP(3)=FX(3)  + FX(2)*(2.5*PF-1.0)
      FP(3)=FP(3)  + FX(4)*(12.25-12.5*PF)
C NEAR
      FP(4)=FX(4)  + FX(3)*(10.0*PF-8.0)
      FP(4)=FP(4)  + FX(5)*(1.0-PF)*50.
C SLIGHTLY LOW
      FP(5)=FX(5)  + FX(4)*(12.5*PF - 11.25)
      FP(5)=FP(5)  + FX(6)
C HIGH
      FP(6)=FX(6)  + FX(5)*(50.0*PF - 49.0)
C-----------------------------------------------------------------
      DO 320 I = 1, 10    ! CLASSIFICATION OF CONTROL ROD HEIGHT
  320 FX(I) = 0.0
      IF ( FHRR .LE. 6.0 )  FX(1)=1.0
      IF (  6.0 .LT. FHRR .AND. FHRR .LE. 10.0)  FX(2)=1.0
      IF ( 10.0 .LT. FHRR)  FX(3)=1.0
C HIGH
      FH(1)=FX(3)  + FX(2)*(0.25*FHRR - 1.5)
C-----------------------------------------------------------------
      DO 420 I=1,10    ! CLASSIFICATION OF ROD WITHDRAWAL
  420 FX(I)=0.0
      IF (HDEL .LE. 2.0)  FX(1)=1.0
      IF ( 2.0 .LT. HDEL .AND. HDEL .LE. 4.0)  FX(2)= 1.0
```

```
      IF( 4.0 .LT. HDEL) FX(3)=1.0
C EXCESSIVE
      FD(1)=FX(3) + FX(2)*(0.5*HDEL-1.0)
C=================================================================
C RULES EVALUATION
      R(1) = FT(1)
C-----------------------------------------------------------------
      R(2) = FT(2)
      IF(R(2) .GT. FP(1)) R(2) = FP(1)
C-----------------------------------------------------------------
      R(3) = FT(2)
      IF(R(3) .GT. FP(2)) R(3) = FP(2)
C-----------------------------------------------------------------
      R(4) = FT(2)
      RO   = FP(3)
      DO 440 I = 4, 6
  440 IF(RO   .LT. FP(I)) RO   = FP(I)
      IF(R(4) .GT. RO   ) R(4) = RO
C-----------------------------------------------------------------
      DO 480 I = 5, 7
      R(I) = FT(3)
      J = I - 4
  480 IF(R(I) .GT. FP(J)) R(I) = FP(J)
      R(8) = FT(3)
C-----------------------------------------------------------------
      RO = FP(4)
      DO 485 I = 5, 6
  485 IF(RO   .LT. FP(I)) RO   = FP(I)
      IF(R(8) .GT. RO   ) R(8) = RO
C-----------------------------------------------------------------
      R(9) = FT(4)
      RO   = FP(1)
      IF(RO   .LT. FP(2)) RO   = FP(2)
      IF(R(9) .GT. RO   ) R(9) = RO
C-----------------------------------------------------------------
      DO 510 I = 10, 11
      R(I) = FT(4)
      J = I - 7
  510 IF(R(I) .GT. FP(J)) R(I) = FP(J)
C-----------------------------------------------------------------
      R(12) = FT(4)
      RO    = FP(5)
      IF(RO    .LT. FP(6)) RO    = FP(6)
      IF(R(12) .GT. RO   ) R(12) = RO
C-----------------------------------------------------------------
      R(13) = FT(5)
      RO    = FP(1)
      DO 530 I = 2, 3
  530 IF(RO .LT. FP(I)) RO = FP(I)
      IF(R(13) .GT. RO) R(13) = RO
C-----------------------------------------------------------------
      DO 540 I = 14, 16
      R(I) = FT(5)
      J = I - 10
  540 IF(R(I) .GT. FP(J)) R(I) = FP(J)
C-----------------------------------------------------------------
      R(17) = FT(6)
      RO    = FP(1)
      DO 570 I = 2, 4
  570 IF(RO .LT. FP(I)) RO = FP(I)
      IF(R(17) .GT. RO) R(17) = RO
C-----------------------------------------------------------------
      DO 580 I = 18, 19
      R(I) = FT(6)
      J = I - 13
  580 IF(R(I) .GT. FP(J)) R(I) = FP(J)
C-----------------------------------------------------------------
      R(20) = FH(1)
      IF(R(20) .GT. FD(1)) R(20) = FD(1)
      IF(PF    .LT. 0.40 ) R(20) = 0.0
C-----------------------------------------------------------------
C RULE WEIGHTING
      W1 = 0.0
      W2 = 0.0
```

```
      DO 800 I = 1, 20
      W1 = W1 + R(I)*UX(I)
      W2 = W2 + R(I)
  800 CONTINUE
      IF(W2 .EQ. 0.0) W2 = 1.0
      SIGNAL = W1/W2
      IF ( SIGNAL .GT. 1.0 ) SIGNAL = 1.0
      IF ( SIGNAL .LT.-1.0 ) SIGNAL =-1.0
C-------------------------------------------
      U3(IDROD(2)) = SIGNAL
C------------------------------------------
      RETURN
      END
      FUNCTION GAINH(ID)   | ON-LINE DEMO AND SIMULATION ROUTINE
C================================================================
C GAIN AS A FUNCTION OF HEIGHT
C================================================================
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      GAINH = 1.0
      IF (ID.LE. 0) GO TO 900
  100 IF (ID.GT. 1) GO TO 200    | REG ROD
      IF(FHRR.LE. 8.) GAINH = 1.0 - 0.025*FHRR
      IF(FHRR.GT. 8.) GAINH = 0.5 + 0.025*FHRR
      GO TO 900
  200 CONTINUE                   | SHIM BLADE
      IF(FHSB(1).LE.10.) GAINH = 1.0 - 0.025*FHSB(1)
      IF(FHSB(1).GT.10.) GAINH = 0.5 + 0.025*FHSB(1)
  900 CONTINUE
      IF( GAINH.LT.0.75) GAINH =  0.75
      IF( GAINH.GT.1.00) GAINH =  1.00
      RETURN
      END
      SUBROUTINE IDAC ( IDROD, SIGNAL )    | SIMULATION ROUTINE
C===============================================================
C SIMULATES ACTUATOR INTERFACE: RR & 1/6 SB
C===============================================================
      COMMON /SSENS / RN, HRR, HSB(6), TPC, SIGRR, SIGSB(6)
      IF ( IDROD .GT. 0 ) GO TO 600
      SIGRR = 0.0
      DO 100 I = 1, 6
  100 SIGSB(I) = 0.0
      GO TO 900
  600 CONTINUE
      IF ( IDROD .EQ. 1 ) SIGRR    = SIGNAL
      IF ( IDROD .EQ. 2 ) SIGSB(1) = SIGNAL
  900 RETURN
      END
      SUBROUTINE INITSE      | ON-LINE DEMO & SIMULATION ROUTINE
C=====================================================
C CLASSIFIES FEATURES OF POWER MANEUVER
C=====================================================
      IMPLICIT LOGICAL*1 (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON /CREF  / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CCONF/ ICONF(5), KFLAGS, ISCOM
C---------------------------------------------------------------
      IRSHIM = 0           | NO "RESHIM"
      ITRAN  = 0           | "SMALL' POWER CHANGE
      IF ( KFLAGS .LT. 0 ) GO TO 600
      ITRAN = 1                                   | RAISE POWER
      IF ( ABS(PREF-PSET) .LT. 1020. ) GO TO 200
      ITRAN = 10                                  | LARGE POWER CHANGE
      IRSHIM = 1                    | RESHIM:  LARGE POWER CHANGE
      GO TO 900
  200 IF ( HRRREF .GT. 5. ) IRSHIM = 1    | RESHIM: REG ROD "HIGH"
      GO TO 900
C---------------------------------------------------------------
  600 CONTINUE                                | LOWER POWER
      ITRAN = -1
```

```
      IF ( ABS(PREF-FPOW(2)) .LT.  500. ) GO TO 700
      ITRAN = -10                  | LARGE POWER CHANGE
      IRSHIM = 1                   | RESHIM
      GO TO 900
  700 IF ( HRRREF .LT. 7. ) IRSHIM = 1     | RESHIM: REG ROD "LOW'
  900 CONTINUE
      IF ( .NOT. QMOTOR ) IRSHIM = 0
      RETURN
      END
      SUBROUTINE INTER    | SIMULATION ROUTINE
C================================================================
C INTERFACES WITH THE SIMULATOR
C ASSUMES 9 SENSORS: POWER, TEMP, 1 HRR, 6 HSB
C================================================================
      DIMENSION HSBX(2)
      DIMENSION UPOW(2), UTPC(2), UHRR(2), UHSB(6), HSBO(6),UHSBO(6)
      COMMON /CTIME / TIME, TSAM
      COMMON /SSENS / RN, HRR, HSB(6), TPC, SIGRR, SIGSB(6)
      COMMON /SPARAM/ XBIAS(9), XNOISE(9), XSCALE(9), XTAU(9)
C------------------------------------------------------------------
      IF ( TIME .GT. 0.0 ) GO TO 90
      CALL PARAMS                  | READ SENSOR PARAMETERS
      CALL CPARAM                  | READ CONTROLLER PARAMETERS
      CALL IDAC ( 0, 0.0)          | ACTUATOR ROUTINE
C------------------------------------------------------------------
C SIMULATE SENSOR SIGNALS
   90 CONTINUE
      CALL SENSOR( RN,       RNO,       UPOW(2),   UPOW(1),    | POWER
     1             XBIAS(1), XNOISE(1), XSCALE(1), XTAU(1) )
      CALL SENSOR( TPC,      TPCO,      UTPC(2),   UTPC(1),    | TEMPERATURE
     1             XBIAS(2), XNOISE(2), XSCALE(2), XTAU(2) )
      CALL SENSOR( HRR,      HRRO,      UHRR(2),   UHRR(1),    | REG ROD
     1             XBIAS(3), XNOISE(3), XSCALE(3), XTAU(3) )
C------------------------------------------------------------------
      DO 100 I = 1, 6
      K = 3 + I
  100 CALL SENSOR( HSB(I),   HSBO(I),   UHSB(I),   UHSBO(I),   | SHIM BLADE
     1             XBIAS(K), XNOISE(K), XSCALE(K), XTAU(K) )
C------------------------------------------------------------------
C CALL INTERFACE ROUTINE: RR & 1 SB CONTROL
      HSBX(1) = UHSB(1)
      HSBX(2) = UHSB(2)
      CALL RCON (UPOW(2), UHRR(2), HSBX, UTPC(2))
      RETURN
      END
      SUBROUTINE KBOVER     | ON-LINE DEMO & SIMULATION ROUTINE
C====================================================
C POSSIBLE OVERSHOOT OR UNDERSHOOT
C INSERT RR UNTIL IT HITS 3" ( RAISE AND LOWER )
C    SUBSTATES: TA5 OR TB3
C====================================================
      IMPLICIT LOGICAL*1 (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CCON  / U1(2), U2(2), U3(2), U4(2)
      COMMON /CCONF / ICONF(5), KFLAGS, ISCOM
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
C--------------------------------------------------------------
      CONT(1) = 0.0
      CONT(2) = 0.0
      IDROD(2) = 2
      CALL SRELAY ( CONT(2) )
      IF ( .NOT. QMOTOR ) GO TO 900
      IF ( DEVP(2) .LT. 0.0 ) CONT(1) = 1.
      IF ( DEVP(2) .GT. 0.0 ) CONT(1) =-1.
  900 CONTINUE
      IDCON(2) = 5
      IPOS = 9
      IF ( .NOT. QMOTOR ) IPOS = 17
      RETURN
```

```
      END
      SUBROUTINE LAMDA      | SIMULATION ROUTINE
C=====================================================================
C COMPUTES THE EFFECTIVE ONE-GROUP DECAY CONSTANT.
C=====================================================================
      COMMON/A/RL,BETA,RD(6),B(6),DN(6),DECAY
      DECAY  = 0.0
      CTOT   = 0.0
      DO 100 I=1,6
      DECAY = DN(I)*RD(I)+DECAY
  100 CTOT  = DN(I)+CTOT
      DECAY = DECAY/CTOT
      RETURN
      END
      SUBROUTINE LEARN ( NTOT, NIN, ISEL, PU, HU, ISTAR )
C ON-LINE DEMO AND SIMULATION ROUTINE
C================================================================
C LRP ALGORITHM:        MAX NO. OF CONTROL OPTIONS = 5
C SEE APPENDIX B & F
C================================================================
      IMPLICIT LOGICAL*1  (O)
      DIMENSION H(5), ISEL(5), PU(5)
      COMMON /LPARAM/ ARP, BRP
      DATA PMIN / 0.00001 /
C-----------------------------------------
      IF ( NIN .EQ. NTOT ) GO TO 100
      NIN1 = NIN + 1
      DO 50 I = NIN1, NTOT                | CONTROL OPTIONS WITH
   50 PU(ISEL(I)) = 0.0                   | "BAD" TAGS
C-----------------------------------------
  100 CONTINUE
      PSUM = 0.0
      FSUM = 0.0
      GSUM = 0.0
      AHU = ABS ( HU )                    | HU = REINFORCEMENT FUNCTION
C-----------------------------------------
      DO 200 I = 1, NIN                    | LRP ALGORITHM
      II = ISEL(I)                         | LEARNING COEFFICIENTS ARE
      IF ( II .EQ. ISTAR ) GO TO 200       | SCALED BY HU
      FSUM = FSUM + AHU*ARP*PU(II)
      GSUM = GSUM + AHU*BRP*( 0.5 - PU(II) )
  200 CONTINUE
C-----------------------------------------
      DO 360 I = 1, NIN
      II = ISEL(I)
      IF ( II .NE. ISTAR ) GO TO 340           | ISTAR IS THE PREVIOUSLY
      IF ( HU .GT. 0 ) PU(II) = PU(II) + FSUM  | IMPLEMENTED OPTION
      IF ( HU .LT. 0 ) PU(II) = PU(II) - GSUM
      GO TO 350
  340 IF ( HU .GT. 0 ) PU(II) = PU(II)*( 1. - AHU*ARP )
      IF ( HU .LT. 0 ) PU(II) = PU(II)*( 1. - AHU*BRP ) + 0.5*BRP*AHU
  350 CONTINUE
      IF ( PU(II) .LE. PMIN ) PU(II) = PMIN     | SET TO MINIMUM
  360 PSUM   = PU(II) + PSUM
C-----------------------------------------------------
      DO 400 I = 1, NIN                         | NEEDS TO BE RE-NORMALIZED
      II = ISEL(I)                              | BECAUSE OF ROUND-OFFS
  400 PU(II) = PU(II)/PSUM
  900 RETURN
      END
      SUBROUTINE LOWER(SIGNAL)  | ON-LINE DEMO AND SIMULATION ROUTINE
C===============================================================
C NLDC:  LOWER POWER ( REFERENCE: J. A. BERNARD'S THESIS)
C===============================================================
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CREF  / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CRHO  / DKRR, DKSB, DKT, DELK, DELREF, DC
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /JPARAM/ RX(2), VAL1(2), VAL2
C---------------------------------------------------------------
   SAFETY SECTION.  CHECKS ALLOWED PSET, PERIOD, AND CONTROLLABILITY.
      IF(FPOW(2).GE. PREF) GO TO 900            | POWER
```

```
      IF(DELK .GT. 100.)         GO TO 900      | REACTIVITY
      IF(0.0 .LT. FTAU(2) .AND. FTAU(2) .LE. 115.0) GO TO 900
C------------------------------------------------------------------
      SIGSAV = CONT(IDROD(2))
      SIG1=-1.0
      IF(-100. .LE. FTAU(2). AND. FTAU(2) .LT. 0.0) GO TO 455
      IF(DELK .LT. -100.)                           GO TO 455
C--------------------------------------------------------------
      IF(VAL2            .GT.  0.0) GO TO 458  | REQUIRED TIME
      IF(VAL1(IDROD(2)) .LT.  VAL2) GO TO 455  | AVAILABLE TIME
      GO TO 458
  455 CONTINUE
      SIG1=1.0
      IF(SIGSAV .LT. 0.0) SIG1=0.0
  458 SIGNAL = SIG1
      GO TO 990
  900 CONTINUE
      SIGNAL=-1.0
  990 CONTINUE
      RETURN
      END
      SUBROUTINE MINMAX ( NIN, ISEL, PU )
C ON-LINE DEMO AND SIMULATION ROUTINE
C===============================================================
C SEARCHES FOR THE CONTROL OPTION WITH MAX PROBABILIT (PU)
C===============================================================
      DIMENSION ISEL(5), PU(5)
      CALL MINMX1 ( NIN, ISEL, PU, IDUM )
      NMAX = IDUM
      NDUM = NIN
  200 CONTINUE
      NDUM = NDUM - IDUM
      IF ( NDUM .LE. 1 ) GO TO 900
      CALL MINMX1 ( NDUM, ISEL, PU, IDUM )
      GO TO 200
  900 RETURN
      END
      SUBROUTINE MINMX1 ( NIN, ISEL, PU, NMAX )
C ON-LINE DEMO AND SIMULATION ROUTINE
C===============================================================
C EVALUATES THE MAXIMUM ELEMENT(S) IN THE PU VECTOR,
C FINDS THE NUMBER OF SUCH MAXIMUM ELEMENTS, AND
C PLACES THEM IN THE HIGH END OF THE SELECTION VECTOR ISEL.
C===============================================================
      DIMENSION PU(5), ISEL(5), IDUM(5)
C FIND THE MAXIMUM VALUE AND TEMPORARILY STORE ISEL INTO IDUM
      PMAX = PU(ISEL(1))
      DO 100 I = 1, NIN
      II = ISEL(I)
      IDUM(I) = II
  100 IF ( PMAX .LE. PU(II) ) PMAX = PU(II)
C SEPARATE THOSE PU THAT ARE EQUAL TO PMAX FROM THOSE LESS THAN PMAX
      NSEL = NIN + 1
      NMAX = 0
      DO 400 I = 1, NIN
      II = IDUM(I)
      IF ( PU(II) .GE. PMAX) GO TO 300
      NMAX = NMAX + 1
      ISEL(NMAX) = II
      GO TO 400
  300 NSEL = NSEL - 1
      ISEL(NSEL) = II
  400 CONTINUE
      NMAX = NIN - NMAX
      RETURN
      END
      SUBROUTINE MODE  | SIMULATION AND ON-LINE
C==================================================================
C DRIVER ROUTINE IN THE "STATE" LEVEL
C==================================================================
      IMPLICIT LOGICAL*1 (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CCONF / KDUM(5), KFLAGS, ISCOM
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
```

