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For the period Sept. 1991 to June 1993 (Sept. 1989 to June 1993)
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INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

(DOE GRANT DE-FG07-89ER12889)

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**FINAL (THIRD ANNUAL, SEPT 1991 to JUNE 1993) 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 **Final (Third Annual)** Technical Progress report emphasizes the period from September 1991 to June 30, 1993 and tabulates thesis and publication data for the entire project. The period from September 1992 to June 1993 was conducted as a no cost extension which was necessary due to the scheduling requirements at the Experimental Breeder Reactor (EBR-II) as well as the need for more time to develop and process test procedures to conduct an in-plant experiment .

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 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. The final third year milestone was achieved on April 1, 1993 when an intelligent control experiment was conducted on the steam plant of EBR-II.

First year tasks accomplished and reported in the First Annual Technical Progress Report¹ 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 Report³ 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.

Described in this **Final (Third Annual) Technical Progress Report** is the accomplishment of the project's final milestone, an in-plant intelligent control experiment conducted on April 1, 1993. The development of the experiment included: simulation validation, experiment formulation and final programming, procedure development and approval, and experimental results. Other third year developments summarized in this report are: 1) a theoretical foundation for *Reconfigurable Hybrid Supervisory Control*, 2) a steam plant diagnostic system, 3) control console design tools and 4) other advanced and intelligent control.

Short descriptions of these third year activities are presented in Section 4 while an appendix contains significant third year publications with more detailed descriptions. The first and second annual reports contain earlier publications. A complete three year project bibliography of theses which contain further discussions of project tasks, reports and publications is provided on the following pages.

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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 was 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 Intelligent Distributed Controls Research Laboratory (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. OVERVIEW OF EBR-II AND THE FIRST TWO YEARS OF THE PROJECT

This intelligent distributed control research project was focused for application on the steam plant of EBR-II. Figure 1 summarizes the major components of the complete power plant. At the left is the **PRIMARY SYSTEM** which contains the reactor (at bottom), intermediate sodium to sodium heat exchanger (top center), primary reactor circulation pumps (left&right top), and passive heat removal system (above everything else). Passive safety of this liquid metal reactor design is due to the large heat capacity of the sodium pool, low pressure operation, and desirable metallic fuel characteristics. This passive safety has been demonstrated in actual EBR-II experiments.⁷

In the center of Figure 1 is the **SECONDARY SYSTEM** or intermediate sodium loop which isolates the radioactive primary tank sodium by circulating sodium between the intermediate heat exchanger and the **STEAM SYSTEM**. The steam system is similar to a fossil power plant steam system in that it incorporates a natural circulation steam drum boiler-evaporators with superheaters. The superheat allows for much better thermodynamic efficiency than is obtained from commercial water cooled nuclear power plants. The feedwater system consists of a low pressure condensate system (150 psig) with pump, closed feedwater heater, and open feedwater heater and a high pressure subsystem (1250 psig) with feedwater pump and 2 closed feedwater heaters.

To effectively develop intelligent control research for implementation on the EBR-II steam plant, real-time simulation capability was created during the first two years of the project by dividing the steam plant into three major subsystems. As indicated in Figure 2, the condensate (low pressure), feedwater (high pressure), and steam generation system are modeled as three individual simulations using the Babcock and Wilcox Modular Modeling System (B&W MMS).⁸ At the boundaries of the subsystem simulations (indicated by the curved lines) pressure and flow related information is exchanged using a computer network. The validity of this distributed simulation technique in comparison to a steam plant simulation implemented in one large program was checked and found to very good.⁹ This distributed simulation approach provides better real-time simulation performance by using smaller more efficient subsystem simulations which are operated on different computers in our Intelligent Distributed Control Research Laboratory, Figure 3.¹⁰ The required boundary data and other internal system variables for display and monitoring purposes is transmitted via TCP/IP and ETHERNET to a centralized plant data base maintained in a real-time UNIX computer system (Concurrent 6350). A Distributed Simulation Manager coordinates the timing of the distributed simulations in addition to sending and receiving data from any process.

EXPERIMENTAL BREEDER REACTOR (EBR-II) POWER PLANT SCHEMATIC

10

Figure 1: Major Components of the EBR-II Power Plant

Figure 2. Subsystems and components in a Distributed Simulation of the EBR-II Steam Plant

- DISTRIBUTED SIMULATION

- ETHERNET COMMUNICATION

- SIMULATION MANAGER

Multiple concurrent processes
Global shared memory
Multiple access protocols

Figure 3: Computer Architecture for Real-Time Distributed Simulation of Power Plants

The local control network in this block diagram represents the Bailey NETWORK 90 microprocessor-based control system which participates in exchanging data with the centralized plant data base of the UNIX Coordinating Computer. Local intelligent control applications in the advanced multifunction microprocessor-based controllers are programmed using a combination of general purpose C-language and standard function block routines. Hardware-in-the-loop simulation testing thus consists of the local controller receiving plant process data from the centralized plant data base and sending control action variables (valve position commands) to the data base. The distributed simulations conduct the complementary communication of sending simulated plant process data *to* and receiving control actions *from* the data base.

4. THIRD YEAR ACCOMPLISHMENTS

The major accomplishment of the project was the successful conduct of an in-plant intelligent control experiment on the steam plant at EBR-II on April 1, 1993 and is emphasized in Section 4.1. Other third year results for a theoretical foundation for hybrid supervisory control, diagnostics, control console design, and other advanced and intelligent control are described in Sections 4.2 to 4.5.

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) described in the previous section. 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 represented 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 was conducted, a major effort of both EBR-II and project personnel was needed.

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

A learning systems-based reconfigurable controller was demonstrated on the deaerating feedwater heater at the Experimental Breeder Reactor (EBR-II) on April 1, 1993.^{11,12} This intelligent control approach provides fault accommodating characteristics by learning to choose appropriate control actions to achieve required system performance objectives. In the in-plant experiment, a failure of the normal pressure regulating process was simulated by reducing the steam flow to the heater by as much as 10%. The controller maintained pressure in the heater at acceptable levels for several minutes whereas operator intervention would have otherwise been required within a few seconds. This experiment demonstrates the potential of advanced control techniques for improving safety, reliability, and performance of power plant operations as well as the utility of EBR-II as an experimental power plant controls facility.

Figure 4 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 4, 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 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.¹³⁻¹⁵

4.1.1 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

Figure 4: The EBR-II Deaerator and Condensate System

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.¹⁶ 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 5 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 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 5 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 Network 90 Distributed Control System
(Controller Test Stand)

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Figure 5. Hardware-in-the-loop Controller Testing Using Simulation at EBR-II

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 5 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.⁸ 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.

4.1.2 Experiment Formulation and Final Programming

Figure 6 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.

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 algorithm¹⁴ 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.¹⁶ 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.

Figure 6. Architecture of the Intelligent Controller for the In-plant Test.

4.1.3 Procedure Development and Approval

The development and approval of a test procedure to conduct the control experiment was 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 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 and again in mid November. The design package and hardware-in-the-loop demonstrations on site at EBR-II identified several problems in the initial draft procedure as well as heightened concerns for plant equipment, particularly for NPSH at the feedwater pumps. A third demonstration was conducted in mid December and definitive NPSH requirements for the feedwater pumps were identified for the first time. The programming of the reconfigurable controller and test procedure were modified to accommodate NPSH requirements.

The test was conducted for the first time on February 27, 1993 and consisted of three Controller Tuning Sessions and two tests of the reconfigurable controller for 2% closure of the steam supply valve to heater number 2. Final operator training was conducted on the simulator immediately prior to execution of each part of test and included hypothesized controller failures and recommended operator actions. All of the operations were conducted near 40MWt with the turbine/generator off line. The alternative pressure controller tuning sessions demonstrated that heater 2 pressure can be effectively controlled via manipulation of the condensate valve positions. However, the test procedure was not flexible enough to account for sticky steam valve characteristics where the prescribed 2% change in steam valve position command did not cause a steam flow perturbation. It was not practical to modify and verify the test procedure for the sticky steam valve characteristic before EBR-II was required to be connected to the grid at steady conditions on March 1. Therefore the test procedure was modified and verified during March back at Penn State. The revised test procedure insured that significant (5 to 10%) reductions in steam flow were achieved to test the reconfigurable controller. Additional refinement to the intelligent controller algorithm were also implemented to better account for realistic observed disturbances in feedwater flow as well as the sticky steam valve characteristics.

4.1.4 Results from April 1, 1993 Experiment

The experiment consisted of three major parts each conducted at 40 and 60 MW. The first part at each power level was controller gain verification and tuning of the alternative pressure controller using the condensate flow control valves. The second and third part of the test consisted of a target 5% and 10% reduction in steam flow to the heater. The length of the operator training and the test itself resulted in the use of two different operating crews.

Figure 7 shows the plant response near the end of the controller tuning at 40 MW. In this part of the experiment, the alternative pressure control algorithm is continuously enforced while the normal pressure control using the steam supply is in manual mode of operation. Operator positioning of the steam supply valve (Y510) is manually performed to produce steam flow changes to test the alternative pressure controller's manipulation of the condensate supply valves (Y619 is the large condensate valve and Y619A is the small condensate valve position). Two significant steam flow reductions (-11% at ≈ 2450 seconds and -18% at ≈ 2670 seconds) were handled well by the alternative pressure controller maintaining pressure above 146 and 143 psig, respectively. Pressure was maintained by reducing the condensate flow by primarily closing the small condensate valve although the large condensate valve began to participate during the second steam flow reduction when the small valve became fully closed. The final selection of alternative pressure controller gains emphasized proportional action using the small condensate valve and integral action using the large condensate valve. Furthermore, on large pressure error signals (pressure less than 8 psig below setpoint or greater than 5 psig above), the proportional gain associated with the large valve is increased.

