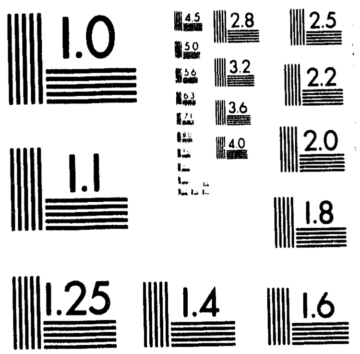
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THE PENNSYLVANIA STATE UNIVERSITY

College of Engineering

THIRD ANNUAL TECHNICAL PROGRESS REPORT

For the period September 1991 to October 1992

INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

(DOE GRANT DE-FG07-89ER12889)

PRINCIPAL INVESTIGATOR:

Edward H. Klevans

ADDITIONAL INVESTIGATORS:

Robert M. Edwards
Kwang Y. Lee
Asok Ray

STUDENT INVESTIGATORS:

Humberto E. Garcia
James A. Turso
Carlos Chavez-Mercado
Phillip B. Walter
Adel BenAbdennour
Pramath Ramaswamy
Chao-Chee Ku
Chen-Kuo Weng

September 30, 1992

THIRD ANNUAL, SEPT 1991 to OCT. 1992) TECHNICAL PROGRESS REPORT

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1.0 SUMMARY:

This project was initiated in September 1989 as a three year project to develop and demonstrate Intelligent Distributed Control (IDC) for Nuclear Power Plants. The body of this **Third Annual** Technical Progress report summarizes the period from September 1991 to October 1992. A no cost extension was processed and granted to permit the completion of an in-plant demonstration at the Experimental Breeder Reactor (EBR-II) beyond the original project completion date of this third and final year of project funding. The extension was needed due to scheduling requirements at EBR-II as well as the need for more time to develop test procedures.

There were two primary goals of this research project. **The first goal** was to combine diagnostics and control to achieve a highly automated power plant as described by M.A. Schultz, a project consultant during the first year of the project.[1,2] His philosophy, as was presented in the first annual technical progress report, is to improve public perception of the safety of nuclear power plants by incorporating a high degree of automation where a greatly simplified operator control console minimizes the possibility of human error in power plant operations. To achieve this goal, a hierarchically distributed control system with automated responses to plant upset conditions was pursued in this research. **The second goal** was to apply this research to develop a *prototype* demonstration on an actual power plant system, the EBR-II steam plant. Yearly milestones were identified in the original proposal. The first year milestone was to demonstrate a steam cycle diagnostic operating on-line at the EBR-II plant in a single SUN computer. The second year milestone was to demonstrate distributed diagnostics on-line at EBR-II and the third year milestone was demonstration of distributed control acting on the input provided by the distributed diagnostics.

First year tasks accomplished and reported in the First Annual Technical Progress Report[1] were: 1) Simulation of the EBR-II steam plant, 2) development of steam plant diagnostics, 3) simulation testing of diagnostics, 4) demonstration of diagnostics at EBR-II, 5) evaluation of improvements for diagnostics, 6) plant design for automatic control, and 7) learning systems reconfigurable control.

Second year tasks accomplished and reported in the Second Annual Technical Progress Report[3] were: 1) learning systems demo programmed in a Bailey Multifunction Controller (MFC), 2) robust fault-accommodating controller design, 3) VAX Cluster <-> UNIX network distributed simulation, 4) Programming of Schultz's automatic control, 5) distributed diagnostics, and 6) verification and validation.

Emphasized in this **Third Annual** Technical Progress Report is the continuing development of the in-plant intelligent control demonstration for the final project milestone and includes: simulation validation and the initial approach to experiment formulation. The **FINAL REPORT** at the end of the no cost extension period will discuss the final experiment implementation and results as well as a summary of the entire project.

