An invited paper and presentation for the U.S. - Korea Seminar on Application of Expert Systems to Power Systems and Industires, Seoul, Korea, August 13-18, 1989

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Conf-890899--3

CONF-890899--3
DE91 013741

AN INTEGRATED REAL-TIME DIAGNOSTIC CONCEPT USING EXPERT SYSTEMS, QUALITATIVE REASONING & QUANTITATIVE ANALYSIS

by

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ABSTRACT

An approach for an integrated real-time diagnostic system is being developed for inclusion as an integral part of a power plant automatic control system. In order to participate in control decisions and automatic closed loop operation, the diagnostic system must operate in real-time. Thus far, an expert system with real-time capabilities has been developed and installed on a subsystem at the Experimental Breeder Reactor (EBR-II) in Idaho, USA. Real-time simulation testing of advanced power plant concepts at the Pennsylvania State University has been developed and was used to support the expert system development and installation at EBR-II. Recently, the U.S. National Science Foundation (NSF) and the U.S. Department of Energy (DOE) have funded a Penn State research program to further enhance application of real-time diagnostic systems by pursuing implementation in a distributed power plant computer system including microprocessor based controllers. This paper summarizes past, current, planned, and possible future approaches to power plant diagnostic systems research at Penn State.

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FG07-89ER12899

HISTORICAL PERSPECTIVE ON THE DISYS DIAGNOSTIC SYSTEM

The DISYS diagnostic system, recently installed on a SUN computer network at EBR-II[1], was substantially developed at Westinghouse for the Department of Energy (DOE) during the period of 1982 to 1986. During 1982, Alan Christie of the Westinghouse Advanced Reactors Division conducted an extensive review of the then state-of-the-art in diagnostics for power plant applications, including human factors considerations, and prepared the first version of DISYS (also called DICON) in the BASIC computer language implemented on a microcomputer[2]. Although perceived as a general approach to power plant systems diagnostics, application of DISYS has focused on liquid metal reactor systems because of its origin in the DOE Breeder Reactor Technology program. The first demonstration application of DISYS in BASIC was developed for the proposed Clinch River Breeder Reactor shutdown heat removal system.

DISYS was further enhanced using PASCAL language on DEC VAX computers under both VMS and UNIX operating systems and a real world application was developed for the Argon Cooling System (ACS) of fuel handling operations at EBR-II[3]. In 1986, Westinghouse research and development of DISYS was completed with the beginning of implementation at EBR-II[4]. The VAX version included an interface to live plant data from the then recently completed centralized data acquisition system (DAS). Other EBR-II applications, advanced displays, and network communications of DAS data were, however, being developed on a SUN computer network using C language; so, it was naturally desirable that DISYS be converted to C language also. The PASCAL to C conversion was performed by the Penn State Nuclear Engineering department in a DOE funded project[1] recently completed in May of 1989.

DESCRIPTION OF THE EBR-II ARGON COOLING SYSTEM

Although the DISYS diagnostic system should be generally applicable to many different types of power plant systems, the only current demonstration has been developed for the Argon Cooling System (ACS) for fuel handling operations at EBR-II shown in figure 1. The primary function of the EBR-II ACS is to provide cooling for spent fuel or preheating to new fuel. The major components shown are the reactor primary tank, Argon Cooling System Pumps (electrically driven turbines), Fuel Unloading Machine (FUM), Fuel Transfer Port (FTP), Vapor Traps, Molecular Sieves, air heat exchanger, Interbuilding Coffin (IBC) and various preheaters and valves. The primary tank (in the lower left of the figure) contains the reactor core, intermediate sodium to sodium heat exchanger, primary sodium pumps, storage area for fuel elements and a large pool of molten sodium maintained at around 700^{o}F. (The systems contained in the primary tank are not detailed in figure 1.) The sodium pumps draw sodium from the pool and direct it through the reactor core where it is additionally heated. The heated primary system sodium then transfers its heat to an intermediate sodium loop which in turn transports the intermediate sodium outside of the primary tank to a steam electric plant in another building. The cooled primary system sodium is then simply returned to the large pool of the tank. Primary tank sodium, which becomes highly radioactive as a result of neutron activation, does not leave the primary tank. While all this power production and heat transfer activity is taking place in the primary tank, fuel handling operations can simultaneously take place by moving fuel elements from the storage area in the primary tank to the fuel handling machine or vice versa. The primary tank Argon Cover Gas, indicated in figure 1, is at near atmospheric pressure thus permitting practical design of the FTP and FUM including necessary purging mechanisms. The ACS Pumps consist of one turbine driven by AC current and a backup turbine driven on DC current. The