At approximately 2940 seconds, the alternative pressure controller was tested with an 18% increase in steam flow. Pressure rose quickly, the small condensate valve saturated to the fully open position, the proportional gain of the large valve was adapted to a larger value and pressure was maintained less than 164 psig. The capability of the alternative pressure controller demonstrated in this part of the test is considered excellent. Figure 7 highlights the nonlinear characteristic of the deaerator process in that pressure increase transients tend to be larger than pressure decrease transients for similar sized disturbances. A feature exemplified by the controller tuning procedure is the possibility of completely reversing the roles of steam and condensate flow adjustments to achieve level and pressure regulation in the deaerator during normal operation. Because of the condensate flow manipulation of the alternative pressure controller, decreasing steam flow causes the level to go down and increasing steam flow causes the level to rise. In

Figure 7: On-line Tuning of the Alternate Deaerator Pressure Control Algorithm.

Figure 7, the steam flow adjustments and level changes were achieved by manual adjustment of the steam supply valves and an automatic level control could be considered.

Figure 8 shows the results of a test of the learning systems based reconfigurable controller decision making to automatically choose between the normal level control and alternative pressure controller for a 9% reduction in steam flow at approximately 230 seconds. When nonzero, the **switch** curve at the bottom of the figure indicates when the alternative pressure controller was enforced. After choosing and enforcing the alternative pressure controller for a period of time, pressure recuperates and then the learning systems-based controller chooses to again return to level control. As can be seen, with appropriate cycling between pressure and level control algorithms, pressure was maintained above 143 psig for over 10 minutes while level drifted downward by 12 inches. If the initial rate of pressure decrease at the onset of the steam flow reduction had not been abated, operator intervention would have been required within a few seconds (at 135 psig).

Since the deaerator process is clearly multivariable with condensate flow and steam flow affecting both pressure and level, advanced multivariable control algorithms have also already been considered for achieving improved performance and fault accommodating behavior¹⁷ and could be explored in future tests.

4.2 Theoretical Foundation for Reconfigurable Hybrid Supervisory Control

The in-plant demonstration of intelligent reconfigurable control for accommodating system faults was conducted on a single component of a much larger system. Although it was not practical to develop an in-plant demonstration involving more components and systems of the EBR-II steam plant as part of this project, the theoretical framework for pursuing a plant-wide implementation was extensively developed as a major portion of the PhD dissertation of Humberto E. Garcia¹¹ and is briefly introduced in the following paragraphs.

Complex dynamic processes such as fossil and nuclear power plants are usually difficult to control because they are: (i) operated over wide ranges; (ii) subjected to unpredictable or partially predictable large disturbances; and (iii) controlled by spatially distributed sensors and actuators. To meet the performance specifications, the control system should include different strategies for each individual operating condition, adaptive behavior to react under uncertain or unfamiliar situations, and the capability to coordinate distributed controllers to accomplish the system task in a coherent way. A reconfigurable approach to decision and control systems for complex dynamic processes which extends the architecture utilized in the actual in-plant deaerator experiment is proposed.

Figure 8. Intelligent Controller Response to a 9% Reduction in Deaerator Steam Flow at 40 MW.

The proposed Supervisory Control System (SCS) is an hierarchy structured into three levels, namely, the execution, supervision, and coordination levels. These layers are in part ordered according to the principle of increasing intelligence with decreasing precision.¹⁸ The execution level refers to the process dynamics. In particular, the execution level generates direct control actions over the process (or subprocesses). The entities responsible for implementing the control policies would be named *executors*. In general, an executor is capable of exercising more than one control algorithm by incorporating a set of available subcontrollers. These executors are governed by *supervisors* at the supervision level. The supervisors assign *control patterns* to the executors to select the control policies to be used on the plant. And, at the highest layer of the hierarchical structure, the coordination level overlooks the operations of the supervisors. For simplicity, a single entity called the *coordinator* is initially proposed to implement this layer. The coordinator dynamically selects appropriate supervisors and assigns *strategy patterns* to them to assure that the process behaves in a desirable manner. Because process information is treated differently, each level operates at different time scales and levels of abstraction as seen in Figure 9. Specifically, this hierarchy accommodates a foreground/background operation with the execution level operating at the foreground and the other two levels operating at the background in support of the foreground operations. Similarly, different models describe the process at each level.

At the execution level, process variables are observed and controlled directly and quantified by numerical or symbolic values. In general, the dynamics of the process is better described by differential or difference equations and control algorithms are usually designed according to continuous or discrete time dynamics models. Symbolic models can also be used to devise controllers that mainly perform symbolic processing of the information. On the other hand, at the supervision level, process variables are observed and controlled indirectly. Process information is better represented by event-driven rather than by time-driven dynamics. Specifically, the dynamics of the processes are described by discrete event equations and supervisory algorithms are usually designed based on discrete event models or DES.¹⁹ Finally, at the coordination level, process information is treated as decision problems. The decision models define the hypothetical states of the process with every decision problem exhibiting four elements: acts, outcomes, probabilities, and payoff. Thus, a unique physical process is analyzed under three different contexts, that is, as a continuous (or discrete) variable system (CVS) at the execution level, as a discrete event system (DES) at the supervision level, and as a decision system at the coordination level. Because decision systems are modeled in the discrete-event settings, the coordination level is also a discrete event process.

Figure 9. Abstract Models in the Supervisory Control System

In general, a complex process may originate two implementation problems for supervisory control. First, with respect to the execution level, there may not exist a single control algorithm that can satisfy the performance criteria for the complete spectrum of process operating conditions. Second, with respect to the supervisory level, a single "overly complex" supervisor may be required to accommodate the overall supervising process requirements. This may unnecessarily complicate the formulation, verification, maintenance, and upgrading of the supervisory system.

To overcome these problems, reconfiguration at both levels is proposed. A reconfigurable strategy is a dynamic scheme that identifies the current operating status of the controlled environment, evaluates control performances by dynamically monitoring process behavior, and then select the appropriate system configuration based on this process observation as discussed below:

A. Reconfigurable Executing Strategy

To facilitate the analysis and synthesis of control algorithms, the divide-and-conquer approach²⁰ is well suited for complex processes. Specifically, the operating range of the process is partitioned into a number of mutually exclusive and exhaustive subranges and then controllers are designed for each subrange to meet the specified performance criteria. The transitions among subranges may cause the control system to switch from one control scheme to another. When there is more than one controller for a given subrange, dynamic control-confident measurements computed based on observed performance are assigned to each controller. The controller with the highest confident value is chosen as the current best controller to act on the plant. Learning algorithms²¹ can then be used by the supervisors to select the control strategy expected to be the current optimal choice.

B. Reconfigurable Supervisory Strategy

Similarly, the DES model of the process is partitioned into a number of DES subsystems. Supervisors are designed for each of the subsystems, and the overall system response is then obtained by reconfiguring the supervising strategy based on current state of the process. A one-to-one correspondence between the set of operating condition regimes and the set of supervising algorithms (i.e., supervisors) exist. The process (or each subprocess) is governed by a supervisor that belongs to the set of all supervisors designed for the complete operating regime. Decision algorithms²² can then be used by the coordinator to select the supervisory strategy expected to be the current optimal choice.

The mathematical framework for this reconfigurable supervisory control strategy is developed in Garcia's dissertation.¹¹

4.3 Steam Plant Diagnostic System

A real-time distributed simulation of the EBR-II steam plant was established during the first two years of the project for development and testing of diagnostic concepts. In the final year of the project, the simulation was used to develop a DISYS diagnostic system to identify a set of ten fault conditions prescribed by EBR-II personnel.^{23,24} These ten fault conditions are:

1. Feedwater pump trips,
2. Feedwater recirculation valve fails open,
3. Feedwater flow control valve fails open,
4. Feedwater flow control valve fails closed,
5. Feedwater #2 pressure relief valve opens,
6. Condensate pump trips,
7. Steam bypass valve fails open,
8. Steam bypass valve fails closed,
9. Steam drum blow down flow shuts down, and
10. Secondary sodium pump shuts down.

These diagnostics could be expanded and incorporated as part of a plant-wide Supervisory Control System implementation described in the previous section in order to provide essential information to aid the decision for control system reconfiguration.

4.3.1 Feedwater Pump and Recirculation Valve Failures.

The development of the diagnostic rules to correctly and distinctly identify each of the above ten fault conditions was accomplished by first simulating each fault with the distributed simulation and logging the plant responses to data files. The feedwater pump trip and recirculation valve failure are selected for illustration, because, of the ten fault conditions, they were initially the most difficult to differentiate. The purpose of the feedwater pump is to provide adequate high pressure feedwater flow to the steam drum. (Refer to previous Figure 2). Loss of feedwater flow will cause the steam drum level to drop, leading to evaporator dryout and undesirable plant transients. The purpose of the feedwater recirculation line is to provide a minimum flow rate through the feedwater pump in the event that the downstream pressure becomes too high. A loss of flow rate through the multistage centrifugal type feedwater pump could result in pump damage due to overheating. The recirculation valve is normally closed except possibly during certain start-up conditions. When fully open, the recirculation line diverts about 30 percent of the normal feedwater flow back to the number 2 heater, which is the low pressure water source for the feedwater pump. The recirculation valve automatically opens when the flow rate through the pump falls below a setpoint value and, if it fails to subsequently close, the pump outlet pressure will fall, resulting in degraded plant performance.

The simulation of these two fault conditions assume that: initial full power equilibrium conditions exist, secondary sodium flow and temperature into the superheaters remain constant, feedwater flow is available from only one feedwater pump (i.e. the second and emergency feedwater pumps do not operate), and the condensate pump does not trip.

