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B&W PWR ADVANCED CONTROL SYSTEM ALGORITHM DEVELOPMENT

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ABSTRACT

In 1987 the B&W Owners Group (B&WOG) initiated a development program to design and implement an advanced plant control system for the domestic B&W-designed nuclear power plants. The key requirements for the advanced control system (ACS) include application of state-of-the-art digital control equipment and advanced control algorithms to achieve a highly reliable and versatile plant control system.

Development of advanced control system algorithms that could be implemented on the state-of-the-art control equipment was carried out by the Oak Ridge National Laboratory (ORNL) and the B&W Nuclear Service Company (BWNS). The advanced algorithm development program utilized a Modular Modeling System (MMS) based digital simulation model of the B&W-designed nuclear plants. The advanced algorithms were also programmed on the simulation model and their performance was evaluated against the algorithm's functional requirements as provided by the B&WOG.

After the algorithms were developed, including approval of the advanced control algorithms by the B&WOG, and selection by the B&WOG of the equipment supplier (Foxboro/Triconex), they were translated into a symbology compatible with the control equipment. The software was partitioned and loaded onto the hardware to achieve the desired levels of redundancy and equipment cycle time. Following installation of the

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algorithm on the control hardware, verification and validation of the algorithm translation in the vendor's control equipment was carried out using the B&W plant simulation model and one channel of the triply redundant control hardware.

This paper describes the advanced algorithm development process and the process by which the algorithm was translated into the hardware symbology, including the initial verification and validation steps. The paper emphasizes the lessons learned in the overall transformation of advanced algorithms to state-of-the-art control hardware.

1.0 INTRODUCTION

This paper discusses algorithm development of an Advanced Control System for the B&W Pressurized Water Reactor (PWR) nuclear power plant. The paper summarizes the history of the project, describes the operation of the algorithm, and presents transient results from a simulation of the plant and control system. The history discusses the steps in the development process and the roles played by the utility owners, B&W Nuclear Service Company (BWNS), Oak Ridge National Laboratory (ORNL), and the Foxboro Company. The algorithm description is a brief overview of the features of the control system. The transient results show the operation of the algorithm in a normal power maneuvering mode and in a moderately large upset following a feedwater pump trip.

2.0 DEVELOPMENT HISTORY FOR THE CONTROL ALGORITHM

The B&W Owners Group, consisting of Duke Power Company, Toledo Edison Company, GPU Nuclear Corporation, Florida Power Corporation, and Entergy Operations Incorporated (formerly Arkansas Power and Light) initiated a program in 1987 to replace the Bailey Controls Company analog-based Integrated Control System (ICS) with modern digital control hardware. The primary motives of the changeover were to improve the reliability of the control system by utilizing triply redundant hardware and to eliminate the eventual obsolescence of analog components by the analog equipment manufacturer. The B&W Owners Group also recognized the opportunity to develop an improved control algorithm. Some of the improvements sought by the owners are listed below:

- Direct control of reactor thermal power at the licensed power level through on-line heat balance calculation.
- Full automatic control from 1% to 100% of full power.
- Prioritized control of system parameters to maintain control of the most important parameters despite actuators reaching limits or hand/auto stations being placed in manual.
- Coordination of reactor coolant pressure system and inventory controls with the heat transport controls.
- Automatic loading and unloading of the main turbine and the turbine driven feedwater pumps.

- Elimination of windup problems in the integral functions used for power calibration between the heat transport systems.

- Improvement in transitions between control modes, especially between the steam generator level and reactor coolant average temperature control mode.

The B&WOG recognized the need to capture the objectives and ideas of their operations staffs in a functional requirements document that would serve as a guide to the controls developers and a benchmark against which control designs could be measured. The document took shape in a series of working meetings under the direction of the B&WOG Advanced Controls Task Force. The Task Force included representatives from the Owners Group utilities and BWNS and an advisory panel with representatives from EPRI, NASA, and ORNL. The functional requirements document was a key element in the success of the Advanced Control System project. The Task Force was careful to limit the document to stating *what* the control system was to do and not *how* it was to do it. In preparing the requirements document, the Task Force had to come to a consensus about their preferences and objectives for the new control system. Thus, the functional requirements were primarily determined by the personnel who would have to actually use the control system. The designer's job was to determine how to implement these requirements.

To encourage new ideas for the control system design, the B&WOG contracted an independent control system designer to develop preliminary system designs. The Oak Ridge National Laboratory was selected as the contractor not only because of its experience in control system design and nuclear power plant modeling but also because of their fresh perspective on the B&W plant controls. BWNS supplied an expert in plant operation and in the existing ICS who worked at ORNL for most of the design development. BWNS also supplied a simulation of the B&W plant with the existing control system.

A number of alternative control concepts were developed and compared with each other and the functional requirements in a competitive evaluation process. In the first round of evaluations, three designs were presented along with simulations of their performance on a series of transients. In meetings with the B&WOG, the concepts were assessed and the best ideas of each identified. The transient comparisons were difficult and imprecise because the plant simulation models for each were different.

As a next step, two of the preliminary concepts were further developed and the transient assessments were made using identical plant models. The evaluation reviewed the transient performance of the two concepts on approximately 60 transients. Again, the B&WOG assessed the performance and compared the control system design with the functional requirements. The final design incorporated the best features of all the designs. This completed the algorithm design phase. The performance of the final control algorithm was demonstrated by simulations of more than 100 transients shown to the B&WOG for final acceptance.

The next phase of the development was implementation. About the time the algorithm development was completed, the B&WOG selected Foxboro as the hardware vendor. The control algorithm, existing at ORNL as a computer code written in the Advanced Continuous Simulation Language (ACSL), had to be converted to the application language of the Foxboro Intelligent Automation (I/A) series of digital control hardware. The ORNL designers converted the algorithm into a set of schematics using the symbols and diagramming format of the Scientific Apparatus and Makers Association (SAMA) Functional Diagramming Standard. The B&WOG felt that the SAMA diagrams would give a standard representation of the mathematical steps in the control algorithm. Our experience revealed that the SAMA schematics have several important deficiencies for representing a digital control algorithm:

- Integral functions have no standard input for setting or resetting the initial condition.
- Integral functions have no standard hold or track feature for implementing anti-windup and bumpless transfer.
- No provision is made for specifying the order of execution for a digital implementation that must execute the function blocks serially.
- No standard format is given for specifying parameters and constants for function blocks.

The translation of the schematics into the Foxboro I/A application language was a cooperative effort involving BWNS and Foxboro. BWNS supplied the expertise on the operating characteristics and control actuators of the B&W-designed plants. Foxboro brought to the translation task their experience in the operation of I/A system function modules and in applying the I/A system to a control system development environment. Foxboro trained B&WOG personnel using their standard training courses. Implementation proceeded as a team effort. The ORNL SAMA schematics were translated almost directly into the Foxboro I/A symbology. However, it was necessary to redraw the control system schematics to conform to Foxboro conventions and represent the algorithm as implemented.

One of the difficulties in the translation step was communicating from designer to implementer. The set of schematics can be difficult to understand because they represent all possible control modes as well as the logic for transferring among control modes. Locating the active mode among all possible modes can be confusing. The set of schematics needs to be accompanied by written documentation to explain how the algorithm works and lay out the function the designer intended.

Another task at Foxboro was developing of the hardware and software for a triply redundant control system. The I/A system has been installed in many production sites in singly and dually redundant configurations. The B&WOG project is the first instance of a triply redundant control system. The B&WOG has played a key role in decision-making on the design of the software system for the triply redundant configuration. Again, close communication and frequent review have ensured that the product meets both the specifications and the needs of the B&WOG while still meeting the schedule for prototype delivery.

The testing and verification of the control system as implemented on a Foxboro I/A system consists of the preliminary review using the I/A System's Engineering Test Lab followed by a detailed verification and validation program. The checkout on the Foxboro Engineering Test Lab was limited to exercising the control system with open loop steps and ramps on the system inputs. Closed loop transients were not possible because a full plant simulation of the B&W plant was not available on the Engineering Test Lab. The detailed verification and validation program will use both the plant model from the ORNL design step as well as a B&W plant training simulator to drive the Foxboro hardware in closed loop real time execution.