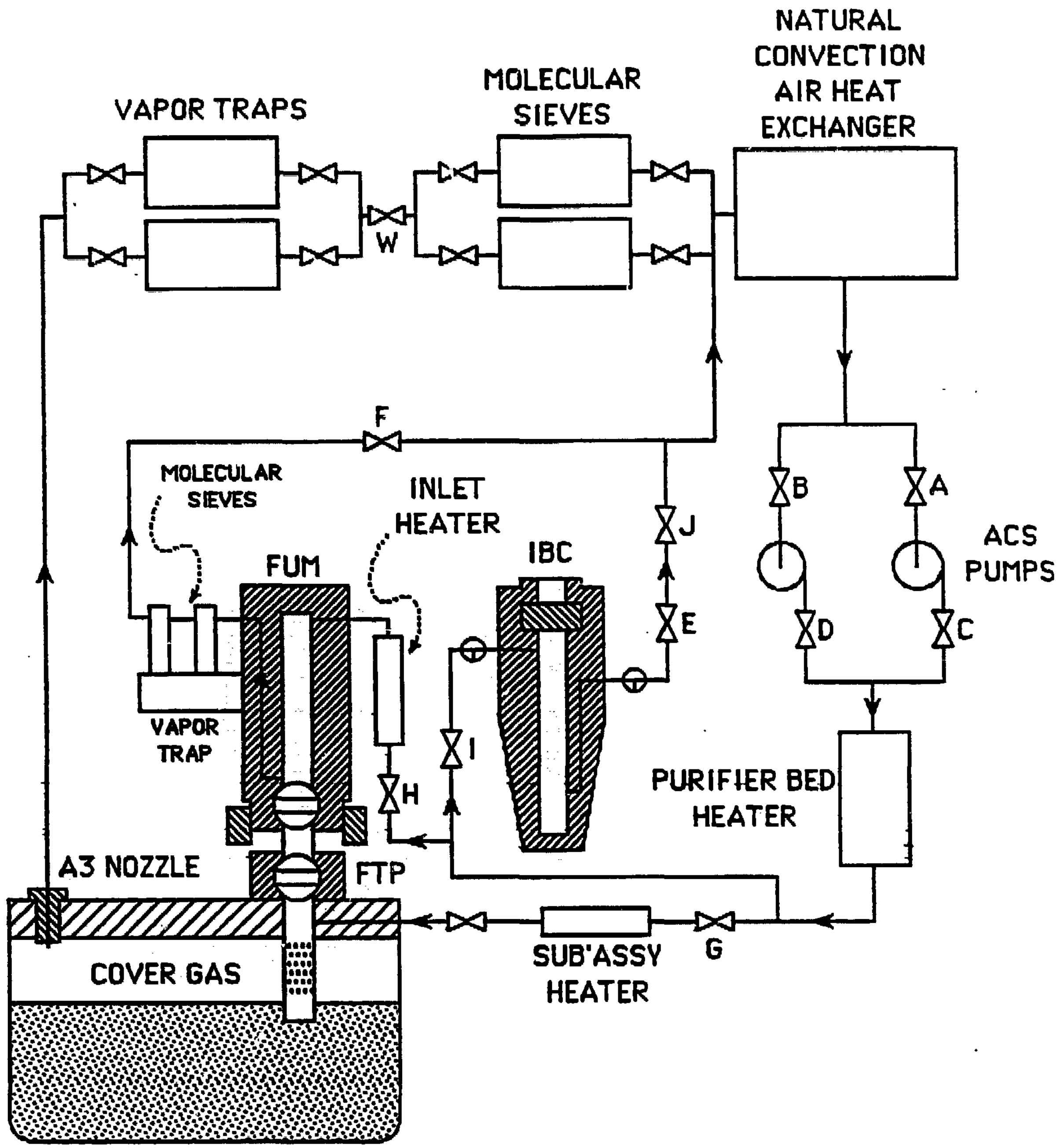

FIGURE 1: EBR-II ARGON COOLING SYSTEM FOR FUEL HANDLING

heavily shielded FUM contains the fuel element gripping mechanisms and attaches to the FTP in order to move fuel between the primary tank and FUM. The FUM, detached from the FTP, is physically moved between the primary tank and IBC in order to transport fuel. The IBC can be physically moved outside of the reactor building to the next stage of fuel reprocessing. The Molecular Sieves and Vapor Traps remove sodium vapor from the circulating Argon coolant. The air heat exchanger cools the Argon to near ambient temperatures in order to permit efficient turbine operation.

The EBR-II ACS was originally chosen for demonstration of DISYS diagnostics because it is relatively small, compact and reasonably isolated from other systems. Yet it contains many of the features seen in larger systems which are not often seen in small systems. Specifically it contains multiple well defined operating modes; four of which were included in the initial diagnostic data base[4]:

1) Fuel Unloading Machine (FUM) mode.
2) Fuel Transfer Port Mode (FTP) mode.
3) FUM + FTP Mode.
4) Shutdown Mode.

In the FUM Mode, Argon coolant is circulated only through the FUM and air heat exchanger. Valves F and H are open while G (to FTP), I (to the IBC), and the FTP valve are closed. Fuel inside the FUM would either be in the process of being preheated or being cooled dependent on where the fuel would be moved in the next operation. If going into the reactor tank, the fuel is being preheated. If going to the interbuilding coffin, it is being cooled.

In the FTP Mode, Argon coolant is circulated through the reactor tank, vapor traps, molecular sieves, and air heat exchanger. Valves G and W are open while H (to the FUM), I (to the IBC), and the FTP valve are closed. A special function of the FTP mode is to blow excess sodium off of a fuel element while it is held above the sodium pool.

In the FUM+FTP Mode, Argon enters the FUM as in the FUM mode; however, it is directed into the reactor tank through the open FTP and returns to the air heat exchanger via the return path of the FTP mode. Valves H and W are open while G (to the FTP), F (from the FUM) and I (to the IBC) are closed.

In the shutdown mode, a flow path is maintained as in the FUM only mode.

