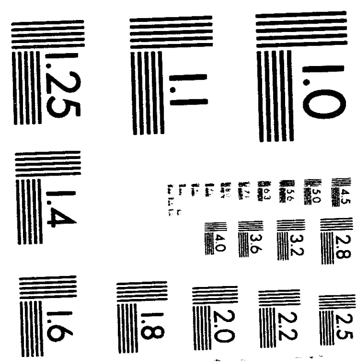

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FEEDWATER SYSTEM DIAGNOSTIC DEVELOPMENT USING DISTRIBUTED SIMULATION

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ABSTRACT

A real-time diagnostic system for the EBR-II steam plant has been developed using the DISYS Diagnostic and Control Guidance Expert System. Diagnostic rules were developed to distinctly identify ten specific fault conditions and were tested using a real-time distributed simulation of the EBR-II steam plant. The distributed simulation is implemented in three separate programs in a VAX cluster and is coordinated through a distributed simulation manager operating in a UNIX workstation. The multi-program DISYS system currently operates in the same UNIX workstation as the simulation manager and obtains the simulated data from a shared memory segment maintained by the simulation manager. Future work includes modifying the DISYS system to improve the fault detection of rapid transients and enable it to detect gradual long term trends.

INTRODUCTION

A real-time distributed simulation of the Experimental Breeder Reactor (EBR-II) steam plant was developed at The Pennsylvania State University to support the continuing development and testing of advanced diagnostic and control systems[1]. One recent use of this distributed simulation was in the development of feedwater system diagnostics for the EBR-II steam plant using the DISYS Diagnostic and Control Guidance Expert System[2,3,4]. EBR-II plant personnel have identified a set of ten fault conditions as the basis for developing the DISYS diagnostic rule base. 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.

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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 simulation data includes sensor data, control signals, and simulation boundary condition data. Second, this data was analyzed to select sensor sets to distinctly identify each fault condition. Only actual EBR-II sensors and control signals were considered for inclusion in any of these sensor sets. Diagnostic mapping of these sensor sets to correctly identify the appropriate fault symptoms were developed based on the analysis of the simulation data and prior knowledge of plant conditions during the fault transient. The sensor sets and appropriate diagnostic mappings were then programmed into the DISYS Diagnostic Nodal Network for the steam plant. Finally, the simulation data was used to test the diagnostic system performance and the diagnostic mappings were adjusted as required to improve the fault detection performance.

This paper briefly describes the real-time distributed simulation implementation and discusses the above diagnostic development process using the first two fault conditions for illustration.

REAL-TIME DISTRIBUTED SIMULATION SYSTEM

The steam electric system at EBR-II has many similarities to conventional steam electric systems used in fossil and nuclear power plants, with the major exception being that the heat source is liquid sodium. Figure 1 shows the main components of the steam plant that are modeled in three independent simulation programs that comprise the real-time distributed simulation. The condensate system simulation program includes the condensate pump, the first two feedwater heaters, and associated valves and piping. The feedwater system simulation program includes the feedwater pump, the second two feedwater heaters, and associated valves and piping. The steam system simulation program includes the steam drum, the evaporators, the superheaters, the main steam bypass valve, and associated piping[1]. In previous work at The Pennsylvania State University, these components were modeled in one large combined simulation program. The accuracy of this comprehensive simulation was analytically verified with actual EBR-II plant data[5]. The distributed simulation programs were subsequently developed to improve real-time performance and the overall accuracy verified by comparing the results with the large combined simulation program[1]. The turbine and condenser systems are not currently modeled because a mode of operation during reactor experiments at EBR-II is to completely bypass the turbine by dumping steam directly to the condenser and using the main steam bypass valve to regulate steam pressure.

The implementation of the distributed simulation system is diagramed in Figure 2. Each simulation program has a local communications manager which communicates with the Distributed Simulation Manager (DSM) program via an ethernet network using the TCP/IP communication protocol. The DSM program coordinates the boundary interfaces between the simulation programs and maintains the Centralized Plant Data Base (CPDB). The CPDB is stored in shared memory on a UNIX-based workstation to allow access to the DISYS Diagnostic and Control Guidance Expert System and other control or user interface processes[1,4].

SIMULATION OF EXAMPLE FAULTS

The feedwater pump trip and recirculation valve failure were selected for illustration, because, of the ten fault conditions, they are the most difficult to differentiate with the current DISYS diagnostic system. The system has difficulty in discriminating between these two faults, because it does not presently incorporate a process variable time rate of change calculation in its diagnostic process. Several schemes to incorporate