2. BACKGROUND:

The potential **benefits** of this research are the identification and evaluation of techniques for safer and more reliable nuclear power plant operation as well as education and training of students in advanced control techniques. Although the final milestone demonstration of intelligent distributed control will be conducted at an experimental power plant facility, the ultimate benefit will come from incorporation in existing and future commercial nuclear power plants. Since this project was initiated in 1989, the need to upgrade existing Nuclear Power Plant I&C systems has come to the forefront. In 1991 the Electric Power Research Institute and Nuclear Utility Industry initiated a program with the goal of modernizing at least 10 existing U.S. nuclear power plants by the year 2000.[4]

The main **relationship** of this research to existing DOE programs is through EBR-II which is operated by the Argonne National Laboratory. EBR-II's current emphasis is on demonstration of the Integral Fast Reactor (IFR) concept but one of their secondary objectives is development and demonstration of *Advanced Control & Diagnostic System Technology*. Over the last few years, the Experimental Breeder Reactor II has been conducting modernization of their plant under an **Advanced Control and Diagnostic System Technology Program**. In the mid 1980s they added a Digital Data Acquisition System with monitoring capability for about 1000 points. They also replaced some obsolete analog controls with a distributed microprocessor-based control system, a Bailey NETWORK 90 system. Most of these digital controllers were added to the steam side of the plant. (On the primary system, the microprocessor based controllers are used for primary pump speed control.)

EBR-II has pioneered the development of graphics-based displays of plant information using UNIX based DATAVIEWS Software. In 1991, EBR-II modernized their Cover Gas Cleanup System (CGCS) with a distributed microprocessor-based system interfaced to a graphics-based operator console.[5] A feature of the EBR-II steam plant which enabled the development of a prototype intelligent control experiment is that they already had in place a digital data acquisition system and distributed microprocessor-based control system. Through a major NSF equipment grant a Bailey NETWORK 90 microprocessor-based control system was incorporated in a unique university laboratory at Penn State during the first year of the project.[6] In the second year of the DOE project, a Concurrent 6350 real-time UNIX-based computer system was added to the lab. The **I**ntelligent **D**istributed **C**ontrols **R**esearch **L**aboratory (IDCRL) then had complete compatibility with EBR-II hardware and software systems for finalizing the design and development of an intelligent distributed control experiment.

3. THIRD YEAR PROGRESS

Distributed diagnostics and intelligent control concepts for demonstration at EBR-II were initially developed and demonstrated on the hardware-in-the-loop distributed simulation capability of the Intelligent Distributed Controls Research Laboratory (IDCRL). However, the development and conduct of an in-plant experiment turned out to be much more involved. Additional refinement in the implementation of the intelligent control, development and validation of a special EBR-II compatible real-time simulation, as well as conformance to EBR-II test procedure development and scheduling represents major and time consuming efforts. Final development of the in-plant test started in April 1992 with the preparation and submission of a *Technical and Program Feasibility Design Package* to the EBR-II Experiment Review Committee. A major conclusion of that review was that the desired controls experiment on the steam plant could be developed and conducted as a *plant test procedure* with a much simpler safety review than experiments directly involving the reactor portion of the plant. Although the preservation of steam plant equipment is essential from an economic and personnel safety perspective, nuclear safety at EBR-II would not be compromised if a complete failure of the steam plant were hypothesized. Despite the simpler *plant test* development protocol under which the intelligent control demonstration will be conducted, a major effort of both EBR-II and project personnel is needed.

3.1 The In-plant Intelligent Distributed Control Experiment at EBR-II

Figure 1 indicates that the EBR-II deaerator is vertically oriented. Normal liquid level of near 170 inches represents an approximate six minute supply of feedwater at full power conditions and is regulated by manipulating the condensate flow control valves. As shown in Figure 1, there are actually two parallel flow paths, with associated flow control valves, for manipulating condensate flow at EBR-II. Steam header pressure, which supplies the deaerating steam, is regulated to 150 psig by manipulating a valve in a steam extraction line taken from the