SUMMARY OF DISYS DIAGNOSTIC TECHNIQUE:

References 2, 3, and 4 describe the DISYS diagnostic system; however, it is worthwhile to provide another descriptive example here so that this paper can be somewhat self contained. Figure 2 represents an example of a DISYS diagnostic data base which includes all of the most commonly used features. The DISYS knowledge representation (KR) scheme is a nodal network which resembles a fault tree where each node represents real systems, components, sensors and concepts such as fault symptoms and diagnostic evaluations. Other Expert systems based on fault tree analysis are also being developed[5]. Once created, the DISYS nodal network is a fixed tree-like structure whereas a conventional expert system dynamically modifies a semantic network structure or knowledge base as a problem is evaluated. (Strictly speaking, the DISYS tree-like knowledge representation is really a graph structure where there are potentially multiple paths upward from a node; e.g. the MAP node linked below to turbine outlet temperature in figure 2 is linked above to two nodes: 1) Air HX Fault and 2) AC Turbine Failure. The term tree is liberally used in describing DISYS because it invokes a better visual perception of the nodal

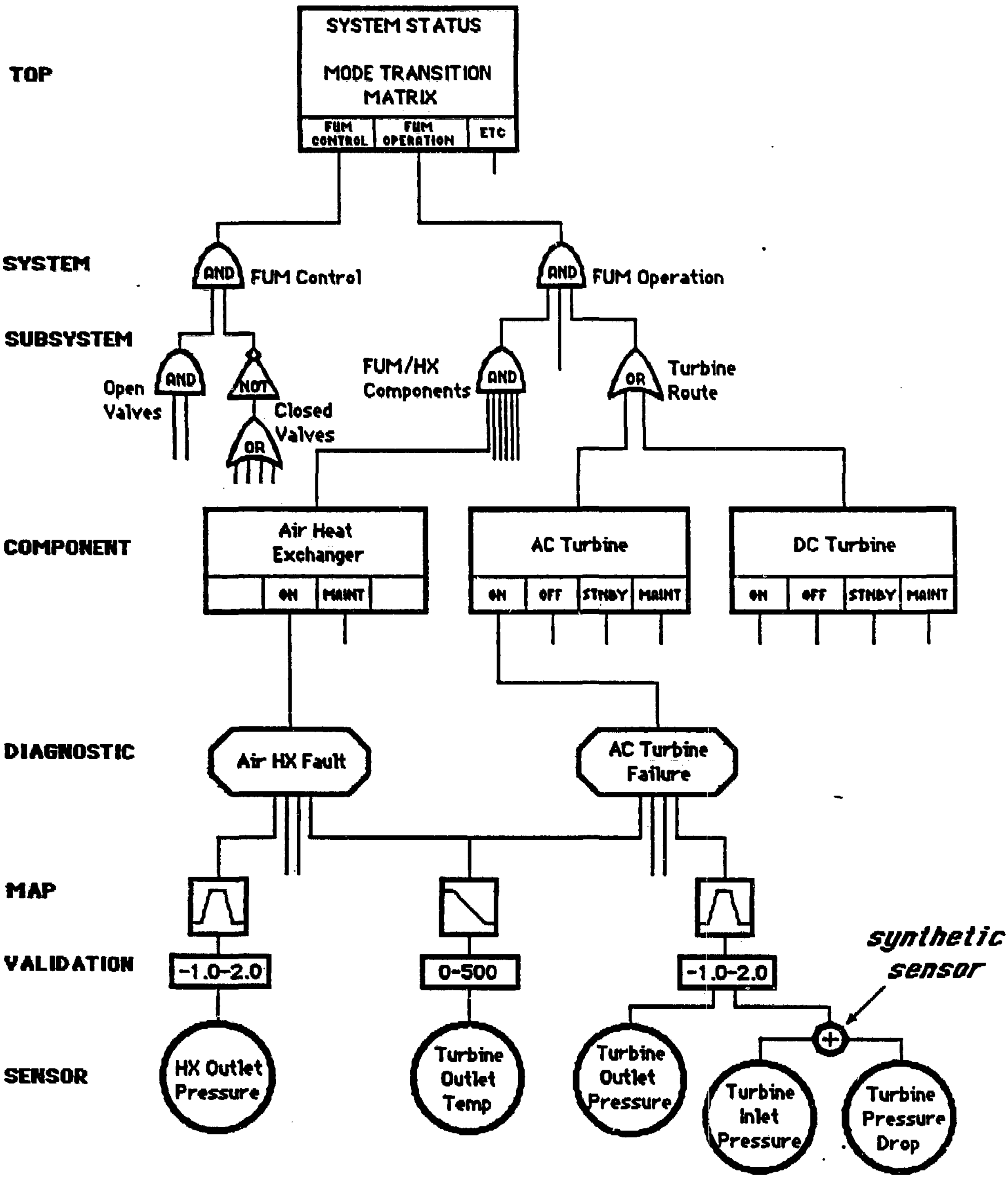

FIGURE 2: DISYS nodal network knowledge representation

network than by calling the structure a graph.) The hierarchical arrangement of the KR was specifically chosen as a human factors consideration to facilitate understanding of the diagnostic calculation. The network layout is meant to match an operator's mental model of a plant where systems and subsystems are collections of components and various instruments (SENSORS at the bottom of the network) are used to assess the health of the components. The operational status or health of each of the interconnected nodes is computed according to the type of node and the status of each subordinate or child node that links to the node. Status is a numerical value, continuous on the interval 0 to 1 with: 1 indicating a fully operational (completely healthy) node, 0 indicating a completely faulted node, and 0.5 indicating unknown node status. A high status for a complete plant, represented by the TOP node of figure 2, requires that certain combinations of components (SYSTEMS) be operational while other components must be deactivated. The specific combinations depend on the mode of plant operation so the mode must be first identified. The top node has a list of control paths (or sub-trees) that are evaluated to determine operational mode. In the example of figure 2, the control path for the mode is identified by checking active control signals that have directed certain valves to be open and other valves to be closed. If all the conditions of a control path are satisfied then the evaluation of plant status is directed to a corresponding operation path for appropriate diagnostics. For simplicity of explanation, figure 2 shows only a portion of the FUM control and FUM operation trees; there are normally several pairs of control and corresponding operation trees, each pair representing a specific mode of plant operation. The logical AND nodes (figure 2) indicate the required components of a system or subsystem for the FUM mode. The operational status of a system or subsystem, indicated with an AND node, is taken to be that of the component with least status linked to the AND node.