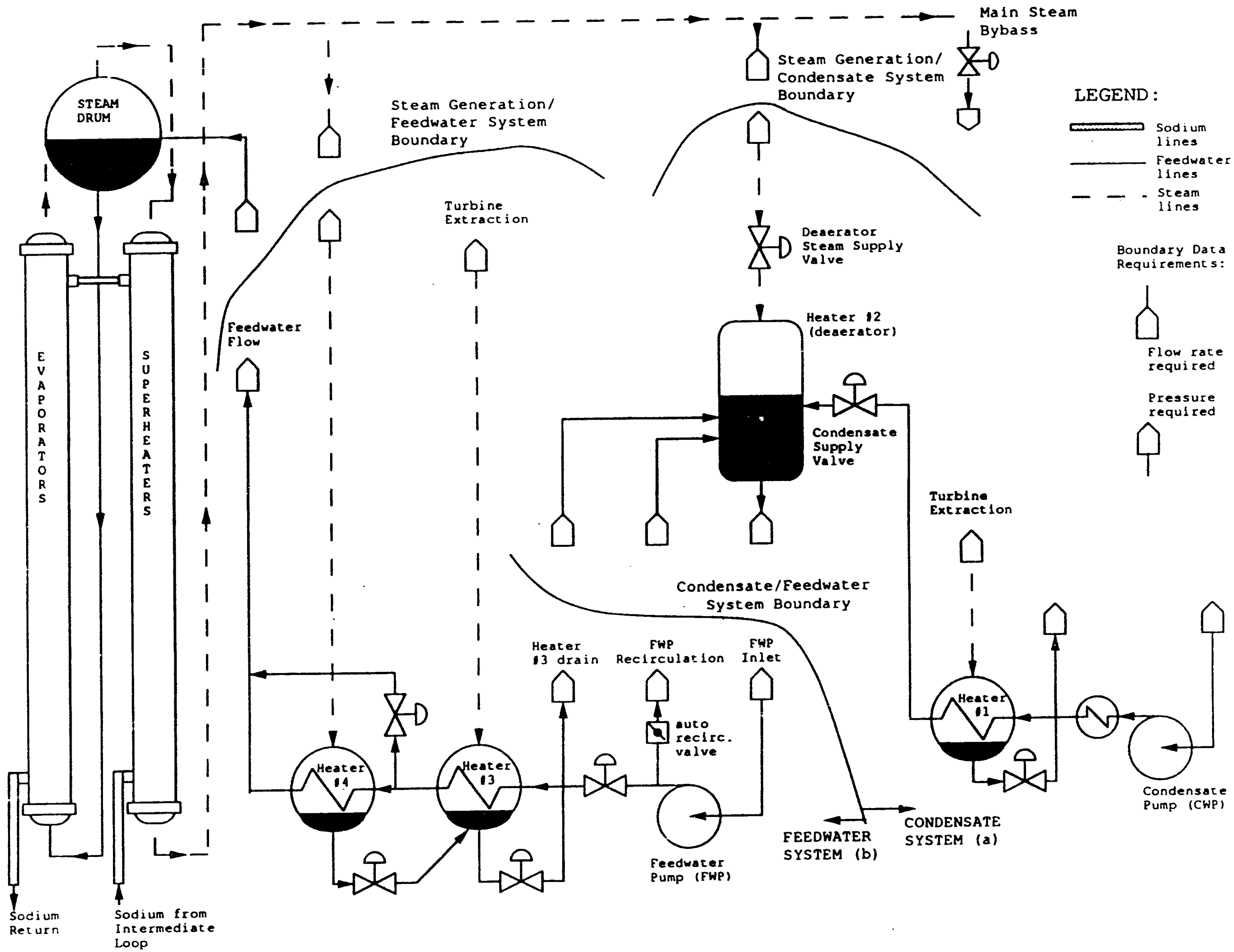

Figure 1: EBR-II Steam Plant Components and Subsystem Organization for Distributed Simulation