```
      COMMON /CSEL   / IDCON(2), IDROD(2)
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1                ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /JPARA1/ VALB(2),  VALK(2),
     1                IRHOB(2), IRHOK(2), QVRHO(4), QCONS(2), IRHO(2)
      COMMON /CNFLAG/ NJRHO, IPOSO
      COMMON /CCON   / U1(2), U2(2), U3(2), U4(2)
      DATA IC / 0 /
      DATA NJRHOX/0/
C---------------------------------------------------------------
      IF ( QVRHO(4) ) GO TO 100      | REACTIVITY VALIDITY SEQUENTIAL TEST
      NJRHOX = NJRHOX + 1            | REACTIVITY NOT VALID
      IF ( NJRHOX .GE. 3 ) NJRHOX = 3
      IF ( NJRHOX .GE. 3 ) NJRHO  = 3
      GO TO 150
  100 NJRHOX = NJRHOX - 1            | REACTIVITY VALID
      IF ( NJRHOX .LE. 0 ) NJRHOX = 0
      IF ( NJRHOX .LE. 0 ) NJRHO  = 0
C---------------------------------------------------------------
  150 CONTINUE                 | COUNT NO. OF TIMES SS CRITERIA IS MET
      IF ( KFLAGS .EQ. 0 ) GO TO 160
      NFLAGS = 0               | TRANSIENT STATE
      GO TO 200
  160 NFLAGS = NFLAGS + 1      | STEADY STATE
      IF ( NFLAGS .GT. 30 ) KFLAG = 0
  200 CONTINUE
C---------------------------------------------------------------
      IF ( NFLAGS .LE. 5 ) GO TO 500
      IF ( IRSHIM .GE. 1 ) GO TO 500
C---------------------------------------------------------------
      CALL SS                  | STEADY STATE
      GO TO 900
  500 CONTINUE
      CALL TRANS               | TRANSIENT STATE
  900 CONTINUE
C---------------------------------------------------------------
      CALL SATUR               | CHECK FOR SATURATION CONDITION
C---------------------------------------------------------------
      IPOSO = IPOS
      IF ( IDROD(2) .EQ. 2 ) IDCON(2) = IDCON(2) + 5
      RETURN
      END
      SUBROUTINE NLDC    | ON-LINE DEMO AND SIMULATION ROUTINE
C==============================================================
C NLDC ALGORITHM:          REFERENCE: J. A. BERNARD'S THESIS
C MODIFIED BY R.S.O.
C DOES NOT INCLUDE THE "INSTRUCTION" SECTION
C==============================================================
      COMMON /CSEL   / IDCON(2), IDROD(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1                ,ADEMP(2), FASUR, FATAU, HDEL(2)
      COMMON /CIOCON/ IINP,IOUT, KPRIN
      COMMON /CCON   / U1(2), U2(2), U3(2), U4(2)
      COMMON /JPARAM/ RX(2), VAL1(2), VAL2
      COMMON /CCONF / ICONF(2), ISTATE, JDEV, JSUR, KFLAGS, ISCOM
C------------------------------------------------------
      IF ( KFLAGS .GE. 0 ) CALL RAISE ( U2(IDROD(2)) )
      IF ( KFLAGS .LT. 0 ) CALL LOWER ( U2(IDROD(2)) )
C------------------------------------------------------
      RETURN
      END
      SUBROUTINE NOISE ( SN )    | SIMULATION ROUTINE
C===================================================================
C RANDOM NUMBER GENERATOR
C              1. NSEED = SEEDING INTEGER ( 0 < NSEED < 1000 )
C              2. VAR   = VARIANCE     (SET TO 1)
C              3. AMU   = MEAN         (SET TO 0)
C===================================================================
      DATA AMU / 0.0 /, IG / 0 /, NSEED / 864 /, VAR / 1.0 /
      IF ( VAR .NE. 0. ) GO TO 100
         SN = AMU
         GO TO 900
  100 CONTINUE
```

```
      IALFA = 2 ** 10 + 3
  200 IRN = MOD ( NSEED * IALFA, 2 ** 20 )
      RSTN = IRN
      RSTN = RSTN * 2. ** ( -20 )
      IF( IG - 1 ) 500, 600, 500
  500 IG = IG + 1
      NSEED = IRN
      RSTN1 = RSTN
      GO TO 200
  600 Z = SQRT( -2. * ALOG( RSTN1 ) ) * SQRT( VAR )
      SN = Z * SIN( 6.28318 * RSTN ) + AMU
      IG = 0
      NSEED = IRN
  900 CONTINUE
      RETURN
      END
      SUBROUTINE OUTPUT     | SIMULATION ROUTINE
C=================================================================
C PRINTS RESULTS
C=================================================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON/A/RL,BETT,RD(6),B(6),DN(6),DECAY
      COMMON /CTIME / TIME, TSAM
      COMMON /CIOCON/ IINP, IOUT, KPRIN
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON /CREF  / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CRHO  / DKRR, DKSB, DKT, DELK, DELKRF, DC
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CFILT / TFILTP, TFILTS
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG,
     1                ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CCONF / ICONF(2), ISTATE, JDEV, JSUR, KFLAGS, ISCOM
      COMMON /LPARAM/ ARP, BRP
      COMMON /RPARAM/ BAND(2,2), GAIN(4,2), TRHO, BETA(3), DEL(3)
      COMMON /SPARAM/ XBIAS(9), XNOISE(9), XSCALE(9), XTAU(9)
      COMMON /JLIMIT/ TLIM, SIGX(2)
      COMMON /RTEMP/ RHOKIN, AD(6)
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /JPARA1/ VALB(2),  VALK(2),
     1                IRHOB(2), IRHOK(2), QVRHO(4), QCONS(2), IRHO(2)
C-----------------------------------------------------------------
      IF ( KPRIN .EQ. 0 ) GO TO 900
      IF ( TIME .GT. 0.0 ) GO TO 200
C-----------------------------------------------------------------
      WRITE(IOUT,100)
  100 FORMAT (1X, '  PSET,   DESDP,     DESSUR,    DESTAU   '/
     1         1X, '  ARP,    BRP                            '/
     2         1X, '  BAND,   BANDIN,    TRHO                '/
     3         1X, '  GAINP,  GAIND,     GAINI,     GAINR    '/
     3         1X, '  TFILTP, TFILTS     PREF                '/
     3         1X, '  XBIAS,  XNOISE,    XSCALE,    XTAU     '/
     3         1X, '========================================')
C-----------------------------------------------------------------
      WRITE(IOUT,110)  PSET, DESDP, DESSUR, DESTAU
      WRITE(IOUT,112)  ARP, BRP
      WRITE(IOUT,115)  BAND(1,1), BAND(2,1), TRHO
      WRITE(IOUT,115)  BAND(1,2), BAND(2,2), TRHO
      WRITE(IOUT,110)   (GAIN(I,1), I=1,4)
      WRITE(IOUT,110)   (GAIN(I,2), I=1,4)
      WRITE(IOUT,115)  TFILTP, TFILTS, PREF
      DO 105 I = 1, 9
  105 WRITE(IOUT,110)   XBIAS(I), XNOISE(I), XSCALE(I), XTAU(I)
  110 FORMAT (1X, 1P, 4(E10.3,1X) )
  112 FORMAT (1X, 1P, 2(E10.3,1X) )
  115 FORMAT (1X, 1P, 3(E10.3,1X) )
C-----------------------------------------------------------------
      WRITE(IOUT, 190 )
  190 FORMAT (1X, '  TIME    DEVP, FSUR, FTAU, PFAC,               '/
     1         1X, '  FPOW    FTPC , FHRR, FHSB, CONRR, CONSB      '/
     2         1X, '  RHOKIN, DELK, DKRR, DKT, DKSB, DC            '/
     3         1X, '  ICONF, KFLAG, KFLAGS, IDCON, IDROD,          '/
     4         1X, '  IPOS,NFLAGS,IRHO(1,2),IRHOK,B(1,2)          '/
```

```
     5         1X, '======================================')
C------------------------------------------------------------
  200 CONTINUE
      WRITE (IOUT,210)  TIME, DEVP (2) , FSUR (2) , FTAU (2) , PFAC
      WRITE (IOUT,220)  FPOW (2) , FTPC, FHRR, FHSB (1) , CONT (1) , CONT (2)
      WRITE (IOUT,220)  RHOKIN,  DELK,    DKRR, DKT,  DKSB, DC
      WRITE (IOUT,230)  ICONF (2) , KFLAG, KFLAGS, IDCON (2) , IDROD (2) ,
     1                 IPOS,NFLAGS,IRHO (1) ,IRHO (2) ,IRHOB (1) , IRHOK (1) ,
     2                 IRHOB (2) ,IRHOK (2)
  210 FORMAT  ( 1X, F7.1, 1X,1P, 4 (E10.3,1X))
  220 FORMAT  ( 1X,   7X, 1X,1P, 6 (E10.3,1X))
  230 FORMAT  ( 1X,   7X, 1X,     13 (I3   ,1X)  )
  900 RETURN
      END
      SUBROUTINE PARAMS       | SIMULATION ROUTINE
C============================================================
C READS AND WRITES SENSOR INPUT PARAMETERS
C============================================================
      COMMON /SPARAM/ XBIAS (9) , XNOISE (9) , XSCALE (9) , XTAU (9)
      COMMON /CSEL   / IDCON (2) , IDROD (2)
      COMMON /CIOCON/ IINP, IOUT, KPRIN
      DO 100 I = 1, 9
      XBIAS (I)   = 0.0
      XNOISE (I)   = 0.0
      XSCALE (I)  = 1.0
  100 XTAU (I)    = 0.0
C----------------------------------------------------------------
      READ (IINP,*)  (XBIAS (I)  ,   I=1,9)
      READ (IINP,*)  (XNOISE (I) ,   I=1,9)
      READ (IINP,*)  (XSCALE (I) ,   I=1,9)
      READ (IINP,*)  (XTAU (I)   ,   I=1,9)
      READ (IINP,*)  IDCON (2) , IDROD (2)
      IDCON (1)  = IDCON (2)
      IDROD (1)  = IDROD (2)
      RETURN
      END
      SUBROUTINE PERIOD ( SUR, ASUR, TAU, ATAU )
C================================================================
C ON-LINE DEMO AND SIMULATION ROUTINE
C COMPUTES REACTOR PERIOD
C================================================================
      ASUR = ABS ( SUR )
      IF  ( ASUR  .LT. 0.0026 ) GO TO 100
      TAU = 26.06/SUR
      GO TO 200
  100 CONTINUE
      TAU = 1000.
      IF  ( SUR  .LT. 0.0 ) TAU = -1000.
  200 CONTINUE
      ATAU = ABS ( TAU )
      RETURN
      END
      SUBROUTINE PID   | ON-LINE DEMO AND SIMULATION ROUTINE
C==========================================================
C PID ALGORITHM
C MODIFIED VERSION OF A. RAY'S  POWER-REACTIVITY FEEDBACK CONTROLLER
C REFERENCE: A. RAY, ET AL. KNOXVILLE PAPER 1983
C   C    = C*L/BETA    PRECURSOR CONCENTRATION
C   RHO = RHO/BETA     REACTIVITY
C==========================================================
      IMPLICIT LOGICAL*1  (Q)
      DIMENSION CDEL (3)
      COMMON /CCON/ U1 (2) , U2 (2) , U3 (2) , U4 (2)
      COMMON /CTIME / TIME, TSAM
      COMMON /CIOCON/ IINP, IOUT, KPRIN
      COMMON /CRHO   / DKRR, DKSB, DKT, DELK, DELKRF, DC
      COMMON /CSEL   / IDCON (2) , IDROD (2)
      COMMON /RESET  / QCSET, QPSET, QRSET
      COMMON /CSET   / PSET, DESDP, DESSUR, DESTAU
      COMMON /CFSENS/ FPOW (2) , FTPC, FHRR, FHSB (2) , CONT (2)
      COMMON /CSTATE/ DEVP (2) , FSUR (2) , FTAU (2) , PFAC, KFLAG,
     1                ADEVP (2) , FASUR, FATAU, HDEL (2)
      COMMON /CCONF/  ICONF (2) , ISTATE, JDEV, ISUR, KFLAGS,ISCOM
      COMMON /RPARAM/ BAND (2,2) , GAIN (4,2) , TRHO, BETA (3) , DEL (3)
```

```
      COMMON /RTEMP / RHOKIN, AD(3), BD(3)
      DATA QIC /.FALSE. /
C-----------------------------------------------------------------
      IF ( QIC ) GO TO 90
      QIC = .TRUE.                    | INITIALIZE VARIABLES
      TRHOX = TRHO/(TRHO+TSAM)
      ERRSUM = 0.0
      POWF = FPOW(2)
      RHOF = 0.001*RHOKIN
C-----------------------------------------------------------------
   90 CONTINUE  | FILTER REACTIVITY AND POWER
      RHOF = TRHOX*RHOF + (1.- TRHOX)*RHOKIN*0.001   | IN MILLIBETAS
      POWF = TRHOX*POWF + (1.- TRHOX)*FPOW(2)
C-----------------------------------------------------------------
      ERRSUM = ERRSUM + PSET - POWF
      IF ( KFLAGS .NE. 0 ) ERRSUM = 0.0  | RESET INTEGRAL TO ZERO
      ERR  = GAIN(1,IDROD(2))*(PSET - POWF) + GAIN(2,IDROD(2))*ERRSUM
     1      - GAIN(3,IDROD(2))*FSUR(2)        - GAIN(4,IDROD(2))*RHOF
C-----------------------------------------------------------------
      IF (ABS(ERR) .LT. BAND(1,IDROD(2))) GO TO 500
      SIGNAL = ERR*GAINH( IDROD(2) )/BAND(2,IDROD(2))
      GO TO 900
  500 SIGNAL =  0.0
C-----------------------------------------------------------------
  900 CONTINUE
      IF ( SIGNAL .GT.  1.0 ) SIGNAL = 1.0         | NORMALIZE SIGNAL
      IF ( SIGNAL .LT.- 1.0 ) SIGNAL =-1.0
      IF ( IDROD(2)  .EQ. 1 ) GO TO 920            | FIXED SPEED MOTOR
      IF ( SIGNAL .LT. -0.5 ) SIGNAL = -1.0
      IF ( SIGNAL .GT.  0.5 ) SIGNAL =  1.0
      IF ( ABS(SIGNAL) .LE. 0.5 ) SIGNAL = 0.0
  920 CONTINUE
      U1(IDROD(2)) = SIGNAL
C-----------------------------------------------------
      RETURN
      END
      SUBROUTINE PLOT    | SIMULATION ROUTINE
C==============================================================
C WRITES VARIABLES TO BE PLOTTED
C==============================================================
      IMPLICIT LOGICAL*1  (Q)
      DIMENSION S(50)
      COMMON /CTIME / TIME, TSAM
      COMMON /CRHO  / DKRR, DKSB, DKT, DELK, DELKRF, DC
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG,
     1                ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CCONF / ICONF(2), ISTATE, JDEV, JSUR, KFLAGS, ISCOM
      COMMON /CUSENS/ RNX, TPCX, HRRX, HSBX(2)
      COMMON /JLIMIT/ TLIM, SIGX(2)
      COMMON /CCON/ U1(2),U2(2),U3(2),U4(2)
      COMMON /JPARAM/ RX(2), VAL1(2), VAL2
      COMMON /RTEMP/  RHOKIN, AD(3), BD(3)
      COMMON /CMODE/  IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /JPARA1/ VALB(2), VALK(2),
     1                IRHOB(2), IRHOK(2), QVRHO(4), QCONS(2), IRHO(2)
C-------------------------------------------------------------
      IF(TIME.EQ.0) CALL UNITS
      S( 1) = TIME
      S( 2) = DEVP(2)
      S( 3) = FSUR(2)
      S( 4) = FTAU(2)
      S( 5) = PFAC
      S( 7) = FPOW(2)
      S( 8) = FTPC
      S( 9) = FHRR
      S(10) = FHSB(1)
      S(11) = CONT(1)
      S(12) = CONT(2)
      S(13) = RNX
      S(14) = TPCX
      S(15) = HRRX
      S(16) = HSBX(1)
```

```
      S(17) = DELK
      S(18) = DKRR
      S(19) = DKT
      S(20) = DKSB
      S(21) = SIGX(2)
      S(22) = DC
      S(23) = ICONF(2)
      S(24) = KFLAG
      S(25) = KFLAGS
      S(26) = IDCON(2)
      S(27) = IDROD(2)
      S(28) = ISTATE
      S(29) = JDEV
      S(30) = JSUR
      S(31) = U1(1)
      S(32) = U2(1)
      S(33) = U3(1)
      S(34) = U4(1)
      S(37) = DELK - RHOKIN
      S(38) = IRHOB(1)
      S(39) = IRHOK(1)
      S(40) = RHOKIN
      S(41) = U1(2)
      S(42) = U2(2)
      S(43) = U3(2)
      S(44) = U4(2)
      S(45) = 0
      S(46) = 0
      IF(.NOT.QCONS(1)) S(45) = 1
      IF(.NOT.QCONS(2)) S(46) = 1
      S(47) = IPOS
      S(48) = 0
      IF(.NOT.QVRHO(4)) S(48) = 1
      S(49) = IRSHIM
      WRITE(7) S
      RETURN
      END
      SUBROUTINE POSSHI     | SIMULATION ROUTINE
C==========================================================
C CLASSIFIES RESHIM CONDITIONS: ONLY IN CONFIGURATION "A"
C==========================================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON /CREF  / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CCONF / ICONF(5), KFLAGS, ISCOM
      COMMON /JPARA1/ VALB(2), VALK(2),
     1                IRHOB(2), IRHOK(2), QVRHO(4), QCONS(2), IRHO(2)
      COMMON /CNFLAG/ NJRHO, IPOSO
      DATA IC, NPOS / 2*0 /
C--------------------------------------------------------------
C KRSHIM =  0 ======> USE REG ROD
C KRSHIM =  1 ======> USE SB; ROD POSITION CRITERION NOT MET
C KRSHIM = 10 ======> USE SB; ROD POS & POWER MET BUT RHO CONST NOT MET
C--------------------------------------------------------------
      IHRR = 0                              | REG ROD STATUS
      IF ( 3. LE. FHRR .AND. FHRR .LE. 5. ) IHRR = 1
C---------------------------------------------------------------
      IF ( IC .EQ. 0 ) KRSHIO = IRSHIM
      IC = 10
      KRSHIM = IRSHIM
      IF ( KFLAGS .LT. 0 ) GO TO 500                | RAISE POWER
      IF ( KRSHIM .GE. 1 ) GO TO 300                | KRSHIM = 0
      IF ( FHRR .GT. 9.0 ) KRSHIM = 1               | RESHIM IN THE MIDDLE
      GO TO 900
  300 CONTINUE                                      | KRSHIM = 1
      IF ( .NOT.QCONS(2) ) GO TO 900
      IF ( IHRR .EQ. 1 .AND. ADEVP(2) .LE. DESDP ) KRSHIM = 10
      IF ( KRSHIM .EQ. 10 .AND. QCONS(1) ) KRSHIM = 0
```