4.3.2 DISYS Diagnostic System Example

The DISYS Diagnostic and Control Guidance Expert System is a highly structured, multiple program process that currently operates in real-time on a UNIX-based workstation.²⁵ The organization of the process is illustrated in Figure 10. The system can use live plant data directly from EBR-II's data acquisition system (DAS), live data from a simulation process, or data from stored files. The primary user interface is a real-time intelligent process schematic which depicts the major plant components and selected associated sensors²⁶. A black and white rendition of this display for the feedwater pump trip at 20 seconds into the fault transient, is shown in Figure 11. Each major active component has an associated status with a range from zero, indicating a completely failed component, to one, indicating a completely operational component. Components not used in the current mode of operation are indicated with a N.A. (not active) status. The overall system status is displayed in a box at the top of the display and is determined by logically combining the statuses of the individual active components. The process control program automatically highlights the status box of the lowest status component and the sensors responsible for this status. Figure 11 shows the feedwater pump with a fully failed status (status = 0.00), and the feedwater flow rate, sodium flow rate, and feedwater pump flow control valve sensor icons highlighted because they are symptomatic of the fault.

The component and overall system status is determined by processing the sensor set data through the DISYS Diagnostic Nodal Network. This is a hierarchically arranged knowledge representation scheme that processes sensor data to detect deviations from nominal plant behavior in real-time. A tree-like display of the real-time diagnostic information contained in the nodal network for each component is available by selecting the desired component status box with the mouse.²⁶ The diagnostic information tree for the feedwater pump trip at 20 seconds into the transient is shown in Figure 12. As this figure shows, the current feedwater pump status is determined by two possible fault conditions, the feedwater pump trip and the recirculation valve fault. At the bottom of the display are the sensor sets that are processed to identify these conditions. The sensor data are updated in real-time and validated based on the parity space representation and analytical redundancy approach.²⁷ The validated data can then be algebraically

Figure 10. DISYS Multiple Program Process

08:34:00 STATUS = 0.0 STEADY OPERATION with Steam BYPASS

Figure 11. EBR-II Steam Plant Intelligent Process Display for Feedwater Pump Trip at 20 Seconds.

Figure 12. Diagnostic Information Tree for The Feedwater Pump Trip at 20 Seconds.

combined into synthetic measurement nodes as illustrated by the heptagonal box for the feedwater to sodium flow rate node. The resulting signals are mapped to indicate a measure of presence or absence of a fault symptom. The output of the map nodes ranges from zero to one, where a one denotes the complete absence of the fault symptom. The map node outputs can be logically combined or routed directly to the diagnostic nodes, indicated by the hexagonal boxes. The diagnostic calculation performed on the mapped outputs is based on Baye's conditional probability rule and measures of belief and disbelief for each symptom. This yields a diagnostic status which indicates the presence or absence of the fault condition. A diagnostic status of zero indicates that the fault condition exists, while a status of one indicates that the fault condition does not exist. These diagnostic statuses are combined in a logical AND to give the component status, where a component status of zero indicates a completely failed component and a status of one indicates the component is completely operational. Figure 11 shows the feedwater pump in a completely failed status (status = 0.00) and the number 2 heater with a status of 0.81. Generally, a component status of 0.50 and below is indicative of an actual failed component. Above 0.50, the component is considered only a possible candidate to be in a faulted condition.

4.4 Control Console Design

In the second year of the project a simplified control panel for directing plant-wide operation was incorporated in a model-based display of EBR-II plant information as shown in Figure 13.^{28,29} Although in-plant demonstration of intelligent control could not be developed for a plant-wide implementation where such a control panel could have been evaluated on-line, the control panel and display were implemented on the distributed simulation of the EBR-II plant in the Intelligent Distributed Control Laboratory at Penn State.

In the third year of the project, a more immediate need for control console display development came to the forefront at EBR-II in the context of replacing the central control console while leaving plant control essentially unchanged. A primary objective is to add modern CRT plant information displays to replace existing strip chart recorders in the existing console. The experience and capability that Carlos Chavez-Mercado had achieved while developing the simplified control panel concept in the first two years were applied in this new direction as briefly summarized in the following paragraphs.³⁰ Although this new direction was outside of the scope of this DOE project, Carlos was able to pursue this expanded research on the basis of his independently funded fellowship.

Figure 13. Simplified Control Panel (lower left corner) Incorporated in a Model-Based Display.

4.4.1 Background for EBR-II Control Console Upgrade

Early nuclear power plant control rooms have been upgraded in pieces as various instruments became obsolete and unmaintainable. The Experimental Breeder Reactor II (EBR-II) control room was designed in the 50's. The major elements of the existing control console are 5 strip chart recorders, alarm panel, key lock system, and selector switches. A straight forward initial objective is to replace the functionality of the existing console with a computer driven CRT information display system while maintaining the hardwired selector switches. This approach maintains simplicity and a high degree of familiarity with the existing console. However, current efforts aim beyond this single objective.

4.4.2 The Development of a Control Console Simulator:

Ongoing work is the programming of the graphic interface for the simulated control console and preliminary displays using the DATAVIEWS graphical data base display software on a UNIX computer platform (SUN or CONCURRENT). DATAVIEWS comprises DV-Draw and DV-Tools. The DV-DRAW graphic-package software allows construction of complex drawings with static and dynamic components that can be easily modified and relocated. The drawing process requires no programming. DV-TOOLS is a powerful library of graphics routines in C language that extend DV-Draw's capabilities for manipulating static and dynamic drawings and their components.

The interface incorporates a complete graphic representation of a preliminary control console configuration, Figure 14. This configuration reflects proposed modifications to the current control console as result of a survey involving 19 EBR-II operators. The survey was carried out via written questionnaire.³¹ Main changes include the replacement of all chart recorders by CRT's, rearrangement of the key lock system, alarm panel and instrumentation. The interface is mainly operated via mouse interaction. At the bottom of the screen is the user input area for control of the interface. There are several mouse-driven object menus. Two of the object menus (pan and zoom) have interaction handlers that allow the user to easily choose the desired panning and zooming factor. The console menu is used to select the control panel of interest. The selected panel remains highlighted as a way of mapping the user selection. By direct manipulation of these object menus, the user can easily isolate any region of any size for subsequent interaction.

Figure 15 is an example of the interface panning and zooming capabilities and shows the control rod selector switches and control pushbuttons, as well as a simulated CRT display for

Figure 14. Top View of EBR-II Control Console Simulation Interface.

Figure 15. Zoomed View of Console Simulation Showing Control Rod Selectors and a Simulated CRT for Monitoring Power, Control Rod Selection and Movement.

monitoring power, control rod selection and movement. An initial dynamical simulation of the EBR-II primary system³² was modified and coupled to the graphics through UNIX shared memory.

The interface is intended to serve several purposes:

- Provide computer aided design capability of the control console and display system.
- Provide a favorable environment that an operator can experience for display testing and evaluation, rendering valuable feedback for subsequent iterations.
- The interface can be advantageously used to evaluate and predict operator performance with different control console configurations.
- The interface can be used to determine underlying principles for effective control console design and computer-based display system design.
- The interface can be used with purposes of training that will facilitate the acceptance of the new control console.

4.5 Other Advanced and Intelligent Control

Although this DOE Project was limited in its original objective to developing a demonstration of intelligent distributed control for the EBR-II steam plant, it was hoped that this initial work would eventually lead to the development and demonstration of a highly automated plant-wide control system as originally envisioned by Schultz.^{1,2} Such a system would of course involve the nuclear portion of the plant and theoretical and simulation based research was conducted to examine optimal³²⁻⁴⁰ robust³⁹⁻⁴¹, neural network⁴²⁻⁴⁷ and fuzzy logic reactor control⁴⁸⁻⁵³, Figure 16. The significant number of refereed journal articles and conference proceedings in this area was due in large part to contributions from several students independently supported from the project. In particular, a good summary is contained in reference 54 provided in Appendix B and will not be repeated here. One aspect of this work that made a direct contribution to the development of the in-plant demonstration at EBR-II was the implementation of an optimal controller on the Penn State TRIGA reactor using the same type of Bailey microprocessor-based controllers.⁵⁵ This activity provided general familiarization with the requirements for interfacing the controllers to a real world process instead of just a simulation.

OPTIMAL

ROBUST

FUZZY LOGIC

NEURAL

Figure 16: Optimal, Robust, Fuzzy Logic, and Neural Network Architectures for Nuclear Reactor Control

5. CONCLUSIONS

The overall project is considered to have successfully achieved the original objective of developing a demonstration of intelligent distributed control at EBR-II. Over the three year project, simulation modeling of the EBR-II steam plant was developed for real-time operation in a distributed computer environment. The simulation was utilized to develop a diagnostic system to recognize a number of steam plant faulted conditions. A simplified control panel as a high level interface to a human operator was developed, integrated into an existing model-based display and implemented for control of the simulation. An intelligent control experiment was developed for the steam plant at EBR-II and verified using the distributed steam plant simulation in a hardware-in-the-loop configuration. The experiment procedures and approvals were developed and the experiment successfully conducted on April 1, 1993. The mathematical framework for a plant-wide supervisory control system architecture was also developed. Finally, optimal, robust, fuzzy logic and neural network control were studied for nuclear reactor control.

In reviewing this report, it should be clear that much more could be done to extend this work to an even more meaningful plant-wide demonstration where diagnostic, control console design, advanced and intelligent control are more fully integrated and their interactions with human operators more completely investigated. Although continuing funding to extend this work for application to EBR-II has not been secured, proposals to do so will be prepared whenever appropriate funding sources and continued cooperation and availability of the EBR-II plant can be identified. Furthermore, two new major projects with National Science Foundation (NSF) and Electric Power Research Institute (EPRI) funding are underway which are extending this research to a comprehensive experimental program at the Penn State TRIGA reactor and to research and curriculum development for power plant intelligent distributed control. The theoretical and simulation based study of optimal, robust, neural network and fuzzy logic control is being demonstrated on the TRIGA reactor and intelligent reconfigurable control in a multivariable environment will be developed and demonstrated in coming years. Research and curriculum development is being developed for both fossil and nuclear plants by building on the distributed simulation capability established in this now completed DOE project. The research conducted in this DOE project clearly enabled the continuing NSF and EPRI projects. When combined, the current NSF and EPRI projects are funded at a level approximately one and half times this DOE project. It is our goal that this research continue to expand through acceptance and implementation in commercial power plants, both fossil and nuclear.