In the case of the OR node, the status is taken to be that of the component with the best status linked to the OR node. The nature of these logic operators is of the so-called fuzzy logic[6]. For the OR node labeled Turbine Route in figure 2, either the AC turbine component or the DC Turbine Component is required to have a high operational status; only one turbine is required for this system to be operational. Similar to the TOP node, a COMPONENT node has several possible paths that can be activated. The appropriate path to follow is dependent on the required state of the component for a particular mode of operation. The required component state for each mode is predefined and the appropriate diagnostic path is activated when the mode of operation is identified at the TOP node. In the example of figure 2, the Air Heat Exchanger Component and AC Turbine are required to be in the "ON" state and the appropriate diagnostic paths are activated to determine if they are operationally healthy in those states. In some other mode of operation the air heat exchanger might be required to be "OFF" and a different diagnostic path would be followed. The DIAGNOSTIC nodes identified by the COMPONENT nodes evaluate the possibilities (status) of preselected faults based on Baye's theorem of conditional probabilities. The diagnostic calculation uses an odds likelihood ratio formulation incorporating measures of belief and disbelief for a predefined set of possible symptoms[7]. Consistency of the symptom set affects the status of the diagnostic node; e.g., for a set of symptoms with equal measures of belief and disbelief and half the symptoms fully indicative of a fault (status=0) and half indicative of no fault (status=1), then the status of the diagnostic node evaluates to 0.5 (unknown status). The MAP nodes determine if a symptom is present using a predefined continuous linear functional relationship with validated sensor data as the independent variable. The current DISYS VALIDATION nodes use the parity space approach[8]. The parity space algorithm uses multiple sensor readings of the same process signal to determine an average value and credibility for the set of measurements. If all sensors read the same value in the range of the instruments' capabilities, the credibility of the average measurement is high. As the spread in the readings become larger, the credibility is correspondingly diminished. Sensor measurement credibility is propagated upward through the diagnostic tree with a unique uncertainty propagation technique. Each node status has an associated credibility measure, continuous on the interval 0 to 1 with: 1 indicating completely credible and 0 indicating completely unusable data. The credibility is used to modify the status of a node; e.g., if the status of a node initially evaluates to 1 but the credibility evaluates to 0, then the status is modified to 0.5 to indicate an unknown status. (Status is modified to 0.5 regardless of initial status value if the credibility is 0.) Provisions for simple analytic redundancy, or easier to interpret parameters, is provided by SYNTHETIC sensors which perform predefined algebraic operations on sensor readings. In figure 2, the SYNTHETIC sensor calculates turbine outlet pressure by adding a pressure drop measurement to the turbine inlet pressure measurement.

The DISYS nodal network representation of the Argon Cooling System diagnostics now recognizes 8 modes of operation and contains approximately 400 nodes consisting of 39 components and 61 sensors. During the March 1989 on-line testing of DISYS[1] an assessment of the time required to perform a diagnostic calculation for the more complex FUM only mode of operation was determined. On a SUN 3/60 computer running at about 3 MIPS, the computation time was around 0.2 seconds per cycle. It is believed that a diagnostic evaluation on a 5 second cycle will be adequate for fuel handling operations. The real-time performance of DISYS is therefore currently satisfactory.