```
      GO TO 900
C-------------------------------------------------------------
  500 CONTINUE                                   | LOWER POWER
      IF ( KRSHIM .GE. 1 ) GO TO 800             | KRSHIM = 0
      IF ( FHRR .LT. 4. .AND. (FPOW(2)-PSET) .GT. 500.) KRSHIM = 1
      GO TO 900
  800 CONTINUE                                   | KRSHIM = 1
      IF ( .NOT.QCONS(2) ) GO TO 900
      IF ( IHRR .EQ. 1 .AND. ADEVP(2) .LE. DESDP ) KRSHIM = 10
      IF ( KRSHIM .EQ. 10 .AND. QCONS(1) ) KRSHIM = 0
      GO TO 900
C-------------------------------------------------------------
  900 CONTINUE
      IF ( KRSHIM .NE. KRSHIO ) GO TO 950 | SEQUENTIAL TEST
      NPOS = NPOS + 1
      IF ( NPOS .GE. 3 ) IRSHIM = KRSHIM
      GO TO 960
  950 NPOS = 0                    | IRSHIM IS NOT CHANGED
  960 KRSHIO = KRSHIM             | OLD = NEW
      RETURN
      END
      SUBROUTINE POSTRA      | ON-LINE DEMO & SIMULATION ROUTINE
C=================================================================
C CLASSIFIES FEATURES OF TRANSIENT SUBSTATES
C    "RESHIM" AND OVERSHOOT/UNDERSHOOT CONDITIONS
C=================================================================
      IMPLICIT LOGICAL*1 (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON /CCONF / ICONF(5), KFLAGS, ISCOM
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
C-------------------------------------------------------------
      IF ( QMOTOR ) CALL POSSHI         | ONLY IF REG ROD & SHIM BLADE
      QOVER = .FALSE.                   | ARE AVAILABLE
      IF ( KFLAGS .GE.0 .AND. DEVP(2) .GT. 3.*DESDP ) QOVER = .TRUE.
      IF ( KFLAGS .LE.0 .AND. DEVP(2) .LT.-3.*DESDP ) QOVER = .TRUE.
      RETURN
      END
      SUBROUTINE PSTATE  | ON-LINE DEMO & SIMULATION ROUTINE
C=====================================================
C STATE IDENTIFICATION: BASED ON POWER AND
C   RATE OF CHANGE OF POWER
C DECLARES  STEADY STATE OR TRANSIENT STATE
C=====================================================
      IMPLICIT LOGICAL*1 (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CREF  / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CCONF / ICONF(2), ISTATE, JDEV, JSUR, KFLAGS, ISCOM
      COMMON /RESET / QCSET, QPSET, QRSET
      COMMON /CDESP/ STEADY
      STEADY = 2.5
C-----------------------------------------------------------------
      IF ( QPSET ) KFLAGS = KFLAG
      JDEV = 0
      JSUR = 0
      IF ( FASUR .LT. DESSUR ) GO TO 160
      JSUR = 1
      IF ( FSUR(2) .LT. 0.0 ) JSUR = -1
  160 CONTINUE
      IF ( ADEVP(2) .LT. DESDP ) GO TO 180
      JDEV = 1
      IF ( DEVP(2) .LT. 0.0 ) JDEV = -1
  180 CONTINUE
C-----------------------------------------------------------------
      ISTATE = 1
      IF ( JDEV ) 210, 230, 220
  210 ISTATE = 3
      GO TO 230
```

```
  220 ISTATE = 2
  230 IF ( JSUR ) 260, 280, 270
  260 ISTATE = ISTATE + 6
      GO TO 280
  270 ISTATE = ISTATE + 3
  280 CONTINUE
      IF ( ISTATE .EQ. 1 )  KFLAGS   = 0
C-----------------------------------------------------------------------
C IDENTIFY STATES
C-----------------------------------------------------------------------
      IF (KFLAGS) 500, 300, 400
C-----------------------------------------------------------------------
  300 CONTINUE                                 | STEADY STATE
      ICONF(2)=1
      KFLAGS=0
      IF (ISTATE.EQ.2 .OR. ISTATE.EQ.5 .OR.
     1    ISTATE.EQ.4 .OR. ISTATE.EQ.8) ICONF(2) = 10   | INSERT
      IF (ISTATE.EQ.3 .OR. ISTATE.EQ.9 .OR.
     1    ISTATE.EQ.7 .OR. ISTATE.EQ.6) ICONF(2) = 11   | WITHDRAW
      IF (ADEVP(2).LT.STEADY) GO TO 900    | LARGER STEADY STATE BAND
      KFLAGS=-1
      IF (DEVP(2).LE.0) KFLAGS=1
      IF (KFLAGS) 500, 900, 400
C---------------------------------------------------
  400 CONTINUE                                 | RAISE POWER
      ICONF(2)=10
      IF (ISTATE.EQ.3 ) ICONF(2)=3
      IF (ISTATE.EQ.6 ) ICONF(2)=6
      IF (ISTATE.EQ.7  .OR. ISTATE.EQ.9) ICONF(2)=11
      IF ( ( FSUR(2)  .LE. 0.0 ) .AND. ( DEVP(2)  .LT. 0.0 ) )
     1ICONF(2) = 11
      IF (FPOW(2).LT.PREF) ICONF(2)=11
      GO TO 900
C---------------------------------------------------
  500 CONTINUE                                  | LOWER POWER
      ICONF(2)=11
      IF (ISTATE.EQ.2 ) ICONF(2)=2
      IF (ISTATE.EQ.8 ) ICONF(2)=8
      IF (ISTATE.EQ.4 .OR.ISTATE.EQ.5) ICONF(2)=10
      IF ( ( FSUR(2)  .GE. 0.0 ) .AND. ( DEVP(2)  .GT. 0.0 ) )
     1ICONF(2) = 10
      IF (FPOW(2).GT.PREF) ICONF(2)=10
C---------------------------------------------------
  900 CONTINUE                                  | "COMMON SENSE" CONTROL
      IF ( ICONF(2)  .GE. 10 ) GO TO 910        | OR "HARD-BOUND" CONTROL
      ISCOM = 0                                 | HOLD
      GO TO 990
  910 IF ( ICONF(2)  .EQ. 10 ) ISCOM = -1       | INSERT
      IF ( ICONF(2)  .EQ. 11 ) ISCOM =  1       | WITHDRAW
  990 CONTINUE
      RETURN
      END
      SUBROUTINE RAISE(SIGNAL)    | ON-LINE DEMO AND SIMULATION ROUTINE
C=====================================================================
C NLDC: RAISE POWER      ( REFERENCE: J. A. BERNARD'S THESIS
C VAL2(TREQ) HAS TO BE GREATER THAN VAL1(TAVAIL)
C=====================================================================
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON /CRHO  / DKRR, DKSB, DKT, DELK, DELREF, DC
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /JPARAM/ RX(2), VAL1(2), VAL2
C-------------------------------------------------------------------
      SIGSAV = CONT(IDROD(2))
      SIG1=1.0
      IF(FPOW(2).GE. PSET) GO TO 900
      IF(DELK .GT. 165.)       GO TO 900
      IF(0.0 .LE. FTAU(2) .AND. FTAU(2) .LE. 50.0) GO TO 900
C-------------------------------------------------------------------
      IF(VAL2            .LT.  0.0) GO TO 408
      IF(VAL1(IDROD(2)) .GE. VAL2) GO TO 405
      GO TO 408
```

```
  405 CONTINUE
      SIG1=-1.0
      IF (SIGSAV .GT. 0.0) SIG1=0.0
  408 SIGNAL = SIG1
      GO TO 990
  900 CONTINUE
      SIGNAL=-1.0
  990 CONTINUE
      RETURN
      END
      SUBROUTINE RCTEST ( SIGNAL )    | SIMULATION ROUTINE
C=================================================================
C REACTIVITY CONSTRAINT REVIEW BASED ON THE RECOMMENDED CONTROL
C   ACTION OBTAINED FROM THE REACTIVITY CONSTRAINT RELATIONSHIP
C=================================================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON /CSEL/ IDCON (2) , IDROD (2)
      COMMON /CCONF / ICONF (5) , KFLAGS, ISCOM
      COMMON /JPARA1/ VALB (2) ,  VALK (2) ,
     1                IRHOB (2) , IRHOK (2) , QVRHO (4) , QCONS (2) , IRHO (2)
      COMMON /CSTATE/ DEVP (2) , FSUR (2) , FTAU (2) , PFAC, KFLAG
     1               ,ADEVP (2) , FASUR, FATAU, HDEL (2)
C----------------------------------------------------------------
      IF  ( KFLAGS ) 212, 214, 216
  212 IF  ( SIGNAL .LT. IRHO (IDROD (2)) ) GO TO 800
      GO TO 900
  214 IF  ( KFLAG ) 212, 216, 216
  216 IF  ( SIGNAL .GT. IRHO (IDROD (2)) ) GO TO 800
      GO TO 900
  800 CONTINUE
      NPOS = NPOS + 1
      IF  ( NPOS  .GT. 3) NPOS = 3
      IF  ( NPOS  .LE. 1 ) GO TO 990
      SIGNAL = IRHO (IDROD (2))
      GO TO 990
  900 NPOS = 0
  990 CONTINUE
      RETURN
      END
      SUBROUTINE RCON ( RN, HRR, HSB, TPC )    | SIMULATION ROUTINE
C=================================================================
C CALLED BY INTER: RR & 1/6 SB CONTROL
C=================================================================
      IMPLICIT LOGICAL*1  (Q)
      DIMENSION HSB (2)
      COMMON /BSAFE/ QSAFE (5)
      COMMON /CUSENS/ RNX, TPCX, HRRX, HSBX (2)
      COMMON /CTIME / TIME, TSAM
      COMMON /CSEL  / IDCON (2) , IDROD (2)
      COMMON /CFSENS/ FPOW (2) , FTPC, FHRR, FHSB (2) , CONT (2)
      COMMON / CCON / U1 (2) , U2 (2) , U3 (2) , U4 (2)
C-----------------------------------------------------------------
      RNX  = RN       | SET "UNFILTERED" SIGNAL = "SIMULATED" SIGNAL
      TPCX = TPC
      HRRX = HRR
      HSBX (1)  = HSB (1)
      HSBX (2)  = HSB (2)
C-----------------------------------------------------------------
      IF  ( TIME .GT. 0.0 ) GO TO 500
      CONT (1)  = 0.0       | INITIALIZE CONTROL SIGNALS
      CONT (2)  = 0.0       |   (REG ROD AND SHIM BLADE)
C-----------------------------------------------------------------
  500 CONTINUE
      FHRR = HRRX
      FHSB (1)  = HSBX (1)
      FHSB (2)  = HSBX (2)
      FTPC =     TPCX
      FPOW (2)  = RNX
C-----------------------------------------------------------------
      CALL STATE
      CALL RHOVAL
      CALL SAFETY
      IF  ( .NOT. QSAFE (5)  ) GO TO 800
      CALL MODE
```

```
      CALL USEL
  800 CALL OUTPUT
C------------------------------------------------------------------
      CALL IDAC (1, CONT(1) )      | CALL ACTUATOR INTERFACE
      CALL IDAC (2, CONT(2) )
  900 CONTINUE
      CALL TSAVE
      RETURN
      END
      FUNCTION REACRD(H)   | ON-LINE DEMO AND SIMULATION ROUTINE
C******************************************************************
C A FUNCTION WHICH RETURNS DIFFERENTIAL REGULATING ROD WORTH IN
C MILLIBETA PER INCH GIVEN ROD HEIGHT IN INCHES. 26-NOV-84
C******************************************************************
      IF(H .LT. 0.0) H = 0.0
      IF(H .GT. 18.) H = 18.
      IF(H .LE. 1.75) GO TO 550
      IF(H .LE. 6.50) GO TO 555
      IF(H .LE. 8.00) GO TO 560
      IF(H .LE. 9.50) GO TO 565
      IF(H .LE. 11.5) GO TO 570
      IF(H .LE. 13.0) GO TO 575
      IF(H .LE. 14.5) GO TO 580
      IF(H .LE. 16.0) GO TO 585
      GO TO 590
550   REACRD=29.2
      RETURN
555   REACRD=29.2 - 3.54*(H- 1.75)
      RETURN
560   REACRD=12.4 - 2.00*(H- 6.50)
      RETURN
565   REACRD= 9.4 - 1.87*(H- 8.00)
      RETURN
570   REACRD= 6.6 - 1.40*(H- 9.50)
      RETURN
575   REACRD= 3.8 - 1.07*(H- 11.5)
      RETURN
580   REACRD= 2.2 - 0.60*(H- 13.0)
      RETURN
585   REACRD= 1.3 - 0.20*(H- 14.5)
      RETURN
590   REACRD= 1.0
      RETURN
      END
      FUNCTION REACRR(H)   | ON-LINE DEMO AND SIMULATION ROUTINE
C******************************************************************
C A FUNCTION WHICH RETURNS REGULATING ROD WORTH IN MILLIBETA GIVEN
C ROD HEIGHT IN INCHES. 26-NOV-84
C******************************************************************
      IF(H .LT. 0.0) H = 0.0
      IF(H .GT. 18.) H = 18.0
      IF(H .LE. 4.0) GO TO 350
      IF(H .LE. 5.5) GO TO 355
      IF(H .LE. 7.5) GO TO 360
      IF(H .LE. 10.0) GO TO 365
      IF(H .LE. 14.0) GO TO 370
      GO TO 375
350   REACRR=27.50*H
      RETURN
355   REACRR=20.0*(H-4.0) + 110.
      RETURN
360   REACRR=12.0*(H-5.5) + 140.
      RETURN
365   REACRR= 8.0*(H-7.5) + 164.
      RETURN
370   REACRR= 3.5*(H-10.) + 184.
      RETURN
375   REACRR= 1.5*(H-14.) + 198.
      RETURN
      END
      FUNCTION REACSD(H)   | ON-LINE DEMO AND SIMULATION ROUTINE
C******************************************************************
C A FUNCTION WHICH RETURNS DIFFERENTIAL SHIM BLADE WORTH IN
```

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C MILLIBETA PER INCH GIVEN SHIM BLADE HEIGHT IN INCHES. 03-DEC-84
C*****************************************************************
      IF ( H .LT. 0.0 ) H = 0.0
      IF ( H .GT. 21.0) H = 21.0
      IF ( H .LE.  1.0) GO TO 700
      IF ( H .LE.  2.0) GO TO 705
      IF ( H .LE.  5.0) GO TO 710
      IF ( H .LE.  6.0) GO TO 715
      IF ( H .LE.  7.0) GO TO 720
      IF ( H .LE.  8.0) GO TO 725
      IF ( H .LE.  9.0) GO TO 730
      IF ( H .LE. 10.0) GO TO 735
      IF ( H .LE. 10.5) GO TO 740
      IF ( H .LE. 16.5) GO TO 745
      IF ( H .LE. 19.5) GO TO 750
      GO TO 755
700   REACSD= 4.0*H + 76.
      RETURN
705   REACSD= 3.5*(H- 1.0) +  80.0
      RETURN
710   REACSD=11.0*(H- 2.0) +  87.0
      RETURN
715   REACSD= 7.5*(H- 6.0) + 120.0
      RETURN
720   REACSD= 5.0*(H- 6.0) + 127.5
      RETURN
725   REACSD= 3.5*(H- 7.0) + 132.5
      RETURN
730   REACSD= 1.5*(H- 8.0) + 136.0
      RETURN
735   REACSD=-3.0*(H- 9.0) + 137.5
      RETURN
740   REACSD=-2.0*(H- 10.) + 134.5
      RETURN
745   REACSD=-10.4167*(H- 10.5) + 130.5
      RETURN
750   REACSD=- 6.1667*(H- 16.5) +  68.0
      RETURN
755   REACSD=- 7.6667*(H- 19.5) +  49.5
      RETURN
      END
      FUNCTION REACSB(H)    | ON-LINE DEMO AND SIMULATION ROUTINE
C*****************************************************************
C A FUNCTION WHICH RETURNS SHIM BLADE WORTH IN MILLIBETA GIVEN
C SHIM BLADE HEIGHT IN INCHES. 03-DEC-84
C*****************************************************************
      IF ( H .LT. 0.0 ) H = 0.0
      IF ( H .GT. 21.0) H = 21.0
      IF (H .LE.  2.5) GO TO 600
      IF (H .LE.  4.0) GO TO 605
      IF (H .LE.  6.0) GO TO 610
      IF (H .LE. 11.0) GO TO 615
      IF (H .LE. 14.0) GO TO 620
      IF (H .LE. 15.0) GO TO 625
      IF (H .LE. 17.0) GO TO 630
      IF (H .LE. 19.0) GO TO 635
      IF (H .LE. 20.0) GO TO 640
      GO TO 645
600   REACSB= 80.0*H
      RETURN
605   REACSB= 94.0*(H- 2.5) + 200.
      RETURN
610   REACSB=124.5*(H- 4.0) + 341.
      RETURN
615   REACSB=131.0*(H- 6.0) + 590.
      RETURN
620   REACSB=108.0*(H-11.0) +1245.
      RETURN
625   REACSB= 91.0*(H-14.0) +1569.
      RETURN
630   REACSB= 77.5*(H-15.0) +1660.
      RETURN
635   REACSB= 55.0*(H-17.0) +1815.
```