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APPENDIX A: QUARTERLY PROGRESS REPORTS

1Q/93

QUARTERLY PROGRESS REPORT

Institution: The Pennsylvania State University

Date: March 31, 1993

Principal Investigator: Edward H. Klevans

Contract: DE-FG07-89ER 12889

Title: INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

ACTIVITY:

This report covers the second quarter of a no-cost extension period which was requested to allow the completion of actual in-plant tests at the Experimental Breeder Reactor (EBR-II). A comprehensive Final Technical Report for the entire project is planned for June 30, 1993.

LEARNING SYSTEMS, TEST PROCEDURES AND DATA PACKAGES. The learning systems reconfigurable control demonstration for the deaerator at EBR-II was substantially improved to incorporate a dynamic estimate of available Net Positive Suction Head (NPSH) at the Feedwater Pumps. The NPSH estimate is now used in the learning systems decision making process to choose control actions. Because of NPSH concerns, the original proposed test procedure of substantially reducing steam flow to the deaerator by as much as 80 percent was reduced to 10 percent. New pretest predictions were simulated and the test was conducted on February 27 and 28th. The test did not proceed as expected because of inconsistent deaerator steam flow behavior to prescribed steam supply valve positioning during the test procedure. Steam flow was not noticeably reduced during the test, deaerator pressure increased instead of decreasing as expected, and the test was terminated. The month of March was spent on revising the procedure to insure that desired steam flow changes were achieved and the learning systems-based reconfigurable controller was modified to better accommodate high pressure conditions. New pretest predictions were simulated and the revised test was successfully conducted on April 1, 1993. A detailed report and several papers are planned to describe the tests. (Humberto Garcia, E.E. Ph.D. candidate, James A. Turso, Nuc.E. Ph.D. candidate, and R.M. Edwards, Asst. Prof of Nuc.E.)

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: Approaches to coordinating intelligent deaerator and steam generation subsystems continue to be considered for the distributed simulation testing environment of the Penn State Intelligent Distributed Control Research Laboratory. This effort is part of completing the Ph.D. dissertation of Humberto Garcia by the summer of 1993. (Humberto Garcia and R.M. Edwards)

EBR-II CONTROL CONSOLE REPLACEMENT: Carlos Chavez visited EBR-II on March 11 and 12 to conduct more discussions on his computer driven graphical representation of proposed EBR-II control console layouts. Carlos' console simulation is also now being used at the University of Southern California Institute of Safety and Systems Management on an NRC funded research project under the direction of Dr. Najm Meshkati. Continued direct ANL support of Carlos' work will begin this summer through his participation as a summer student at EBR-II. (Carlos Chavez, Nuc.E. Ph.D. candidate, Yangping Zhao, Nuc.E. Ph.D. student, and R.M. Edwards)

OTHER MEETINGS: Rick Vilim of ANL East presented a seminar at Penn State on January 19, 1993. Discussions were conducted about how Penn State could help support his development of an advanced multivariable reactor inlet temperature control experiment at EBR-II. Direct support of Humberto Garcia from February to June was arranged through an ANL student program. This support effort will use many of the deaerator learning systems development and implementation techniques: Bailey multifunction controller C language programming and hardware in-the-loop simulation testing and demonstration of the controller.

Five papers were prepared and submitted for the ANS Topical Meeting on Instrumentation and Control in Oak Ridge, Tennessee, April 19-21. Dr. Edwards and eight students are expected to attend the meeting and make the presentations.

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QUARTERLY PROGRESS REPORT

Institution: The Pennsylvania State University

Date: December 31, 1992

Principal Investigator: Edward H. Klevans

Contract: DE-FG07-89ER 12889

Title: INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

ACTIVITY:

This report covers the first quarter of a no-cost extension period which was requested to allow the completion of actual in-plant tests at the Experimental Breeder Reactor (EBR-II).

LEARNING SYSTEMS, TEST PROCEDURES AND DATA PACKAGES. A test data package for *Heater Number 2 Intelligent Control Demonstration* was submitted to EBR-II in October, 1992. The package included: a full description of Bailey controller program changes, simulation validation, pretest predictions, and a draft test procedure. Professor Robert M. Edwards visited EBR-II on October 31 and conducted a hardware in-the-loop demonstration of the proposed test using a simulation of the EBR-II condensate system interfaced to a Bailey Controller teststand. Dr. Edwards and Humberto Garcia (EE. Ph.D. Candidate) visited EBR-II on November 19 and 20 to conduct further simulation demonstrations and to seek approval for conducting the test. The simulation testing demonstration was conducted for plant operations and engineering staff. Dr. Edwards again visited EBR-II on December 15 and 16 to assist in finalizing the test procedure and to conduct demonstrations. The test data package, previously submitted in October, motivated EBR-II engineering staff to take a closer examination of the minimum Net Positive Suction Head Requirements for the EBR-II feedwater pumps. Based on the information provided to Dr. Edwards on December 15, it appears that substantial changes to the test procedure may be required to ensure that minimum NPSH requirements will not be violated during the test. (Humberto Garcia, James A. Turso, Nuc.E. Ph.D. candidate, and R.M. Edwards)

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: Although the main goal of the remaining work has been reduced to an in-plant demonstration of intelligent control on the deaerator system at EBR-II, some work continues to design a potential follow-on test of a fault-accommodating control strategy for the EBR-II steam pressure and steam drum level control loops. Approaches to coordinating intelligent deaerator and steam generation subsystems are also being considered. Due to the delays in achieving an in-plant test for the deaerator subsystem, implementation of this follow-on test is now expected to be limited to the distributed simulation testing environment of the Penn State Intelligent Distributed Control Research Laboratory. (Humberto Garcia and R.M. Edwards)

EBR-II CONTROL CONSOLE REPLACEMENT: This *new task* was initiated as a spinoff activity of the original proposal during the last quarter and is being pursued primarily as an independent research activity of a self-supporting fellowship student (Carlos Chavez) and as part of a new NSF project for *Research and Curriculum Development for Power Plant Intelligent Control*, EID-9212132. The objective is to establish an approach for conducting human factors and man machine interface research in support of an EBR-II control console upgrade. A complete computer driven graphical representation of an initially proposed control console layout is now driven by a dynamical simulation of the EBR-II primary system. This console simulation has been made available to EBR-II, ANL East, and ORNL personnel. (Carlos Chavez, Yangping Zhao, and R.M. Edwards)

MEETINGS: Kenney Gross of ANL East presented a seminar at Penn State on October 6. In addition to the trips to EBR-II mentioned above in the first activity, Dr. Edwards attended an initial meeting of an IEEE committee on Instrumentation and Control for nuclear power plants in Orlando on October 28. Dr. Edwards also presented two papers at the ANS meeting in Chicago on November 18.

QUARTERLY PROGRESS REPORT

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Institution: The Pennsylvania State University

Date: September 30, 1992

Principal Investigator: Edward H. Klevans

Contract: DE-FG07-89ER 12889

Title: INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

ACTIVITY:

Due to the delays in getting final EBR-II experiments conducted, a formal no-cost-extension to the contract was requested to extend the completion date beyond the September 30 scheduled completion to March 31, 1993. Quarterly progress reports will continue to be issued.

VERIFICATION AND VALIDATION: A special data logging test (TST-292) was conducted at EBR-II on September 1, 1992. The test recorded plant data during manipulation of normal deaerator level and pressure controller setpoints. The data was used to validate the PC-based simulation of the EBR-II condensate system developed and demonstrated over the summer at EBR-II. (James A. Turso, NucE PhD candidate and R.M. Edwards, NucE professor)

LEARNING SYSTEMS, TEST PROCEDURES AND DATA PACKAGES. Work to prepare a test procedure and data package for conducting a demonstration of intelligent control involving the EBR-II deaerating feedwater heater was initiated with the goal of conducting the test during a November shutdown. The test will utilize modified Bailey Controller programming and a UNIX computer graphics-based interface for monitoring the test. The test objective is to demonstrate fault-accommodating behavior which can be obtained through control system reconfiguration. The procedure is being developed in consultation with EBR-II Bailey control specialists and operations personnel requests to consider hypothesized failures during the tests. The data package will include pretest predictions using the simulation validated against TST-292. (Humberto Garcia, EE PhD candidate and R.M. Edwards)

STEAM PLANT DIAGNOSTICS: The proposed November test will incorporate diagnostic input from the DISYS system operating in the same UNIX computer as the graphics-based display. (Phillip Walter, NucE PhD candidate and R.M. Edwards)

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: Work continued to design a follow on test with a learning systems-based fault-accommodating control strategy for the EBR-II steam pressure and steam drum level control loop. Approaches to coordinating intelligent deaerator and steam generation subsystems are also being examined. With a successful November intelligent control demonstration centered around the deaerating feedwater heater, this follow on test will be pursued for an in-plant demonstration in early 1993 during the no-cost extension. (Humberto Garcia and Adel BenAbdenour, EE PhD candidate.)

EBR-II CONTROL CONSOLE REPLACEMENT: Carlos Chavez (NucE PhD candidate) visited EBR-II in August and collected input from engineering staff and operations personnel on their desire to upgrade the EBR-II control console and incorporate CRT displays of plant information. Brian Haiback, a Penn State Nuclear Engineering undergraduate student, initiated this new activity as an IFR summer student at EBR-II. To continue this work one step further, a DATAVIEWS simulation of the proposed console configuration is being explored. The objective of this work is to establish an approach for conducting human factors and man machine interface research in support of a control console upgrade. If this exploratory effort succeeds, this task could extend beyond the no cost extension period as an ANL funded project and eventually lead to expanded research in advanced and intelligent control.