Checkout with the simulation program used by ORNL, is currently underway. A single channel of the triply redundant system has been developed at BWNS and the ORNL plant simulation model is connected to it via a Foxboro data handling component. A program of 40 transients similar to the set performed by ORNL will be run to verify the single channel implementation. Next, a complete triply redundant system will be tested at the Advanced Control System Test Facility at Toledo Edison's Davis-Besse Nuclear Station. The test program for the triply redundant system using the training simulator is still under development.

3.0 OVERVIEW OF THE ADVANCED CONTROL SYSTEM

The Advanced Control System (renamed the Plant Control System or PCS) coordinates control of major power transport systems: the reactor, the feedwater system and the steam system. It also controls support systems such as the makeup and letdown control valves, pressurizer heaters and spray valves, and feed pump recirculation valves. Special circuits provide automatic loading/unloading of a second feedwater pump and the loading/unloading of the main turbine. The PCS can operate in fully automatic with either the turbine or turbine bypass system providing the steam path. The range of fully automatic control is from 1 to 100% power. All operations, including sequencing valves and starting pumps, are automatically controlled throughout this range.

The PCS control algorithm makes extensive use of digital switching logic to reconfigure the control scheme automatically to match the algorithm to the current condition of the plant. The PCS, although not impossible to construct in conventional analog components, would be impractical in size and cost because of the triple redundancy and the extensive use of switching components. Nonetheless, the normal, full-power, fully automatic control mode of the PCS control algorithm retains the basic function and control philosophy of the present BWNS Integrated Control System (ICS).

The basic control strategy of the PCS and the ICS is the feedforward-feedback design. The feedforward signal in the PCS is a centrally generated core thermal power demand signal that establishes an approximate operating point for the main power transport systems. Proportional and integral feedback actions are added to account for small errors in the feedforward function. The feedforward signal is used to maneuver the actuators to positions that correspond to the power demand. Actuators, such as the reactor control rods, feedwater valve positioners, and feedwater pump turbine governor valves, receive a direct signal to adjust to a new power setting due only to the feedforward action. The feedback gains are relatively low, so that the feedback action is slow, stable, and robust to variations in plant parameters. The combination of feedforward and feedback action in the control system gives fast response to changes in power demand while maintaining a high stability margin. The feedforward/feedback design is a key element in the PCS design for overcoming the process delay and for meeting the functional requirements on maneuverability and maximum deviations from setpoint while maintaining a smooth and stable response.

A new strategy called Control Priority specified in the functional requirements has a major impact on the design of the new control algorithm. The PCS is designed to recognize when actuator controls are in manual or when an actuator reaches the limit of its travel. The Control Priority strategy reassigns feedback errors to the available actuators as needed, so that the highest priority parameters are continually controlled.

The inputs to the control loops in the PCS are multivariate. That is, the PCS, like the ICS, combines a number of measured signals to produce each control system output signal. The difference between the PCS and the ICS is in the control strategy for the multivariate terms. The PCS strategy designates one of the errors as the primary responsibility of the control loop. The primary errors are reassigned automatically by the PCS when actuators become unavailable to implement the Control Priority strategy. Additional errors are added to the primary errors either to improve the system response or to allow fast actuators to assist weaker ones in transients for reactor trip avoidance.

Figure 1 shows the general design of the multivariate controller used in several instances in the PCS. Important characteristics of the controller are:

- Feedforward action
- Proportional and integral feedback action
- Primary error
- Auxiliary error feed through deadband or other limited action blocks.

An overview of the PCS control algorithm is shown in Figure 2. The PCS consists of the top-level core thermal power demand calculator, integrated master controller, and six system level controllers. The core thermal power demand calculator receives the operator's setting for power, modifies it for power and rate of change limits, and calculates the main demand signals which are fed forward to the subsystems. The integrated master determines which systems are available for control of the plant and feeds back the highest priority error signals with appropriate gains to the available systems. (A system is unavailable for control when it is on a limit or when it is in manual.) The system controllers handle manual/automatic transitions and cause the manipulated variable to track the demand signal. The system level controllers also determine their own status and communicate status and error signals to the integrated master controller.

4.0 PCS TRANSIENT RESULTS

During the algorithm development, ORNL tested the PCS control algorithm with more than 100 transients. The testing demonstrated that the control performance is smooth and stable over a wide range of conditions and plant operating states.

Figure 3 shows the system response to a fully automatic power ramp from 1 to 100%. At low power, the PCS must control the steam generator levels to a constant value. In this control mode, the unit average temperature varies with power level. The rate of change of power is limited to 1% per minute to allow time for the pressurizer to control the pressure and inventory changes that result from the change in temperature. At about 20 minutes, the control strategy changes from a steam generator level control to temperature control. In this mode, the steam generator levels vary with power while the temperature is held constant. The rate of change of power in this control mode can be increased to 5% per minute. The primary objectives for this transient is for the control to be smooth and fully automatic. The control algorithm handles all control mode transitions, valve sequencing, and automatic starting of the pumps and turbine. The temperatures are well controlled and all parameters remain well within their specified operating bands.

Figure 4 shows the PCS response to a more severe transient, the trip of one of the two feedwater pumps at 100% power. The reduction in feedwater flow occurs very quickly, considerably faster than either the reactor or turbine can follow. Approximately two minutes elapse before a balance between the flux, thermal power and feedwater flow can be achieved. The objective for the control system is to avoid a reactor trip by moving the actuators as fast as possible to reduce power and bring the plant smoothly into steady state operation without any integral windup and overshoot. The PCS response on this transient demonstrates the maximum rate response to a large upset disturbance.

5.0 CONCLUSIONS

A new control algorithm has been developed for implementation on B&W-designed nuclear power plants. The new design takes advantage of the capabilities of modern digital controllers to improve the control system performance and ease the operator burden in controlling the plant. The algorithm development and implementation is completed and is now progressing through a formal testing program. Yet to be completed are plant specific designs that incorporate the exact interface requirements for the individual B&W-designed plants.

The lessons learned so far from our experience are the following:

1. A detailed functional requirements document is necessary to guide the design effort for the new control algorithm.

2. Each innovation that was considered had to comply with the functional requirements and demonstrate improved performance during simulation testing.

3. Documentation of the control algorithm should consist of both a set of schematic drawings of functions and logic and a system description that explains the intent and basis for the design choices.

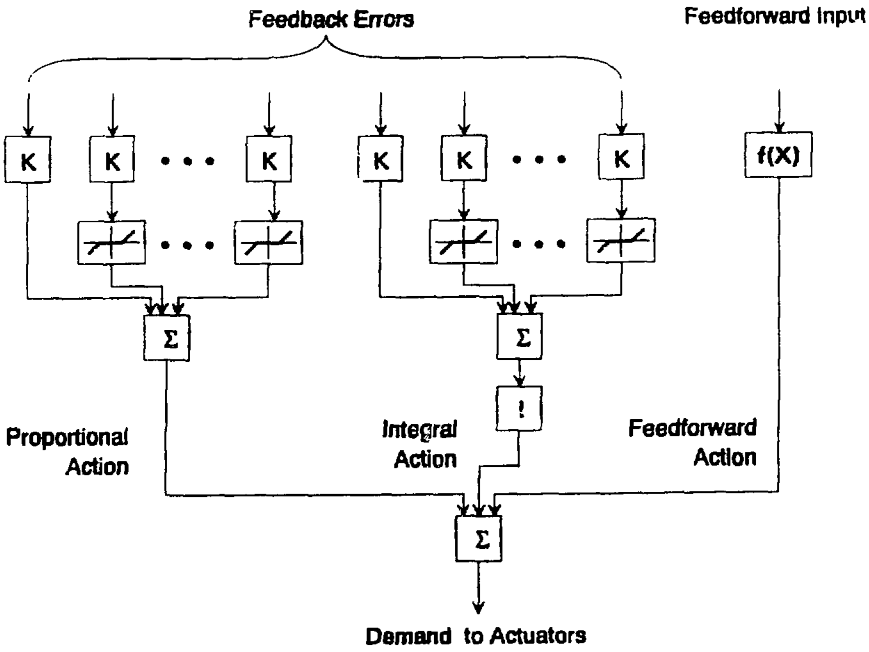

Figure 1. General arrangement of the multivariate controller.