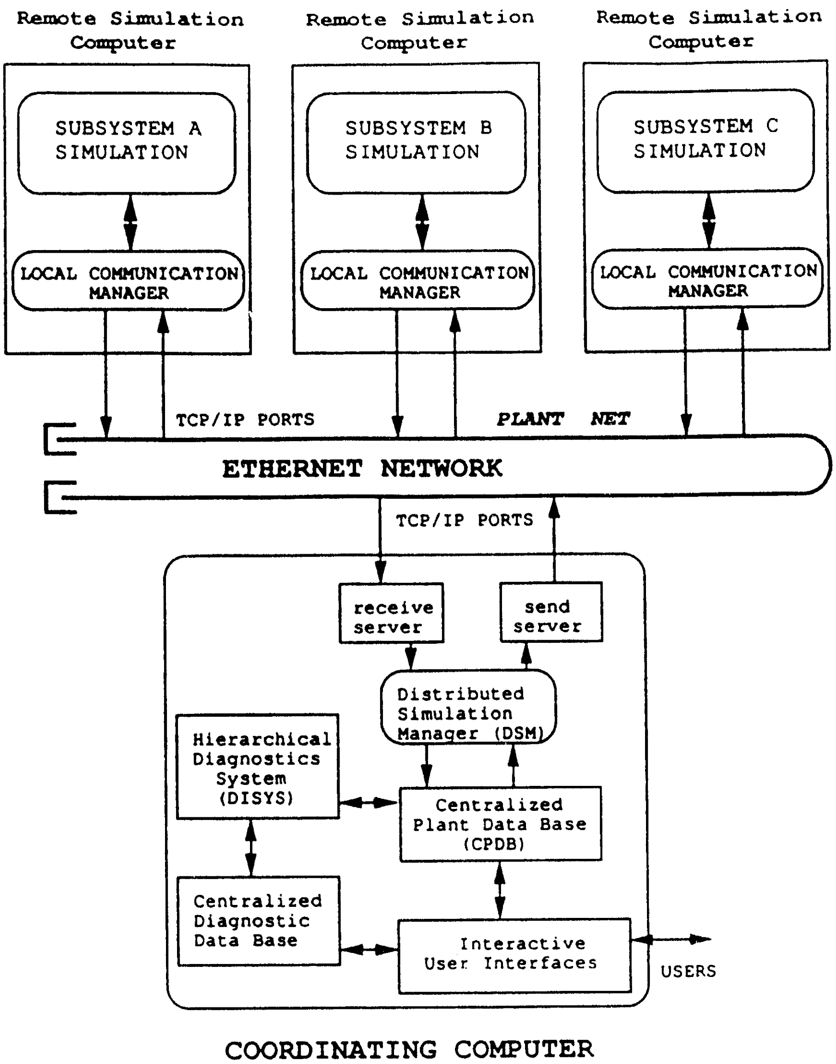

Figure 2: Distributed Simulation Implementation

such a calculation in the diagnostic system are currently being considered. The resulting diagnostic system would have no difficulty discriminating between these fault conditions and could detect them faster than reported in this paper.

The purpose of the feedwater pump is to provide adequate high pressure feedwater flow to the steam drum. 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. The feedwater pump trip was modeled as a coast down on a first order time lag and the recirculation valve fault was modeled by opening the recirculation valve to the full open position on a first order time lag.

SENSOR SELECTION

Examination of the resulting simulated plant process variables for these two fault conditions showed that many possible variables could be used to detect these two faults. However, initial differentiation between these two fault conditions is difficult to achieve, because these faults cause the process variables to change in the same direction, and the variables' time rate of change are not currently computed in the DISYS system. Therefore, the approach used relies on the differences in the maximum magnitudes that the variables reach during the transients. For example, one of the variables chosen to discriminate between these faults, the condensate pressure before the condensate supply valve, is plotted against time for both faults in Figure 3. This graph shows that, about 15 seconds after the fault, the condensate pressure during the feedwater trip transient exceeds the maximum condensate pressure for the entire recirculation valve fault transient. Accordingly, use of this variable alone, will permit discrimination between these two faults during a feedwater pump trip transient, but will not allow discrimination during a recirculation valve

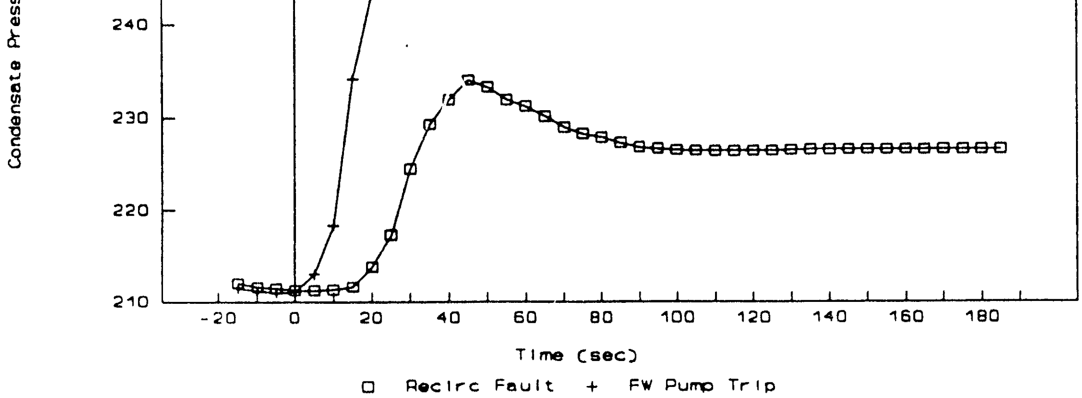

Figure 3: Condensate Pressure Before the Condensate Supply Valve

transient. The solution is to use another variable such as the feedwater flow control valve position and logically combine the values. Figure 4 shows a plot of this control valve position for these fault transients. The next section of this paper shows that these two variables, correctly mapped and logically combined, can differentiate between these two faults without using a time rate of change calculation.

It was determined that another variable is also needed to discriminate these faults from the feedwater flow control valve fails open fault. Selection of the feedwater flow rate for this purpose provided the additional advantage of faster detection of the feedwater pump trip fault. The secondary sodium flow rate was also included in the sensor set, because actual EBR-II data shows that the feedwater to sodium flow rate ratio yields an almost constant value over a wide power range. This ratio will be used in future diagnostic development for faults occurring at other power levels. Presently, the four variables which comprise the sensor set used to detect the two example fault conditions are: feedwater flow rate to the steam drum, the secondary sodium flow rate to the superheaters, the feedwater flow control valve position, and the condensate pressure before the condensate supply valve.