MEETINGS: Humberto Garcia gave a presentation at a Society for Industrial and Applied Mathematics (SIAM) meeting in Minneapolis Minnesota in September on the subject of reconfigurable control. Kenney Gross of ANL East is scheduled to give a seminar at Penn State on October 6.

QUARTERLY PROGRESS REPORT

Institution: The Pennsylvania State University

Date: June 30, 1992

Principal Investigator: Edward H. Klevans

Contract: DE-FG07-89ER 12889

Title: INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

ACTIVITY:

INTERACTIVE SIMULATION USING VAX <-> SUN COMPUTERS: A PC-based real-time simulation of the EBR-II steam plant was modified and interfaced to the Bailey Test Stand at EBR-II using an older model Computer Interface Unit (CIU-01) available at EBR-II. This setup will allow demonstration of fault-accommodating reconfigurable control in a hardware-in-the-loop simulation testing setup at EBR-II during the remainder of the summer. Since only one CIU is available in the EBR-II test stand, the simulation interface is now being modified to work with a Serial Port Module. The CIU will then be available for a UNIX-based graphics interface; See Learning Systems below. (James A. Turso, Nuc.E. Phd candidate and Humberto Garcia, EE PhD candidate.)

STEAM PLANT DIAGNOSTICS: Development of a UNIX-based DATAVIEWS graphics interface for creating and modifying DISYS diagnostic data bases continued with the goal of demonstration at EBR-II in August. (Carlos Chavez, NucE PhD candidate)

LEARNING SYSTEMS: Development of UNIX-based DATAVIEWS graphics interface for the intelligent distributed control experiments was initiated. The first interface will be for the learning systems based reconfigurable control of the EBR-II deaerator. These interfaces will utilize a serial interface between a UNIX computer and a Bailey Computer Interface Unit and special communication software developed at Penn State. (Humberto Garcia and Carlos Chavez)

VERIFICATION AND VALIDATION: The *Technical and Program Feasibility Design Package*, which describes a set of seven progressively more sophisticated experiments to achieve the goals and objectives of the grant, was reviewed by the EBR-II Experiment Planning and Scheduling Committee on April 27. Technical Feasibility was granted for experiments two through four; these experiments involve reconfigurable control on the deaerator subsystem. Experiment DATA Packages must still be prepared and approved before the experiments can be conducted. The previously approved first experiment involving simple data logging during a normal plant startup (or shutdown) was not conducted during the end of June startup because of EBR-II priorities to complete a two month continuous run during July and August. Penn State experiments are being considered for September. **Due to the delays in getting experiments conducted, a formal no-cost-extension to the contract will be requested to extend the completion date beyond the current September 30 scheduled completion.** (R.M. Edwards, NucE professor)

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: New work was initiated to design a learning systems-based fault-accommodating control strategy for the EBR-II steam pressure and steam drum level control loop. Approaches to coordinating intelligent deaerator and steam generation subsystems are also being examined. Implementation of a bank of preprogrammed controllers for the steam system in the Bailey test stand at Penn State and interfacing for distributed simulation testing was also initiated. (Humberto Garcia and Adel BenAbdennour, EE PhD student.)

MEETINGS: Four papers were presented at the Eighth Power Plant Dynamics Conference, May 27-29, by Drs. K.Y. Lee and R.M. Edwards and graduate assistants Phillip Walter and Adel BenAbdennour. Carlos Chavez presented a paper at the Boston ANS meeting in June. James Turso and Brian Haiback began their summer assignments at EBR-II the end of May. Professor Edwards participated in the IFR technology workshop at EBR-II the last two weeks of June and will remain at EBR-II through August 14. An EBR-II objective for Penn State personnel during the summer is to assume the lead role in a long-desired and often-postponed control console

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QUARTERLY PROGRESS REPORT

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Institution: The Pennsylvania State University

Date: March 31, 1992

Principal Investigator: Edward H. Klevans

Contract: DE-FG07-89ER 12889

Title: INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

ACTIVITY:

INTERACTIVE SIMULATION USING VAX <-> SUN COMPUTERS: The UNIX workstation to Bailey Computer Interface Unit (CIU-04) serial communication programming has been configured into a general purpose library. B&W Nuclear Services has also agreed to allow Penn State to operate the Penn State Copy of the Modular Modeling System at EBR-II this summer. This capability will enable the setup of a limited-scope hardware-in-the-loop simulation testing capability at EBR-II using a PC computer. Conversion of the general purpose serial communication library for the NDP C language has been initiated because the B&W MMS utilizes NDP languages. (Humberto Garcia, EE PhD candidate and James A. Turso, Nuc.E. Phd candidate)

STEAM PLANT DIAGNOSTICS: The simulation of the 10 steam plant faults in the real-time distributed simulation is complete and finalization of a DISYS diagnostic data base to identify the faults is proceeding. (Phillip Walter, NucE PhD candidate)

LEARNING SYSTEMS: The learning systems reconfigurable control was developed for an initial demonstration on a Bailey test stand at EBR-II. (Humberto Garcia and R.M. Edwards, Nuc.E. Professor)

VERIFICATION AND VALIDATION: Robert M. Edwards spent the week of March 9th at EBR-II and demonstrated implementation of the proposed reconfigurable control on a Bailey equipment test stand at EBR-II. (This test stand is not connected to the plant but contains the same type of equipment which is employed in the plant. EBR-II upgraded their Multifunction Controller to C Language programming to enable the March demonstrations and eventual in-plant experiments.) The *Technical and Program Feasibility Design Package* prescribed in the EBR-II Experiment Guide was finalized and submitted to EBR-II on March 27. It describes a set of seven progressively more sophisticated experiments to achieve the goals and objectives of the grant during the *upcoming final 6 months*. The first in-plant experiment consists of data logging during setpoint manipulation of the EBR-II deaerator. This experiment and its associated test procedure (TST-292) were reviewed by the Experiment Planning and Scheduling Committee on March 10. On March 17, it was recommended for Division approval for preparation and conduct. It is expected to be conducted during a normally scheduled plant startup or shutdown.

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: The DATAVIEWS-based interface is now complete enough to be routinely used for monitoring and selecting the power level of the distributed simulation of the EBR-II steam plant. New work was initiated to develop a graphical interface for manipulating DISYS diagnostic databases. (Carlos Chavez, Nuc.E. PhD candidate)

MIMOML ROBUST CONTROL: An application of the LQG/LTR robust control technique was successfully applied to a simulation of the EBR-II steam drum level and steam header pressure control loops. A model order reduction was required to eliminate a non-minimum phase condition. Work was also initiated at identifying desirable fault-accommodating control actions for the steam generation system as the basis of intelligent reconfigurable control experiments involving that system. (Adel BenAbdennour, E.E. PhD student and James Turso)

MEETINGS: In addition to R.M. Edwards spending the week of March 9th at EBR-II, he also presented a paper at an EPRI meeting in February, *Advanced Control Research at Penn State*. Dr. Lee of Electrical Engineering presented a paper at the IEEE Power Systems Winter Meeting in January, *The Penn State Intelligent Distributed Control Research Laboratory*. Four papers were prepared and submitted for the Eighth Power Plant Dynamics Conference, May 27-29. Dr. Sam Palusamy of Westinghouse also visited EBR-II during the week of March 9. He made a presentation on Westinghouse's commercial monitoring and maintenance products and proposed an advanced monitoring and maintenance demonstration for EBR-II.

QUARTERLY PROGRESS REPORT46/91
K**Institution:** The Pennsylvania State University**Date:** December 31, 1991**Principal Investigator:** Edward H. Klevans**Contract:** DE-FG07-89ER 12889**Title:** INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS**ACTIVITY:**

INTERACTIVE SIMULATION USING VAX <-> SUN COMPUTERS: Work continued on the expansion of the distributed simulation testing environment to improve the interface of the Bailey NETWORK 90 system. The new interface will connect a UNIX workstation directly to a Bailey Computer Interface Unit (CIU). This communication protocol is also expected to be used in proposed experiments at EBR-II. (Humberto Garcia, EE PhD candidate)

STEAM PLANT DIAGNOSTICS: Work continued on simulation of additional steam plant faults for developing DISYS diagnostic rules to identify the faults. A new data base was provided to EBR-II for evaluation by their Engineering support staff. (Phillip Walter and James Turso, NucE PhD students)

LEARNING SYSTEMS: The learning systems approach to reconfigurable control is being developed for an EBR-II experiment. A two step experimental sequence is now recommended. The first step will demonstrate the stability and performance of a deaerator pressure regulating algorithm which manipulates the condensate flow control valve. The second step will demonstrate automatic selection of control laws using the learning algorithm implemented in a Bailey Multifunction Controller. (Humberto Garcia and James Turso)

VERIFICATION AND VALIDATION: A data logging program for collecting transient data directly from the EBR-II Bailey system was developed and demonstrated on a Bailey test setup at EBR-II. A test procedure (TST-292) for operating the program was drafted and is being reviewed by EBR-II personnel. The data obtained by the data logging program will be used to validate simulations used in developing EBR-II experiments. (James Turso and R.M. Edwards)

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: Work continued on improving the top level operator control interface with the EBR-II main iconic display using DATAVIEWS software. This interface is used for monitoring and selecting the power level of the distributed simulation of the EBR-II steam plant. (Carlos Chavez, Nuc.E. PhD student)

MIMOML ROBUST CONTROL: The robust control techniques which were successfully applied to a simulation of the EBR-II deaerator are now being developed for application to the steam drum level and steam header pressure control loops. Initial work is tailoring the existing simulation of the steam generation and high pressure feedwater train simulations for this purpose. (Adel BenAbdenmour, E.E. PhD student and James Turso)

MEETINGS: R.M. Edwards spent the week of December 9th at EBR-II to update them on the project's progress. The week of March 9th was also suggested for the next visit in order to facilitate the development of test procedures needed for actual intelligent distributed control experiments during 1992. A draft paper was prepared for the Advanced Nuclear Power (ANP'92) conference to be held in Tokyo in October.