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      RETURN
640   REACSB= 40.0*(H-19.0) +1925.
      RETURN
645   REACSB= 20.0*(H-20.0) +1965.
      RETURN
      END
      FUNCTION REACT(T)    | ON-LINE DEMO AND SIMULATION ROUTINE
C*****************************************************************
C A FUNCTION WHICH RETURNS THE REACTIVITY ASSOCIATED WITH TEMPERATURE
C IN MILLIBETA GIVEN TEMPERATURE IN DEGREES CENTIGRADE. (1984 DATA)
C*****************************************************************
      IF(T .LE. 13.0) GO TO 310
      IF(T .LE. 20.0) GO TO 315
      IF(T .LE. 24.0) GO TO 320
      IF(T .LE. 28.0) GO TO 325
      IF(T .LE. 36.0) GO TO 330
      IF(T .LE. 44.0) GO TO 335
      GO TO 340
310   REACT=-53.0 + 6.4*(T-8.)
      RETURN
315   REACT=-21.0 + 3.0*(T-13.)
      RETURN
320   REACT=0.0
      RETURN
325   REACT=-2.75*(T-24.)
      RETURN
330   REACT=-11.0 - 5.5*(T-28.)
      RETURN
335   REACT=-55.0 - 9.25*(T-36.)
      RETURN
340   REACT=-129.0 - 11.667*(T-44.)
      RETURN
      END
      SUBROUTINE RELAY  | FOR SIMULATION
C=============================================================
C CONTROL ALGORITHM #4: RELAY ALGORITHM
C==============================================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON /CTIME/TIME, TSAM
      COMMON /CIOCON/ IINP, IOUT, KPRIN
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON /CCONF / ICONF(2), ISTATE, JDEV, JSUR, KFLAGS, ISCOM
      COMMON /CSTATE/ DEVP(2), FSUR(2),FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CPLANE/ DTAUS(2), PS, DBUF1, DBUF2
      COMMON /CCON/ U1(2), U2(2), U3(2), U4(2)
      COMMON /JPARA1/ VALB(2), VALK(2),
     1                IRHOB(2), IRHOK(2), QVRHO(4), QCONS(2), IRHO(2)
      DATA GTAU/1.5/
C------------------------------------------------------
      DTAU = DTAUS(IDROD(2))                  | SWITCHING CURVE
      IF ( ADEVP(2) .GT. PS ) GO TO 140
      DTAU = DTAU + GTAU*(DESTAU-DTAU)*(PS-ADEVP(2))/(PS-DESDP)
      IF ( ADEVP(2) .LT. DESDP )  DTAU = GTAU*DESTAU
  140 CONTINUE
C-------------------------------------------------------
      IF ( KFLAGS ) 200, 300, 400             | LOWER POWER
  200 IF ( FTAU(2) .GT. 0 ) GO TO 910                   | IN
      IF ( FPOW(2) .LT. PSET ) GO TO 920                | OUT
      SIGNAL = -1.0
      IF ( FATAU .LT. DTAU ) GO TO 920                  | OUT
      IF ( FATAU .LT.(DTAU+DBUF1) ) GO TO 930           | HOLD
      GO TO 940
C-------------------------------------------------------
  300 CALL SRELAY ( SIGNAL )                  | PROPORTIONAL ACTION
      GO TO 940
C-------------------------------------------------------
  400 IF ( FTAU(2) .LT. 0 ) GO TO 920         | RAISE POWER
      IF ( FPOW(2) .GT. PSET ) GO TO 910
      SIGNAL =  1.0
      IF ( FATAU .LT. DTAU ) GO TO 910
      IF ( FATAU .LT.(DTAU+DBUF2) ) GO TO 930
```

```
      GO TO 940
C-------------------------------------------------------
  910 SIGNAL = -1.
      GO TO 940
  920 SIGNAL =  1.
      GO TO 940
  930 SIGNAL =  0.
      GO TO 940
  940 CONTINUE
C-----------------------------------------------------
      IF ( IDROD(2)  .EQ. 1) GO TO 950       ! FOR SHIM BLADE MOTOR
      IF ( SIGNAL .LT. -0.5 ) SIGNAL = -1.0
      IF ( SIGNAL .GT.  0.5 ) SIGNAL =  1.0
      IF ( ABS(SIGNAL) .LE. 0.5 ) SIGNAL = 0.0
C-----------------------------------------------------
  950 CONTINUE
      U4(IDROD(2)) = SIGNAL
      CALL RCTEST ( U4(IDROD(2)) )
  990 RETURN
      END
      FUNCTION RHORR(H)          ! SIMULATION ROUTINE
C*****************************************************************
C A FUNCTION WHICH RETURNS REGULATING ROD WORTH IN MILLIBETA GIVEN
C ROD HEIGHT IN INCHES.  26-NOV-84
C*****************************************************************
      IF(H .LT. 0.0) H = 0.0
      IF(H .GT. 18.) H = 18.
      IF(H .LE. 4.0) GO TO 350
      IF(H .LE. 5.5) GO TO 355
      IF(H .LE. 7.5) GO TO 360
      IF(H .LE. 10.0) GO TO 365
      IF(H .LE. 14.0) GO TO 370
      GO TO 375
350   RHORR=27.50*H
      RETURN
355   RHORR=20.0*(H-4.0) + 110.
      RETURN
360   RHORR=12.0*(H-5.5) + 140.0
      RETURN
365   RHORR= 8.0*(H-7.5) + 164.0
      RETURN
370   RHORR= 3.5*(H-10.) + 184.0
      RETURN
375   RHORR= 1.5*(H-14.) + 198.0
      RETURN
      END
      FUNCTION RHOSB(H)        ! SIMULATION ROUTINE
C*****************************************************************
C A FUNCTION WHICH RETURNS SHIM BLADE WORTH IN MILLIBETA GIVEN
C SHIM BLADE HEIGHT IN INCHES. 03-DEC-84
C*****************************************************************
      IF ( H .LT. 0.0 ) H = 0.0
      IF ( H .GT. 21.0) H = 21.0
      IF(H .LE.  2.5) GO TO 600
      IF(H .LE.  4.0) GO TO 605
      IF(H .LE.  6.0) GO TO 610
      IF(H .LE. 11.0) GO TO 615
      IF(H .LE. 14.0) GO TO 620
      IF(H .LE. 15.0) GO TO 625
      IF(H .LE. 17.0) GO TO 630
      IF(H .LE. 19.0) GO TO 635
      IF(H .LE. 20.0) GO TO 640
      GO TO 645
600   RHOSB= 80.0*H
      RETURN
605   RHOSB= 94.0*(H- 2.5) + 200.
      RETURN
610   RHOSB=124.5*(H- 4.0) + 341.
      RETURN
615   RHOSB=131.0*(H- 6.0) + 590.
      RETURN
620   RHOSB=108.0*(H-11.0) +1245.
      RETURN
625   RHOSB= 91.0*(H-14.0) +1569.
```

```
      RETURN
630   RHOSB= 77.5*(H-15.0) +1660.
      RETURN
635   RHOSB= 55.0*(H-17.0) +1815.
      RETURN
640   RHOSB= 40.0*(H-19.0) +1925.
      RETURN
645   RHOSB= 20.0*(H-20.0) +1965.
      RETURN
      END
      FUNCTION RHOTC(T)      | SIMULATION ROUTINE
C******************************************************************
C A FUNCTION WHICH RETURNS THE REACTIVITY ASSOCIATED WITH TEMPERATURE
C IN MILLIBETA GIVEN TEMPERATURE IN DEGREES CENTIGRADE.
C******************************************************************
      IF(T .LE. 13.0) GO TO 310
      IF(T .LE. 20.0) GO TO 315
      IF(T .LE. 24.0) GO TO 320
      IF(T .LE. 28.0) GO TO 325
      IF(T .LE. 36.0) GO TO 330
      IF(T .LE. 44.0) GO TO 335
      GO TO 340
310   RHOTC=-53.0 + 6.4*(T-8.)
      RETURN
315   RHOTC=-21.0 + 3.0*(T-13.)
      RETURN
320   RHOTC=0.0
      RETURN
325   RHOTC=-2.75*(T-24.)
      RETURN
330   RHOTC=-11.0 - 5.5*(T-28.)
      RETURN
335   RHOTC=-55.0 - 9.25*(T-36.)
      RETURN
340   RHOTC=-129.0 - 11.667*(T-44.)
      RETURN
      END
      SUBROUTINE RHOVAL  | ON-LINE DEMO AND SIMULATION ROUTINE
C==========================================================
C REACTIVITY VALIDATION PROCEDURE
C=========================================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON /CCONF / ICONF(5), KFLAGS, ISCOM
      COMMON /CRHO  / DKRR, DKSB, DKT, DELK, DELKRF, DC
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /JPARAM/ RX(2), VAL1(2), VAL2
      COMMON /JPARA1/ VALB(2),  VALK(2),
     1                IRHOB(2), IRHOK(2), QVRHO(4), QCONS(2), IRHO(2)
      COMMON /RTEMP / RHOKIN, AD(3), BD(3)
      COMMON /ERHOV / ERHO
C--------------------------------------------------------------
C CHECK IF REACTIVITY IS "VALID"
      DO 100 I = 1, 4
  100 QVRHO(I) = .TRUE.
      DO 110 I = 1, 2
  110 IF ( IRHOB(I) .NE. IRHOK(I) )      QVRHO(I) = .FALSE.
      IF ( ABS(DELK-RHOKIN) .GT. ERHO ) QVRHO(3) = .FALSE.
      DO 120 I = 1, 3
  120 IF ( .NOT. QVRHO(I) ) GO TO 130
      GO TO 140
  130 QVRHO(4) = .FALSE.          |REACTIVITY NOT VALID
  140 CONTINUE
C--------------------------------------------------------------
C CONSERVATIVE ACTION IRHO(I); SELECT VAL1(I); CONSTRAINT SATISFIED
      DO 230 I = 1, 2
      QCONS(I) = .TRUE.
      IRHO(I) = 1
      VAL1(I) = VALB(I)
      IF ( KFLAGS) 212, 214, 216
  212 IF ( VALK(I) .LT. VALB(I) ) VAL1(I) = VALK(I)       | LOWER
      IF ( VAL1(I) .GE. VAL2    ) IRHO(I) = -1            | INSERT IF
      IF ( VAL2 .GT. 0.0 )        IRHO(I) = -1            | VAL1 .GE. VAL
      IF ( IRHO(I) .EQ.  1      ) QCONS(I) =  .FALSE.
```