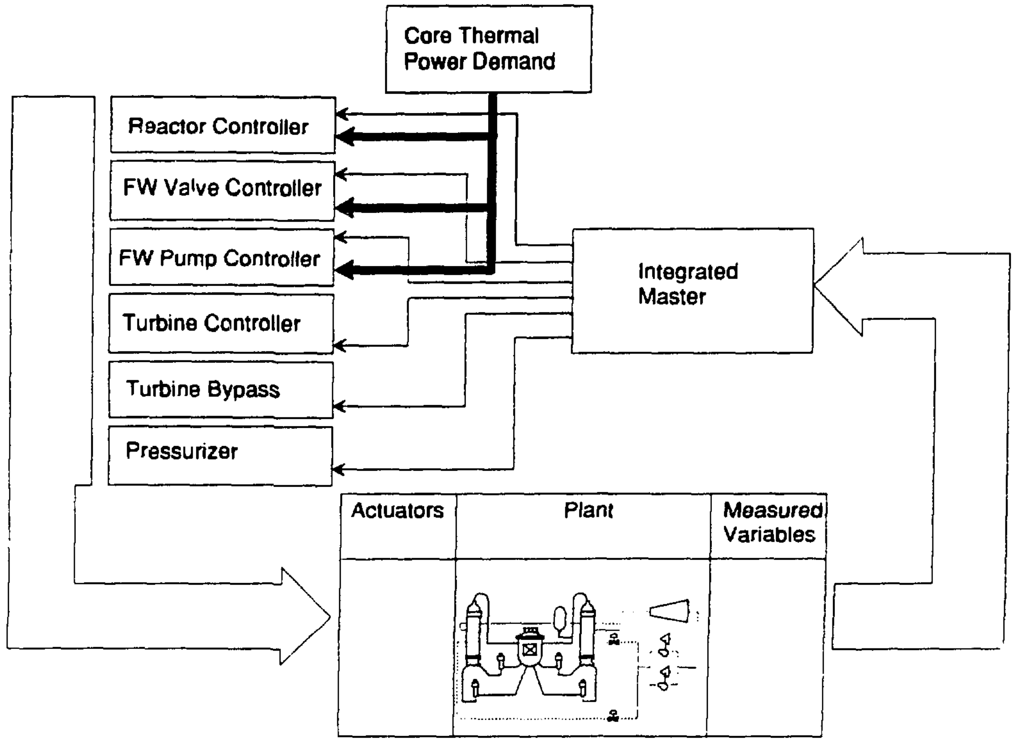

Figure 2. Control system overview shows Core Thermal Power Demand providing a feedforward action based on operator power setpoint, Integrated Master assigning feedback errors on the basis of the error priority and systems available for control action, and system level controllers operating on the plant control actuators.

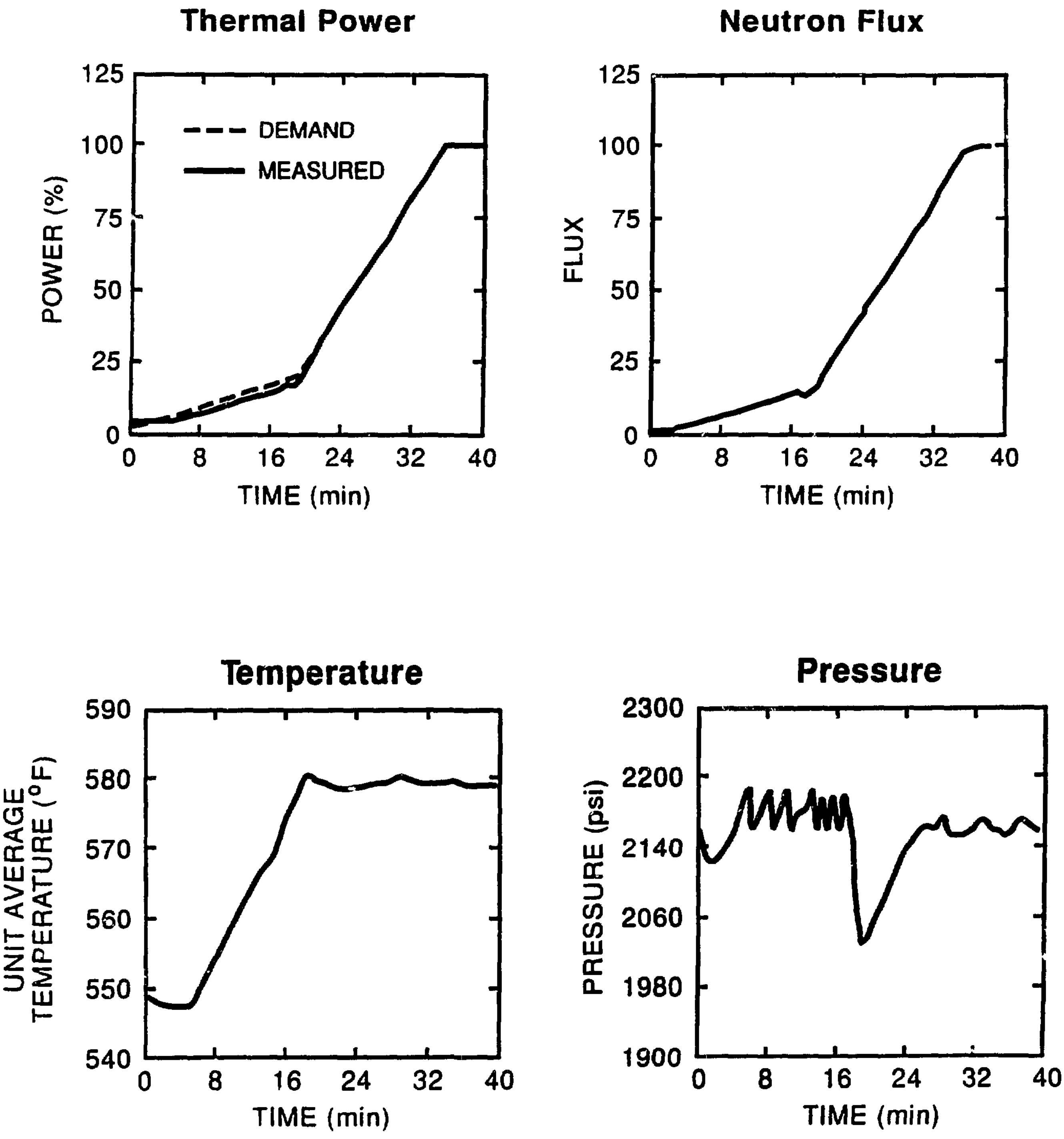

Figure 3. The normal power ramp demonstrates performance of the control system in fully automatic mode.