A conference call with Sam Palusamy of Westinghouse, Pete Planchon, Reed Monson, Dick Lindsay, Kenny Gross, Ralph Singer, and R.M. Edwards discussed possibilities for demonstrating Westinghouse technologies for monitoring and maintenance at EBR-II. A two day visit by Westinghouse personnel to EBR-II in March was suggested to follow-up on this discussion. Bell Upadhyaya also visited EBR-II for a day during that week and discussions on EBR-II projects involving universities was conducted.

Leo Beltrachi of the NRC and James Easter of Westinghouse presented seminars at Penn State in December. The presentations related human factors considerations to control room design and model based plant information displays. Distributed simulation testing of the Intelligent Distributed Control research for EBR-II was also demonstrated for them.

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QUARTERLY PROGRESS REPORT

Institution: The Pennsylvania State University

Date: September 30, 1991

Principal Investigator: Edward H. Klevans

Contract: DE-FG07-89ER 12889

Title: INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

ACTIVITY: This report covers the 4 month period from June through September 1991 in order to adjust the quarterly progress reporting interval to the end of the 2nd year budget period. The major accomplishment of this period was the preparation and presentation of 4 papers at the ANS meeting *AI 91: Innovative Frontiers in Innovative Computing for the Nuclear Industry*, September 15-17 1991, in Jackson Wyoming: 1) H.E. Garcia, et al, "On-line Diagnostics and Intelligent Control for the Steam Plant at EBR-II", 2) C.M. Chavez, et al, "A Human Factors Evaluation of a Highly Automated Nuclear Power Plant", 3) J.A. Turso, et al, "Experience with Developing a Real-World Advanced Control and Diagnostic Testbed Using a University Research Reactor", and 4) Adel Ben-Abdenmour, et al, "MIMOML Robust Control for Accommodating EBR-II Feedwater System Faults". Each paper is a good summary of the second year's effort on the related task(s).

INTERACTIVE SIMULATION USING VAX <-> SUN COMPUTERS: (AI 91 paper 1) All three subsystems of the EBR-II steam plant are now operational in the distributed simulation testing environment. The three subsystems are the condensate system with the condensate pump and feedwater heaters #1 and #2, the feedwater system with the feedwater pump and heaters #3 and #4, and the steam system with the evaporators, steam drum, superheaters, and main steam bypass valve. Each subsystem simulation operates in a VAX computer and transfer required data using a centralized data base in a UNIX based computer. (Humberto Garcia, EE PhD candidate, and James Turso, NucE PhD student)

STEAM PLANT DIAGNOSTICS: (AI 91 paper 1) The DISYS diagnostic system was also made operational with the complete distributed steam plant simulation and the current effort is refining the data base to identify steam plant faults directly from real-time simulated data. (Phillip Walter, NucE PhD student, and R.M. Edwards, NucE professor.)

LEARNING SYSTEMS: The learning systems approach to reconfigurable control is implemented in a Bailey Multifunction Controller (MFC). All previous simulation testing of this algorithm has interfaced the MFC directly to a VAX computer. Current work is developing an interface to the centralized plant data base in the UNIX computer of the distributed simulation using both serial and IEEE 488 communication procedures. This capability will provide more flexibility in interfacing simulations with the Bailey system and in actual EBR-II experiments. EBR-II has UNIX computers more readily available than VAX computers for communicating with Bailey controllers and monitoring experiments. (Humberto Garcia)

VERIFICATION AND VALIDATION: (AI 91 paper 2) The optimal temperature control algorithm for the Penn State TRIGA reactor has now been successfully demonstrated using a Bailey MFC and provides practical experience to help prepare experiment design (data) packages for the proposed intelligent distributed control demonstrations at EBR-II. (James Turso and R.M. Edwards)

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: (AI 91 paper 3) Carlos Chavez (Nuc.E. PhD fellowship student) implemented the top level operator control interface with the EBR-II main iconic display using DATAVIEWS software. This operator interface is now used for monitoring and selecting the power level of the distributed simulation of the EBR-II steam plant through the centralized plant data base.

MIMOML ROBUST CONTROL: (AI 91 paper 4) The E.E. master thesis of Adel Ben-Abdenmour on multivariable robust control of the EBR-II deaerator was completed.

OTHER MEETINGS: R.M. Edwards presented two summaries at the ANS Annual Meeting in Orlando in June. Harry Alter, DOE technical co-monitor for the project, visited Penn State on July 30 and 31st, received demonstrations of most of the activities, and met with students and faculty working on the project.

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QUARTERLY PROGRESS REPORT

Institution: The Pennsylvania State University

Date: May 31, 1991

Principal Investigator: Edward H. Klevans

Contract: DE-FG07-89ER 12889

Title: INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

ACTIVITY:

INTERACTIVE SIMULATION USING VAX <-> SUN COMPUTERS: The distributed simulation approach to achieving real-time performance is now operational. The initial system interfaced a simulation of the EBR-II condensate and feedwater systems coordinated through a distributed simulation manager and centralized data base in a Concurrent 6350 UNIX based workstation. Analytical results of the decomposed simulations were compared with a batch mode simulation of the combined system and were found to be in excellent agreement. The distributed simulation protocol has been generalized to facilitate additional decomposed simulations of other subsystems and applications during the remainder of the project. (Humberto Garcia, EE PhD candidate, and James Turso, NucE PhD student)

STEAM PLANT DIAGNOSTICS: The steam plant diagnostics for the EBR-II deaerator has been expanded to begin utilization with the reconfigurable controller for accommodating deaerator steam supply failure. The DISYS system, operating in a UNIX computer, provides an additional assessment of deaerator health for the learning systems performance evaluator. (H.E. Garcia, and R.M. Edwards, NucE PhD)

LEARNING SYSTEMS: The learning systems reconfigurable control was adapted to use the output of the DISYS diagnostic system in its performance evaluator. In the current simulation testing, a real-time EBR-II condensate system simulation uses the distributed simulation manager to provide real-time data to DISYS operating in the Concurrent Computer. The DISYS system uses the distributed simulation manager to return data to the simulation which in turn transfers the DISYS status to the learning systems algorithm operating in the Bailey MFC. With the distributed DISYS activity in the coming quarter, a direct method of transferring the diagnostic status to the learning systems controller will bypass the VAX computer and then become adaptable for experimental demonstration at EBR-II. (Humberto Garcia)

VERIFICATION AND VALIDATION: To develop some real-world expertise in implementing advanced control concepts, an optimal temperature control algorithm for the Penn State TRIGA reactor is being developed for application using a Bailey MFC. The EBR-II experiment guide will begin to be used to develop control experiment design (data) packages for the proposed intelligent distributed control demonstrations at EBR-II. (James Turso and R.M. Edwards)

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: Carlos Chavez (Nuc.E. PhD fellowship student) created an initial operator interface for Schultz's 8 pushbutton control panel as part of an Industrial Engineering Human/Computer Interface Course. The interface uses the EBR-II main iconic display and allows the operator to interactively select the desired power level for the plant. This interfaced was a prototyped on a PC computer and will be incorporated in the DATAVIEWS version of the EBR-II main iconic display in the Concurrent computer in the next quarter.

MIMOML ROBUST CONTROL: Testing of the robust fault-accommodating controller for the EBR-II deaerator has been completed to permit finalization of the E.E. master thesis of Adel Ben-Abdenour.

MEETINGS: James Turso presented a paper at the ANS student conference in March on verifying the EBR-II simulation incorporating a Bailey controller. R.M. Edwards presented papers on the distributed simulation and MIMOML robust controller design at an EPRI conference in April. Drs. Klevans and Edwards attended the DOE review meeting at Savannah River in April. Drs. Edwards and Kumara (I.E.) visited Westinghouse and gave a presentation on the DOE project. Westinghouse expressed an interest in expanding the Penn State activities in diagnostics at EBR-II into a more broad role suitable for commercial nuclear power plant applications. Westinghouse wants to approach EPRI to help support such a Penn State research expansion.

QUARTERLY PROGRESS REPORT

Institution: The Pennsylvania State University

Date: February 28, 1991

Principal Investigator: Edward H. Klevans

Contract: DE-FG07-89ER 12889

Title: INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

ACTIVITY:

INTERACTIVE SIMULATION USING VAX <-> SUN COMPUTERS: The development of the distributed simulation using a VAX Cluster has suffered a setback as the student assigned to the task last semester failed to return to Penn State in January. Humberto Garcia, in command of the learning systems task, and James Turso, in command of the verification and validation activities are additionally taking on this task.

STEAM PLANT DIAGNOSTICS: The Concurrent 6350 computer was installed on January 15th and the DISYS diagnostic system, previously established for SUN computers, was loaded on to the system. Some changes have had to be made to accommodate the idiosyncracies of the real-time UNIX of the Concurrent computer. We have been able to get assistance with some of the required software changes from EBR-II staff because of their experience with this particular type of equipment. The DISYS diagnostic system will be distributed between the Concurrent 6350 and the Bailey NETWORK 90 system during the remaining half of the first year. (R.M. Edwards, NucE PhD)

LEARNING SYSTEMS: Nothing new was added to the learning systems reconfigurable control during the last quarter and it remains in its advanced state of development. (Humberto Garcia, E.E. PhD student)

VERIFICATION AND VALIDATION: The EBR-II experimenter's guide has been obtained. Although the guide is focused on experiments involving fuel testing, we plan to initiate the experiment review and approval process for the proposed learning systems and distributed diagnostics demonstrations. (James Turso, NucE Phd Student)

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: Carlos Chavez (Nuc.E. PhD fellowship student) is conducting the initial programming and human factors assessment of the simplified operator interface as part of a semester project for an Industrial Engineering Human Factors course.