```
      GO TO 230
  214 IF  ( KFLAG ) 212, 216, 216
  216 IF  ( VALK(I)  .GT. VALB(I)  )  VAL1(I)  = VALK(I)          | RAISE
      IF  ( VAL1(I)  .GE. VAL2     )  IRHO(I)  = -1               | INSERT IF
      IF  ( VAL2 .LT. 0.0          )  IRHO(I)  =  1               | VAL1 .GE. VAL
      IF  ( IRHO(I)  .EQ.-1        )  QCONS(I) =   FALSE.         | CONST NOT SAT
  230 CONTINUE
C-----------------------------------------------------------------
      RETURN
      END
      SUBROUTINE RSHIM    | SIMULATION ROUTINE
C=================================================================
C "RESHIM" PROCEDURE:
C  NOTE: BOTH REG ROD AND SHIM BLADE ARE ADJUSTED CONCURRENTLY
C       TRANSIENT SUBSTATES: TA3 OR TA4
C=================================================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON /CREF  / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CCON / U1(2), U2(2), U3(2), U4(2)
      COMMON /CCONF/ ICONF(5), KFLAGS, ISCOM
      COMMON /CNFLAG/ NJRHO, IPOSO
C-----------------------------------------------------------------
      IDROD(2) = 2                       | USE SB FOR CONTROL
      IF ( NJRHO .GE. 3 ) GO TO 400      | REACTIVITY NOT VALID
      IF ( ADEVP(2) .LE. 1.5*DESDP ) GO TO 460
C-----------------------------------------------------------------
      IPOS = 7               | REACTIVITY VALID: TA3
      CALL NLDC
      CONT(2) = U2(2)
      IDCON(2) = 2
      GO TO 500
C-----------------------------------------------------------------
  400 CONTINUE
      IPOS = 8               | REACTIVITY NOT VALID: TA4
      CALL RELAY
      CONT(2) = U4(2)
      IDCON(2) = 4
      GO TO 500
C-----------------------------------------------------------------
  460 CONTINUE     | CLOSE
      CALL PID
      CONT(2) = U1(2)
      IDCON(2) = 1
      CALL RCTEST  ( CONT(2) )    | REACTIVITY CONSTRAINT REVIEW
C-----------------------------------------------------------------
  500 CONTINUE                    | REG ROD CONTROL: HEURISTICS
      IF ( FHRR .GT. 5. ) CONT(1) = -1.0      | CHECK FOR DESIRED
      IF ( FHRR .LT. 3. ) CONT(1) =  1.0      | REG ROD HEIGHT
      IF ( 3. LE. FHRR .AND. FHRR .LE. 5. ) CONT(1) = 0.0
C-----------------------------------------------------------------
      RETURN
      END
      SUBROUTINE SAFETY  | ON-LINE DEMO AND SIMULATION ROUTINE
C============================================================
C  SAFETY ROUTINE: POWER, PERIOD, & REACTIVITY LIMITS
C============================================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON /CREF  / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CRHO  / DKRR, DKSB, DKT, DELK, DELKRF, DC
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG,
     1               ADVEP(2), FASUR, FATAU, HDEL(2)
      COMMON /BSAFE / QSAFE(5)
      COMMON /CSEL  / IDCON(2), IDROD(2)
```

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      COMMON /RTEMP / RHOKIN, AD(3), BD(3)
C-------------------------------------------------------------
      DO 220 I = 1, 5           | RESET FLAGS
  220 QSAFE(I) = .TRUE.
C-------------------------------------------------------------
C POWER LIMIT: UPPER BOUND
      IF (FPOW(2).GT. 4200. ) QSAFE(1) = .FALSE.
C PERIOD LIMIT
      IF (0.0 .LT. FTAU(2).AND. FTAU(2) .LE. 50.) QSAFE(2) = .FALSE.
C REACTIVITY LIMIT: BALANCE AND INVERSE KINETICS MODELS
      IF ((DELK.GT.165.) .OR. (RHOKIN .GT. 165.)) QSAFE(3) = .FALSE.
C POWER LIMIT: EXCEEDS SET POINT
      IF ((KFLAG .GE. 0).AND.(FPOW(2) .GT. 1.25*PSET)) QSAFE(4) =.FALSE.
C-------------------------------------------------------------
      DO 250 I = 1, 4
      IF ( .NOT. QSAFE(I)) GO TO 300
  250 CONTINUE
      GO TO 900
C-------------------------------------------------------------
  300 CONTINUE
      DO 350 I = 1, 2           | INSERT REG ROD & SHIM BLADE IF
  350 CONT(I) = -1.             | THERE IS A VIOLATION.
      QSAFE(5)   =   .FALSE.
      IDCON(2) = 20             | CONTROL LAW IDENTIFICATION TAG
C-------------------------------------------------------------
  900 RETURN
      END
      SUBROUTINE SATUR
      IMPLICIT LOGICAL*1 (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CCONF / KDUM(5), KFLAGS, ISCOM
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2),CONT(2)
      COMMON /CREF  / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CNFLAG/ NJRHO, IPOSO
      COMMON /CSAV  / CONSAV(2)
      IF ( IPOS .EQ. 4 .OR. IPOS .EQ. 14 ) RETURN
      IF ( IPOS .EQ.10 .OR. IPOS .EQ. 18 ) RETURN
      ISAT = 0
      IF ( IDROD(2) .EQ. 2 ) GO TO 500
C REG ROD SATURATION
      IF ( CONT(1) .LT. 0.0 .AND. FHRR .LE.  2. ) ISAT =  1
      IF ( CONT(1) .GT. 0.0 .AND. FHRR .GE. 12. ) ISAT = 10
      IF ( ISAT .EQ. 0 ) GO TO 900
      CONT(1) = 0.0
      IDCON(2) = 5
      IPOS = 4
      GO TO 900
C--------------------------------------------------------------------
  500 CONTINUE
      IF ( FHSB(1).LT.  1.0 .AND. CONT(2) .LT. 0.) ISAT = 101
      IF ( FHSB(1).GT. 20.0 .AND. CONT(2) .GT. 0.) ISAT = 110
      IF ((HSBREF -FHSB(1)).GE.2.0  .AND. CONT(2).LT.0.0) ISAT=101
      IF ((FHSB(1)-HSBREF ).GE.2.0  .AND. CONT(2).GT.0.0) ISAT=110
      IF ( ISAT .EQ. 0 ) GO TO 900
      IDCON(2) = 5
      CONT(2) = 0.0
      IF ( 5  .LE. IPOS .AND. IPOS .LE.  9 ) IPOS = 10
      IF ( 11 .LE. IPOS .AND. IPOS .LE. 13 ) IPOS = 14
      IF ( 15 .LE. IPOS .AND. IPOS .LE. 17 ) IPOS = 18
C--------------------------------------------------------------------
  900 CONTINUE
      RETURN
      END
      SUBROUTINE SENSOR (X, XO, Y, YO, XBIAS, XNOISE, XSCALE, XTAU )
C===================================================================
C SENSOR MODEL
C===================================================================
      COMMON /CTIME/ TIME, DT
      IF ( TIME .GT. 0.0 ) GO TO 100
      XO   = X
      YO   = X
  100 CONTINUE
```

```
      Y      = X
      IF ( XTAU.GT. 0.0 ) Y = YO + DT*(XO - YO)/XTAU     | TIME LAG
      CALL NOISE ( SN )                                  | NOISE
      Y      = Y*( 1. + 0.01*(XBIAS+XNOISE*SN) )*XSCALE  | BIAS, NOISE, SCALE
      XO     = X
      YO     = Y
      RETURN
      END
      SUBROUTINE SORT ( NTOT, NIN, QU, ISEL )
C ON-LINE DEMO AND SIMULATION ROUTINE
C=================================================================
C ELIMINATE OPTIONS WITH "BAD" TAGS
C=================================================================
      IMPLICIT LOGICAL*1  (Q)
      DIMENSION QU(5), ISEL(5)   | ISEL = SELECTION VECTOR
      NN = NTOT                 | TOTAL NUMBER OF CONTROL OPTIONS
      NIN  = 0
      DO 140 I = 1, NTOT        | COUNT NUMBER OF ADMISSABLE CONTROL
      IF ( QU(I) ) GO TO 120    | CONTROL LAW I IS "GOOD"
      ISEL(NN) = I              | SELECTION VECTOR
      NN = NN - 1
      GO TO 140
  120 NIN = NIN + 1
      ISEL(NIN) = I
  140 CONTINUE
      RETURN
      END
      SUBROUTINE SRELAY ( SIGNAL )
C=====================================================
C STEADY STATE ON/OFF CONTROL
C=====================================================
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON /CCONF / ICONF(2), ISTATE, JDEV, JSUR, KFLAGS, ISCOM
      COMMON /CSTATE/ DEVP(2), FSUR(2),FTAU(2), PFAC, KFLAG
     1                ,ADEVP(2), FASUR, FATAU, HDEL(2)
      SIGNAL = 0.0
      IF ( ICONF(2)  .EQ. 10 ) SIGNAL = -1. | "HARD-BOUND" CONTROL
      IF ( ICONF(2)  .EQ. 11 ) SIGNAL =  1.
      IF ( ADEVP(2)  .GE. DESDP ) GO TO 900
      SIGNAL = -DEVP(2)/DESDP
      IF ( ADEVP(2)  .GE. 0.5*DESDP) GO TO 900
      IF ( ADEVP(2)  .LT. ADEVP(1) ) SIGNAL = 0.0
  900 CONTINUE
      IF ( IDROD(2)  .EQ. 1 ) GO TO 950
      IF ( SIGNAL .LT. -0.5 ) SIGNAL = -1.0
      IF ( SIGNAL .GT.  0.5 ) SIGNAL =  1.0
      IF ( ABS(SIGNAL)  .LE. 0.5 ) SIGNAL = 0.0
  950 CONTINUE
      RETURN
      END
      SUBROUTINE SS     | ON-LINE DEMO AND SIMULATION ROUTINE
C===================================================================
C STEADY STATE "DRIVER" ROUTINE
C===================================================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /JPARA1/ VALB(2),  VALK(2),
     1                IRHOB(2), IRHOK(2), QVRHO(4), QCONS(2), IRHO(2)
      COMMON /CNFLAG/ NJRHO, IPOSO
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      DATA NNRHO1 / 0 /
C------------------------------------------------------------
      IF  ( .NOT.QCONS(1) ) GO TO 150     | MCO: REG ROD REACTIVITY
      NNRHO   = 0                         | CONSTRAINT TEST
      NNRHO1 = 0
      GO TO 180
  150 NNRHO = NNRHO + 1                   | CONSTRAINT NOT SATISFIED
      IF ( NNRHO .GE. 3 ) NNRHO   = 3
      IF ( NNRHO .GE. 3 ) NNRHO1 = 3
  180 CONTINUE
C------------------------------------------------------------
      IF  ( IPOSO .EQ. 4 .OR. IPOSO .EQ. 14 ) GO TO 600  | SATURATION
C------------------------------------------------------------
```

```
  190 CONTINUE
      IF ( NJRHO   .GE. 3 ) GO TO 500     | REACTIVITY NOT VALID
  195 CONTINUE
      IF ( .NOT. QCONS(2)) GO TO 300      | SHIM BLADE REACT CONST NOT MET)
      IF ( .NOT. QMOTOR ) GO TO 200       | CONFIGURATION B (SHIM BLADE ONLY)
C------------------------------------------
      IF ( NNRHO1 .GE. 3 )  GO TO 300     | REG ROD REACT CONST NOT MET
  200 CALL SS1       | SUBSTATE SA1 OR SB1
      GO TO 900
  300 CALL SS2       | SUBSTATE SA2 OR SB2
      GO TO 900
  500 CONTINUE
      IF ( NFLAGS .GT. 30 ) GO TO 195     | REACT NOT VALID BUT SS SATISFIED
      CALL SS3       | SUBSTATE SA3 OR SB3
      GO TO 900
  600 CONTINUE
      IF ( .NOT. QMOTOR) GO TO 620
      IF ( 3 .LE. FHRR .AND. FHRR .LE. 5. ) GO TO 190
  620 CALL SS4       | SUBSTATE SA4 OR SB4
  900 RETURN
      END
      SUBROUTINE SS1    | SIMULATION ROUTINE
C================================================================
C STEADY SUBSTATE: REACTIVITY VALID; REACTIVITY CONSTRAINTS MET
C    PERFORMANCE EVALUATION IS DEMONSTRATED IN SUBSTATE SA1 ONLY
C       SUBSTATES: SA1 AND SB1
C================================================================
      IMPLICIT LOGICAL*1  (Q)
      DIMENSION PU(5), ISEL(5), QU(5)
      COMMON /CTIME / TIME, TSAM
      COMMON /CCONF / KDUM(5), KFLAGS, ISCOM
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON /RPARAM/ BAND(2,2), GAIN(4,2), TRHO, BETA(3), DEL(3)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CCON  / U1(2), U2(2), U3(2), U4(2)
      COMMON /CNFLAG/ NJRHO, IPOSO
      COMMON /CFUZ /  IFUZ1, IFUZ2
      DATA IC, ISEL, QU, PU / 0, 1, 2, 3, 4, 5, 5*.TRUE., 5*0.0 /
      DATA ISTAR / 1 /, NSTAR, NPEN /2*0/, ISTARO / 1 /
      DATA IOVER / 0 /
C-----------------------------------------------------------------
      ERR = ABS( FPOW(2) - PSET )
      IF ( .NOT. QMOTOR ) GO TO 800
      IPOS = 1                      | CONFIGURATION "A:" SUBSTATE SA1
      CONT(2) = 0.0                 | NO SHIM BLADE CONTROL
      IDROD(2) = 1
      IF ( IPOS .EQ. IPOSO ) GO TO 5
      NREW = 0                      | RESET FLAGS
      NPEN = 0
      IOVER = 0
C--------------------------------------------------------------------
      IF ( IPOSO .EQ. 2 .AND. IC .NE. 0 ) GO TO 4
      GO TO 5
    4 CONTINUE
      HU = -0.5            | OVERRIDE: REACTIVITY CONSTRAINT VIOLATION
      IF ( NSTAR .LE. 3 ) HU = 0.0   | TO ACCOUNT FOR DELAYED FEEDBACK
      IF ( DU .LE. 1.0 )  HU = 0.0   | SINCE PREVIOUS ACTION IS GOING IN
      GO TO 60                       | THE RIGHT DIRECTION
    5 CONTINUE
C--------------------------------------------------------------------
      IF ( IC .EQ. 0 ) GO TO 80
      IF ( IOVER .GT. 0 ) GO TO 6
      GO TO 7
    6 CONTINUE            | OVERRIDE: LARGE DEVIATION
      HU = -0.5
      IF ( NSTAR .LE. 3 ) HU = 0.0   | TO ACCOUNT FOR DELAYED FEEDBACK
      GO TO 60
    7 CONTINUE
C----------------
      HU = 0.0
```

```
      IF ( ADEVP(2) .LE. ADEVP(1) ) GO TO 30
C-------------------------------------------------------------
      IF ( NSTAR .LT. 5 ) GO TO 40   | GIVE NEW OPTION A CHANCE
      IF ( ERR .LE. 0.5*BAND(2,1) ) GO TO 40 | ERROR WITHIN DEADBAND
      NREW = NREW - 1     | PENALTY FLAG
      NPEN = NPEN + 1
      IF ( NPEN .GE. 5 ) NPEN = 5
      IF ( NREW .LE. 0 ) NREW = 0
C-------------------------------------------------------------
      HU = -1.0                | REINFORCEMENT FUNCTION
      IF ( ERR .GT. 0.5*BAND(2,1) .AND. ERR .LE. BAND(2,1) )
     1HU = -ERR/BAND(2,1)
      IF ( NPEN .EQ. 1 ) HU = 0.1*HU
      IF ( NPEN .EQ. 2 ) HU = 0.2*HU
      IF ( NPEN .EQ. 3 ) HU = 0.5*HU
      GO TO 40
   30 CONTINUE                 | ERROR DECREASING
      NREW = NREW + 1          | REWARD FLAG
      NPEN = NPEN - 1
      IF ( NPEN .LE. 0 ) NPEN = 0
      IF ( NREW .GE. 5 ) NREW = 5
C--------------------------------------------------------
      HU = 0.1
      IF ( NREW .GE. 2 ) HU = 0.2  | REWARD FUNCTION
      IF ( NREW .GE. 3 ) HU = 0.5
      IF ( NREW .GE. 4 ) HU = 1.0
   40 CONTINUE
C--------------------------------------------------------
      DU = ABS(ISCOM-CONT(1))       | ISCOM = "HARD-BOUND" CONTROL
      IF ( DU.GT.1.0) GO TO 50              | PENALIZE AT THIS POINT
      IF ( ISCOM .EQ. CONT(1) ) HU = 1.0    |  SEE OVERRIDE BELOW
      GO TO 60
   50 HU = -1.0
      NREW = 0
   60 CONTINUE
C---------------------------------------------------------
      IF ( HU .EQ. 0.0 ) GO TO 100
      CALL SORT  ( 3, NIN, QU, ISEL )       | SORT CONTROL OPTIONS
      CALL LEARN ( 3, NIN, ISEL, PU, HU, ISTAR )    | LRP ALGORITHM
      CALL MINMAX ( NIN, ISEL, PU )         | FIND MAX PROBABILITY
      ISTAR = ISEL(NIN)                  | OPTION WITH MAX PROBABILITY
      GO TO 100
C--------------------------------------------------------------
   80 CONTINUE
      ISTAR = 1                          | NO PERFORMANCE EVALUATION
      DO 90 I = 1, 5                     | INITIALIZE PROBABILITY
      PU(I) = 0.0
   90 IF ( I .EQ. ISTAR ) PU(I) = 1.0     | A PRIORI SELECTION
C-------------------------------------------------------------
  100 CONTINUE
      IF ( ISTAR .EQ. 2 ) GO TO 120
      IF ( ISTAR .EQ. 3 ) GO TO 130
      CALL PID                               | PID ALGORITHM
      IDCON(2) = 1
      CONT(1) = U1(1)
      GO TO 200
  120 CONTINUE
      CALL FUZZY                           | FUZZY ALGORITHM
      IDCON(2) = 3
      CONT(1) = U3(1)
      IF ( IFUZ1 .EQ. 0 ) GO TO 200       | CONTROL ANOMALY IN FUZZY
      IF ( IFUZ1 .EQ. 1 ) CONT(1) = 0.0   |   ALGORITHM
      IF ( IFUZ1 .EQ. 2 ) CONT(1) = 1.0
      IF ( IFUZ1 .EQ. 3 ) CONT(1) =-1.0
      GO TO 200
  130 CONTINUE
      CALL RELAY                             | RELAY ALGORITHM
      IDCON(2) = 4
      CONT(1) = U4(1)
  200 CONTINUE
C------------------------------------------------------------
      IOVER = 0                 | OVERRIDE: LARGE POWER DEVIATION
      IF ( ERR .GT. 1.5*BAND(2,1) ) GO TO 202
      GO TO 204
```

```
  202 CONTINUE
      DX = ABS ( ISCOM - CONT(1) )
      IF ( DX.LE.0.20) GO TO 205     | CHECK IF CONSISTENT WITH
      CONT(1) = ISCOM                | "HARD-BOUND CONTROL
      IOVER = 1
  204 CONTINUE
C--------------------------------------------------
  205 CONTINUE
C--------------------------------------------------
      IF ( ISTAR .EQ. ISTARO ) GO TO 250   | NO. TIMES ISTAR IS USED
      NSTAR = 0
      NPEN  = 0
      NREW  = 0
      GO TO 270
  250 NSTAR = NSTAR + 1
  270 CONTINUE
C--------------------------------------------------------
  750 CONTINUE
      IC = 10
      ISTARO = ISTAR
      GO TO 900
C-------------------------------------------------------------
  800 CONTINUE             | CONFIGURATION "B:"  SHIM BLADE ONLY
      IF (.NOT. QMOTOR ) IPOS = 11    | SUBSTATE SB1
      CONT(1) = 0.0
      IDROD(2) = 2
      CALL PID
      CONT(2) = U1(2)
      IDCON(2) = 1
  900 CONTINUE
      RETURN
      END
      SUBROUTINE SS2    | ON-LINE DEMO AND SIMULATION ROUTINE
C==============================================================
C STEADY STATE: REACTIVITY VALID AND CONSTRAINT NOT MET
C               SUBSTATES  SA2, SB2
C==============================================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CCON  / U1(2), U2(2), U3(2), U4(2)
      COMMON /CCONF / ICONF(5), KFLAGS, ISCOM
      COMMON /JPARA1/ VALB(2),  VALK(2),
     1                IRHOB(2), IRHOK(2), QVRHO(4), QCONS(2), IRHO(2)
      COMMON /CNFLAG/ NJRHO, IPOSO
C-------------------------------------------------------------
      IPOS = 2
      CONT(1) = 0.0
      CONT(2) = 0.0
      IF ( ADEVP(2)  .LT. ADEVP(1) ) GO TO 100
      IF ( ADEVP(2)  .LE. DESDP    ) GO TO 100
      NPOS2 = NPOS2 + 1
      GO TO 150
  100 CONTINUE
      NPOS2 = 0
  150 CONTINUE
      IF ( .NOT. QMOTOR ) GO TO 300
C-------------------------------------------------------------
      CONT(1) = IRHO(1)           | RHO VALID BUT CONST NOT SATISFIED
C-------------------------------------------------------------
      IF ( .NOT. QCONS(2) ) GO TO 300  | SHIM BLADE VIOLATION
      IDROD(2) = 1
      IF ( NPOS2 .LT. 5 ) GO TO 350
      IDROD(2) = 2
      CONT(2) = IRHO(1)       | HELP REG ROD WITH SHIM BLADE
      GO TO 350
C-------------------------------------------------------------
  300 CONT(2) = IRHO(2)
      IDROD(2) = 2
```

```
  350 CONTINUE
C--------------------------------------------------------------
      IF ( .NOT. QMOTOR ) IPOS = 12    | SUBSTATE SB2
      IDCON(2) = 5                     | HEURISTICS
      RETURN
      END
      SUBROUTINE SS3  | ON-LINE DEMO AND SIMULATION ROUTINE
C==============================================================
C STEADY STATE: REACTIVITY NOT  VALID -  SUBSTATES SA3, SB3
C==============================================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1                ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CCON  / U1(2), U2(2), U3(2), U4(2)
      COMMON /CCONF / ICONF(5), KFLAGS, ISCOM
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
C--------------------------------------------------------------
      IPOS = 3
      CONT(1) = 0.0
      CONT(2) = 0.0
      IF ( ADEVP(2) .GE. DESDP ) GO TO 100
      NPOS3 = 0
      GO TO 150
  100 NPOS3 = NPOS3 + 1
  150 CONTINUE
C--------------------------------------------------------------
      IF ( .NOT. QMOTOR ) GO TO 400
      IDROD(2) = 1
      IDCON(2) = 4
C      CALL SRELAY ( CONT(1) )
      CALL RELAY
      CONT(1) = U4(1)
C---------------------------------------------------------------
      IF ( NPOS3 .LT. 3 ) GO TO 600
  400 CONTINUE          | GOES HERE IF .NOT. QMOTOR
      IDROD(2) = 2      | AND IF REG ROD NEEDS HELP
      IDCON(2) = 5
      CALL SRELAY ( CONT(2) )
  600 CONTINUE
      IF ( .NOT. QMOTOR ) IPOS = 13
      RETURN
      END
      SUBROUTINE SS4