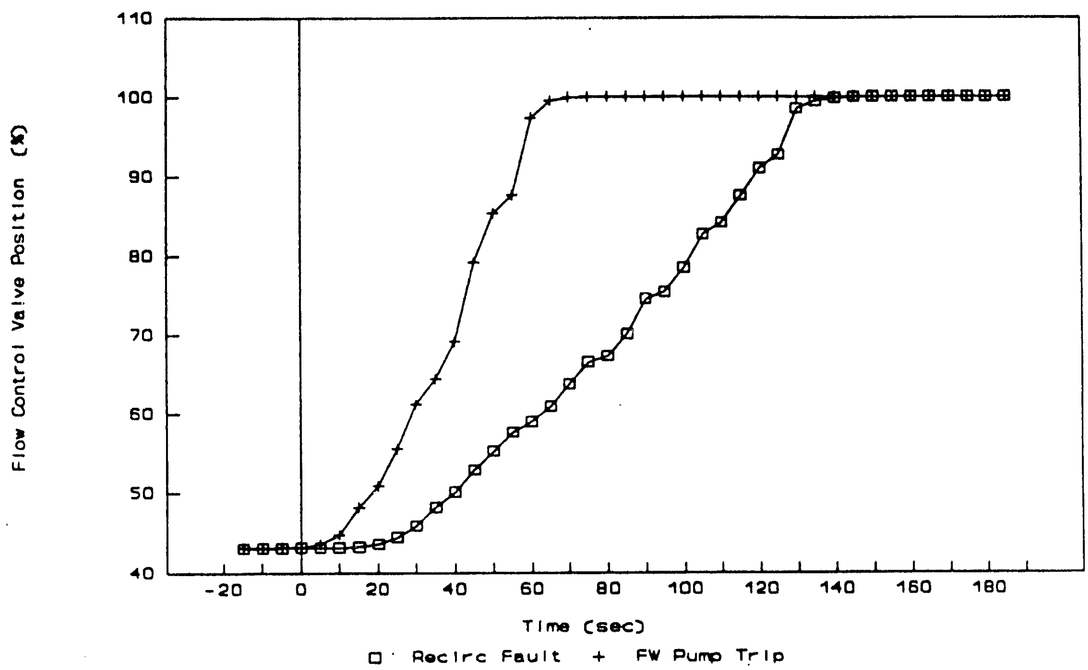

Figure 4: Feedwater Flow Control Valve Position

DISYS DIAGNOSTIC SYSTEM

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[3]. The organization of the process is illustrated in Figure 5. 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 sensors[6]. A black and white rendition of this display for the feedwater pump trip

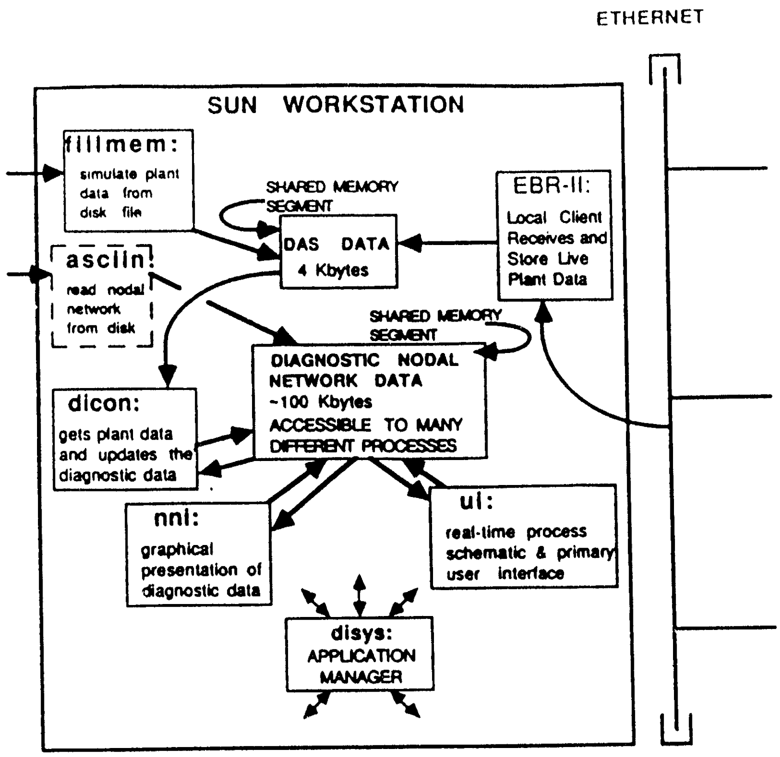

Figure 5: DISYS Multiple Program Process

at 20 seconds into the fault transient, is shown in Figure 6. 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 6 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[6]. The diagnostic information tree for the feedwater pump trip at 20 seconds into the transient is shown in Figure 7. 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[7]. The validated data can then be algebraically 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

