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DEVELOPMENT AND TESTING OF A DIAGNOSTIC SYSTEM FOR INTELLIGENT DISTRIBUTED CONTROL AT EBR-II

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ABSTRACT

A diagnostic system is under development for demonstration of Intelligent Distributed Control at the Experimental Breeder Reactor (EBR-II). In the first phase of the project a diagnostic system is being developed for the EBR-II steam plant based on the DISYS expert systems approach. Current testing uses recorded plant data and data from simulated plant faults. The dynamical simulation of the EBR-II steam plant uses the Babcock and Wilcox (B&W) Modular Modeling System (MMS). At EBR-II the diagnostic system operates in a UNIX workstation and receives live plant data from the plant Data Acquisition System (DAS). Future work will seek implementation of the steam plant diagnostic in a distributed manner using UNIX based computers and Bailey microprocessor-based control system.

INTRODUCTION

Real-time simulation testing of advanced diagnostic and control concepts has become well established at the Pennsylvania University within recent years. In prior projects, an interactive real-time simulation capability was developed by interfacing the B&W MMS to the IBM Advanced Control System installed in a mainframe computer at the University.[1,2] The simulation capability was then subsequently used to modernize and test the DISYS Diagnostic System and complete its installation at EBR-II for the Argon Cooling System of fuel handling operations.[3,4] In 1989 the Department of Energy (DOE) approved a three year university project to develop a demonstration of Intelligent Distributed Control (IDC) at EBR-II. During the first year of the DOE IDC grant, which ends in August 1990, an additional DISYS diagnostic application is being developed for the EBR-II steam plant. The ultimate objective is to use the output of the distributed diagnostics to automatically alter control, intelligent distributed control.

EBR-II STEAM PLANT AND STEAM PLANT SIMULATION

The EBR-II power plant has as its primary system a sodium cooled pool type fast reactor rated at 62.5 MW thermal. An intermediate, or secondary, sodium loop removes heat from the primary system sodium and transfers the energy to a conventional steam electric power producing cycle that generates 20 MWe.

The diagnostic development for the EBR-II steam plant includes utilization of real-plant data recorded during normal startup and continuous operation. However, in order to develop and test diagnostics with data during upset conditions simulated data is desirable because it is more conveniently and safely generated for a wide range of postulated events. A block diagram that summarizes the major components and flow paths in the EBR-II steam plant is given in Figure 1. The condensate pump provides the initial pressure increase (250 psig) to the number 2 feedwater heater (150 psig) which is also a deaerating heater. The main feedwater pump provides the remaining pressurization to around 1700 psig and feeds a natural circulating steam drum boiler system (1360 psig). Saturated water at the