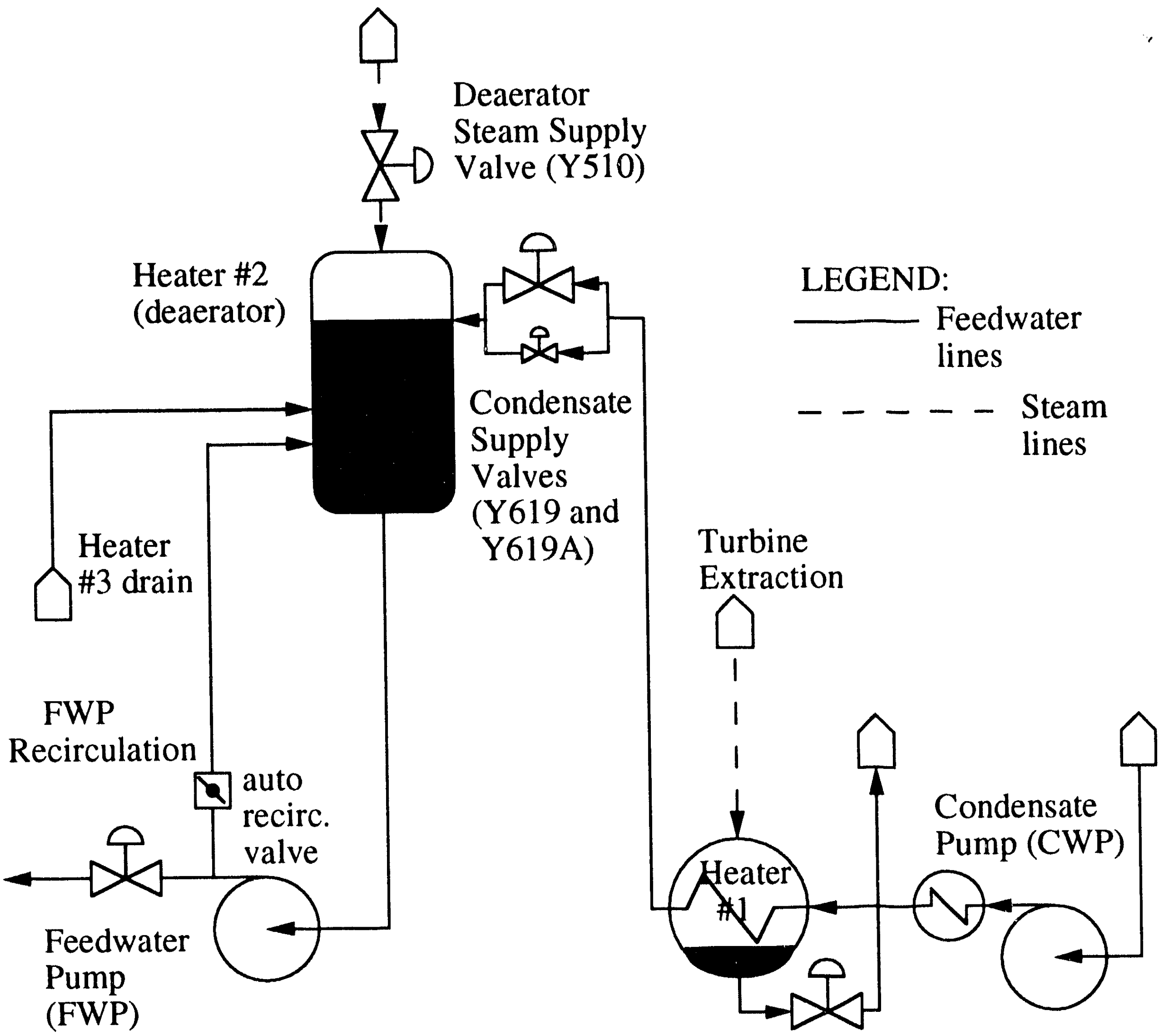

Figure 1. The EBR-II Deaerator and Condensate System

main steam header. Control of these process variables (pressure and level) is performed by single loop PI control algorithms implemented using standard control block programming in Bailey NETWORK 90 microprocessor-based controllers. There are two feedwater pumps, only one of which is used in normal operation. At full power conditions, it takes approximately 12 seconds for water leaving the deaerator to arrive at the inlet to feedwater pump 1 and approximately 24 seconds for water to arrive at the inlet to feedwater pump 2. The deaerator is elevated approximately 25 feet above the feedwater pump suction to provide required net positive suction head (NPSH). However, due to the transport delay from the deaerator to the feedwater pumps, there can be a significant reduction in NPSH if there is a rapid reduction in deaerator pressure. Pressure effects in a deaerator are almost immediately propagated to the feedwater pump inlet whereas change of internal energy at the pump inlet is delayed by the transport time. This potential reduction in NPSH during transients motivated the consideration of a fault-accommodating reconfigurable controller.[7-9]

3.2 Simulation Validation