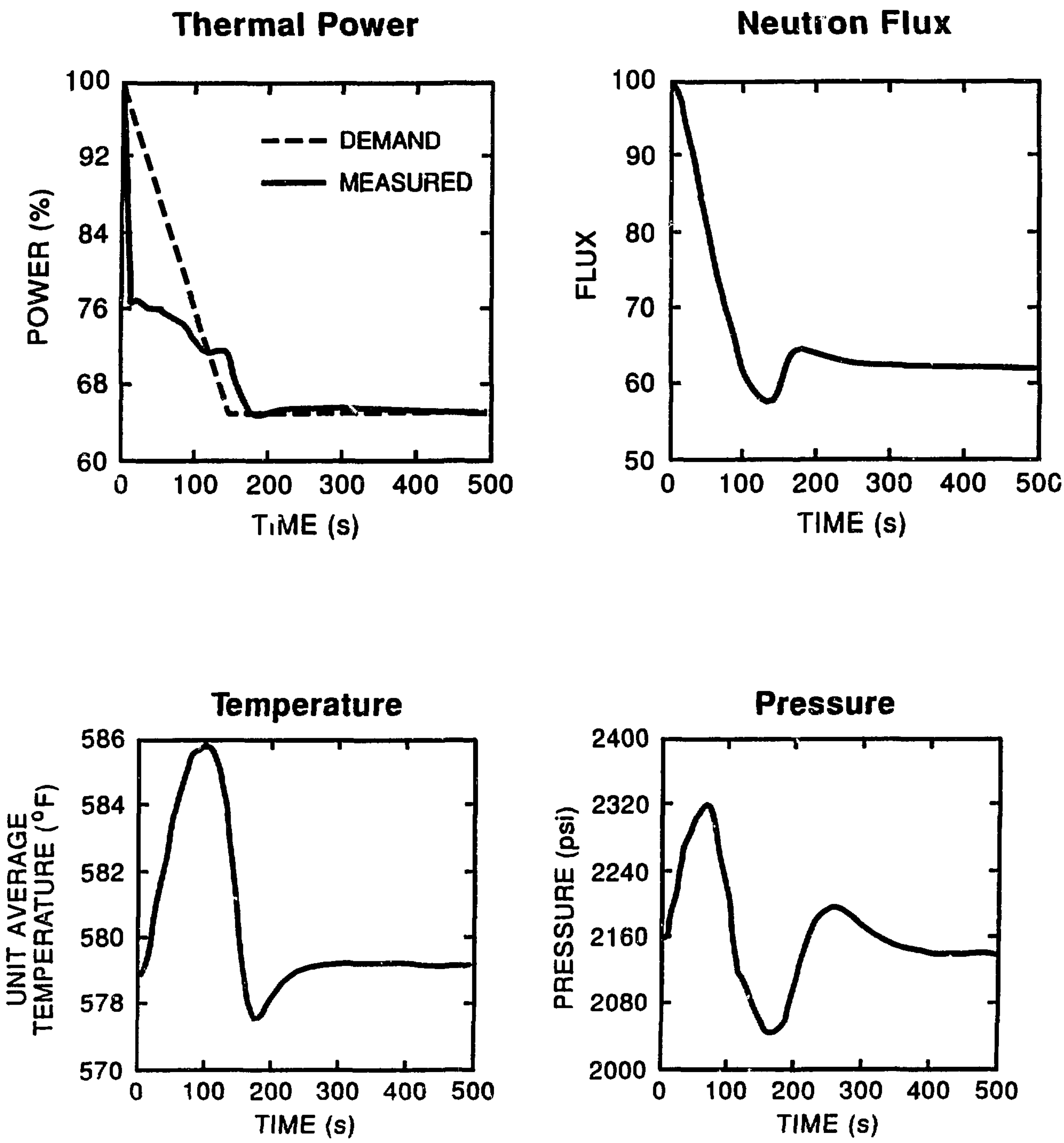

Figure 4. The feedwater pump trip transient demonstrates response to a disturbance that momentarily exceeds the capacity of the actuators.

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Advanced Digital Computers,
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for Power Plants

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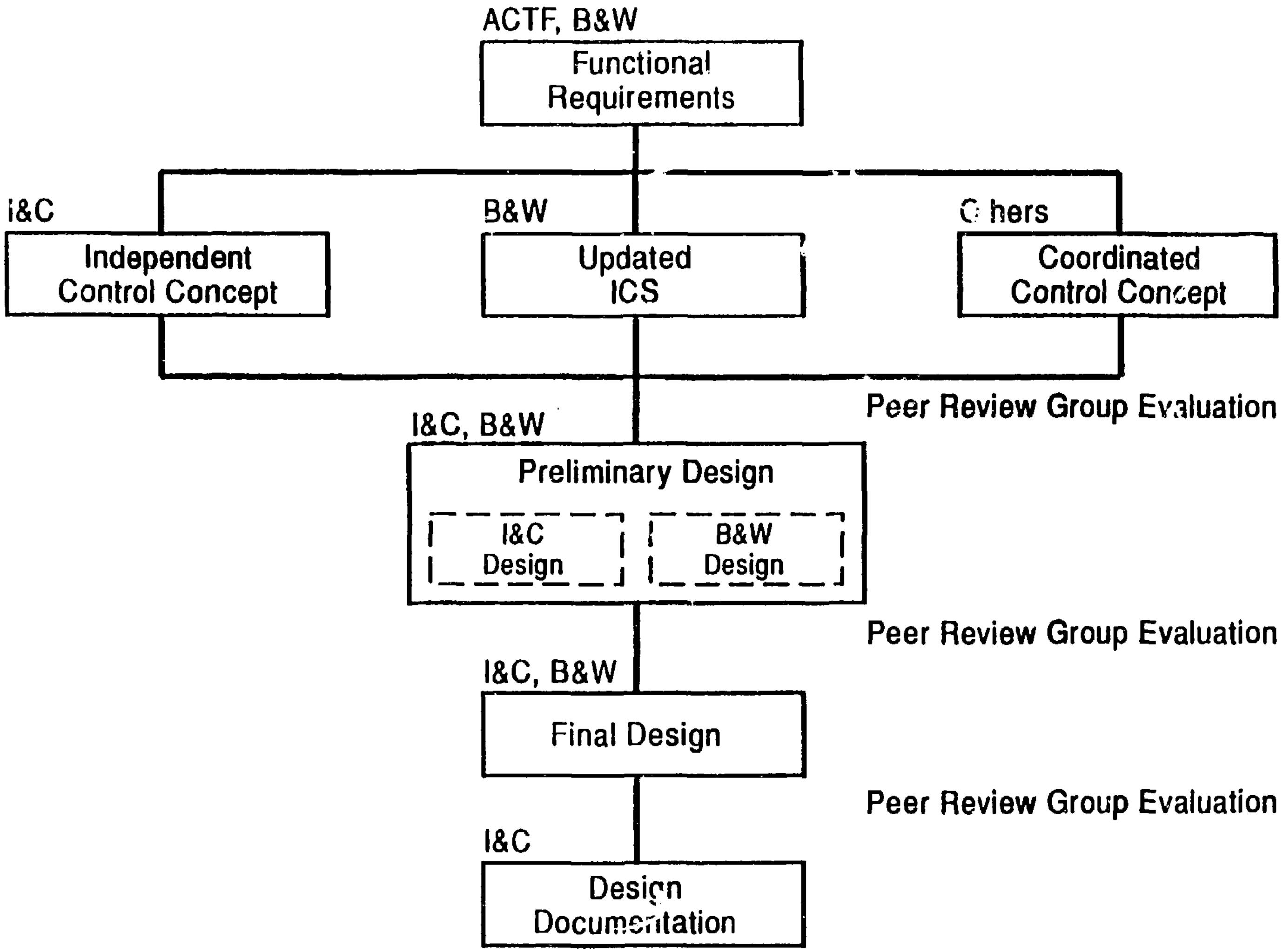
Control Algorithm Development Plan