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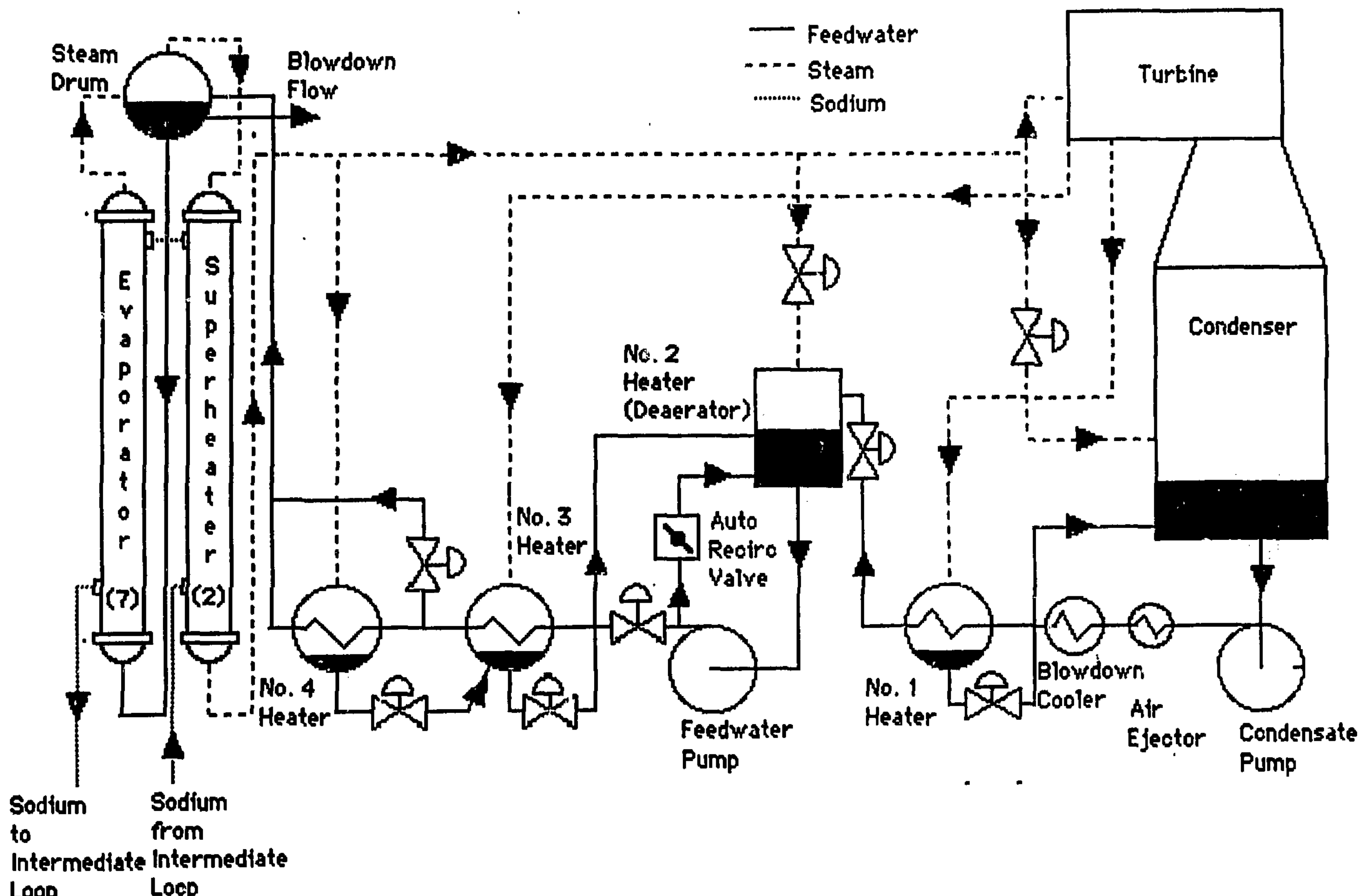

Figure 1: Major Components of the EBR-II Steam Plant

bottom of the steam drum feeds seven parallel evaporators that are heated with the liquid sodium of the EBR-II secondary system. Saturated vapor taken from the top of the steam drum is passed through 2 parallel superheaters that produce high quality steam at 265,000 lb/hr, 1260 psig and 820 degrees Fahrenheit (°F). Secondary system sodium at around 860 °F first enters the superheaters and is then cooled to around 580 °F in the evaporators before returning to the intermediate heat exchanger.

The major control loops of the steam plant modeled in the MMS simulation are main steam header pressure and steam drum level. Steam pressure at the turbine inlet is regulated by a combination of the turbine admission valves and a bypass system to the condenser. Steam drum level is regulated by the feedwater flow control valve at the outlet of the feedwater pump. Other minor control loops modeled in the simulation consist of the heater number 2 level control via a condensate flow control valve at the inlet to the heater, heater number 2 pressure using steam from the main steam header, and closed feedwater heater level controls via heater drain valves. Feedwater temperature to the steam drum is trimmed by manual adjustment of a valve in the bypass line around the number 4 closed feedwater heater.

A blowdown system, not detailed in Figure 1, extracts water from the steam drum at a maximum rate of about 10 percent of the feedwater flow rate which then enters a high pressure and then low pressure flash tank system. Steam from the flash tanks is combined with turbine steam extraction flows for heaters number 3 and 1. The drain flow of the low pressure flash tank is cooled in the blowdown cooler at the outlet of the condensate pump and enters a low temperature cleanup system before being returned to the condenser. Since the blowdown flow is less than 10 percent of the feedwater flow, the details of the blowdown system were not included in the initial simulation model. For the first phase of the simulation development, the turbine and condenser were also not included because a mode of operation sometimes used at EBR-II during reactor experiments is full power operation without the turbine system. In this mode of operation all the steam flow is bypassed to the condenser and steam header pressure is then regulated solely by the valve in the bypass line to the condenser.