C SUBSTATE SA4 AND SB4
      IMPLICIT LOGICAL*1  (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CCONF / KDUM(5), KFLAGS, ISCOM
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2),CONT(2)
      COMMON /CREF  / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1                ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CSAV  / CONSAV(2)
      IF ( .NOT. QMOTOR  ) GO TO 500
C REG ROD SATURATION: SA4
      IPOS = 4
      IDCON(2) = 5
      IDROD(2) = 2
      CALL SRELAY(CONT(2))
      IF ( CONT(2)*CONSAV(2)  .LT. 0.0 ) CONT(2) = 0.0
      IF ( FHRR .GT. 5. ) CONT(1) =-1.0
      IF ( FHRR .LT. 3. ) CONT(1) = 1.0
      GO TO 900
C----------------------------------------------------------------------
C SHIM BLADE SATURATION: SB4
  500 CONTINUE
      IPOS = 14
      IDCON(2) = 5
      IDROD(2) = 2
```

```
      IF ( ADEVP(2) .GT. 3.*DESDP ) WRITE ( 6, 520 )
  520 FORMAT ( 1X, ' SHIM BLADE SATURATION AT STEADY STATE: SB4' )
  900 CONTINUE
      RETURN
      END
      SUBROUTINE STATE    | ON-LINE DEMO AND SIMULATION ROUTINE
C===============================================================
C COMPUTES AND IDENTIFIES SOME OF THE ELEMENTS OF INFO VECTOR
C===============================================================
      IMPLICIT LOGICAL*1  (Q)
      DIMENSION XPOW(2), CDEL(3)
      COMMON/A/RL,BETA,RD(6),B(6),DN(6),DECAY
      COMMON /CTIME / TIME, TSAM
      COMMON /CIOCON/ IINP, IOUT, KPRIN
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON /CREF  / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CFILT / TFILTP, TFILTS
      COMMON /CRHO  / DKRR, DKSB, DKT, DELK, DELKRF, DC
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CCONF / ICONF(2), ISTATE, JDEV, JSUR, KFLAGS, ISCOM
      COMMON /RESET / QCSET, QPSET, QRSET
      COMMON /CSROD / SVRR, SVSB
      COMMON /JPARAM/ RX(2), VAL1(2), VAL2
      COMMON /JPARA1/ VALB(2),  VALK(2),
     1                IRHOB(2), IRHOK(2), QVRHO(4), QCONS(2), IRHO(2)
      COMMON /RPARAM/ BAND(2,2), GAIN(4,2), TRHO, BETT(3), DEL(3)
      COMMON /RTEMP / RHOKIN, AD(3), BD(3)
      DATA PSETO / 0.0 /
C--------------------------------------------------------------
      QPSET = .FALSE.
      IF ( PSET .EQ. PSETO .AND. TIME .GT. 0.0 ) GO TO 200
C--------------------------------------------------------------
C REFERENCE CONDITIONS
      PREF = FPOW(2)
      HRRREF = FHRR
      HSBREF = FHSB(1)
      TPCREF = FTPC
      QPSET  = .TRUE.
C--------------------------------------------------------------
C POWER MANEUVER ( KFLAG = -1/0/1  = LOWER/REG/RAISE )
      IF ( ABS(PSET-PREF) .GT. BAND(2,1)) GO TO 100
      KFLAG = 0
      GO TO 150
  100 CONTINUE
      KFLAG = -1
      IF ( PSET .GT. PREF ) KFLAG = 1
  150 CONTINUE
      KFLAGS = KFLAG
C--------------------------------------------------------------
C ESTIMATE INITIAL REACTIVITY:    REACTIVITY BALANCE
      IF ( TIME .GT. 0.0 ) GO TO 200
      DKRR   = REACRR(HRRREF)
      DKT    = REACT  (TPCREF)
      DKSB   = REACSB(HSBREF)
      DELKRF= DKRR+DKT+DKSB
C--------------------------------------------------------------
      DO 190 I = 1, 3                | 3 DELAYED NEUTRON GROUP MODEL
      AD(I) = EXP(-TSAM*DEL(I))      |   AUXILLIARY VARIABLES
      BD(I) =  (1.-AD(I))*BETT(I)/DEL(I)
  190 CDEL(I) = BETT(I)*FPOW(2)/DEL(I)
C--------------------------------------------------------------
  200 CONTINUE                       | COMPUTE AUXILLIARY VARIABLES
      HDEL(1) = FHRR - HRRREF
      HDEL(2) = FHSB(1) - HSBREF
C--------------------------------------------------------------
      IF ( KFLAG .EQ. 0 ) PFAC = FPOW(2)/PSET
      IF ( KFLAG .NE. 0 ) PFAC    = (FPOW(2)-PREF)/(PSET-PREF)
      DEVP(2) = FPOW(2)/PSET - 1.0
      DEVP(2) = 100.*DEVP(2)
      ADEVP(2) = ABS(DEVP(2))
C--------------------------------------------------------------
      CALL FILTER ( FPOW(2), FPOW(1), XPOW, TFILTS, AS, BS )
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```
      IF ( TIME .GT. 0.0 ) GO TO 310
      FPOW(1) = FPOW(2)
      XPOW(1) = XPOW(2)
  310 USUR = 52.12*(XPOW(2) - XPOW(1))/(TSAM*(XPOW(2) + XPOW(1)))
      CALL FILTER ( USUR, USURO, FSUR, TFILTS, AS, BS )
      CALL PERIOD ( FSUR(2), FASUR, FTAU(2), FATAU )   | PERIOD
C-----------------------------------------------------------------
      DKRR  = REACRR(FHRR)        | REACTIVITY BALANCE
      DKT   = REACT (FTPC)
      DKSB  = REACSB(FHSB)
      DELK  = DKRR  + DKT + DKSB - DELKRF
C----------------------------------------------------------------
      RHOKIN = 0.0       | REACTIVITY ESTIMATE:   INVERSE KINETICS
      DO 650 I = 1, 3
      CDEL(I) = AD(I)*CDEL(I) + BD(I)*FPOW(2)
  650 RHOKIN = RHOKIN + DEL(I)*CDEL(I)
      RHOKIN = 1000.*(1.- RHOKIN/FPOW(2)) + 0.1*FSUR(2)/(BETA*26.06)
C-----------------------------------------------------------------
      CALL PSTATE    | PLANT OPERATING STATE: STEADY OR TRANSIENT
C-----------------------------------------------------------------
C COMPUTE PARAMETERS FOR REACTIVITY CONSTRAINT RELATIONSHIP
      DC    = 0.078742*EXP(0.019867*BETA*10.*DELK)     | DECAY CONSTANT
      DCK   = 0.078742*EXP(0.019867*BETA*10.*RHOKIN)
C-----------------------------------------------------------------
      RX(1) = REACRD(FHRR)*SVRR      | MAX REACTIVITY CHANGE ASSOCIATED
      RX(2) = REACSD(FHSB(1))*SVSB   | WITH REG ROD & SHIM BLADE
      IF ( KFLAGS ) 710, 718, 720
C-----------------------------------------------------
  710 CONTINUE    | COMPUTE AVAILABLE AND REQUIRED TIMES
      VAL2    = FTAU(2)*ALOG(FPOW(2)/PSET)           | LOWER
      IF ( FPOW(2) .LT. PSET ) VAL2 = 0.0
      DO 715 I = 1, 2
      VALB(I) = (DELK   +RX(I)/DC )/RX(I)
      VALK(I) = (RHOKIN+RX(I)/DCK)/RX(I)
      IRHOB(I) = -1
      IRHOK(I) = -1
      IF ( VAL2 .GT. 0.0 ) GO TO 715
      IF ( VALB(I) .LE. VAL2 ) IRHOB(I) = 1
      IF ( VALK(I) .LE. VAL2 ) IRHOK(I) = 1
  715 CONTINUE
      GO TO 740
  718 IF ( KFLAG ) 710, 720, 720
C-----------------------------------------------------
  720 CONTINUE
      VAL2    = FTAU(2)*ALOG(PSET/FPOW(2))           | RAISE
      IF ( FPOW(2) .GT. PSET ) VAL2 = 0.0
      DO 735 I = 1, 2
      VALB(I) = (DELK   -RX(I)/DC )/RX(I)
      VALK(I) = (RHOKIN-RX(I)/DCK)/RX(I)
      IRHOB(I) = 1
      IRHOK(I) = 1
      IF ( VAL2 .LT. 0.0 ) GO TO 735
      IF ( VALB(I) .GE. VAL2 ) IRHOB(I) = -1
      IF ( VALK(I) .GE. VAL2 ) IRHOK(I) = -1
  735 CONTINUE
  740 CONTINUE
C-----------------------------------------------------------------
      PSETO = PSET
      XPOW(1) = XPOW(2)
C-----------------------------------------------------------------
      RETURN
      END
      SUBROUTINE TPERF  | ON-LINE DEMO AND SIMULATION ROUTINE
C=================================================================
C USED TO DEMONSTRATE CONTROLLER RECONFIGURATON IN
C CONFIGURATION "A,"   SUBSTATE = TA2  ( SEE APPENDIX F )
C=================================================================
      IMPLICIT LOGICAL*1  (Q)
      DIMENSION PU(5), ISEL(5), QU(5)
      COMMON /CTIME / TIME, TSAM
      COMMON /CCONF / KDUM(5), KFLAGS, ISCOM
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
```

```
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON /RPARAM/ BAND(2,2), GAIN(4,2), TRHO, BETA(3), DEL(3)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CCON  / U1(2), U2(2), U3(2), U4(2)
      COMMON /CNFLAG/ NJRHO, IPOSO
      COMMON /CFUZ/   IFUZ1, IFUZ2
      DATA IC, ISEL, QU, PU / 0, 1, 2, 3, 4, 5, 5*.TRUE., 5*0.0 /
      DATA ISTAR / 1 /, NSTAR, NPEN, NSLOW /3*0/, ISTARO / 1 /
C--------------------------------------------------------------
      IF ( IPOS .EQ. IPOSO ) GO TO 10
      NREW =  0                       | REINITIALIZE FLAGS
      NPEN =  0
      NSLOW = 0
   10 CONTINUE
      IF ( IC .EQ. 0 ) GO TO 80               | INITIALIZATION FLAG
C-------------------
      HU = 0.0
      IF ( ADEVP(2)  .GT. ADEVP(1) ) GO TO 20 | COUNT NO. OF PENALTIES
      NREW = NREW + 1                         | REWARD CONDITION
      NPEN = NPEN - 1
      IF ( NPEN .LE. 0 ) NPEN = 0
      IF ( NREW .GE. 5 ) NREW = 5
      IF ( NREW .GT. 2 ) HU = 0.5
      IF ( NREW .GT. 3 ) HU = 0.75
      IF ( NREW .GT. 4 ) HU = 1.0
      GO TO 25
   20 NREW = NREW - 1                         | PENALTY CONDITION
      NPEN = NPEN + 1
      IF ( NPEN .GE. 5 ) NPEN = 5
      IF ( NREW .LE. 0 ) NREW = 0
      IF ( NPEN .GT. 2 ) HU = -0.50
      IF ( NPEN .GT. 3 ) HU = -0.75
      IF ( NPEN .GT. 4 ) HU = -1.0
   25 CONTINUE
C-----------------
      IF ( FTAU(2)  .GT. 0.0 .AND. FTAU(2)  .LT. 100. ) HU = -1.0
      IF ( TIME  .LT. 20. ) GO TO 50
      IF ( IDCON(2)  .GT. 3 ) GO TO 50   | NOTE: RELAY IS SLOW
      IF ( FATAU .GT. 300. .AND. FPOW(2) .LT. 1500.) GO TO 30
      NSLOW = 0
      GO TO 50
   30 CONTINUE
      NSLOW = NSLOW + 1
      IF ( NSLOW .GE. 6 ) NSLOW = 6
      IF ( NSLOW .GT. 3 ) HU = -0.5
      IF ( NSLOW .GT. 4 ) HU = -0.75
      IF ( NSLOW .GT. 5 ) HU = -1.0
   50 CONTINUE
C----------
      IF ( HU .EQ. 0.0 ) GO TO 100
      CALL SORT  ( 3, NIN, QU, ISEL )
      CALL LEARN ( 3, NIN, ISEL, PU, HU, ISTAR )
      CALL MINMAX ( NIN, ISEL, PU )
      ISTAR = ISEL(NIN)
      GO TO 100
   80 CONTINUE                          | NO PERFORMANCE EVALUATION
      ISTAR = 1                         | A PRIORI SELECTIOIN
      DO 90 I = 1, 5                    | INITIALIZE PROBABILITY
      PU(I) = 0.0
   90 IF ( I .EQ. ISTAR ) PU(I) = 1.0
C--------------------------------------------------------------
  100 CONTINUE
      IF ( ISTAR .EQ. 2 ) GO TO 120
      IF ( ISTAR .EQ. 3 ) GO TO 130
      CALL FUZZY                        | RAISE POWER
      CONT(IDROD(2)) = U3(IDROD(2))     | FUZZY
      IDCON(2) = 3
      IF ( FPOW(2)  .LT. 1400. ) GO TO 200
      IF ( IFUZ2 .EQ. 0 ) GO TO 200     | INTRODUCE ANOMALY
      IF ( IFUZ2 .EQ. 1 ) CONT(IDROD(2)) = -1.0
      IF ( IFUZ2 .EQ. 2 ) CONT(IDROD(2)) =  0.0
      GO TO 200
  120 CONTINUE
```

```
      CALL RELAY                          | RELAY
      IDCON(2) = 4
      CONT(IDROD(2)) = U4(IDROD(2))
      GO TO 200
  130 CONTINUE
      CALL NLDC
      IDCON(2) = 2
      CONT(IDROD(2)) = U2(IDROD(2))
  200 CONTINUE
C--------------------------------------------------
      IF ( ISTAR .EQ. ISTARO ) GO TO 250    | NO. TIMES ISTAR IS USED
      NSTAR = 0
      NPEN  = 0
      NREW  = 0
      NSLOW = 0
      GO TO 270
  250 NSTAR = NSTAR + 1
  270 CONTINUE
C---------------
      IC = 10
      ISTARO = ISTAR
  900 CONTINUE
      RETURN
      END
      SUBROUTINE TRANNO     ! ON-LINE DEMO & SIMULATION ROUTINE
C===================================================
C DRIVER ROUTINE FOR SUBSTATES TA1, TA2, TB1, TB2
C===================================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CSEL/   IDCON(2), IDROD(2)
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG
     1               ,ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CSET / PSET, DESDP, DESSUR, DESTAU
      COMMON /CREF / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CCONF/ ICONF(5), KFLAGS, ISCOM
      COMMON /JPARA1/ VALB(2), VALK(2),
     1                IRHOB(2), IRHOK(2), QVRHO(4), QCONS(2), IRHO(2)
      COMMON /CCON / U1(2), U2(2), U3(2), U4(2)
      COMMON /CNFLAG/ NJRHO, IPOSO
C-------------------------------------------------------------
      CONT(1) = 0.0
      CONT(2) = 0.0
      IDROD(2) = 1
      IF ( .NOT. QMOTOR ) IDROD(2) = 2  | CONFIGURATION "B"
      IF ( NJRHO .GE. 3 ) GO TO 600
C-------------------------------------------------------------
      IPOS = 5             | REACTIVITY VALID: TA1 OR TB1
      IF ( .NOT. QMOTOR ) IPOS = 15
      CALL NLDC
      CONT(IDROD(2)) = U2(IDROD(2))
      IDCON(2) = 2
      GO TO 900
C-------------------------------------------------------------
  600 CONTINUE
      IPOS = 6             | REACTIVITY NOT VALID: TA1 OR TB1
      IF ( .NOT. QMOTOR ) IPOS = 16
      IF ( .NOT. QMOTOR .OR. ( IDROD(2) .EQ. 2 ) ) GO TO 650
      IF ( KFLAGS .LT. 0 ) GO TO 650
      CALL TPERF     | ONLY FOR POWER INCREASE, CONFIGURATION "A"
      GO TO 900
  650 CALL RELAY                           | LOWER POWER
      CONT(IDROD(2)) = U4(IDROD(2))        | RELAY
      IDCON(2) = 4
  900 CONTINUE
      RETURN
      END
      SUBROUTINE TRANS
C==================================================
C DRIVER ROUTINE FOR TRANSIENT SUBSTATES
C-------------------------------------------------------------
      IMPLICIT LOGICAL*1  (Q)
```

```
      COMMON /CTIME / TIME, TSAM
      COMMON /CMODE / IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /RESET / QCSET, QPSET, QRSET
C-----------------------------------------------------------------
      CALL CMOTOR            | DETERMINE STATUS OF DRIVE MOTORS
      JPOS = IPOS - 10       | SEE CHAPTER 4 FOR DEFINITIONS
      IF ( JPOS .LT. 0 ) JPOS =IPOS     | OF SUBSTATE ID TAGS
      IF ( IPOS .EQ. 10 ) JPOS = IPOS
      IF ( IPOS .LT.  5 ) GO TO 800    | CHECK IF PREV IN SS
      CALL POSTRA                      | CLASSIFY TRANS CONDITION
      IF ( QOVER ) GO TO 900           | OVERSHOOT/UNDERSHOOT
  100 CONTINUE
      IF ( .NOT.QMOTOR) GO TO 200
      IF ( IRSHIM .GE. 1  ) GO TO 600  | CHECK FOR RSHIM CONDITION
  200 CONTINUE
      CALL TRANNO            | TRANSIENT SUBSTATES: TA1,TA2,TB1,TB2
      GO TO 990
  600 CALL RSHIM             | IPOS = 7 & 8: TA3,TA4
      GO TO 990
C------------------------------------------------------------------
  800 IF ( .NOT. QPSET ) GO TO 900     | SETPOINT CHANGE
      CALL INITSE                      | PREVIOUSLY IN SS
      GO TO 100
C------------------------------------------------------------------
  900 CALL KBOVER                      | IPOS = 9 & 17: TA5,TB3
  990 RETURN
      END
      SUBROUTINE TSAVE  | ON-LINE DEMO AND SIMULATION ROUTINE
C==========================================================
C SAVES OLD VALUES OF SELECTED VARIABLES
C==========================================================
      COMMON /CCONF / ICONF(2), ISTATE, JDEV, JSUR, KFLAGS, ISCOM
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSEL  / IDCON(2), IDROD(2)
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG,
     1                ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CSAV  / CONSAV(2)
C-----------------------------------------------------------------
      FPOW(1)   = FPOW(2)
      FTAU(1)   = FTAU(2)
      FSUR(1)   = FSUR(2)
      DEVP(1)   = DEVP(2)
      ADEVP(1)  = ADEVP(2)
      ICONF(1)  = ICONF(2)
C-----------------------------------------------------------------
      IDCON(1)  = IDCON(2)
      IDROD(1)  = IDROD(2)
      CONSAV(1)  = CONT(1)
      CONSAV(2)  = CONT(2)
      RETURN
      END
      SUBROUTINE UNITS
      CHARACTER*12 PN(50),PU(50)
      CHARACTER*72 TITLE
      DO 100 I = 1, 50
      PN(I) = '    '
  100 PU(I) = '    '
      PN( 1) = 'TIME'
      PN( 2) = 'POWER DEV'
      PN( 3) = 'SUR'
      PN( 4) = 'PERIOD'
      PN( 5) = 'POWER FACTOR'
      PN( 7) = 'POWER'
      PN( 8) = 'TEMPERATURE'
      PN( 9) = 'RR HEIGHT'
      PN(10) = 'SB HEIGHT'
      PN(11) = 'RR CONTROL'
      PN(12) = 'SB CONTROL'
      PN(13) = 'RNX'
      PN(14) = 'TPCX'
      PN(15) = 'HRRX'
      PN(16) = 'HSBX'
      PN(17) = 'BALANCE'
      PN(18) = 'RR WORTH'
```

```
      PN(19) = 'TEMP FBACK'
      PN(20) = 'SB WORTH'
      PN(21) = 'SIGX(NLDC)'
      PN(22) = 'DECAY'
      PN(23) = 'ID CONFIG'
      PN(24) = 'MANEUVER'
      PN(25) = 'SS INDIC'
      PN(26) = 'ID CON LAW'
      PN(27) = 'ID CON ROD'
      PN(28) = 'ISTATE'
      PN(29) = 'JDEV'
      PN(30) = 'JSUR'
      PN(31) = 'PID    RR '
      PN(32) = 'NLDC   RR '
      PN(33) = 'FUZZY  RR '
      PN(34) = 'PPLANE RR '
      PN(37) = 'BAL-INV KIN'
      PN(38) = 'BAL RR CONT'      |'IRHOB(1)'
      PN(39) = 'INV RR CONT'      |'IRHOK(1)'
      PN(40) = 'INVERSE KIN'
      PN(41) = 'PID    SB '
      PN(42) = 'NLDC   SB '
      PN(43) = 'FUZZY  SB '
      PN(44) = 'PPLANE SB '
      PN(45) = 'RR CONST MET'    |'QCONS(1)'
      PN(46) = 'SB CONST MET'    |'QCONS(2)'
      PN(47) = 'SUBSTATE ID'     |'IPOS'
      PN(48) = 'REACT VALID'     |'QVRHO(4)'
      PN(49) = 'RESHIM COND'     |'IRSHIM'
C-----------------------------------------------------------
      PU( 1) = 'SEC'
      PU( 2) = 'PERCENT'
      PU( 3) = 'DPM'
      PU( 4) = 'SEC'
      PU( 5) = ' '
      PU( 7) = 'KW'
      PU( 8) = 'DEG-C'
      PU( 9) = 'INCH'
      PU(10) = 'INCH'
      PU(11) = 'IN/OUT=-1/1'
      PU(12) = 'IN/OUT=-1/1'
      PU(13) = 'KW'
      PU(14) = 'DEG-C'
      PU(15) = 'INCH'
      PU(16) = 'INCH'
      PU(17) = 'MILLIBETA'
      PU(18) = 'MILLIBETA'
      PU(19) = 'MILLIBETA'
      PU(20) = 'MILLIBETA'
      PU(21) = 'IN/OUT=-1/1'
      PU(22) = '1/SEC'
      PU(24) = 'LOWER/RAISE'
      PU(25) = 'SS = 0'
      PU(37) = 'MILLIBETA'
      PU(38) = 'IN/OUT=-1/1'
      PU(39) = 'IN/OUT=-1/1'
      PU(40) = 'MILLIBETA'
      PU(45) = 'CONST MET=0'     |'QCONS(1)'
      PU(46) = 'CONST MET=0'     |'QCONS(2)'
      PU(48) = 'VALID = 0'       |'QVRHO(4)'
      PU(49) = 'NO RESHIM=0'     |'IRSHIM'
      TITLE = ' SIMULATON RESULTS: MITR REACTOR POWER CONTROLER'
      WRITE(7) TITLE
      WRITE(7) PN
      WRITE(7) PU
      RETURN
      END
      SUBROUTINE USEL    | ON-LINE DEMO AND SIMULATION ROUTINE
C====================================================
C REVIEWS CONTROL ACTION:  SUPERVISORY SECTION
C====================================================
      IMPLICIT LOGICAL*1 (Q)
      COMMON /BSAFE / QSAFE(5)
      COMMON /CSEL  / IDCON(2), IDROD(2)
```

```
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CSAV   / CONSAV(2)
      COMMON /JLIMIT/ TLIM, SIGX(2)
      COMMON /JPARAM/ RX(2), VAL1(2), TREQ
C--------------------------------------------------
C FOR ON-LINE DEMO ONLY THE REG ROD IS REVIEWED
      IF ( .NOT. QSAFE(5) ) GO TO 50
      IDR = IDROD(2)
      IF ( IDR .LE. 0  .OR. IDR .GT. 2 ) GO TO 50
      CALL CONST ( RX(IDR), VAL1(IDR), TLIM, SIGX(IDR), IDR )
   50 CONTINUE
      DO 100 I = 1, 2
      IDR = I
      CALL CHECK ( CONT(IDR),CONSAV(IDR), IDR )
  100 CONTINUE
C--------------------------------------------------
      RETURN
      END
      SUBROUTINE VERS    | SIMULATION ROUTINE
C==================================================
C PRINTS TIME AND DATE
C==================================================
      CHARACTER*8 C8TIME
      CHARACTER*9 C9DATE
      COMMON/CIOCON/ IINP, IOUT, KPRIN
      CALL DATE(C9DATE)                   | VALID FOR VAX MACHINES
      CALL TIME(C8TIME)
      WRITE(IOUT,100) C9DATE, C8TIME
  100 FORMAT ( ' RECONFIGURABLE CONTROLLER: ',
     1       / ' VERSION = FRI  13-JAN-86 ',  1X,A9,1X,A8)
      RETURN
      END
```