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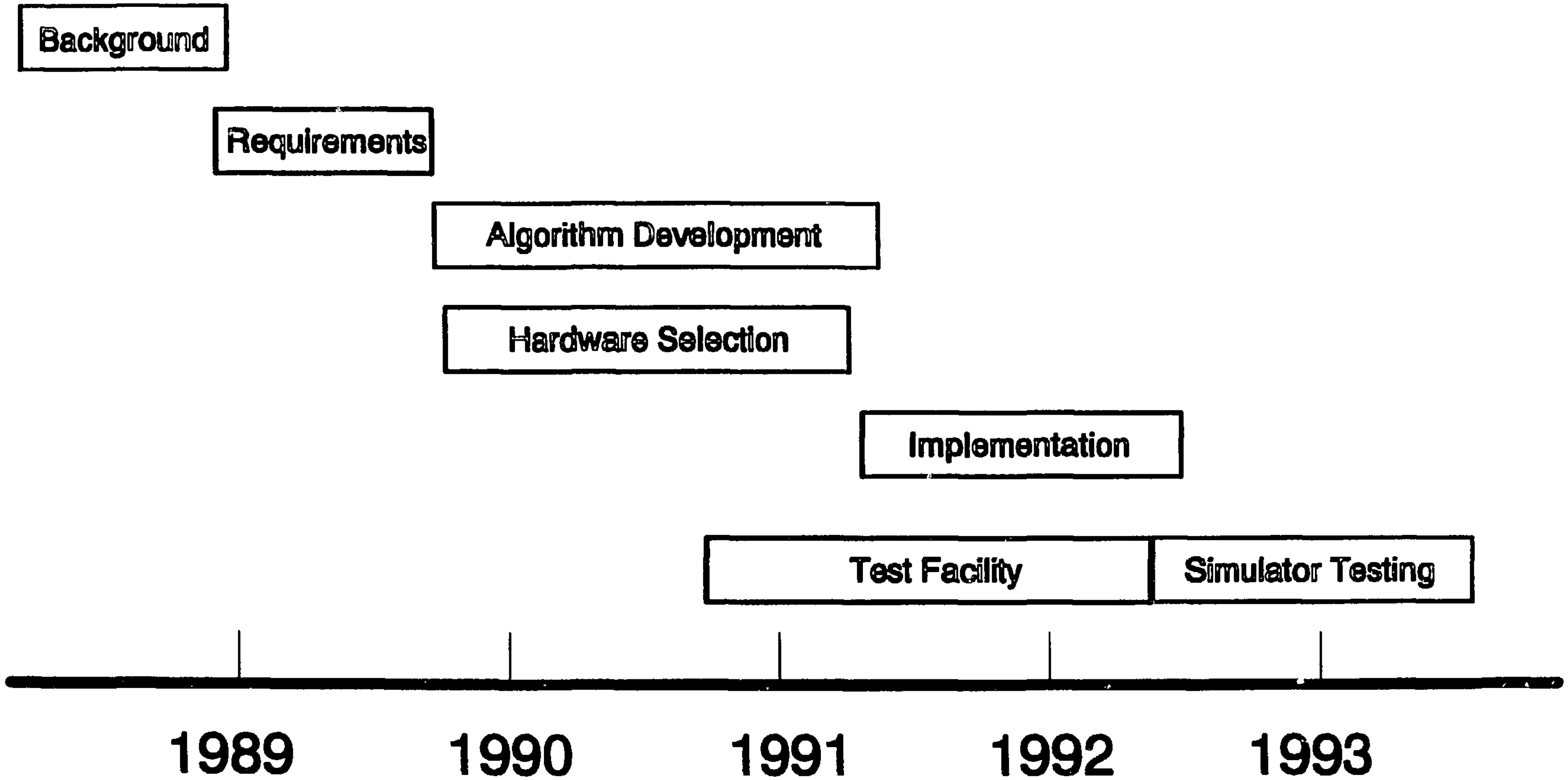
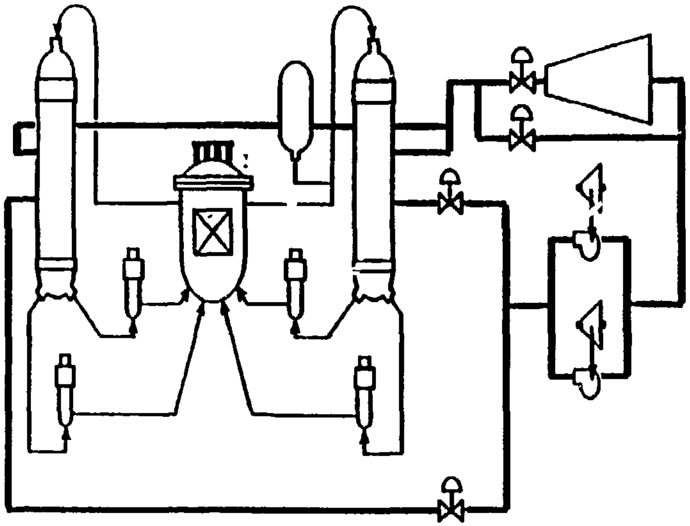
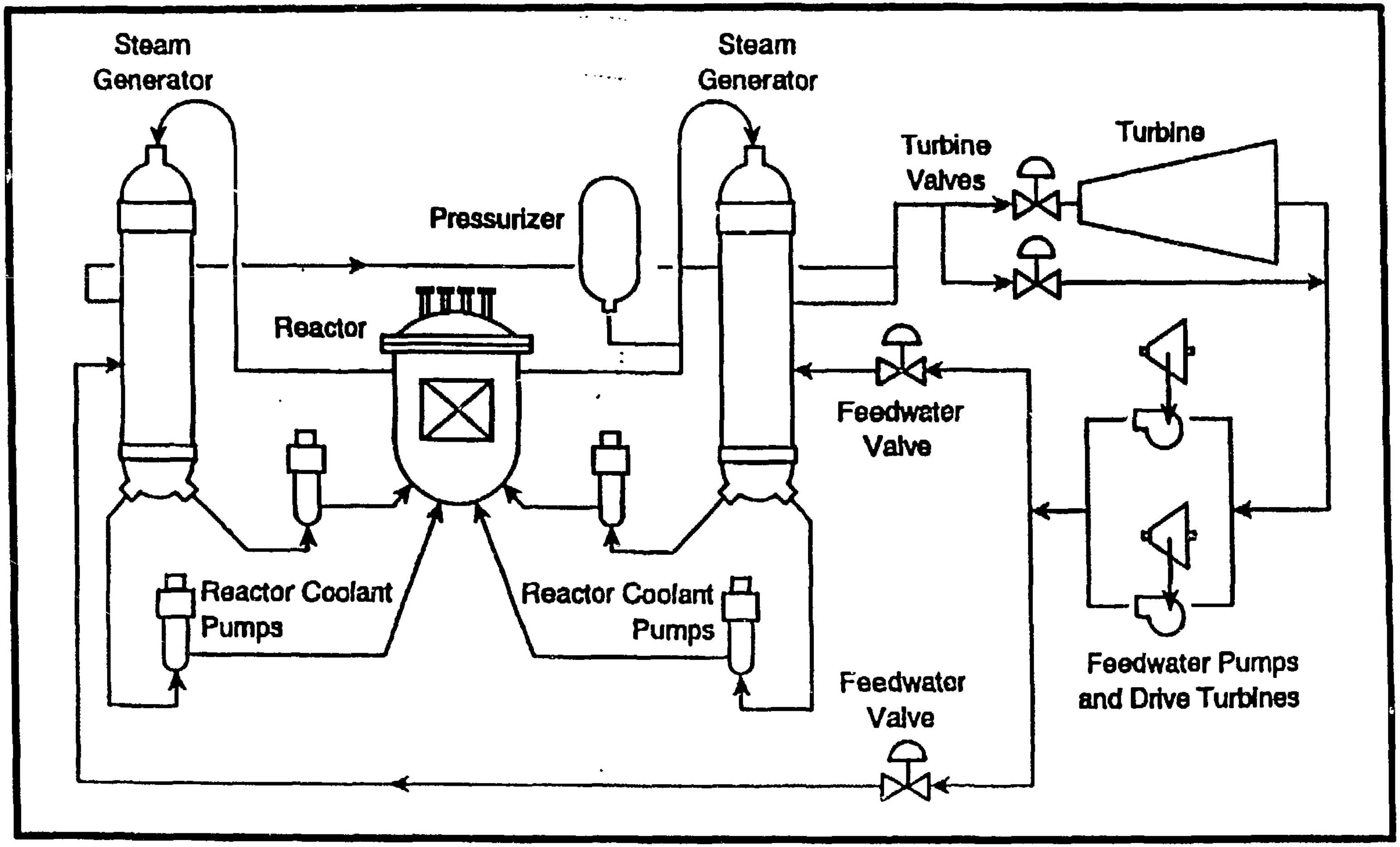
Plant Control System
Project Development Time Span



Actuators and Measured Variables for the Plant Control System

Actuators	Plant	Measured Variables
Press Heaters and Sprays Control Rods Turbine Valves Feedwater Valves (2) Feedwater Pump Speed (2) Makeup and Letdown Flow		RC Pressure RC Average Temperature Steam Pressure SG Outlet Temp Difference Core Thermal Power Minimum Pressure Drop FW Pump Speed Difference Pressurizer Level Neutron Flux Feedwater Flow (2) SG Level (2)

B&W Nuclear Steam Supply System



The Functional Requirements Specify Many Improvements Over the Original Control System

- Correct known problems with original control system
- Meet new control performance specifications
- Automate plant operations previously performed manually