MIMOML ROBUST CONTROL: The robust fault-accommodating controller for the EBR-II deaerator is now being tested with simulation using the Modular Modeling System. A paper has been prepared for the April 1991 EPRI conference on Simulation. (A. Ben-Abdenmour, E.E. Masters Student)

MEETINGS: R.M. Edwards, Asok Ray, K.Y. Lee and Joseph Goldberg attended the ORNL demonstrations and met with Harry Alter in Germantown on January 18th. R.M. Edwards attended the NSF workshop on European Nuclear Instrumentation on January 31st.

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QUARTERLY PROGRESS REPORT

Institution: The Pennsylvania State University
Date: November 30, 1990
Principal Investigator: Edward H. Klevans
Contract: DE-FG07-89ER 12889
Title: INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

ACTIVITY:

INTERACTIVE SIMULATION USING VAX <-> SUN COMPUTERS: A new student from Electrical Engineering (Mohammed Ghie) was assigned to this task late in the semester after 2nd year funds became available. The MMS simulation of the high pressure feedwater train of the EBR-II steam plant operating in a VAX computer has been connected to a real-time interactive operator interface in a UNIX Computer using the same architecture as the low pressure feedwater train VAX/UNIX simulation in the previous quarter. The next step is to interface the low pressure and high pressure feedwater train VAX/UNIX simulations. The distributed simulation is expected to execute faster than a single simulation program containing both subsystems. The goal is to provide real-time simulation for plant wide diagnostic and control testing. (M. Ghie E.E. PhD Student)

STEAM PLANT DIAGNOSTICS: Refinement of the initial DISYS steam plant diagnostic data base to incorporate changes recommended by EBR-II Staff and to identify the complete set of 10 hypothesized failures in the steam plant was suspended in the last quarter as R.M. Edwards completed his PhD and thesis defense in an independent but related area to the project (robust reactor control). Completion of the identified steam plant diagnostic improvements will be a high priority in the next quarter and the distributed aspects of the diagnostic system should begin with the delivery of the MASSCOMP 6450 Computer System and interface to the Bailey Microprocessor-based control system. (R.M. Edwards, NucE PhD)

LEARNING SYSTEMS: The Learning Systems reconfigurable control activity is proceeding at an accelerated pace. The learning algorithm has now been programmed in a Bailey Multifunction Controller (MFC) using C language programming interfaced to standard Bailey Control Block Programming. In principle the fully programmed MFC can be taken to EBR-II where the simulation used to test and demonstrate the concept can be replaced with the actual plant. An experiment interface will be developed using Dataviews Software on the MASSCOMP. (Humberto Garcia, E.E. PhD student)

VERIFICATION AND VALIDATION: The diagnostics and learning systems are being developed as candidate experiments to be conducted at EBR-II. Verification of the fidelity of the Steam Plant Simulation is expected to be an important element of the experiment review process. One approach for validating the simulation has been initiated where the actual programming employed in the Bailey Controllers at EBR-II has also been implemented in the Bailey Control system at Penn State and interfaced with simulations of the EBR-II condensate system. Simulation results for deaerator level and pressure setpoint changes have been provided to EBR-II Staff so that they can begin to help us assess the fidelity of our steam plant simulations. Familiarization with the established EBR-II Experimenter's guide will also begin in the next quarter. (James Turso, NucE PhD Student)

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: James Turso and Carlos Chavez (Nuc.E. PhD fellowship student) will begin working in this area during the spring semester. Together they will build a simulation of Schultz's 8 push button control concept on a UNIX computer using Dataviews Software. This interactive operator interface will be developed to first connect to our distributed simulation in the VAX Cluster to demonstrate power level maneuvering in the normal

operating range (20 to 100 percent power). A longer term goal is to integrate the DISYS diagnostic interface and intelligent control aspects of the project with this display system taking into account human factors considerations. (Carlos Chavez, NucE Phd Student)

MIMOML ROBUST CONTROL: With the addition of a new fellowship student it has become possible to explore an important new aspect of Intelligent Control, Multiple Input Multiple Output Multiple Layer Robust Control. The technique is being applied to the EBR-II deaerator simulation. It is anticipated that the learning systems activity could incorporate selection of this new algorithm in its fault accommodating control response. (A. Benabdenour, E.E. Masters Student)

MEETINGS: Representatives of ANL West, ANL East, and the Universities of Tennessee and Illinois visited Penn State on November 15th for an exchange of ideas on advanced control research. Asok Ray, Professor of Mechanical Engineering, attended the EPRI/NSF workshop on Intelligent Control, and presented a paper on the learning systems activity at the ASME Annual Winter Meeting. Carlos Chavez attended a DATAVIEWS training seminar.

Institution: The Pennsylvania State University

Date: August 31, 1990

Principal Investigator: Edward H. Klevans

Contract: DE-FG07-89ER 12889

Title: INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

ACTIVITY:

CONTINUATION PROPOSAL: The first year of the project has been completed. It has been indicated that 2nd year continuation has been approved at the requested funding level and those activities will be initiated.

EBR-II STEAM PLANT SIMULATION: The master's thesis of Dave Ruhl has been completed. The thesis project provides a dynamic simulation of the EBR-II steam plant. A set of 10 hypothesized failure scenarios have been simulated and are being used to develop the DISYS diagnostic data base for the steam plant. (Dave Ruhl, Nuc.E. M.S. student; and R.M. Edwards, Nuc.E. PhD student)

STEAM PLANT DIAGNOSTICS: An initial steam plant diagnostic system was demonstrated to EBR-II staff in July and included steam plant engineers (Bill Radtke and Russ Crawford) and operations personnel (Gerry Wolz) as well as Computer Applications personnel. Based on this demonstration, several changes to the data base are being incorporated. The 2nd year activity to develop a distributed diagnostic demonstration will begin. Serial communication software provided by EBR-II (Dave Braithwaite) will link a Bailey control system and a UNIX computer. Low level diagnostic functions will execute in a Multifunction controller with the results communicated back to the higher level diagnostic functions in the UNIX computer. (Carlos Chavez, Nuc.E. PhD fellowship student and R.M. Edwards)

LEARNING SYSTEMS: The Learning Systems approach to dealing with failures to the EBR-II deaerating heater steam supply will also be further developed for a possible plant demonstration. The current simulation demonstration at Penn State interfaces a VAX simulation with the learning systems decision making process to select preprogrammed control algorithms in the Penn State Bailey System. The next step is to move the C language learning systems programming from the VAX simulation into a Bailey Multifunction controller. Once this configuration has been thoroughly tested with simulation at Penn State and an EBR-II experiment design review process conducted, then the simulation can be replaced with the actual plant. (Humberto Garcia, E.E. PhD student; R.M. Edwards; Asok Ray, M.E. professor)

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: The overall plant design of distributed control was being conducted by Dana Wood and M.A. Schultz. Dana worked at EBR-II as a summer student and it was expected that he would bring back hands-on knowledge of the plant to continue this activity in coming years. Unfortunately for the proposed 2nd year activities, Dana has accepted full time employment at EBR-II. Until a suitable replacement student or activity is identified, Carlos Chavez will continue some of the work initiated by Dana at EBR-II in the area of a graphics interface to aid plant instrumentation checks during plant startup. (Carlos Chavez, Nuc.E. PhD fellowship student)

INTERACTIVE SIMULATION USING VAX <-> SUN COMPUTERS: A College of Engineering summer project created an interactive simulation capability using a VAX mainframe simulation and a UNIX workstation for an operator to interactively adjust simulation parameters. This capability will be further expanded to develop better real-time simulation capabilities by decomposing a large simulation into smaller simulations operated in parallel on several VAX computers. This activity provides work for a new Nuclear Engineering PhD student, James Turso. Jim has started his familiarization with the project by programming the Penn State Bailey controllers with the actual control algorithms implemented at EBR-II and using them to control a real-time simulation of the plant. (James Turso, Nuc.E. PhD Student and R.M. Edwards)

MEETINGS: E.H. Klevans, Asok Ray, and R.M. Edwards attended a meeting with ORNL, ANL, University of Tennessee, and Illinois University at the June ANS conference. Each organization summarized their activities in controls research. E.H. Klevans and R.M. Edwards attended the DOE review meeting in July and R.M. Edwards worked on the project at the EBR-II site. R.M. Edwards attended the International Fast reactor Safety Meeting in August and presented two papers on this project.

20/90

QUARTERLY PROGRESS REPORT

Institution: The Pennsylvania State University

Date: May 31, 1990

Principal Investigator: Edward H. Klevans

Contract: DE-FG07-89ER 12889

Title: INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

ACTIVITY:

CONTINUATION PROPOSAL: The continuation proposal for the 2nd year of the project was submitted at the end of May and contains a progress report on the activities summarized below.