Although an initial demonstration of the intelligent control was operational on the simulation testing system at Penn State in the first year of the project, progress at developing the necessary test procedures and approvals to conduct an in-plant test accelerated in 1992 when it was decided to create a hardware-in-the-loop testing facility at EBR-II.[10] A test setup for checking-out controller programming was developed when the EBR-II steam plant was upgraded with the distributed digital control system in the mid 1980s. Verification of controller programming prior to incorporation in the plant was limited to simply manipulating the analog inputs to the controllers with a voltage modulated with a simple potentiometer and verifying a proper voltage output response. VAX mainframe computers, as used in the distributed simulation at Penn State, were not available; however, a 486 based PC computer was provided for executing a reduced scope simulation of the EBR-II steam plant most closely associated with the performance of the deaerator.

Figure 2 shows the arrangement of the hardware-in-the-loop simulation testing setup at EBR-II. The PC computer transfers simulated process variables to the Bailey teststand through a Bailey Serial Port Module (SPM). Several basic controller modules for elementary PID control can be simultaneously tested as a unit on the teststand. The basic controllers in routine use at EBR-II can typically handle two unrelated PI control loops through four analog inputs and two analog outputs. Multi-function controllers (MFCs), programmed in the C computer language can execute advanced control algorithms which interface to the plant or other basic controller