CRITICAL REVIEW OF DISYS

It is worthwhile to now attempt to place the DISYS diagnostic system in context with the current state of artificial intelligence (AI) and expert systems for power plant applications in 1989. The field of AI and Expert Systems has undergone substantial growth during the last 10 years and there have been a lot of changes since the DISYS system was conceived back in the early 1980s. The original developers of DISYS recognized the need for real-time capabilities in diagnostics and their resultant approach has significant potential for a role in meeting real-time requirements of large scale systems. According to recent authoritative work by John Bernard of MIT[9] in assembling a book on expert systems applications in the nuclear power industry[10], "it remains an open question as to whether expert systems can be successfully applied to areas including real-time diagnostics and guidance". In regards to meeting real-time requirements, the DISYS diagnostic system is in the main stream of current research of advanced computer applications for power plants. However, the DISYS approach should not be viewed as an expert system in the currently accepted conventional sense. DISYS mimics some of the characteristics of a conventional expert system but performs its diagnostic evaluation in an algorithmic style where the computation time in a diagnostic cycle is entirely fixed due to the knowledge representation (KR) scheme. The DISYS DIAGNOSTIC and MAP node processes embody human expertise in identifying faults from instrument readings. This expertise is similar to that which would be used in a conventional rule-based expert system which creates new facts (or nodes) in a knowledge base as a problem is evaluated. Conventional expert systems do have a problem for meeting real-time requirements of large scale systems because the time to perform a diagnosis is not entirely predictable and can become quite large as a knowledge base is allowed to dynamically grow. There is also the problem of truth maintenance (nonmonotonic reasoning) in conventional expert systems when facts asserted in the knowledge base must be retracted along with all the subordinate facts which were subsequently asserted. Despite the limitations of conventional expert systems for real-time requirements, it is possible to approach the limitations through a variety of realistic techniques[11]. One approach to adapt the conventional expert system for real-time requirements is to focus the expert system to a specific small part of the more comprehensive knowledge base[12]. In this regard, the real-time capabilities of DISYS may be best suited as a focusing tool for a more comprehensive integrated diagnostic system involving a variety of diagnostic methods. Indeed, DISYS already uses focusing by selectively activating only the appropriate portions of the diagnostic nodal network based on the active control signals in a plant. Another approach for adapting conventional expert systems to real time requirements involves translating rule based knowledge representations into a codified nodal network representation in the C computer language[13]. This translation effort is additional evidence that C language implementations of advanced computer applications, like DISYS's C based nodal network representations, are viewed as candidate success routes for large scale real-time applications.

RECENTLY COMPLETED TESTING OF THE DISYS DIAGNOSTIC SYSTEM

The uniquely "new" aspect of diagnostic development and testing introduced by Penn State is the use of the IBM Advanced Control System (IBM ACS) as a real-time simulation tool to test advanced control and diagnostic concepts[14]. The use of the IBM ACS as a realtime simulation tool was developed in a project funded during 1987 by the Nuclear Engineering department's industry affiliates group which is named FERMI. The FERMI group includes 6 electric utility companies from Pennsylvania and surrounding states, Westinghouse, Monsanto Mound Labs, and the U.S. Electric Power Research Institute (EPRI). The real-time simulation technique adapted the B&W Modular Modeling System (originally developed at EPRI) to the IBM ACS[15].

The relationship of the major pieces of software which comprise the IBM ACS is shown in figure 3. At the operating system level, a special real-time operating system is included to provide real-time coordination not normally encountered in IBM mainframe computer applications. The next layer of the Advanced Control System software provides three building blocks for actual implementation of a mainframe based control system. The process I/O access software interfaces to an intermediate layer of computers which in turn interface to plant controllers and instrumentation. The real-time data base includes management of historical data and provides a shared memory accessible to all other programs. Identification of process variables within the real-time data base and plant is accomplished with a 3 part tag name; e.g. AC P 001, where the first two characters indicate a process control unit (AC for Argon Cooling System), the second part is a service identifier (P for pressure), and a numerical index (001). All programs request storage and retrieval of data using this tag name structure. The third building block of the IBM ACS software is the display management system. The display management system provides the process operator and engineer with a wide variety of high level standard display features including: process schematics with display of real-time data, trend displays in a variety of formats, and tabular displays of process data. The display management system is also menu driven permitting definitions of the real-time data base variables and display definitions without requiring the writing or modification of a program by the user.

DISYS testing in the mainframe computer environment was accomplished by creating a mainframe version of DISYS in IBM VM/C. Excellent portability of C