J.2 On-line Code Listing

```
      PROGRAM MITDSP | SIGNAL VALIDATION & DIGITAL CONTROL PROGRAM
C===================================================================
C AUTHOR: A.RAY;
C MODIFIED BY RSO FOR ON-LINE DEMO OF RECONFIGURABLE CONTROLLER
C PURPOSE: MAIN PROGRAM FOR SIGNAL VALIDATION AND CLOSED LOOP
C          DIGITAL CONTROL OF THE REGULATING ROD IN THE
C          MIT NUCLEAR REACTOR;   THE PROGRAM ALSO EXHIBITS
C          A REAL-TIME DISPLAY OF PARAMETERS
C=====================================================================
C
C  PROGRAM STRUCTURE
C
C---------------------------------------------------
C  ON-LINE PROGRAM
C
C    MITDSP I---> CPARAM
C           I
C           I---> INPUTC
C           I
C           I---> DISPLY
C           I
C           I---> FDITST ---> RCON
C
C  MITDSP = MAIN PROGRAM, COLLECTS SENSOR DATA
C  CPARAM = READS CONTROLLER PARAMETERS
C  INPUTC = READS INPUT FROM THE CRT
C  DISPLY = WRITES RESULT ON THE CRT
C  FDITST = INTERFACE BETWEEN MAIN PROGRAM AND CONTROL PROGRAM
C  RCON   = DRIVER ROUTINE FOR CONTROL PROGRAM
C
C----------------------------------------------------
C  CONTROLLER PROGRAM: SEE SIMULATION CODE LISTING
C
C    RCON ---> CONTROL SUBROUTINES (SEE SIMULATION CODE LISTING)
C
C
C=======================================================================
      EXTERNAL FDITST
      LOGICAL*1 LPRN,LLCHAR,LP1,LP2,LDATE,LTIME
      COMMON/AREA01/IPRN,IDSP,NCHN,ADGAIN,NFRQ,PSCAL
      COMMON/AREA02/INFO(18),SENS(16)
      COMMON/AREA03/SCAL(16),SHIM(4),BIAS(16)
      COMMON/LOGIC/LPRN
      COMMON/DATE/LDATE(9),LTIME(8)
      COMMON/SAMPLE/XSAM,SAMTIM,IALARM
C----------------------------------------------------------
      COMMON/CTIME / XTIME, TSAM
      COMMON/CSET  / PSET, DESDP, DESSUR, DESTAU
      COMMON/CIOCON/ IINP, IOUT, KPRIN
C----------------------------------------------------------
C
      CALL CPARAM              | READ INPUT PARAMETERS
      CALL DATE(LDATE)         | CLOCK STARTS TICKING
      CALL TIME(LTIME)
      WRITE (IOUT,710)  (LDATE(I),I=1,9), (LTIME(I),I=1,8)
```

```
  710  FORMAT(' RSO: DATE: ',9A1,10X,' TIME: ',8A1)
C-----------------------------------------------------------------
       XTIME = -1.0
       DO 10 I=1,4
       SHIM(I)=SHIM(I)*PSCAL/ADGAIN**2
       BIAS(I)=BIAS(I)*PSCAL
   10  SCAL(I)=SCAL(I)*PSCAL
       DO 20 I=1,NCHN
   20  SCAL(I)=SCAL(I)/ADGAIN
       CALL INPUTC
C------------------------------------------------------------------
   50  DUM=10.**NFRQ
       PRESET=AINT(DUM*SAMTIM)
       IF(PRESET.LE.65535.) GO TO 40
       NFRQ=NFRQ-1
       GO TO 50
   40  SAMTIM=PRESET/DUM
       NFRQ1=7-NFRQ
C------------------------------------------------------------------
   75  TYPE *,' ENTER POWER SET POINT IN KW ¢1000.,2100.!'
       ACCEPT *,PSET
       IF(PSET.LT.1000..OR.PSET.GT.2100.) GO TO 75
  130  TYPE 600
  600  FORMAT(/' ENTER "GO" TO START')
       ACCEPT 700,DUM
  700  FORMAT(A2)
       IF(DUM.NE.'GO') GO TO 130
C-----------------------------------------------------------------
       CALL DISPLY(2)
       CALL TTINIT
C--------------------------------------------------------------------------
  160  ICMF=0
       ICMFC=0
       CALL SETR(-1,0,,,)
       CALL SETR(NFRQ1,0,9,PRESET,ICMFC)
       XTIME = XTIME + 1.0
C--------------------------------------------------------------------------
C READ A/D CONVERTER OUTPUTS ( INFO )
       CALL RTS(INFO,NCHN,1,1,0,NCHN,1,1,2,ICMF,IBEF,,FDITST)
       LP2=LLCHAR()
       IF(LP2.EQ."377) GO TO 120
       IF(LP2.NE."015) GO TO 140
       IF(LP1.EQ."006) GO TO 906  ! CTRL-F To update screen refresh inter
       IF(LP1.EQ."016) GO TO 916  ! CTRL-N To clean the scroll region
       IF(LP1.EQ."027) GO TO 927  ! CTRL-W To change power set point
       IF(LP1.EQ."031) GO TO 931  ! CTRL-Y To stop the program
       IF(LP1.EQ."067) GO TO 967  ! 7 To freeze/defreeze the screen
       GO TO 150
C-------------------------------------------------------------------------
  967  LPRN=.NOT.LPRN             ! FREEZE/DEFREEZE SCREEN
       GO TO 150
C-------------------------------------------------------------------------
  906  CALL DISPLY(1)             ! REFRESH INTERVAL
       CALL TTRSET
       WRITE(IPRN,*) ' ENTER # OF SAMPLES (>=1) AS SCREEN REFRESHING
     @ INTERVAL'
       ACCEPT *,IDSP
       IF(IDSP.LE.1) IDSP=1
       CALL TTINIT
       GO TO 150
C-------------------------------------------------------------------------
  927  CALL DISPLY(1)              ! SET POINT CHANGE
       CALL TTRSET
  650  WRITE(IPRN,*) ' ENTER NEW SET POINT IN KW ¢1000.,2100.!'
       ACCEPT *,PSET
       IF(PSET.LT.1000..OR.PSET.GT.2100.) GO TO 650
       CALL TTINIT
       GO TO 150
C-------------------------------------------------------------------------
  916  CALL DISPLY(1)      ! CLEAN SCROLL REGION
       GO TO 150
C-------------------------------------------------------------------------
  140  LP1=LP2
```

```
      GO TO 120
C-----------------------------------------------------------------------
  150 LP1="377
  120 CALL LWAIT(ICMF,0)
      GO TO 160
C-----------------------------------------------------------------------
  931 CALL DISPLY(1)        ! CTRL-Y
      WRITE(IPRN,*) ' GRACEFUL TERMINATION OF THE CONTROL & INFOR
     @MATION DISPLAY PROGRAM'
      CALL EXIT
      END
      BLOCK DATA          ! FOR ON LINE-DEMO
C=======================================================================
C PURPOSE: DATA BANK FOR THE MIT REACTOR SIGNAL VALIDATION PROGRAM
C MODIFIED BY RSO FOR THE ON-LINE DEMO OF THE RECONFIGURABLE CONTROLLER
C=======================================================================
      LOGICAL*1 LPRN
      COMMON/AREA01/IPRN,IDSP,NCHN,ADGAIN,NFRQ,PSCAL
      DATA IPRN,IDSP,NCHN,ADGAIN,NFRQ,PSCAL
     $     /7,5,18,409.6,4,965./
C-----------------------------------------------------------------------
       COMMON/AREA03/SCAL(16),SHIM(4),BIAS(16)
C FROM MDATFL.FOR
       DATA SCAL/1.1054,1.281,1.3540,1.2546,520.6,612.6,691.8,691.8
     $,1.530,1000.,15.00,13.96,15.,15.,9.295,9.375/
       DATA BIAS/0.302,0.1817,0.4801,0.4610,-1400.,-668.,0.,0.
     $,-3.0,0.,-15.0,-15.0,-15.,-15.,-49.0,-21.8/
       DATA SHIM/0.,-0.2571,-0.0961,-0.0808/
C-----------------------------------------------------------------------
       COMMON/LOGIC/LPRN
       DATA LPRN/.FALSE./
C-----------------------------------------------------------------------
       COMMON/SAMPLE/XSAM,SAMTIM,IALARM
       DATA XSAM, SAMTIM, IALARM / 0.0, 0.5, 6 /
C-----------------------------------------------------------------------
C RSO'S COMMON BLOCKS
C-----------------------------------------------------------------------
      COMMON /CTIME / TIME, TSAM
      DATA TIME, TSAM / 0.0, 1.0 /
C-----------------------------------------------------------------------
      COMMON /CSET  / PSET, DESDP, DESSUR, DESTAU
      DATA PSET, DESDP, DESTAU / 1000., 0.3, 300. /
C-----------------------------------------------------------------------
      COMMON /CFILT / TFILTP, TFILTS
      DATA TFILTP, TFILTS / 2* 1.0 /
C-----------------------------------------------------------------------
      COMMON /RPARAM/ BAND(2,2), GAIN(4,2), TRHO, BETA(3), DEL(3)
      DATA BAND, TRHO / 2*20., 2*10., 1. /
      DATA GAIN  / 1.0, 0.0, 0.0, 500., 1.0, 0.0, 0.0, 500. /
      DATA BETA, DEL /0.0333, 0.3416, 0.6251,  0.0124, 0.0369, 0.632/
C-----------------------------------------------------------------------
      COMMON /LPARAM/ ARP, BRP
      DATA ARP, BRP / 2*0.5/
C-----------------------------------------------------------------------
      COMMON/A/RL,BETT,RD(6),B(6),DN(6),DECAY
      DATA RL/0.0001/
      DATA RD/0.0124,0.0305,0.111,0.301,1.14,3.01/
      DATA BETT/0.00786/
      DATA B/0.00026,0.00172,0.00154,0.00311,0.00090,0.00033/
C-----------------------------------------------------------------------
      END
      SUBROUTINE CPARAM     ! ON-LINE DEMO
C==============================================================
C READS AND WRITES INPUT PARAMETERS
C==============================================================
      COMMON / CTIME / TIME, TSAM
      COMMON / CSET / PSET, DESDP, DESSUR, DESTAU
      COMMON / CIOCON/ IINP, IOUT, KPRIN
      COMMON / CSROD/ SVRR, SVSB
      COMMON / CFILT/ TFILTP, TFILTS
      COMMON / RPARAM/ BAND(2,2), GAIN(4,2), TRHO, BETA(3), DEL(3)
      COMMON / LPARAM/ ARP, BRP
      COMMON / CPLANE/ DTAUS(2), PS, DBUF(2)
      COMMON / ERHOV / ERHO
```

```
      COMMON / CREV / IREV
      COMMON / CDESP/ STEADY
      COMMON / CFUZ / IFUZ1, IFUZ2
      TIME = 0.0
      TSAM = 1.0
      IINP = 15
      CALL ASSIGN ( IINP, 'T2.DAT' )
      READ ( IINP, * ) IOUT, KPRIN, IREV,IFUZ1,IFUZ2
      READ ( IINP, * ) DESDP, DESTAU, STEADY
      READ ( IINP, * ) TFILTP, TFILTS
      READ ( IINP, * ) SVRR, SVSB
      READ ( IINP, * ) ARP, BRP
      READ ( IINP, * )  (BAND(I,1),I=1,2),(GAIN(I,1), I = 1, 4 ), TRHO
      READ ( IINP, * )  (BAND(I,2),I=1,2),(GAIN(I,2), I = 1, 4 )
      READ ( IINP, * )  (DTAUS(I),I=1,2),PS,(DBUF(I),I=1,2)
      READ ( IINP, * ) ERHO
      IF ( DESDP  .LE. 0.0 ) DESDP  =   1.0
      IF ( DESTAU .LE. 0.0 ) DESTAU = 300.0
      DESSUR = 26.06/DESTAU
      IF ( BAND(2,1) .LE. 0.0 ) BAND(2,1) = 20.0
      IF ( BAND(2,2) .LE. 0.0 ) BAND(2,2) = 20.0
      CLOSE(UNIT=IINP,DISPOSE='SAVE')              ! VALID ONLY IN LSI-11/23
C-----------------------------------------------------------
      IF ( KPRIN .EQ. 0 ) GO TO 900
      WRITE ( IOUT, 100 )
  100 FORMAT ( 1X, 'CONTROLLER PARAMETERS' )
      WRITE (IOUT, 110) PSET, DESDP, DESTAU, DESSUR
      WRITE (IOUT, 120) TFILTP, TFILTS
      WRITE (IOUT, 130) SVRR, SVSB
      WRITE (IOUT, 140)  (BAND(I,1),I=1,2),(GAIN(I,1), I=1,4),TRHO
      WRITE (IOUT, 140)  (BAND(I,2),I=1,2),(GAIN(I,2), I=1,4),TRHO
      WRITE (IOUT, 150)  (DTAUS(I),I=1,2), PS, (DBUF(I),I=1,2)
      WRITE (IOUT, 160) ERHO, ARP, BRP
  110 FORMAT(' PSET, DESDP, DESTAU, DESSUR: ', 1P,4(E9.2,1X))
  120 FORMAT(' FILTER TAUS- TFILTP, TFILTS: ', 1P,2(E9.2,X))
  130 FORMAT(' MOTOR SPEED- SVRR  , SVSB  : ', 1P,2(E9.2,1X))
  140 FORMAT(' BAND,BANDIN,GAIN-PIDR, TRHO: ', 1P,7(E9.2,1X))
  150 FORMAT(' DTAUS, PS, DBUF            : ', 1P,5(E9.2,1X))
  160 FORMAT(' ERHO (MILLIBETA), A, B     : ', 1P,3(E9.2,1X))
C-----------------------------------------------------------
      WRITE(IOUT, 190 )
  190 FORMAT (1X, '  TIME    DEVP, FSUR, FTAU, PFAC,                 '/
     1        1X, '  FPOW    FTPC , FHRR, FHSB, CONRR, CONSB         '/
     3        1X, '  RHOKIN, DELK, DKRR, DKT, DKSB, DC               '/
     4        1X, '  ICONF, KFLAG, KFLAGS, IDCON, IDROD,             '/
     5        1X, '  ISTAR, HU, VAL2, VAL1                             '/
     5        1X, '  IPOS,IRSHIM,ISTAT,NFLAGS,IRHO(1,2)',
     5            'IRHOB-K,QV,QC IOVER'/
     6        1X, '======================================== ')
C---------------------------------------------------------------
  900 CONTINUE
      RETURN
      END
       SUBROUTINE DISPLY(INDEX)
C========================================================================
C AUTHOR: A. RAY
C MODIFIED BY RSO FOR ON-LINE DEMO OF RECONFIGURABLE CONTROLLER
C PURPOSE: TO GENERATE A REAL-TIME DISPLAY OF IMPORTANT PROCESS VARIABLE
C          IN THE MITR-II SIGNAL VALIDATION AND COMPUTER CONTROL PROGRAM
C========================================================================
       LOGICAL*1 LDATE,LTIME
       COMMON/AREA01/IPRN,IDSP,NCHN,ADGAIN,NFRQ,PSCAL
       COMMON/LOGIC/LPRN
       COMMON/DATE/LDATE(9),LTIME(8)
       COMMON/SAMPLE/XSAM,SAMTIM,IALARM
C----------------------------------------------------------------------
       IF(INDEX.EQ.1) GO TO 100
       IF(INDEX.EQ.2) GO TO 200
       GO TO 900
C-----------------------------------------------------------------------