Control Improvements and Corrections

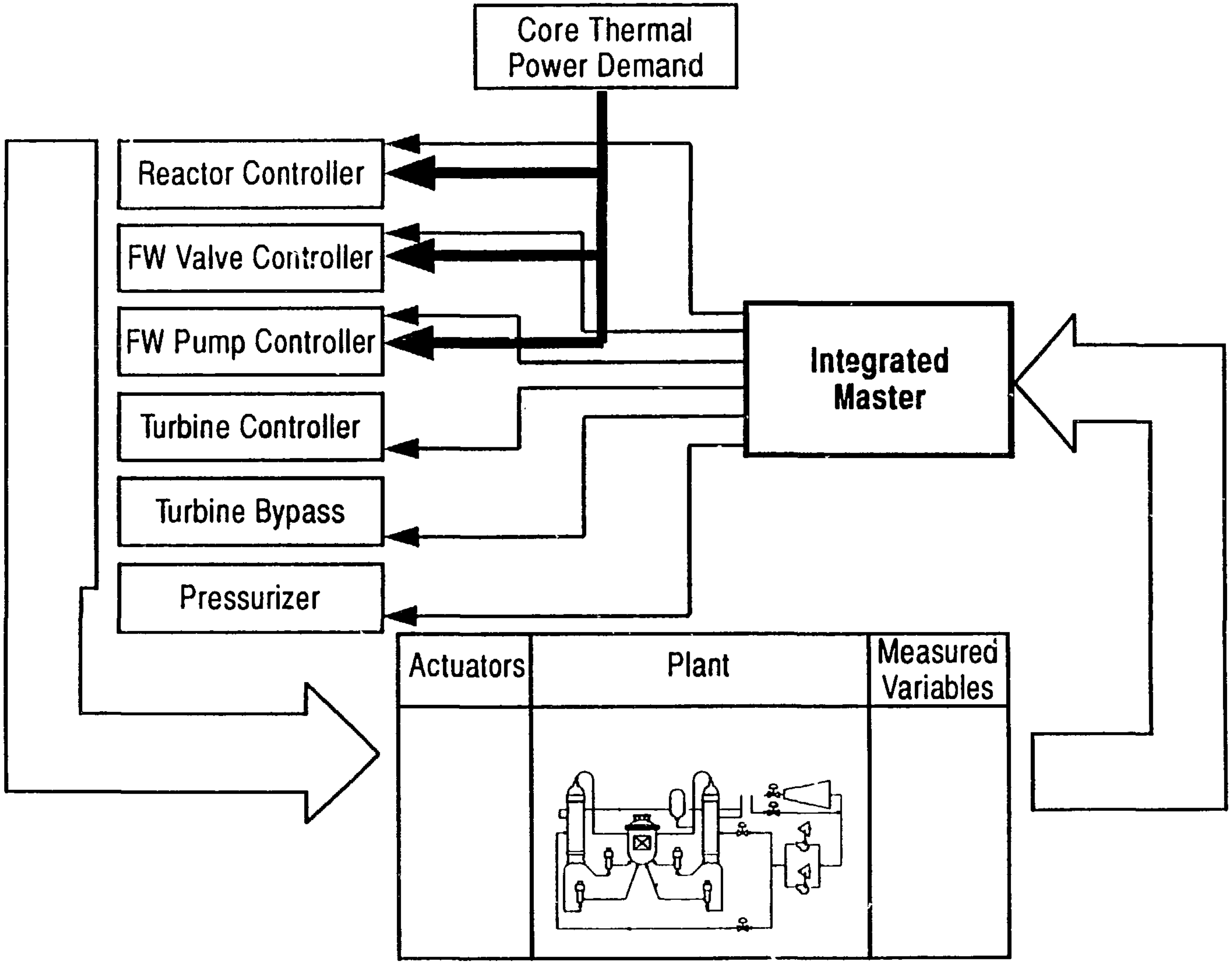
- Solve integral windup problems
- Improve steam generator level to average primary temperature transition
- Increase range of fully automatic control: 1 to 100%
- Maintain control priorities despite manual or limited conditions
- Provide symptomatic trip avoidance

ORNL DWG. 91Z-6943

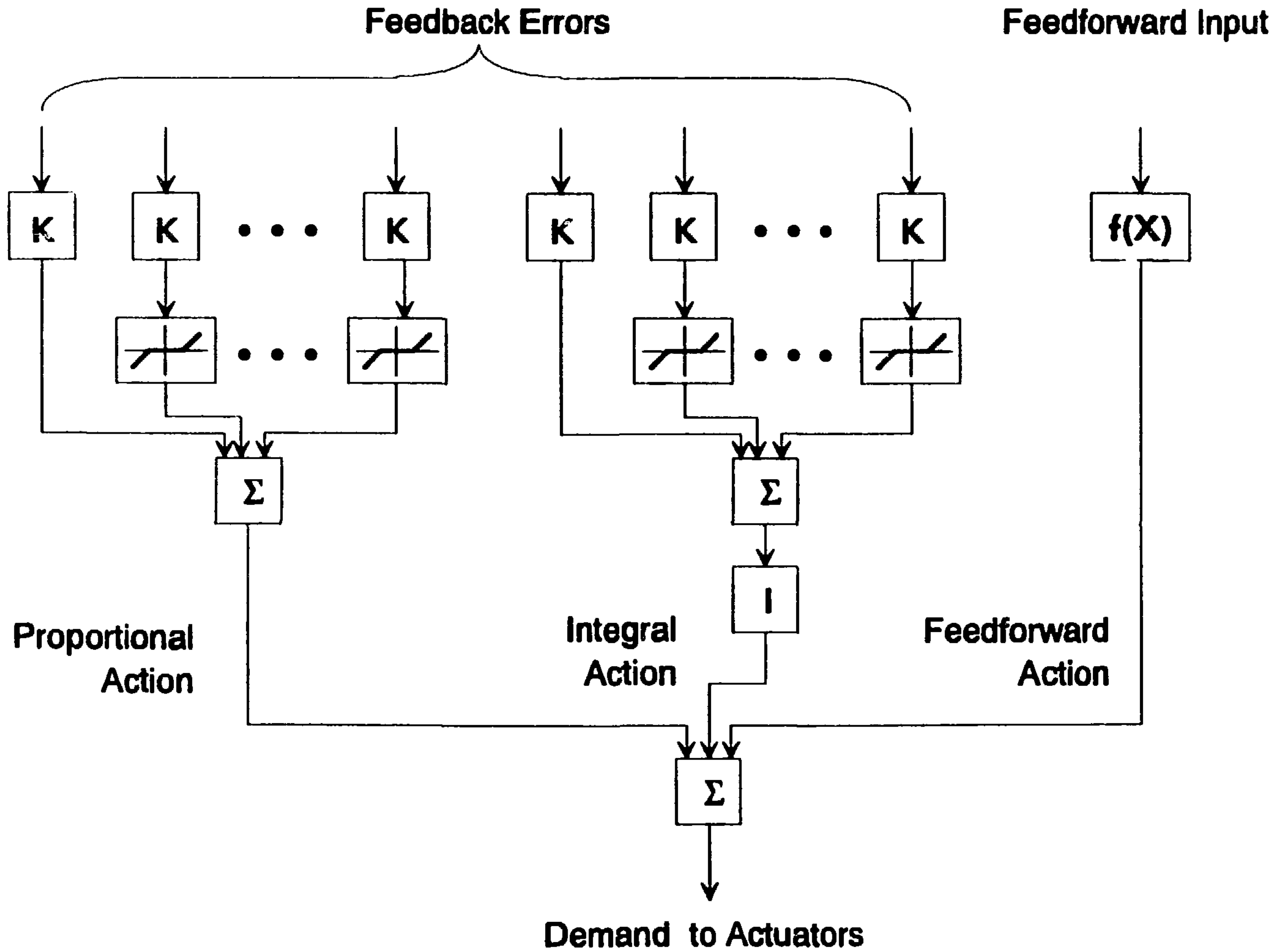
Control Performance Specifications

Measured Variable	Maximum Steady State Error	Maximum Transient Error
Reactor coolant pressure	± 50 psi	± 50 psi
Reactor coolant average temperature	± 1° F	± 3° F
Steam pressure	± 10 psi	± 30 psi
Cold temperature difference	± 2° F	± 15° F
Core thermal power	± 0.2%	± 3%