The B&W MMS[5] was chosen as the simulation tool for the EBR-II steam plant because of the rich library of modules for nuclear and fossil power plant steam plant components such as steam drum boilers, feedwater heaters, turbines, pumps, flash tanks, etc. A sodium heated steam drum boiler model was not available in the MMS library so new modules were created by modifying existing MMS fossil power plant natural circulation steam drum boiler models.[6] The 7 evaporators were modeled as a single unit as were the two superheaters. The resulting MMS Simulation was then tested against recorded plant data for normal startup and during Plant Inherency and Control Tests (PICT).[7] Recorded plant data for the sodium inlet temperature to the steam plant (superheaters), sodium flow rate and blowdown flow rate were used as time varying boundary conditions to drive the MMS simulation model. As an example, the plant data for sodium inlet temperature versus time during the final phase of startup to full power (49 to 62.5 MW) is shown at the top of Figure 2a. The corresponding plant data for the steam plant sodium outlet temperature (outlet of the evaporators) is compared with the results of the MMS dynamical simulation at the bottom of Figure 2a. The sodium outlet temperature does not vary as much as sodium inlet temperature because the water side of the evaporators is at saturation conditions dependent on steam drum pressure. Additional comparisons of plant data versus simulation results for steam drum pressure and feedwater flow is presented in Figure 2b for the same transient. The simulated responses include the response of the controllers modeled in the simulation.