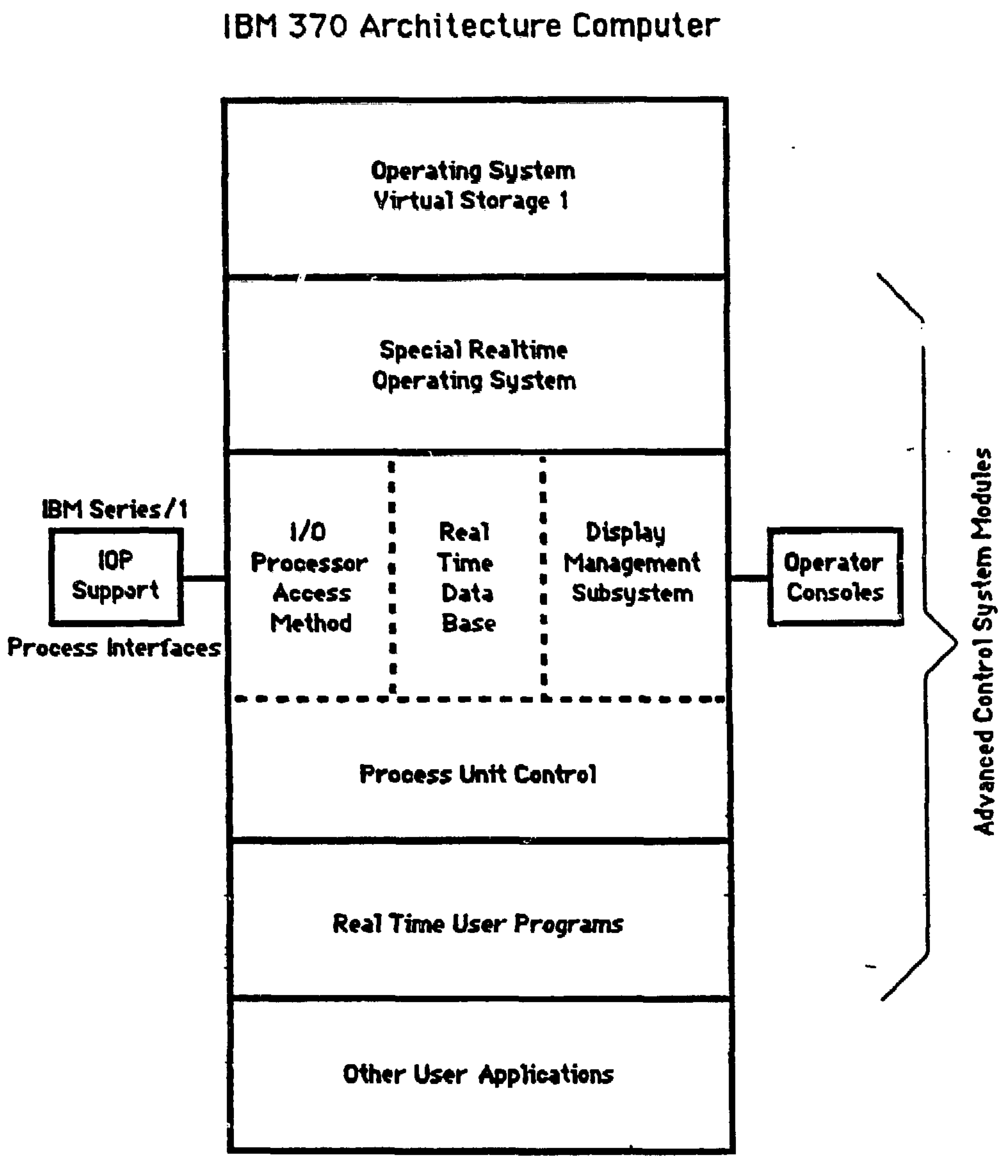

Fig. 3 : IBM Advanced Control System Schematic.

from UNIX to the IBM mainframe was demonstrated. Special features of the IBM VM/C DISYS version include writing the output of the diagnostic to locations in the real-time data base so that it can be displayed and processed using standard features of the IBM ACS. A drawing of the IBM ACS process schematic of the EBR-II Argon Cooling system is shown in figure 4. Other display features include optional trend displays and triggering special effects at certain values of system status. If system status drops below 0.5, a FAILED message is flashed in red at the top of the process schematic display.

Although the analytic capability of the DISYS diagnostic system can be validated and demonstrated in the IBM VM environment, it is still essential to perform testing of the actual SUN UNIX C version of DISYS operated in the actual plant environment. The IBM VM and SUN UNIX DISYS core calculational routines are identical, only the data access and program dialogue are different.

In the UNIX environment of the actual EBR-II plant implementation of DISYS, plant data is made available to applications in a shared memory segment as shown in figure 5. A SUN server workstation receives plant data from the DAS computer system and then broadcasts the data on the ETHERNET network, figure 6. Local workstation client programs receive the data and store it in a local shared memory segment of a workstation which is readily accessible to all applications running on the local workstation. The DISYS system was decomposed to include an interface to external shared memory containing live plant data. This organization was also exploited in developing another efficient mechanism to perform off-line real-time testing and development of DISYS. A stand-alone "playback" program can read a previously stored time history of DAS data and refresh the shared memory segment at the same real-time intervals used to record the data. There is no difference between the