C Bring cursor to 21;1, clear upto end of screen, bring cursor to 21;1
  100  WRITE(IPRN,101) "033,"133,"062,"061,"073,"061,"146, "033,"133,
     @"112, "033,"133,"062,"061,"073,"061,"146 ! ESC¢20;1f ESC¢J ESC¢20;
```

```
      GO TO 900
C-----------------------------------------------------------------
C Draw the statinary format for the display
  200 WRITE(IPRN,101) "033,"133,"062,"112, "033,"133,"062,"061,
     @"073,"062,"064,"162, "033,"133,"061,"073,"061,"146
C ESC¢2J  ESC¢21;24r ESC¢1;1f Clear screen, define scroll, and start fro
      WRITE(IPRN,102)  (LDATE(I),I=1,9),(LTIME(I),I=1,8),SAMTIM
      GO TO 900
C-----------------------------------------------------------------
  101 FORMAT('$',30A1)
  102 FORMAT(T2,79('*')/T2,'*',9X,'SIGNAL VALIDATION AND COMPUTER CONT
     @ROL OF POWER AT MITR-II',T80,'*'/T2,'*',8X,'Date of experimentatio
     @n:',1X,9A1,3X,'Starting time:',1X,8A1,T80,'*'
     @/T2,'*',7X,'RESULTS AT SAMPLE #'
     @,15X,'  Sampling period: ',F5.2,' sec',T80,'*'/T2,'*',T80,'*'/
     @T2,'*',27X,'POWER SENSOR DIRECTORY',T80,'*'/T2,'*',6X,'Sensor',5X,
     @'Output(KW)',5X,'Bias(KW)',5X,'Weight',5X,'Operating status',T80,
     @'*'/T2,'*',
     @7X,'ch-7',T80,'*'/T2,'*',7X,'ch-8',T80,'*'/T2,'*',7X,'ch-9',T80,
     @'*'/T2,'*',7X,'N-16',T80,'*'/T2,'*',T80,'*'/T2,'*',1X,'ESTIMATED
     @POWER: ',7X,'KW as a weighted av
     @erage of ',T80,'*'/T2,'*',T80,'*'/T2,'*',13X,'PRIMARY COOLANT FLOW
     @ AND TEMPERATURE MEASUREMENTS',T80,'*'/T2,'*',1X,'Primary coolant
     @ flow estimate:',33X,' gpm',T80,'*'/T2,'*',1X,'Hot leg to cold leg
     @ temperature difference estimate:',13X,'deg C',T80,'*'/T2,'*',1X,
     @'Analytic Value of temperature difference ¢DTa]:',18X,'deg C',T80,
     @'*'/T2,'*',1X,'Alarm system for deviation of DTa active?',T80,'*'/
     @T2,79('*'))
C-----------------------------------------------------------------
  900 RETURN
      END
      SUBROUTINE FDITST | FDI ALGORITHM TESTING ON MITR
C=========================================================
C AUTHOR: A.RAY
C MODIFIED BY RSO FOR ON-LINE DEMO OF RECONFIGURABLE CONTROLLER
C PURPOSE: GENERATES SENSOR INFORMATION & CALLS CONTROL PROGRAM
C=========================================================
      LOGICAL*1 LPRN
      REAL*8 APWR(4)
      DIMENSION PWR(4)
      COMMON/AREA01/IPRN,IDSP,NCHN,ADGAIN,NFRQ,PSCAL
      COMMON/AREA02/INFO(18),SENS(16)
      COMMON/AREA03/SCAL(16),SHIM(4),BIAS(16)
      COMMON/LOGIC/LPRN
      COMMON/SAMPLE/XSAM,SAMTIM,IALARM
      COMMON/MODEL1/ PWRE
      COMMON/CTIME / TIME, TSAM
      EQUIVALENCE ( SENS(1), PWR(1) )
      DATA IJK/0/
      DATA APWR / 4*' ACTIVE ' /
C-----------------------------------------------------------
      DO 10 I=1,4                                  | POWER SENSORS
      SENS(I)=(SCAL(I)+SHIM(I)*INFO(15))*INFO(I)
      SENS(I)=SENS(I)+BIAS(I)
   10 IF(SENS(I).LE.0.)  SENS(I)=0.
      SENS(10)=SCAL(10)*INFO(10)
C----------------------------------------------------------
      IF  ( TIME .GT. 0.0 ) GO TO 30
      IF(.NOT.LPRN) WRITE(IPRN,101)
     @"33,"133,"64,"73,"63,"61,"146,XSAM,
     @"33,"133,"70,"73,"61,"70,"146,PWR(1),APWR(1),
     @"33,"133,"71,"73,"61,"70,"146,PWR(2),APWR(2)
C-----------------------------------------------------------
      IF(.NOT.LPRN) WRITE(IPRN,102)
     @"33,"133,"61,"60,"73,"61,"70,"146,PWR(3),APWR(3),
     @"33,"133,"61,"61,"73,"61,"70,"146,PWR(4),APWR(4)
C-----------------------------------------------------------
   15 CALL DISPLY(1)
      WRITE (IPRN,*) ' ENTER ID OF POWER SENSOR TO BE USED (1 TO 4)'
      ACCEPT *, IDSEN
      IF ( IDSEN .LT. 1 .OR. IDSEN .GT. 4 ) GO TO 15
      DO 20 I=1,4
   20 IF ( I .NE. IDSEN) APWR(I) = 'INACTIVE'
C-----------------------------------------------------------
```

```
  30  CONTINUE
      PWRE = SENS(IDSEN)
C--------------------------------------------------------------
C D/A CONVERTER OUTPUT OF ESTIMATED POWER
      I=INT(PWRE*.2048)
      IF(I.GE.0.OR.I.LE.2047) GO TO 211
      WRITE(IALARM,712)
      IF(IALARM.EQ.6) REWIND IALARM
      CALL XWAIT(1.5)
      CALL HALT
 211  CALL IDAC(0,0,I)
C--------------------------------------------------------------
      IF(IJK.NE.0) GO TO 820                             | SCREEN
      IF(.NOT.LPRN) WRITE(IPRN,101)
     @"33,"133,"64,"73,"63,"61,"146,XSAM,
     @"33,"133,"70,"73,"61,"70,"146,PWR(1),APWR(1),
     @"33,"133,"71,"73,"61,"70,"146,PWR(2),APWR(2)
C-----
 101  FORMAT('$',7A1,F9.0,  7A1,F7.0,8X,5X,10X,4X,9X,A8,
     @                      7A1,F7.0,8X,5X,10X,4X,9X,A8)
C--------------------------------------------------------------
      IF(.NOT.LPRN) WRITE(IPRN,102)
     @"33,"133,"61,"60,"73,"61,"70,"146,PWR(3),APWR(3),
     @"33,"133,"61,"61,"73,"61,"70,"146,PWR(4),APWR(4)
C-----
 102  FORMAT('$',8A1, F7.0,8X,5X,10X,4X,9X,A8,
     @              8A1, F7.0,8X,5X,10X,4X,9X,A8)
C--------------------------------------------------------------
      IF(.NOT.LPRN) WRITE(IPRN,103)
     @"33,"133,"61,"63,"73,"62,"60,"146,PWRE,"33,"133,"61,"63,"73,"65,
     @"64,"146
C-----
 103  FORMAT('$',8A1,F6.0,8A1)
C--------------------------------------------------------------
 820  CONTINUE
C--------------------------------------------------------------
C PRIMARY COOLANT FLOW MEASUREMENTS                    | 5,6,7,8 = FLOWS
C       DO 50 I=5,9                                    | 9 = DT
C       SENS(I)=SCAL(I)*INFO(I)+BIAS(I)                | 11, 12 = THOT
C   50  IF(SENS(I).LE.0.) SENS(I)=0.                   | 13, 14 = TCOLD
C       DTM(1)=SENS(9)
C       DTM(2)=SCAL(11)*(INFO(11)-INFO(13))
C       DTM(3)=SCAL(12)*(INFO(12)-INFO(14))
C--------------------------------------------------------------
C DIGITAL CONTROLLER ACTION
 60   CALL RCON
      XSAM=XSAM+1
      IJK=IJK+1
      IF(IJK.GE.IDSP) IJK=0
C--------------------------------------------------------------
      RETURN
 712  FORMAT(' D/A CONVERTER OUT OF RANGE; PROGRAM HALTED')
      END
      SUBROUTINE INPUTC
C=====================================================================
C AUTHOR: A. RAY
C MODIFIED BY RSO FOR ON-LINE DEMO OF RECONFIGURABLE CONTROLLER
C PURPOSE: TO INITIALIZE PROGRAM PARAMETERS
C=====================================================================
      COMMON/AREA01/IPRN,IDSP,NCHN,ADGAIN,NFRQ,PSCAL
      COMMON/AREA03/SCAL(16),SHIM(4),BIAS(16)
      COMMON/SAMPLE/XSAM,SAMTIM,IALARM
C---------------------------------------------------------------------
 100  TYPE 110                              | SAMTIM = 0.5
 110  FORMAT('$','Want to modify sample time of .5 s? ')
      ACCEPT 20,DUM
 20    FORMAT(A1)
      IF(DUM.NE.'Y') GO TO 200
 205  TYPE *, ' enter desired value of sample time ( > zero)'
      ACCEPT *,SAMTIM
      IF(SAMTIM.LE.0.) GO TO 205
C---------------------------------------------------------------------
 200  CONTINUE
      RETURN
```

```
       END
      SUBROUTINE OUTPUT     | ON-LINE DEMO
C===================================================================
C PRINTS SELECTED RESULTS
C===================================================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON/A/RL,BETT,RD(6),B(6),DN(6),DECAY
      COMMON /CTIME / TIME, TSAM
      COMMON /CIOCON/ IINP, IOUT, KPRIN
      COMMON /CSET   / PSET, DESDP, DESSUR, DESTAU
      COMMON /CREF   / PREF, HRRREF, HSBREF, TPCREF
      COMMON /CRHO   / DKRR, DKSB, DKT, DELK, DELKRF, DC
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
      COMMON /CFILT  / TFILTP, TFILTS
      COMMON /CSTATE/ DEVP(2), FSUR(2), FTAU(2), PFAC, KFLAG,
     1                ADEVP(2), FASUR, FATAU, HDEL(2)
      COMMON /CSEL   / IDCON(2), IDROD(2)
      COMMON /CCONF  / ICONF(2), ISTATE, JDEV, JSUR, KFLAGS, ISCOM
      COMMON /CUSENS/ RNX, TPCX, HRRX, HSBX(2)
      COMMON /LPARAM/ ARP, BRP
      COMMON /RPARAM/ BAND(2,2), GAIN(4,2), TRHO, BETA(3), DEL(3)
      COMMON /JLIMIT/ TLIM, SIGX(2)
      COMMON /RTEMP/ RHOKIN, AD(6)
      COMMON /CMODE/ IRSHIM, IPOS, NFLAGS, ITRAN, QMOTOR, QOVER
      COMMON /JPARA1/ VALB(2), VALK(2), IRHOB(2), IRHOK(2),
     1                QVRHO(4), QCONS(2), IRHO(2)
      COMMON /CPERF/HU, ISTAR
      COMMON /JPARAM/ RX(2), VAL1(2), VAL2
      COMMON /COVER/ IOVER
C--------------------------------------------------------------------
      IF  ( KPRIN  .EQ.  0 )  GO TO 900
      IF  ( TIME.LE.0.0)  WRITE  (IOUT, 110)  PSET, DESDP, DESTAU, DESSUR
  110 FORMAT(' PSET, DESDP, DESTAU, DESSUR: ', 1P,4(E9.2,1X))
      WRITE(IOUT,210)  TIME, DEVP(2), FSUR(2), FTAU(2), PFAC
      WRITE(IOUT,220)  FPOW(2), FTPC, FHRR, FHSB(1), CONT(1), CONT(2)
      WRITE(IOUT,220)  RHOKIN,  DELK,     DKRR, DKT,  DKSB, DC
      WRITE(IOUT,230)  ICONF(2), KFLAG, KFLAGS, IDCON(2), IDROD(2),
     1             ISTAR, HU,VAL1(1), VAL2
      WRITE(IOUT,240)  IPOS,IRSHIM,ISTAT,NFLAGS, (IRHO(I),I=1,2),
     1 IRHOB(1), IRHOK(1), IRHOB(2), IRHOK(2), QVRHO(4), (QCONS(I),I=1,2)
     2 ,IOVER
  210 FORMAT  ( 1X, F7.1, 1X,1P, 4(E10.3,1X))
  220 FORMAT  ( 1X,    7X, 1X,1P, 6(E10.3,1X))
  230 FORMAT  ( 1X,    7X, 1X,     6(I3   ,1X),1P,3(E10.3) )
  240 FORMAT  ( 1X,    7X, 1X,    10(I3   ,1X),    3(L2,1X),I4 )
  900 RETURN
      END
      SUBROUTINE RCON   | FOR ON-LINE DEMO
C==============================================================
C CALLED BY FDITST: RR , #1 & #4 SB CONTROL
C==============================================================
      IMPLICIT LOGICAL*1  (Q)
      COMMON /CTIME / TIME, TSAM
      COMMON /CSEL   / IDCON(2), IDROD(2)
      COMMON /CSROD / SVRR, SVSB
      COMMON /CFILT  / TFILTP, TFILTS
      COMMON /CFSENS/ FPOW(2), FTPC, FHRR, FHSB(2), CONT(2)
C-----------------------------------------------------------------------
      COMMON /SAMPLE/ XSAM, NITER, XTSAM
      COMMON /MODEL1/ PWRE
      COMMON /AREA02/ INFO(18), SENS(16)
      COMMON /AREA03/ SCAL(16), SHIM(4), BIAS(16)
      COMMON /BSAFE  / QSAFE(5)
C-----------------------------------------------------------------------
      FPOW(2)  =  PWRE                   | SENSOR READINGS
      FTPC     =  SCAL(11)*INFO(11)  + BIAS(11)
      FHRR     =  SCAL(16)*INFO(16)  + BIAS(16)
      FHSB(1)  =  FLOAT(INFO(18)-237  )*6.3586791E-03 + 0.07    | #4
      FHSB(2)  =  FLOAT(INFO(15)-2147)*2.2819956E-02 + 0.03    | #1
C-----------------------------------------------------------------------
      IF  ( TIME  .GT.  0.0 )  GO TO 500
      CONT(1)  =  0.0
      CONT(2)  =  0.0
C-----------------------------------------------------------------------
```

```
  500 CONTINUE
C-----------------------------------------------------------------------
C FILTER SIGNALS: FILTER CONSTANTS CAN BE SCHEDULED
      CALL FILTER ( FPOW(2), RNO,  FPOW, TFILTP, AP, BP )
C-----------------------------------------------------------------------
      CALL STATE
      CALL RHOVAL
      CALL SAFETY
      IF ( .NOT. QSAFE(5) ) GO TO 550
C-----------------
      CALL MODE
      CALL USEL
C----------------
  550 CALL OUTPUT
C-----------------------------------------------------------------------
C CALL ACTUATOR INTERFACE
      CALL DISPLY(1)
      TYPE *, ' TIME, CONRR, CONSB = ', TIME, CONT(1), CONT(2),IDCON(2)
C-----------------------------------------------------------------------
      MSIG = CONT(1)*2047.                ! REG ROD CONTROL SIGNAL
      IF ( MSIG .GT. 2047 ) MSIG = 2047
      IF ( MSIG .LT.-2047 ) MSIG =-2047
      I = MSIG - 1
      CALL IDAC (3, 0, I    )
      CALL IDAC (3, 0, MSIG )
      CALL IDAC (1, 0, I    )
      CALL IDAC (1, 0, MSIG )
C-----------------------------------------------------------------------
C SHIM BLADE
C ADD SHIM BLADE INTERFACE ROUTINE HERE
C-----------------------------------------------------------------------
  900 CALL TSAVE
      RETURN
      END
```

APPENDIX K. LIST OF REFERENCES

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