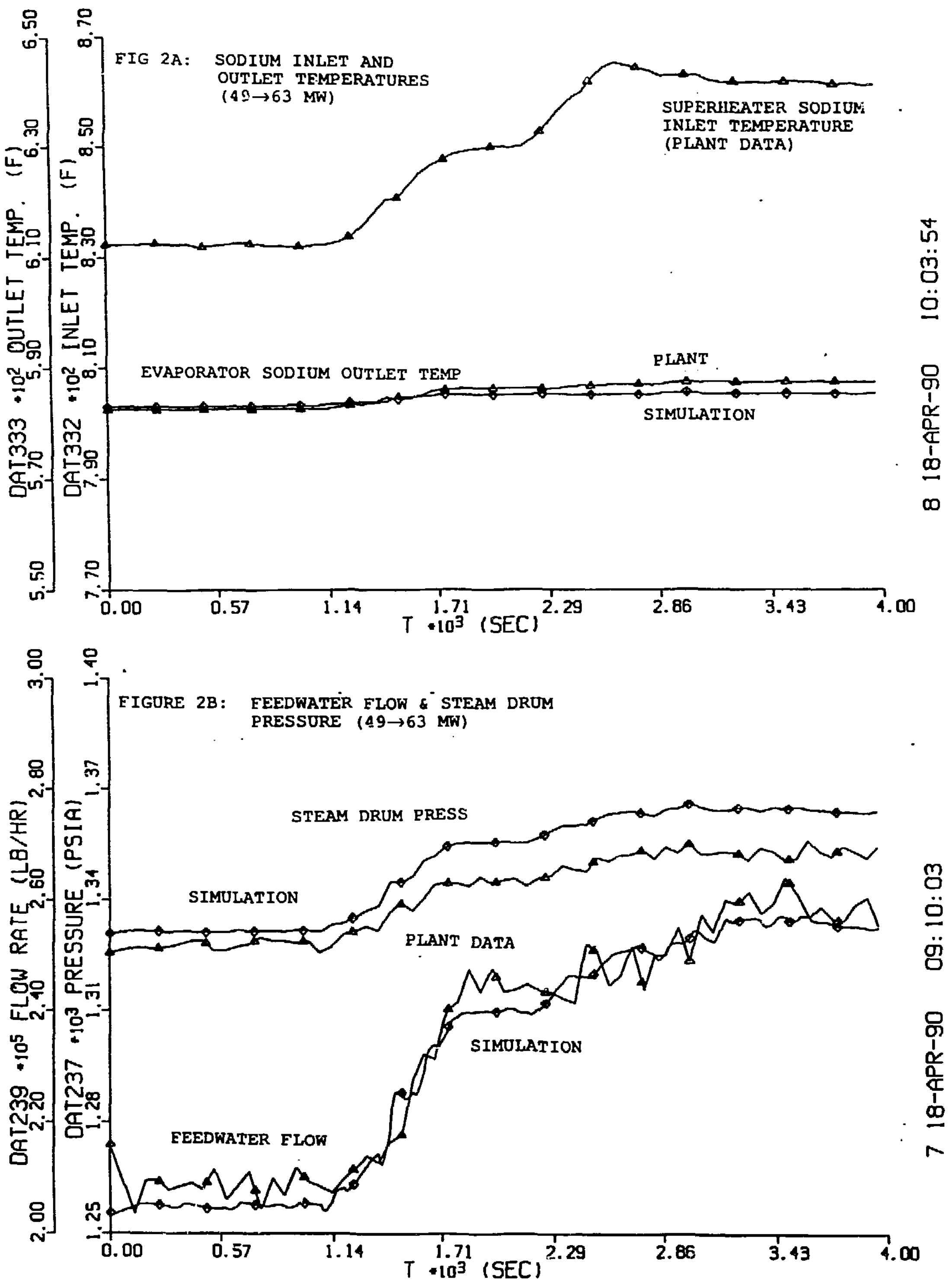

Figure 2: Plant Data for Startup from 49 to 63 MegaWatts Compared with B&W Modular Modeling System Simulation Results.

FEED WATER PUMP AUTO RECIRCULATION VALVE FAILURE SIMULATION

The MMS simulated data for the steam plant compares very favorably with actual plant data thus increasing confidence that it can generate appropriate results for simulated upset conditions. The first upset condition considered for simulation testing of diagnostics is a failure of the feedwater pump recirculation line valve to fully close. This condition was identified by the EBR-II staff as a real-world concern.

As indicated in Figure 1, a feedwater pump recirculation line provides a flow path from the outlet of the pump back to the number 2 feedwater heater, the source of low pressure water for the pump. The purpose of such a recirculation line is to insure a minimum flow rate through the pump in the event that the downstream pressure becomes too high. Flow rate through centrifugal pumps must be greater than some minimum amount in order to prevent deadheading, severe cavitation, and consequent pump damage. There is normally no flow through a recirculation line except possibly during startup conditions. At EBR-II, the automatic recirculation begins to open when the feedwater flow through the pump falls below a setpoint value. The recirculation line for the EBR-II feedwater pumps is sized to provide a flow rate of 150 or 200 gallons per minute dependent on which feedwater pump is in operation. When feedwater pump flow rate falls below the setpoint value, the recirc valve automatically opens; if it fails to later close when flow rate recovers, pressure at the pump outlet will fall and result in an undesirable plant transient and degraded performance. Since the recirc line is sized for a nominal flow rate of around 30 percent of the normal feedwater flow, failure of the recirc valve to close is not a safety consideration as long as other plant operating parameters are adjusted to accommodate the condition.

The consequence of a recirculation valve failure was simulated assuming that the recirc valve failed to the open position over a period of time as shown in Figure 3a (a first order lag with a 10 second time constant). The plant was assumed initially at full power equilibrium conditions with all the normal steam plant controls operating as discussed earlier. The sodium inlet conditions (flow rate and temperature) to the superheaters were held constant during the simulated event. The steam plant parameters most affected initially are feedwater flow rate to the steam drum, steam drum level, and feedwater flow control valve position at the outlet of the pump (Figure 3). Feedwater flow to the steam drum is reduced when flow is diverted into the recirculation line; steam drum level begins to drop due to the loss of input mass. Feedwater pressure to the steam drum however is maintained by the main steam header pressure control loop and the feedwater flow control valve fully opens to try to maintain steam drum level.