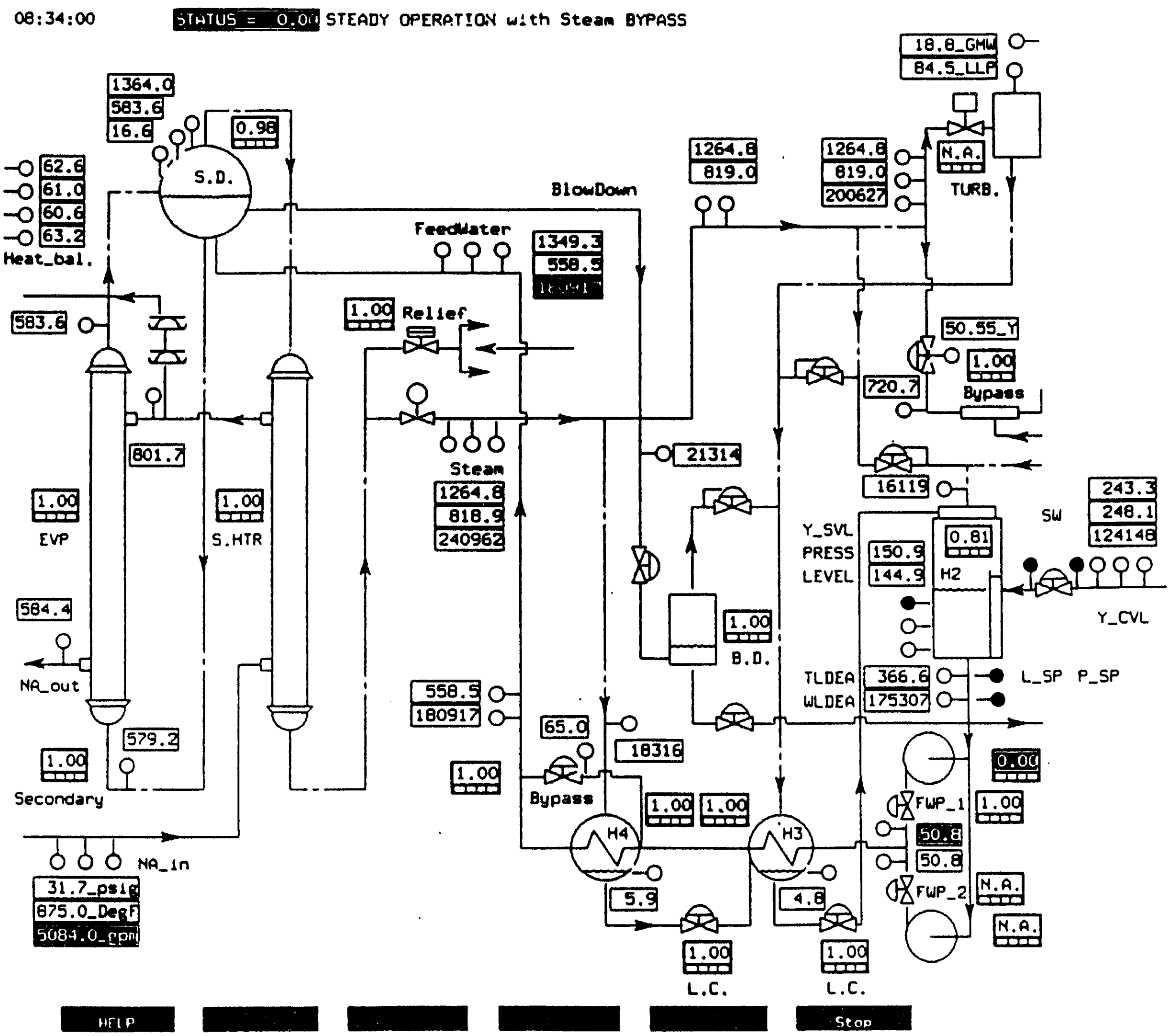

Figure 6: EBR-II Steam Plant Intelligent Process Display for Feedwater Pump Trip at 20 Seconds