EBR-II STEAM PLANT SIMULATION: The master's thesis of Dave Ruhl is undergoing final review. The thesis project provides an initial B&W Modular Modeling System Model of the EBR-II Steam plant including the condensate, feedwater, steam generation and control systems. The model was validated against actual plant data for startup from 49 to 62 Megawatts and a rapid decrease from full power conducted during PICT 6. The simulation response to a hypothesized failure of the feedwater pump recirculation line valve to the fully open position is also reported in the Thesis. A paper, based on the thesis, was prepared for the August Fast Reactor Safety Meeting. A set of 10 hypothesized failure scenarios have been additionally identified in cooperation with EBR-II staff for simulation testing of a diagnostic data base during the remainder of the first year. (Dave Ruhl, Nuc.E. M.S. student; and R.M. Edwards, Nuc.E. PhD student)

STEAM PLANT DIAGNOSTICS: The initial steam plant diagnostic data base was modified such that it recognizes the simulated recirculation failure. Additional refinements to the data base and simulation testing is the major first year task remaining. Due to computer system upgrades at EBR-II during the last few months it has not been possible for the EBR-II staff to operate and evaluate the initial steam plant diagnostic and displays. Robert Edwards will spend the entire week of July 16th in Idaho to obtain feedback from the EBR-II Staff on all aspects of the project but with primary emphasis on finalizing a useful steam plant diagnostic system. (Carlos Chavez, Nuc.E. PhD student; and R.M. Edwards)

LEARNING SYSTEMS: The Learning Systems paper submitted for publication in IEEE Control System Magazine has been accepted, subject to final revision. The self contained VAX computer simulation is being migrated into a demonstration utilizing the Bailey NETWORK90 system and VAX Computers. A new paper is being prepared for the Yale University Conference on Adaptive and Learning Systems, August 15th to 17th. (Humberto Garcia, E.E. PhD student; R.M. Edwards; Asok Ray, M.E. professor)

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: Dana Wood has been hired as an IFR student at EBR-II and began work there May 7th. He has started by charting startup procedures and monitoring actual plant operations. He is also being familiarized with hardware and software packages available at EBR-II for plant automation. (Dana Wood, Nuc.E. PhD student; and M.A. Schultz)

INTERACTIVE SIMULATION USING VAX <-> SUN COMPUTERS: A College of Engineering summer project has been initiated to develop an alternative to the IBM 4341 Mainframe Advanced Control System interactive simulation which is being retired July 1st due to excessive maintenance costs. The alternative is to interface VAX simulations to SUN Workstation display capabilities. (Sanjeev Dahrap, Computer Science PhD student; Suk Lee, recently completed M.E. PhD; and R.M. Edwards)

MEETINGS: The EPRI workshop on Instrumentation and Control was attended by R.M. Edwards. Dave Ruhl gave presentations on his work at the ANS Student Conference and at the B&W MMS User Group Meeting. John Sackett visited Penn State on May 7th, discussed the project and obtained demonstrations of the DISYS diagnostic system and Bailey NETWORK 90 equipment.

BAILEY NETWORK 90 CONTROL SYSTEM: Installation of the NSF supplied Bailey system began in April and has already been interfaced to VAX computer simulations.

QUARTERLY PROGRESS REPORT

Institution: The Pennsylvania State University

Date: February 28, 1990

Principal Investigator: Edward H. Klevans

Contract: DE-FG07-89ER 12889

Title: INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

ACTIVITY:

EBR-II STEAM PLANT SIMULATION: Initial simulation runs with a combined model of the EBR-II low pressure feedwater train, high pressure feedwater train, and steam generation system have now been obtained. The first transient evaluated is a normal power change transient from 50MW to 60MW using actual EBR-II plant data for sodium inlet temperature and flow rate to drive the simulated plant. The model has been constructed using the B&W Modular Modeling System. The combined model or individual subsystem simulations can be used for generating transients for testing diagnostics. In this first year of the contract, simulated data is transferred via disk files to a SUN Workstation where it is played back into a simulated EBR-II Data Acquisition System (DAS) data base at a real-time rate. The response of the diagnostic system to the simulated data can then be demonstrated and evaluated. (Dave Ruhl, Nuc.E. M.S. student; and R.M. Edwards, Nuc.E. PhD student)

STEAM PLANT DIAGNOSTICS: The initial steam plant diagnostic data base and X-window graphics displays of the DISYS diagnostic system was demonstrated to EBR-II personnel in Idaho during early January by R.M. Edwards. Significant input for improving the displays and properly identifying the appropriate sensor locations in the plant were obtained and incorporated in a revised diagnostic interface shipped to EBR-II at the end of February. An upgrade of the X-Window system from release 3 to release 4 has also produced dramatic improvement in the speed of the graphics and response to operator inquiries. In discussing steam plant diagnostic concerns the failure of a feedwater pump recirculation flow valve was identified and subsequently simulated using a combined simulation of the low pressure and high pressure feedwater trains. The results of the simulated failure were included in the February shipment and can be played back into the SUN workstation displays. The dialogue with the EBR-II steam plant experts in further identification of realistic diagnostic concerns and symptom sets to identify faults needs to be increased. The ability to send tapes of simulated data to playback at EBR-II provides a convenient method for EBR-II plant personnel to assess the fidelity of the simulations and diagnostic responses. (Carlos Chavez, Nuc.E. PhD student; and R.M. Edwards)

LEARNING SYSTEMS: Also demonstrated in Idaho during January was the real-time simulated response of the learning systems approach for dealing with deaerator steam flow control failure. An interim report was also provided to EBR-II personnel. The learning systems demonstration was subsequently expanded to include noise on the simulated plant outputs. A full paper was submitted to IEEE Control System Magazine during February. (Humberto Garcia, E.E. PhD student; R.M. Edwards; Asok Ray, M.E. professor)

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: A detailed outline of an 8 push-button completely automated start-up system for EBR-II has been completed. The design proposes a feed-forward demand controller that utilizes the existing EBR-II Bailey controllers. A supervisory loop sets up the controller demand via a small computer. A hardware approach for the logic to eliminate illegal push button sequences and latching requirements has also been designed to provide a specification for the software architecture. The next step in the project is to begin coding the equivalent software strategy. (M.A. Schultz and Dana Wood, Nuc.E. PhD student)

MEETINGS: The NSF Workshop on European Nuclear Instrumentation and Control in early December and the NSF Workshop on Japanese Nuclear Technology in February were attended by R.M. Edwards.

BAILEY NETWORK 90 CONTROL SYSTEM: Delivery of the NSF supplied Bailey Control System has slipped. As of the end of February, it still has not arrived. It will be used in the 2nd year of the DOE grant so the late delivery is not yet critical.

Institution: The Pennsylvania State University
 Date: November 30, 1989
 Principal Investigator: Edward H. Klevans
 Contract: DE-FG07-89ER 12889
 Title: INTELLIGENT DISTRIBUTED CONTROL FOR NUCLEAR POWER PLANTS

ACTIVITY:

EBR-II STEAM PLANT SIMULATION: The B&W Modular Modeling System is being used to develop a dynamic simulation of the steam plant at EBR-II. During the first quarter of this new contract, an MMS model of the EBR-II steam generator, steam drum, and super heater system was initially formulated. The MMS has an extensive library of models of power plant components and an existing fossil power plant steam generation system model was modified for the EBR-II sodium-steam generation configuration. A DSNP model of the EBR-II steam generators will be used to validate the simpler MMS model. The simpler MMS approach is preferred because it is more likely to achieve real-time execution performance on the mainframe computer facilities available to the project. Further refinement of an MMS EBR-II feedwater simulation is being conducted by adding more detail to the piping models which interconnect the various components. The combined steam generation / feedwater simulation will provide a reasonably complete model to begin testing of diagnostics. (Dave Ruhl, Nuc.E. M.S. student; and R.M. Edwards, Nuc.E. PhD student)

STEAM PLANT DIAGNOSTICS: An initial DISYS diagnostic data base has been assembled for the steam plant by identifying available sensor information and obvious component and subsystem organization. A SUN workstation X-Windows 11 graphics display of sensor and diagnostic data was also prepared. The initial diagnostic data base and X-Windows displays will be demonstrated at EBR-II during the week of January 8th. Feedback from the staff at EBR-II will be used to refine the diagnostics and begin conversion of the graphics interface to the V.I. Corporation JATAVIEWS graphics software during the coming semester. Testing of the diagnostics with the dynamic simulation is expected to begin by the end of the next quarter. (R.M. Edwards; and Sagar Kamarthi, I.E. PhD student)

EXAMINATION OF LEARNING SYSTEMS: An initial demonstration of how to use a learning automata for reconfiguring deaerator control to deal with a malfunction in the normal pressure regulating steam supply was studied with an MMS simulation of the EBR-II condensate system. An interim report will be prepared for discussion with EBR-II personnel in January. (Humberto Garcia, E.E. PhD student; R.M. Edwards; Asok Ray, M.E. professor)

OVERALL PLANT DESIGN OF DISTRIBUTED CONTROL: M.A. Schultz prepared a first draft of a report titled, "Reasons for a Completely Automated Control System for a Nuclear Power Plant". An initial specification for the top level control panel is under development. Dana Wood, Nuc.E. PhD student, will begin to assist Schultz in this activity during the spring semester.

MISCELLANEOUS: Two students, who are not supported by the grant, performed independent studies related to the project for academic credit. Wayne Macafee, Nuc.E. M. Engr graduate student, examined the use of the Advanced Continuous Simulation Language (ACSL) multiple derivative section capability for possible techniques to improve real-time performance of MMS models. Carlos Chavez-Mercado, Nuc.E. PhD student with a 3 year Scholarship from Mexico, developed programs for real-time display of mainframe computer ACSL simulation outputs in the graphics-based DISYS system operating in a SUN Computer.

BAILEY NETWORK 90 CONTROL SYSTEM: The Bailey Control System proposed for the 2nd and 3rd years of this DOE project is being obtained through an NSF Equipment Grant. The complete system is to be installed at Penn State in January 1990.

APPENDIX B. SIGNIFICANT THIRD YEAR PUBLICATIONS BY SUBJECT

In-Plant Experiment Related:

- B.1 Results from an In-plant Demonstration of Intelligent Control
- B.2 In-Plant Results of a Reconfigurable Fault-Tolerant Hybrid Supervisory System
- B.3 Fault-Accommodating Feedwater Control Simulation and Verification for In-Plant Test
- B.4 The Penn State Intelligent Distributed Control Research Laboratory
- B.5 Multivariable Robust Control of a Power Plant Deaerator
- B.6 Experimental Development of Power Reactor Intelligent Control
- B.7 Experimental Development of Power Reactor Advanced Controllers
- B.8 Advanced Control Research at the Pennsylvania State University

Steam Plant Diagnostic Related:

- B.9 Feedwater System Diagnostic Development Using Distributed Simulation

Control Console Design Related:

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