The simulation results for the plant parameters versus time were recorded in a disk file and converted to a format suitable for playing back into the diagnostic system in order to develop and test the rule base to identify the fault.

DISYS DIAGNOSTIC SYSTEM

The DISYS diagnostic system, described in more detail in references 3, 4 and 8, uses a structured expert systems approach to achieve real-time performance essential for utilization by an advanced control system. The knowledge representation scheme is a hierarchical semantic network of diagnostic calculational procedures assembled to match a human operator's mental model of system requirements and diagnostic procedures. The primary human interface is a graphics based intelligent process schematic using X-Windows 11 on a SUN color workstation display described in more detail in another paper in this meeting.[9] A black and white rendition of the high

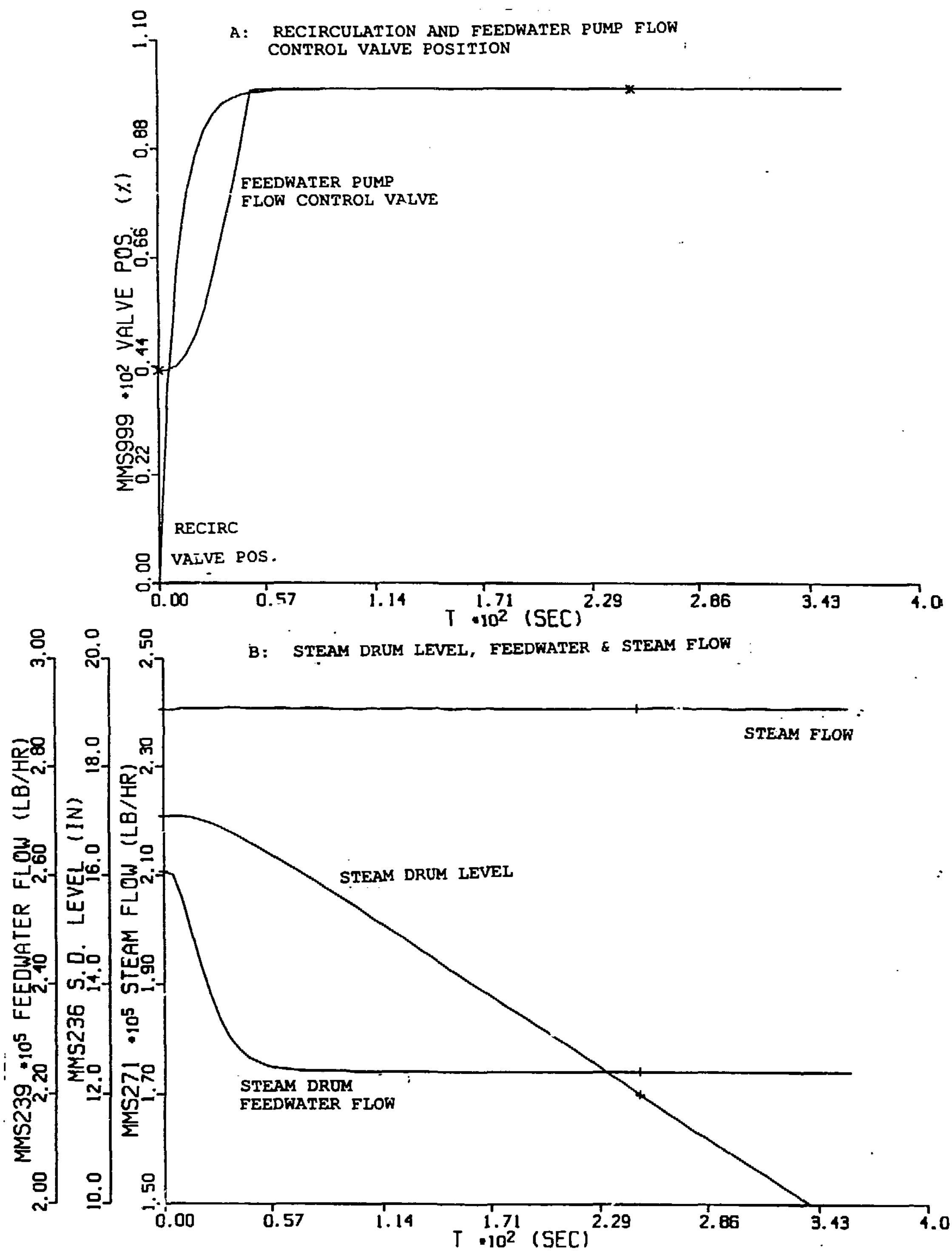

Figure 3: Simulated Steam Plant Response to failure of the feedwater Pump Automatic Recirculation Valve to the Full Open Position.