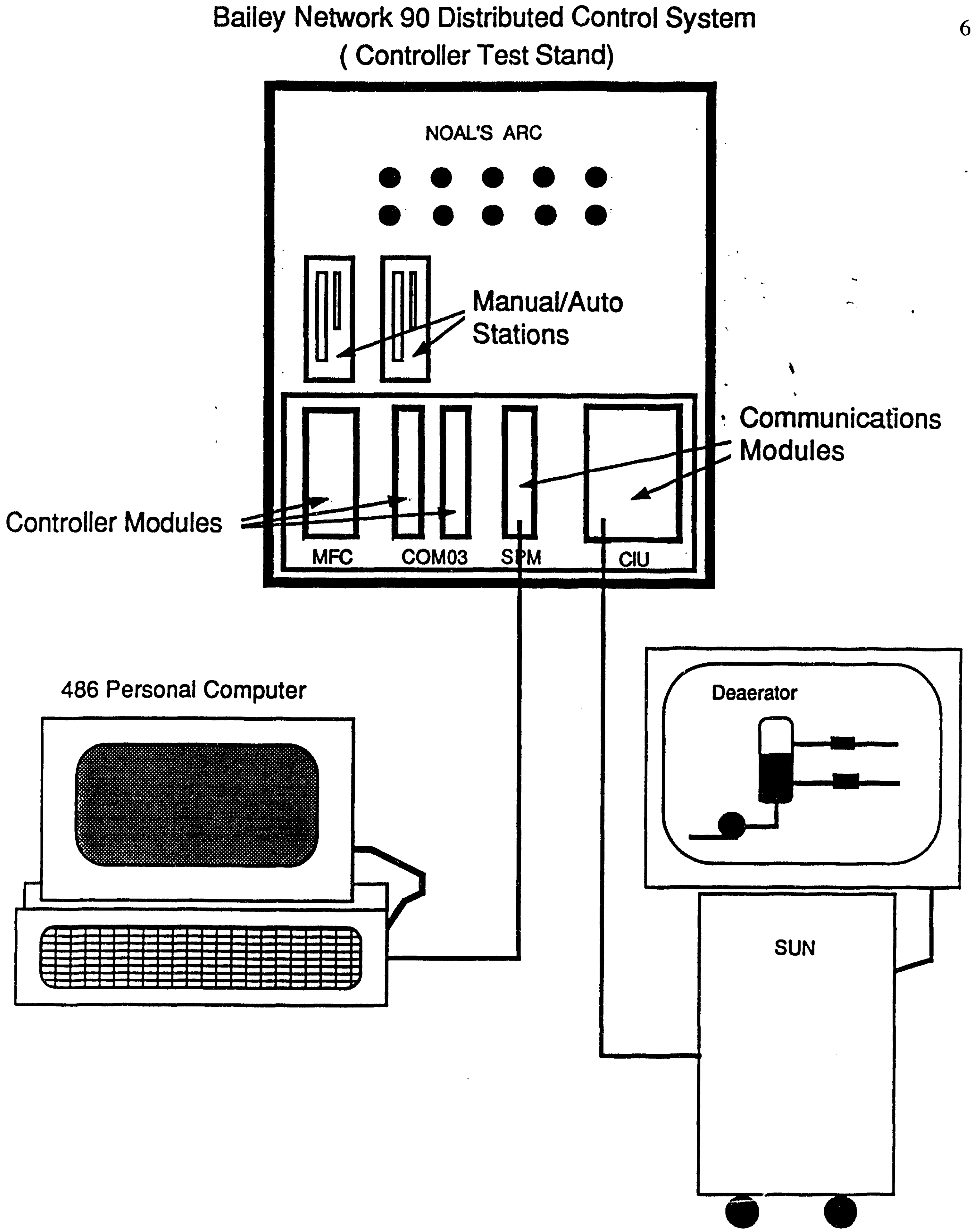

Figure 2. Hardware-in-the-loop Controller Testing Using Simulation at EBR-II

modules. Special consideration for implementation of advanced control in the Bailey system at EBR-II for ease of procedure development and acceptability led to distributed implementation even though an MFC can contain a large program and directly interface to many I/O points. All of the Bailey controller modules in the teststand (as well as in the actual plant) are contained in the same Process Control Unit (PCU) which means that they directly communicate with one another through a high speed module BUS.

When driven by the dynamic simulation, a slightly different version of the module programming is employed to receive the simulated process variables instead of reading the signals as analog inputs as in the in-plant test or input/output testing using the original EBR-II procedure. The MFC programming, on the other hand, is identical to that to be used in the test because the blocks from which it reads pressure and level are independent of whether plant data comes from the simulation or analog inputs.

Also represented in Figure 2 is a real-time graphical interface for monitoring the course of the in-plant test. The interface is implemented in a UNIX computer using VI Corporation DATAVIEWS software. The UNIX computer which can be a CONCURRENT 6300 series workstation or SUN computer is interfaced to the Bailey system through a serial interface and Bailey Computer Interface Unit (CIU). A separate communication program operates as an independent process in the UNIX computer and updates data in shared memory. The graphical interface program reads data from the shared memory updated by the Bailey communication program and also obtains some of its displayed data from the EBR-II data acquisition system which is broadcast on the ANL ETHERNET network. The graphical observation point provided by the UNIX computer is not required for the proper or real-time execution of advanced control algorithms implemented entirely in the microprocessor-based controllers. The digital control stations (Manual/Auto Stations) represented in Figure 2 are locally mounted in the teststand in close proximity to the actual microprocessor-based controllers. The in-plant stations are mounted in the control room while the controllers themselves are located in an instrument room below the control room.