Plant Control System



General Arrangement of the Multivariate Controller



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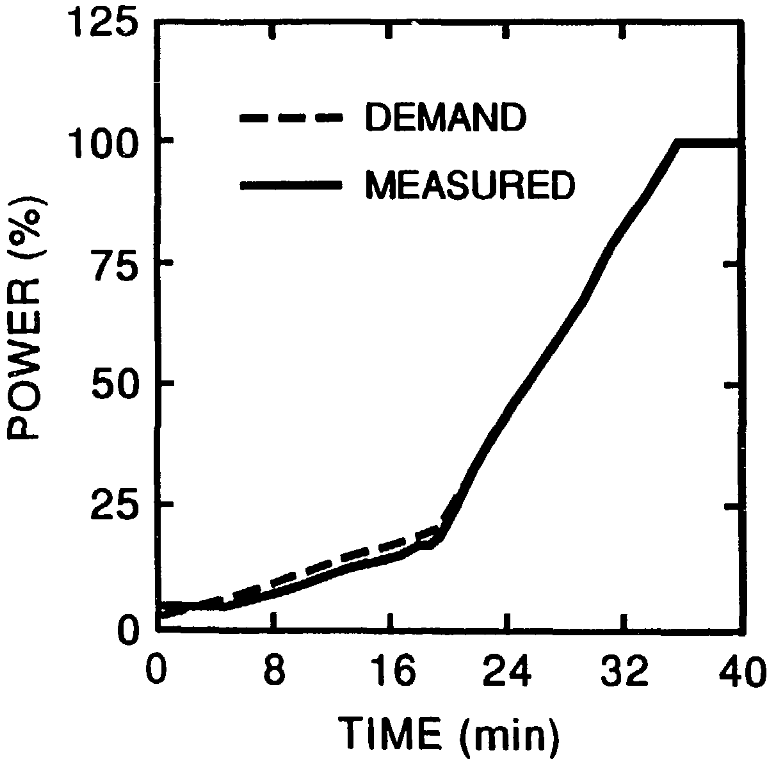
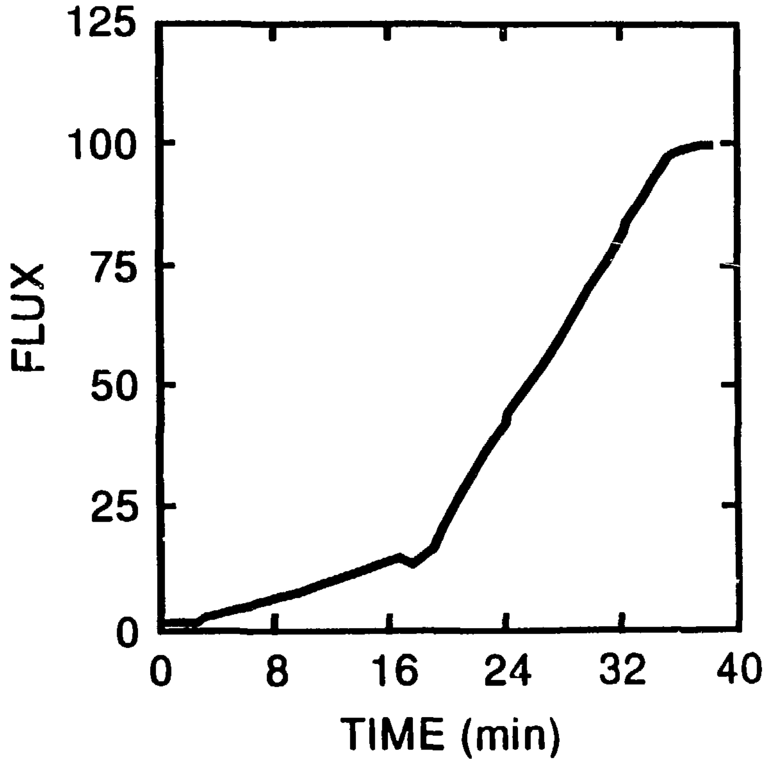
The Normal Power Ramp Demonstrates Performance of the Control System in Fully Automatic Mode