pressure portion of the steam plant process schematic is given in Figure 4 for the plant at equilibrium conditions just prior to the start of the simulated failure of the feedwater pump recirculation valve. Sensor locations are indicated with the circular icons attached to the process schematic through a short line segment (Figure 5a). Diagnostic status of a component or system is computed as a number in the range of 0.0 to 1.0. The 1.0 value indicates the good condition of unfaulted operation, 0.0 indicates fully faulted, and 0.5 indicates that there is equal evidence of faulted and unfaulted conditions (unknown component status). The diagnosed status of each component is displayed on the process schematic in a small rectangular box as shown in Figures 4 and 5b.

The details of the computational steps to arrive at a component's status is available by clicking the computer mouse button on the component icon. The result of clicking the feedwater pump component icon of Figure 4 after detection of the recirc failure at 50 seconds into the transient is given in Figure 6. The diagnostic steps are displayed in a tree like diagram that overlays the upper right portion of the process schematic. Figure 6 indicates that 2 sensors (circular icons at the bottom of the tree) are used to assess the health of the feedwater system for the recirculation valve fault: 1) feedwater flow rate and 2) feedwater pump flow control valve position. The first step of the diagnostic calculation is signal validation currently based on the parity space approach[10]. When only one sensor is available for a process variable, the sensor validation reduces to simply checking to see if the reading is within the accepted range of the instrument. Validated sensor data is then mapped to a measure-of-presence of a symptom of some fault, indicated by the square nodes of Figure 6. The symptom statuses are then processed (hexagon shaped node of Figure 6) using a modified Baye's rule of conditional probability that factors in the consistency of the symptom set. The result of the diagnostic calculation becomes the status of the component represented by the large rectangle at the top of the diagnostic tree and on the process schematic (Figure 5b). The initial rules formulated for diagnosing the recirculation valve failure as depicted in Figure 6 are summarized as follows: if the feedwater flow rate is low and the feedwater flow control valve is much more open than usual, then a recirculation valve failure is a possible fault.

FUTURE WORK

The first year's work in the DOE funded Intelligent Distributed Control Project is to continue the development of a steam plant diagnostic system for the EBR-II plant based on the DISYS diagnostic system. During the first year, which ends in August 1990, the diagnostic system for the steam plant will operate in a single SUN workstation computer interfaced to live EBR-II plant data. In the second year of the project, the diagnostic system will be distributed using a combination of SUN computers and Bailey NETWORK 90 controllers. A Bailey Multifunction Controller, which can handle user defined C language programming as part of executing standard control functions, will be programmed to perform the DISYS low level diagnostic computations for individual plant components. The locally computed component diagnostic assessments will then be transferred from the Bailey System to a UNIX based workstation that performs the high level diagnostic functions and provides the graphics based user interface. The National Science Foundation (NSF) has supplied a grant that has already provided a Bailey system at Penn State in order to permit development and simulation testing of the distributed diagnostic and control activities for the remaining two years of the DOE research grant.