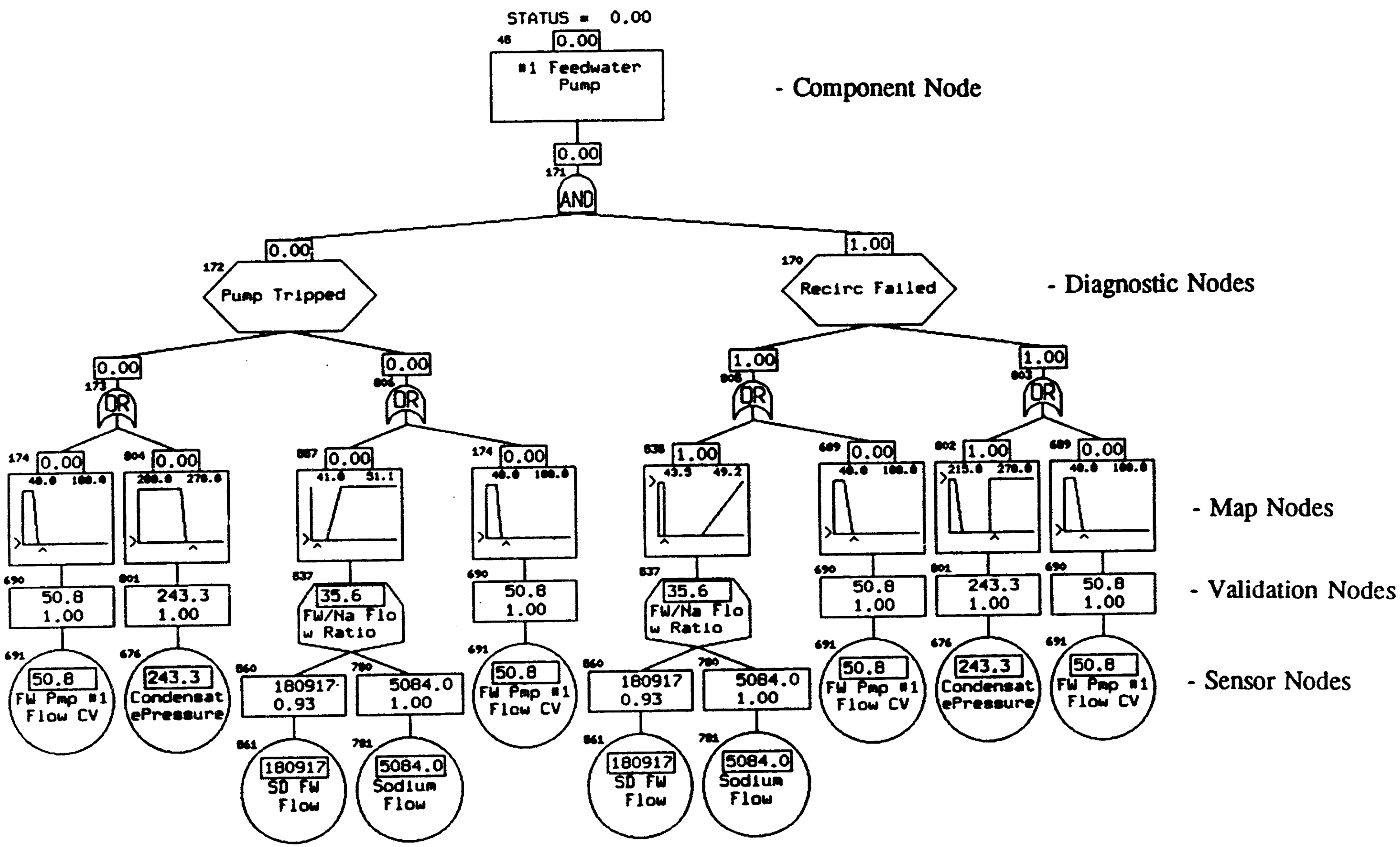

Figure 7: Diagnostic Information Tree for the Feedwater Pump Trip at 20 Seconds

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 6 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.

Figure 8 shows the diagnostic information tree for the feedwater component at 10 seconds into the feedwater pump trip transient. This figure illustrates why the feedwater to sodium flow ratio (FW/Na Flow Ratio) and condensate pressure map outputs are combined in a logical OR with the flow control valve position (FW Pmp #1 Flow CV). For this transient, the feedwater pump trip diagnostic status should always be lower than the recirculation fault diagnostic status. This is achieved by the OR logic combination of the flow ratio map outputs with the control valve position map outputs because, as the condensate pressure and flow ratio map outputs in the recirculation fault tree reach their lowest values, the control valve map outputs maintain high values. As the transient progresses, the control valve opens, giving its mapping a low output. But, by this time, the mappings for the flow ratio and condensate pressure have attained high outputs. By 20 seconds into the transient (Figure 7), the feedwater pump trip fault has a diagnostic status of 0.00 and the recirculation valve failure diagnostic status has risen back up to 1.00. Eventually, this transient produces other component statuses indicative of a faulted condition (0.50 and below), but it is presumed that some action based on this diagnosed condition would take place to end the transient.

The diagnostic information tree for the feedwater pump component at 30 seconds into the recirculation valve failure transient is shown in Figure 9. This figure illustrates how the two faults are differentiated during the recirculation valve fault. The map outputs for both the feedwater to sodium flow ratio and the condensate pressure indicate the complete presence of fault symptoms (map output = 0.00) for a recirculation fault. However, the flow control valve position is still high enough to give a map output of 0.69. This yields a recirculation fault diagnostic status of 0.59. Figure 10 shows the tree for the same fault transient at 35 seconds. Here the flow control valve has opened enough to give a recirculation fault diagnostic status of 0.40. This gives the feedwater component a status of 0.40 which is indicative of a faulted condition. By 45 seconds into this transient the recirculation failure diagnostic status has reached 0.00, giving the pump component a status indicating a fully faulted condition. Throughout this transient, the feedwater pump is the component with the lowest status, and no other component has a status less than 0.97.

The diagnostic logic, mappings, and the measures of belief and disbelief for all ten faults were developed based on the data from the initial simulation of the fault conditions, knowledge of plant conditions during the transients, and trial runs of the system with the simulation data.