Thermal Power

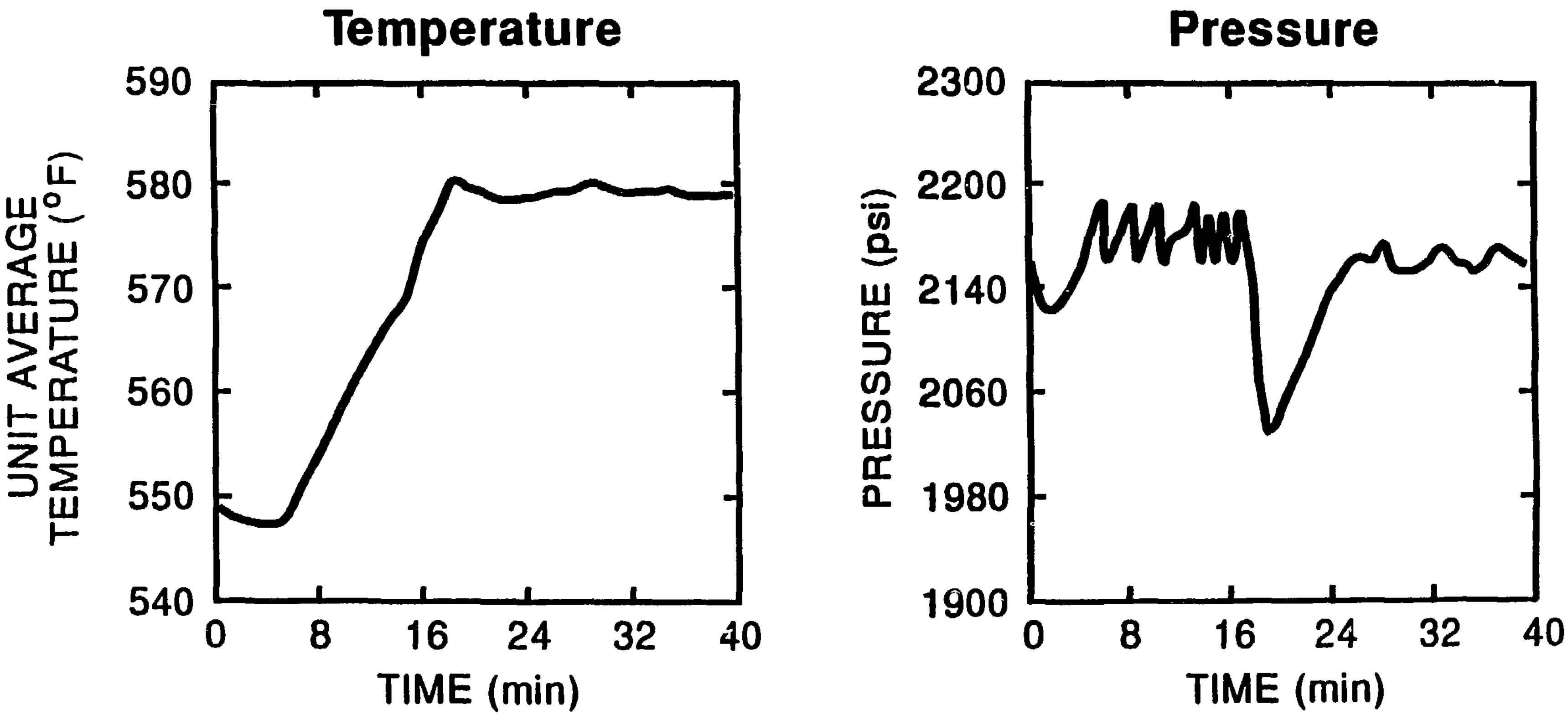


Neutron Flux



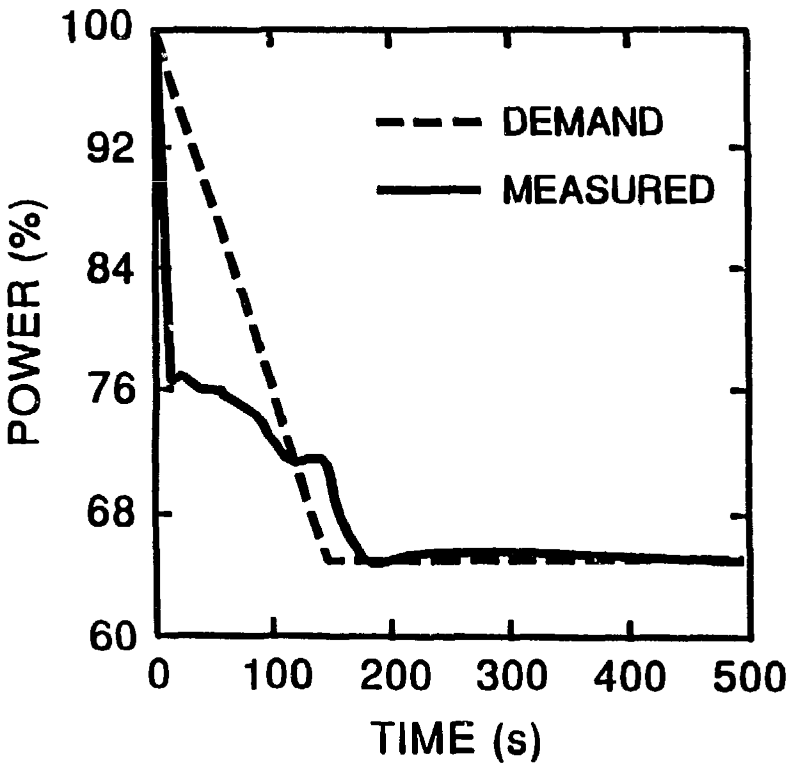
The Normal Power Ramp Demonstrates Performance of the Control System in Fully Automatic Mode (continued)

Reactor Coolant System

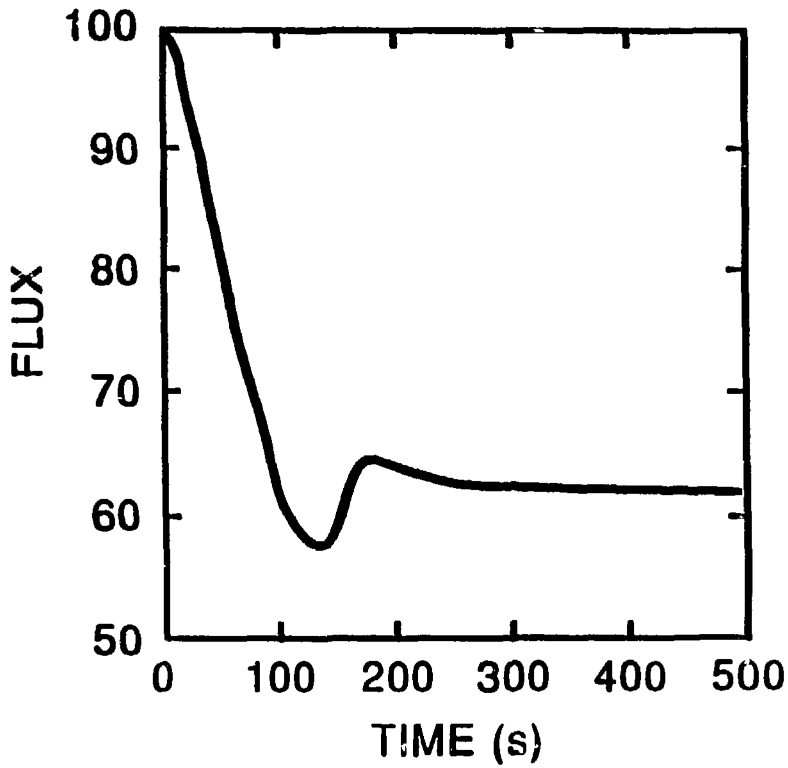


The Feedwater Pump Trip Transient Demonstrates Response to a Disturbance that Momentarily Exceeds the Capacity of the Actuators

Thermal Power



Neutron Flux



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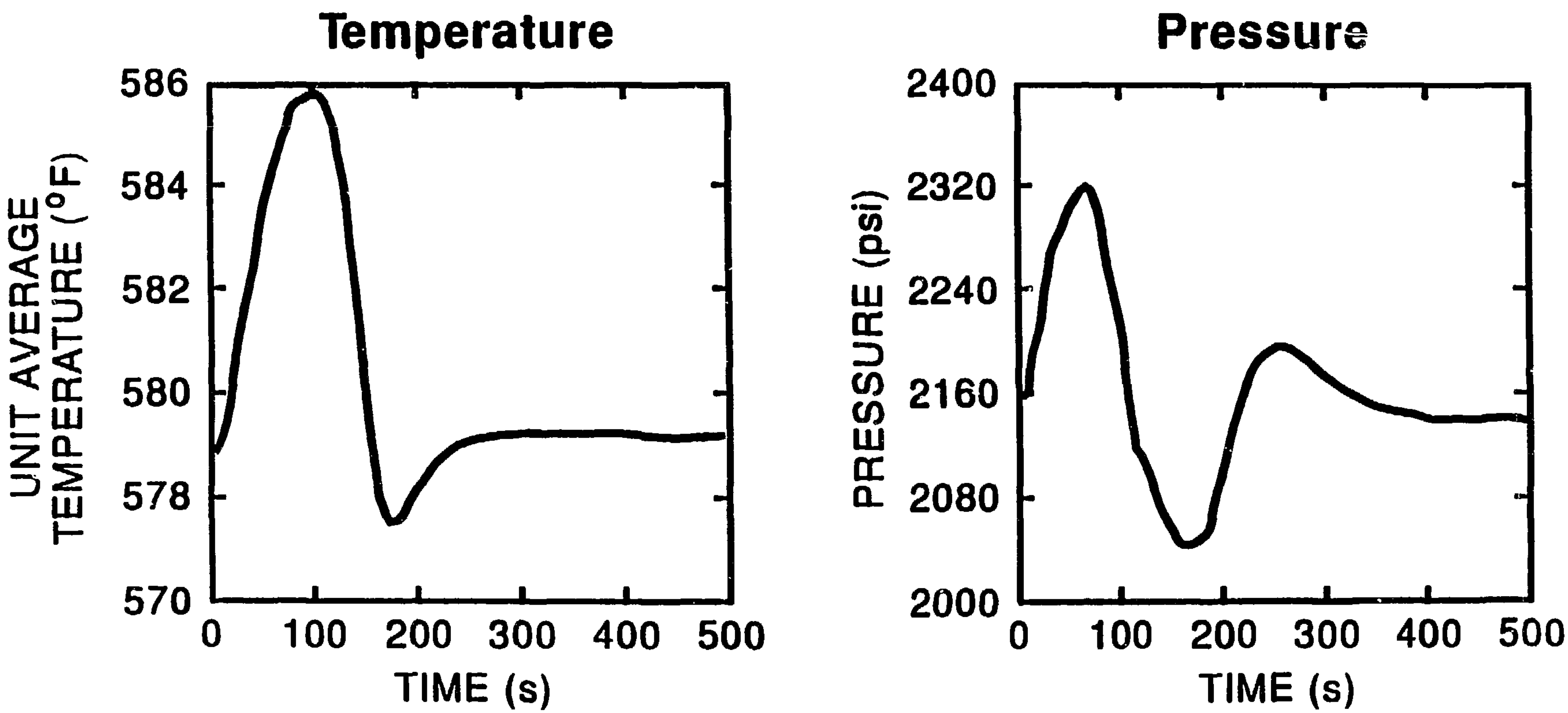
The Feedwater Pump Trip Transient Demonstrates Response to a Disturbance that Momentarily Exceeds the Capacity of the Actuators (continued)

Reactor Coolant System



Major improvements in the new PCS control algorithm include ...

- Automatic limiting of load demand and rate of change of load demand
- Improved Control Priority strategy
- Use of calculated thermal power for long-term calibration of power level
- Fully automatic control over a power range of 1% to 100%
- Use of multivariate controller for demand signals to reactor and feedwater systems

Major improvements in the new PCS control algorithm include ...

- Improved integral action through
  - Anti-windup depending on the feedforward bias
  - Multivariate input error
  - Rate-of-change limits

- Automatic control features
  - Loading and unloading the main turbine
  - Placing second feedwater pump into and out of service
  - Controlling feedwater pump recirculation valves
  - Controlling rate-of-change or RC temperature during heat up and cool down