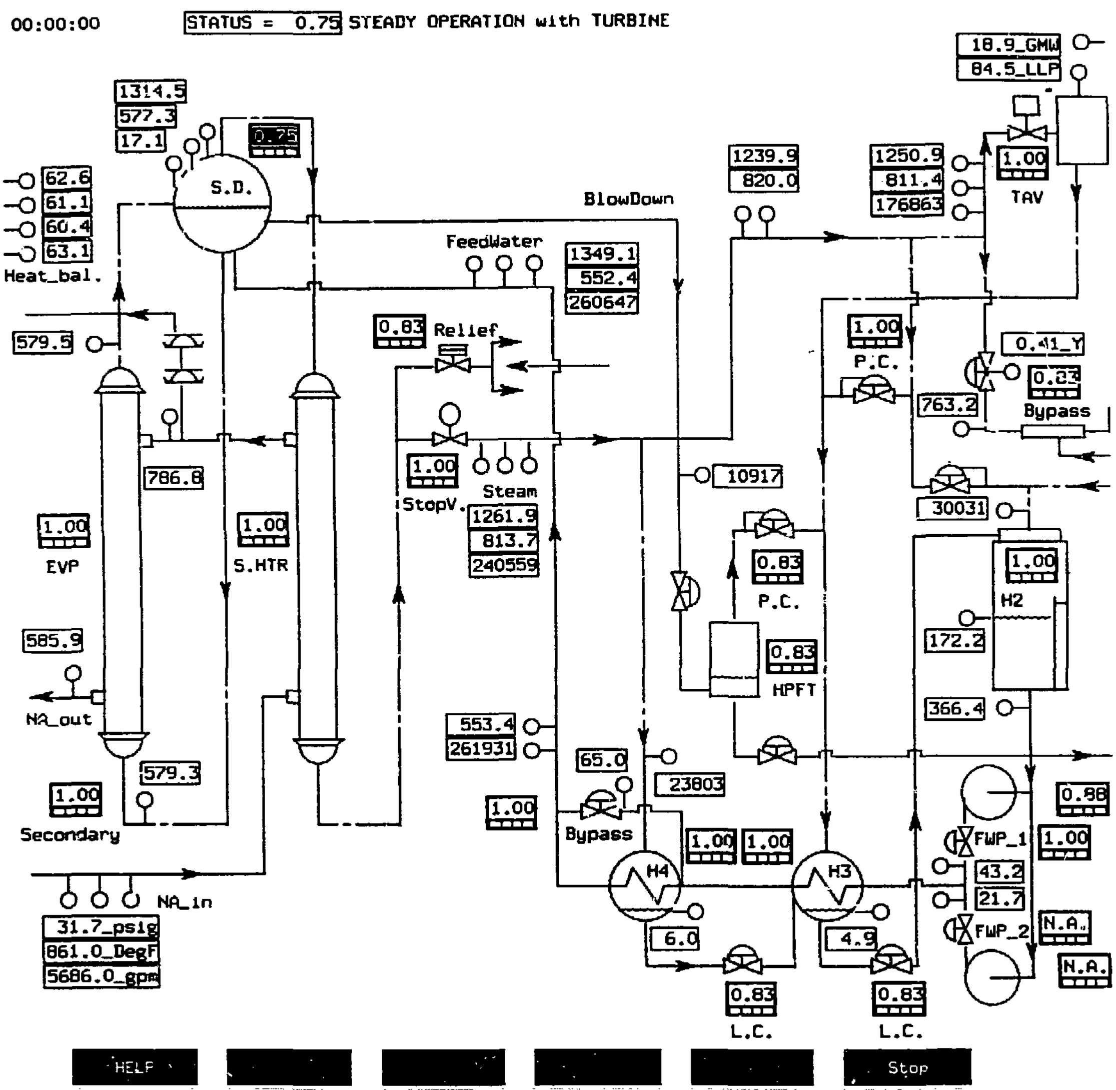

Figure 4: Intelligent Process Schematic for Display of the EBR-II Steam Plant diagnostic information.

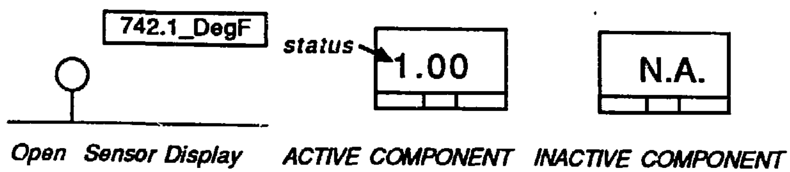

FIG 5A. FIG 5B

Figure 5: Sensor and Component Icons on the Process Schematic Display.