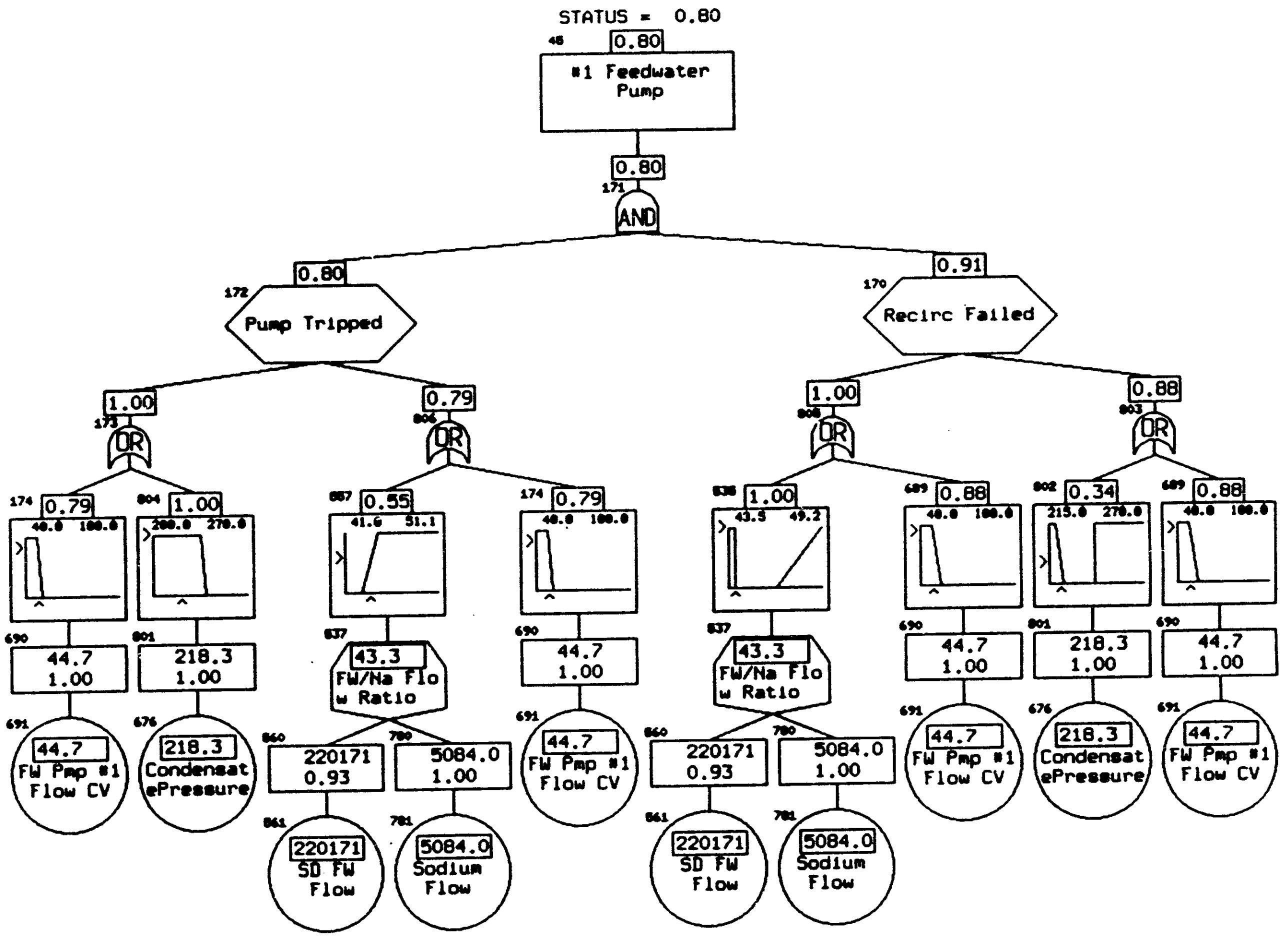

Figure 8: Diagnostic Information Tree for the Feedwater Pump Trip at 10 Seconds

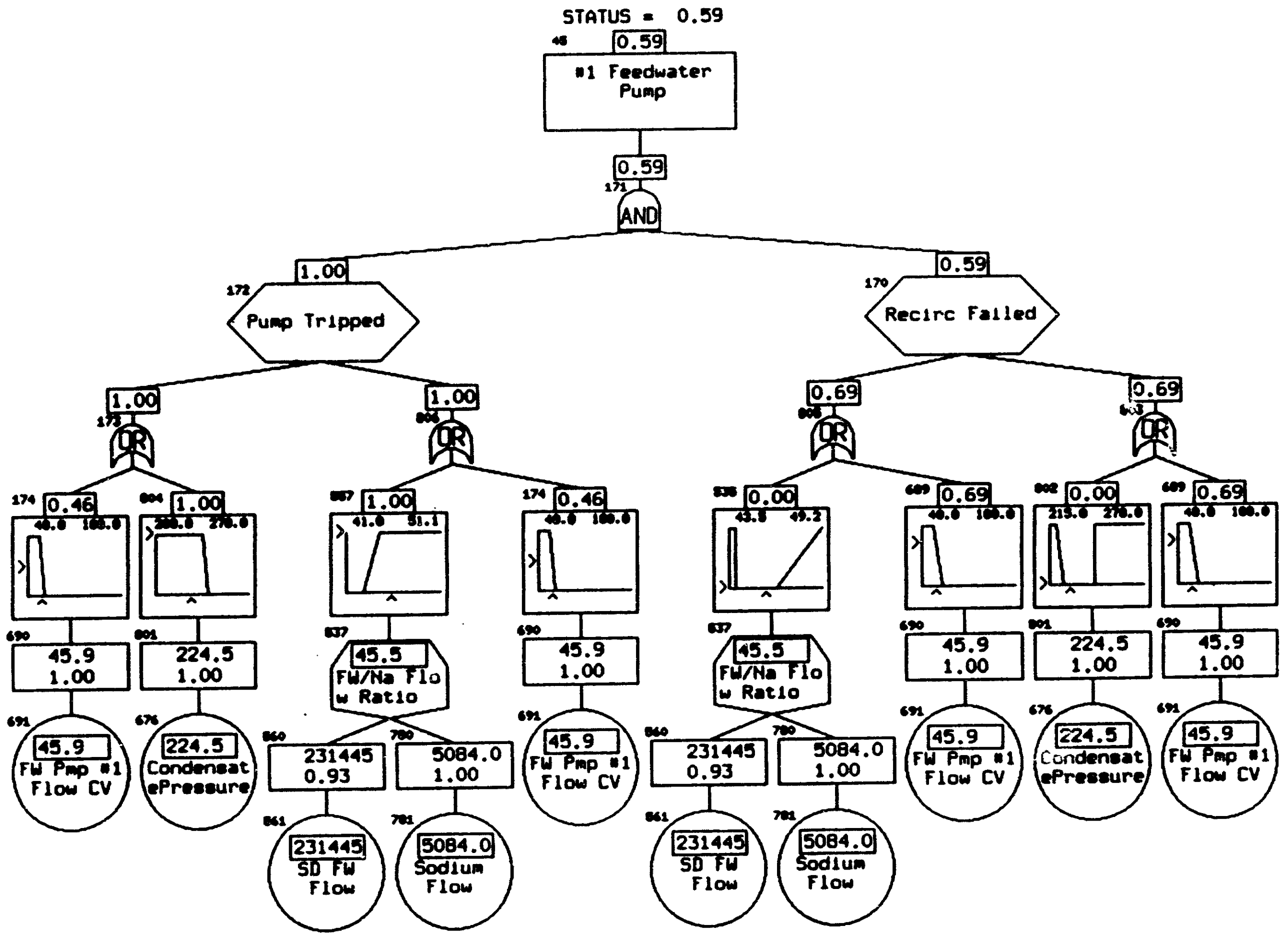

Figure 9: Diagnostic Information Tree for the Recirculation Valve Fault at 30 Seconds