As in the distributed VAX mainframe simulation used at the IDCRL at Penn State, the reduced scope simulation for use in the teststand at EBR-II uses the B&W Modular Modeling System.[11] The 386 version of the Advanced Continuous Simulation Language and NDP FORTRAN and C computer languages provide real-time simulation of the EBR-II condensate system including: the deaerator, closed feedwater heater number 1, blowdown cooler, condensate pump, steam extraction flows, associated piping and valves, and appropriate boundary conditions providing the interface parameters between the condensate system and feedwater and steam generation systems. To determine the fidelity of the condensate system simulation, a testing arrangement utilizing equipment virtually identical to the control system found at EBR-II was used. Only those controllers providing the signals for control of the deaerator were included in the arrangement. These were position signals for condensate flow control valves and steam supply flow control valve. Simulation testing was performed in two phases. The first phase used the pressure and level controllers, with configurations identical to those used in the actual plant, to control the simulation. The objective was to show that the simulation provides a similar response compared to that encountered in the actual plant for a given disturbance, e.g. a 5 inch step change in level setpoint. With a validated simulation, the second phase of testing predicted the response of the proposed reconfigurable control strategy. In other words, the simulation is first tested by the EBR-II original control scheme and then the reconfigurable control scheme is tested by the validated simulation.

Prior to finalizing the reconfigurable control test procedure and pretest predictions, a special data logging test was conducted at EBR-II to validate the simulation. The response of the deaerator pressure and level and flow control valve position commands were recorded during normal level and pressure setpoint change transients at several different power levels. A final *tuneup* of the simulation was performed to obtain the best match possible between the simulation and the actual plant data.

3.3 Experiment Formulation and Initial Programming

Figure 3 summarizes the overall architecture of the learning systems-based controller. The main concept of this controller is to first make available alternative control actions and then use the learning system to identify and enforce the best sequence of controllers to achieve desirable system performance. The alternative control action made available in the in-plant test is an additional means to regulate deaerator pressure via manipulation of the condensate flow control valves. A simple PI control algorithm was designed. Although a reconfigurable controller is not generally limited in the number or type of controllers, this one used only 2 PI controllers for simplicity of an initial experiment. Since the normal manipulation of the condensate valves is to regulate deaerator level, selection of the alternative controller causes the level process variable to be unregulated. Small level fluctuations have little impact on NPSH whereas even small pressure fluctuations (a few psig) can have a severe impact on NPSH if they occur over a short period of time compared to the feedwater transport time from deaerator to feedwater pump.