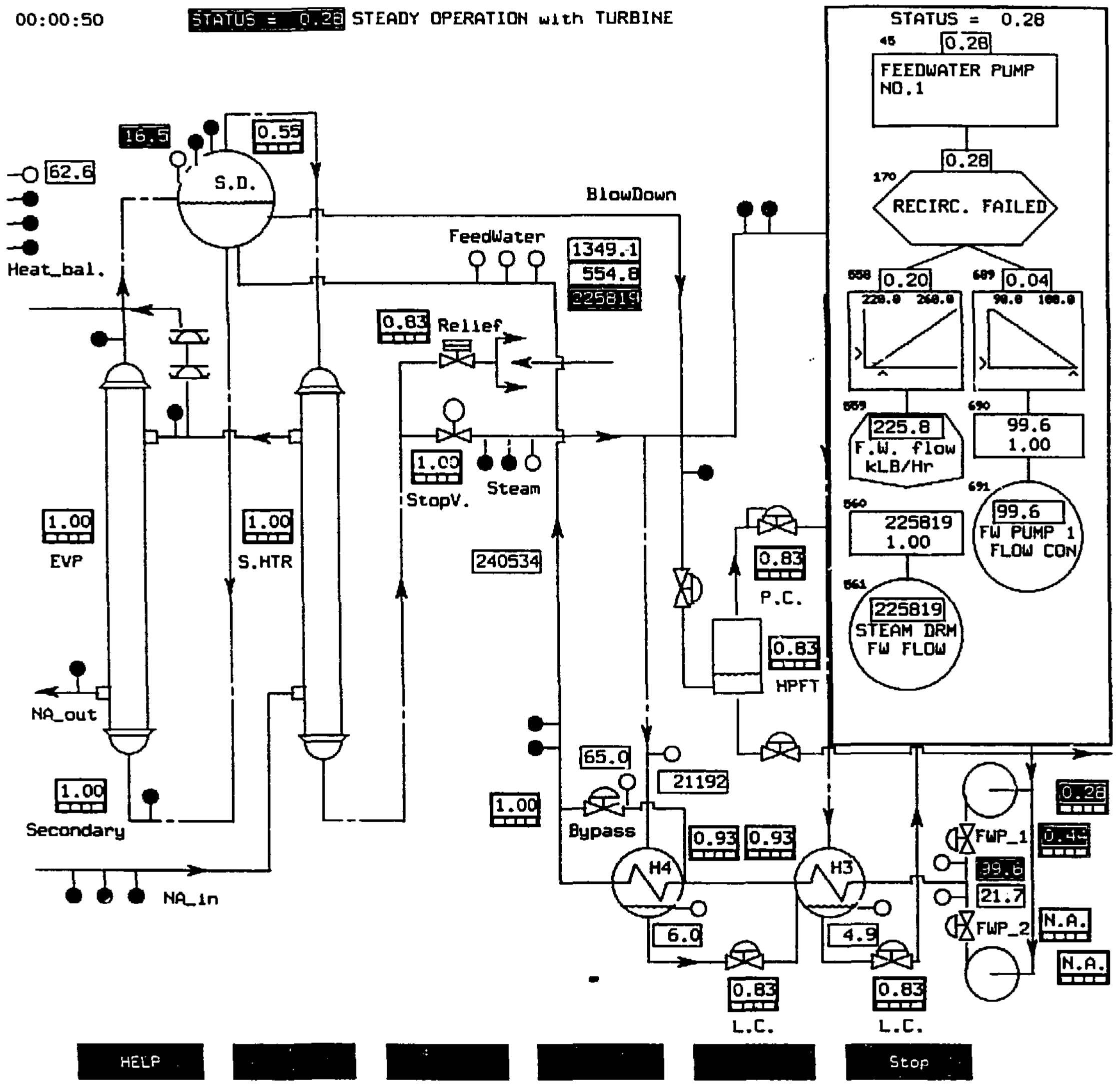

Figure 6: Process Schematic with optional display of tree-like diagnostic calculations for diagnosis of recirc failure.

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