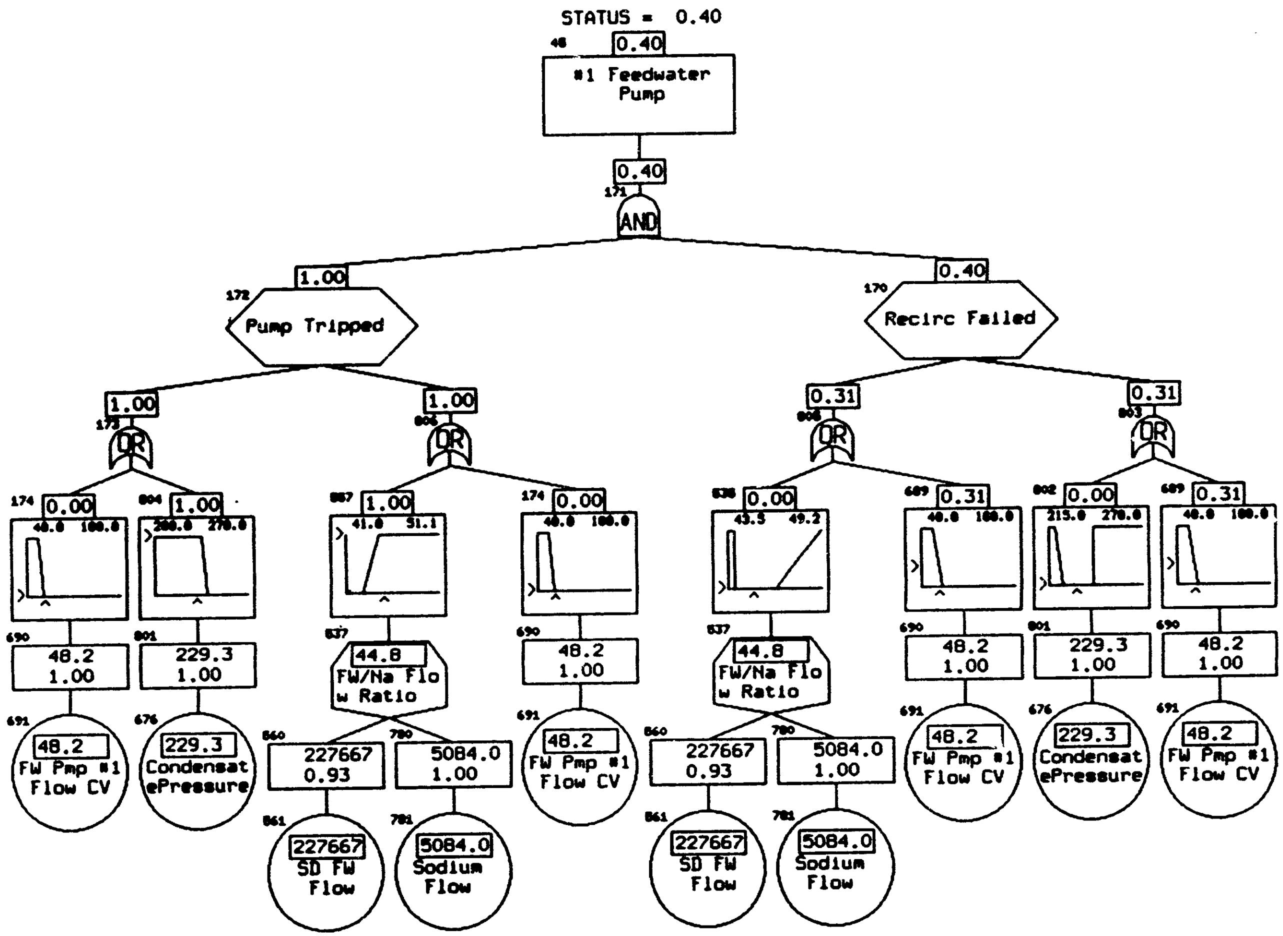

Figure 10: Diagnostic Information Tree for the Recirculation Valve Fault at 35 Seconds

FUTURE WORK

This work could be extended to include diagnosis of these ten or other fault conditions for different initial power levels. Two current projects at The Pennsylvania State University involve improvements to the DISYS Diagnostic and Control Guidance Expert System. The first is the development of a type of map node which includes calculations of the variable's time rate of change. This would give the DISYS system an improved fault detection for rapid transients, the ability to detect gradual long term trends, and the capability to detect oscillatory behavior. The second project is to develop a graphics-based interface for programming the nodal network and diagnostic information into the system. This would permit faster development of diagnostics for new plant systems.

ACKNOWLEDGEMENTS

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