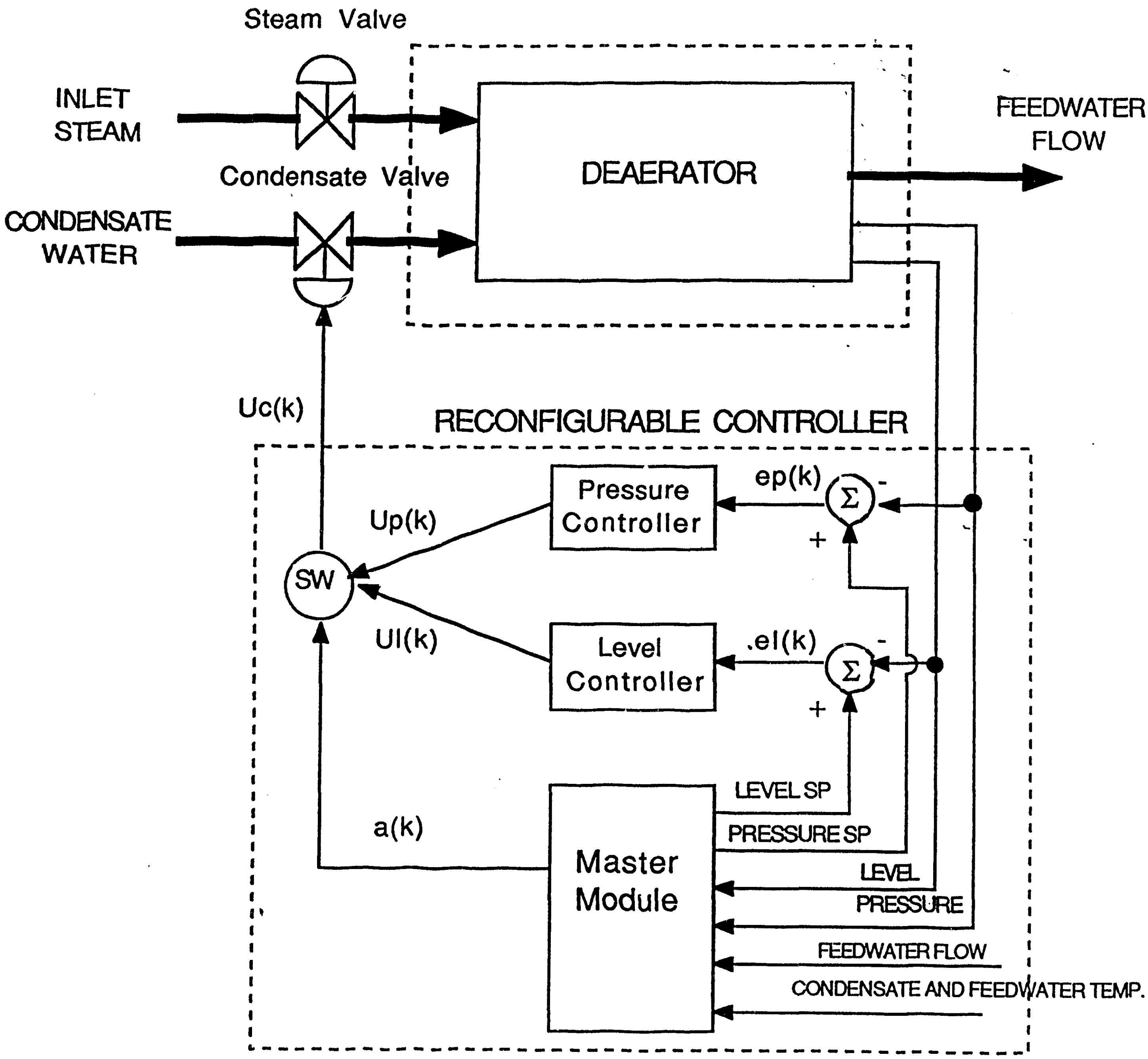

Figure 3. Architecture of the Intelligent Controller for the In-plant Test.

In general, the operation of this reconfigurable control scheme can be divided into four steps: (1) identification of the plant condition, (2) evaluation of the current control performance, (3) learning, to identify the best controller, and (4) selection of a controller from a set of available ones. The performance evaluation is composed of four components which are fused into an overall signal representing good or bad performance: (1) pressure and level trend, (2) rate of change of pressure and estimated NPSH, (3) an expert system diagnostic, and (4) condensate and feedwater temperatures. The learning component of this reconfigurable controller uses a discrete linear reward penalty algorithm[8] to adjust the probabilities of selecting the normal level control algorithm or alternative pressure control algorithm. Finally, the control action selection part of the process includes an anti-spurious algorithm to help avoid unnecessary switching between controllers.

For the reconfigurable control test, the normal deaerator level Bailey controller programming is replaced to contain both the normal level and alternative pressure control algorithms.[10] The learning systems decision on which controller to enforce is made externally in a Bailey Multi-Function Controller and is simply read by the modified basic controller.

3.4 Procedure Development and Approval

The development and approval of a test procedure to conduct the control experiment is significantly aided by the use of hardware-in-the-loop simulation testing and operator training. The first complete test data package was developed in October 1992 (at the beginning of the no cost extension period) and included a full description of the Bailey controller programming, simulation validation, pretest predictions and first draft of a test procedure. The proposed test procedure was demonstrated to EBR-II engineering staff and senior operations personnel on the hardware-in-the-loop testing setup at EBR-II in late October, 1992. Their input will be used to develop an acceptable procedure for an in-plant test expected in early 1993.

4. CONCLUSION

Although the project has entered a no cost extension interval, it is to expected successfully achieve the original objective of developing a demonstration of intelligent distributed control at EBR-II.

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