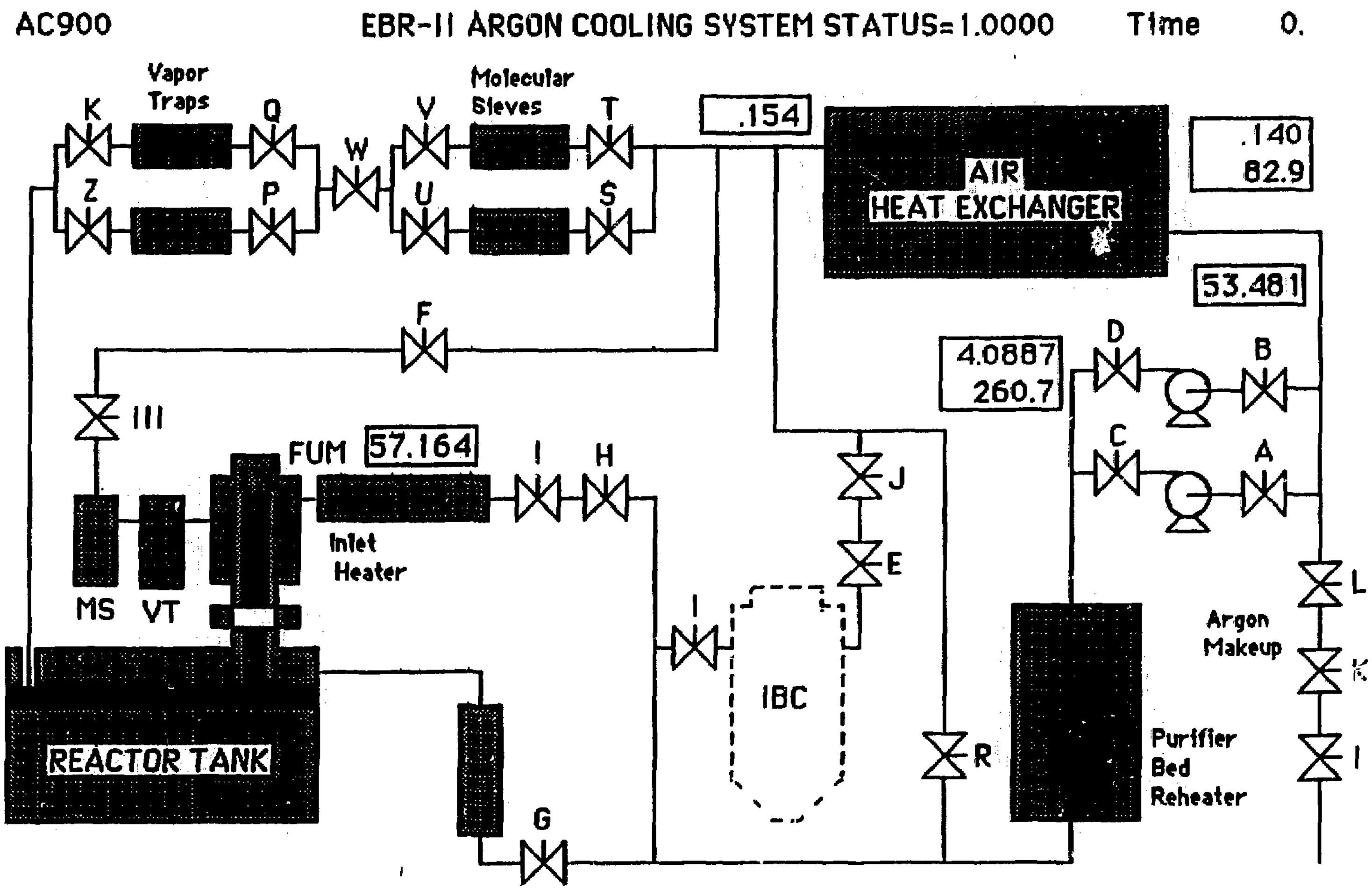

FIGURE 4: IBM ACS REAL-TIME PROCESS SCHEMATIC OF THE EBR-II ACS

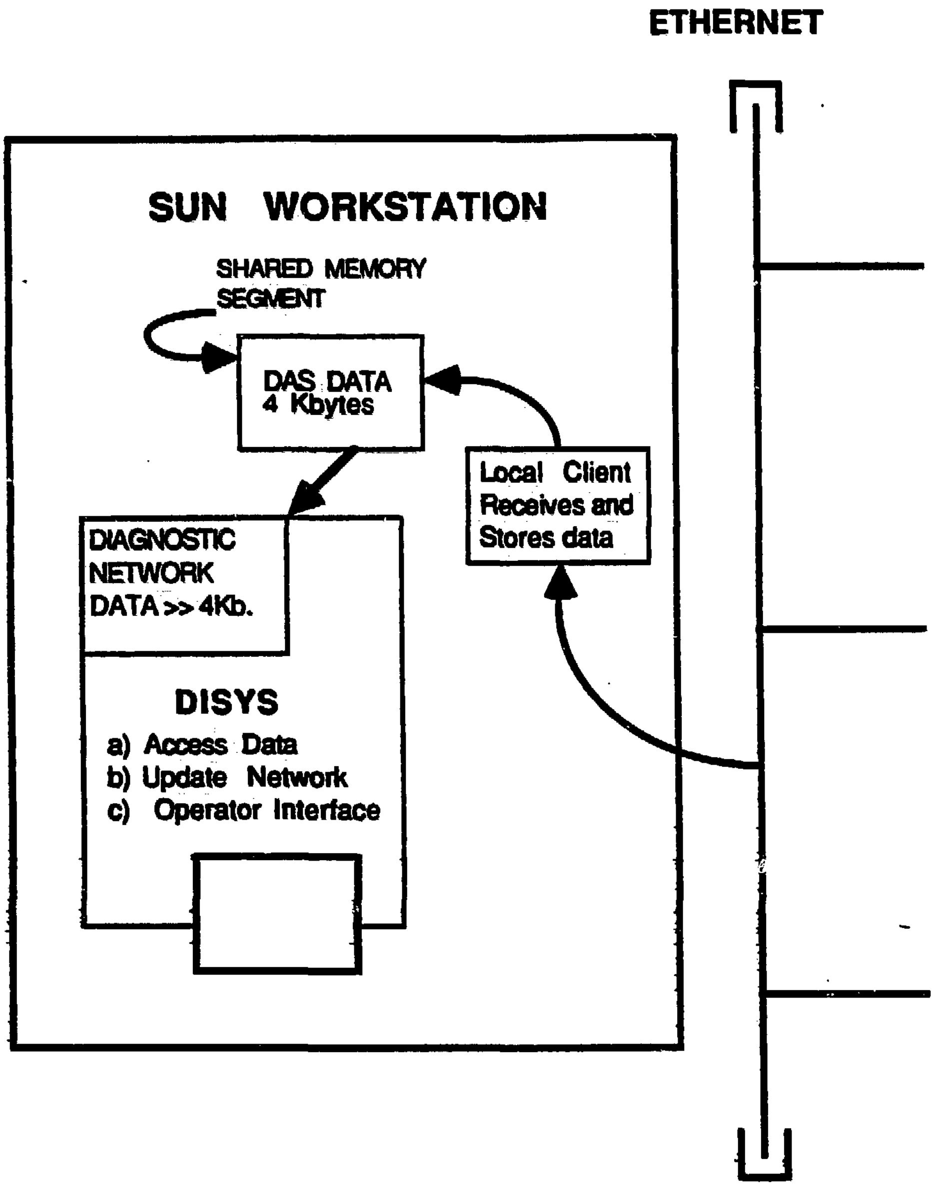

FIGURE 5: DISYS ACCESS TO PLANT DATA THROUGH UNIX SHARED MEMORY SEGMENT

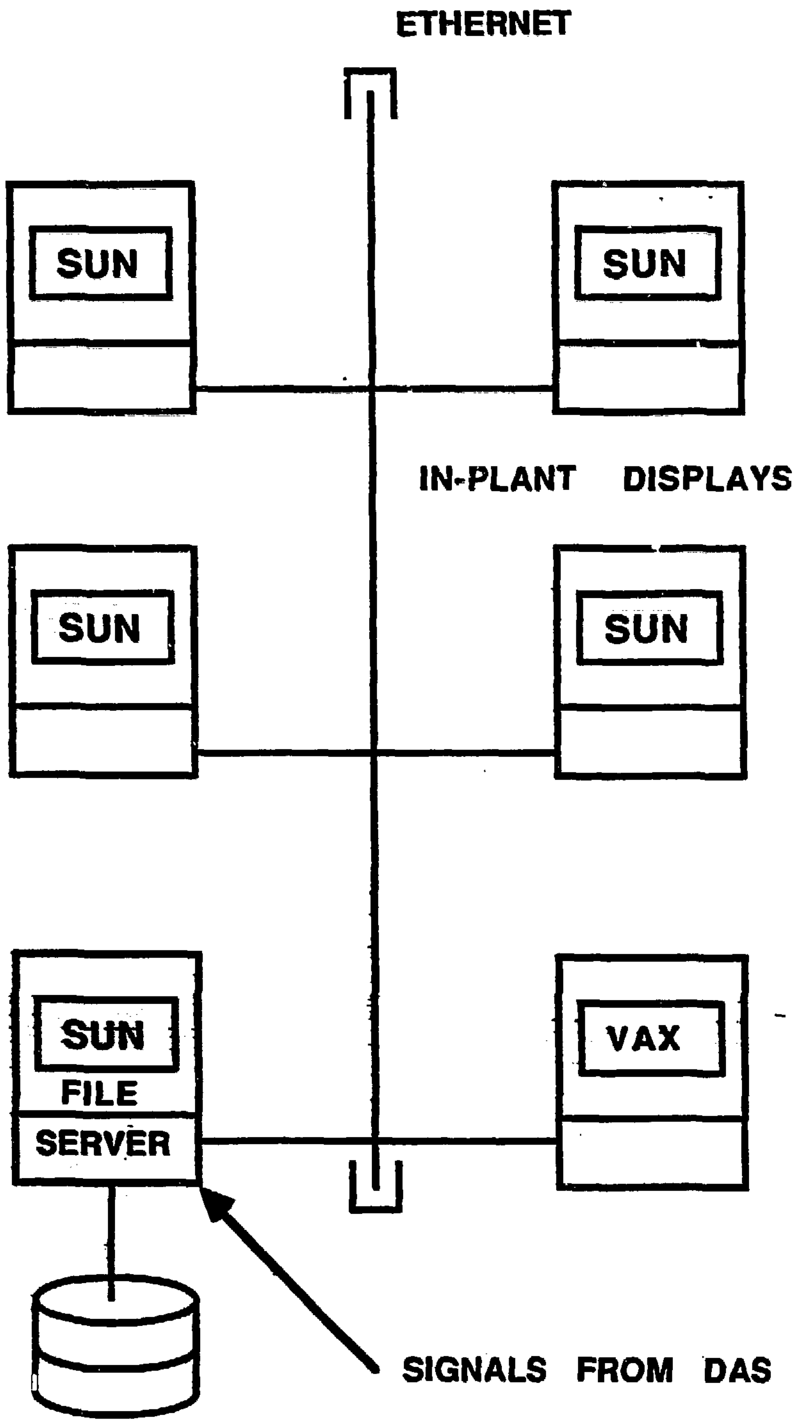

FIGURE 6: EBR-II SUN COMPUTER NETWORK COMMUNICATIONS

UNIX C version of DISYS tested off-line at Penn State and the DISYS system operated on-line at EBR-II. The difference in operation lies solely in the external program that refreshes the shared memory segment of the local work station. At Penn State the "playback" program refreshes the shared memory from a data file; at EBR-II their communications programs refresh shared memory with live DAS data. In either case, the DISYS program is the same. The multi-tasking and shared memory features of UNIX have provided an excellent approach for modularizing, integrating, and testing of advanced applications for power plant operation.

CURRENT DIAGNOSTIC DEVELOPMENTS

As of May 1989, the DISYS system produced a textual explanation of its diagnosis[16] which is excellent for the engineers and programmers that need to verify and validate the calculational process. A more suitable graphics presentation for use by an actual operator is being developed during the remainder of 1989 under a project funded directly by the EBR-II division of the Argonne National Laboratory. The graphics interface is being developed as an intelligent real-time process schematic along the lines of figure 4 with optional generation of the nodal network along the lines of figure 2. The UNIX environment is being further exploited in developing the graphics interface to DISYS. Similar to the externalization of on-line plant data in a shared memory segment external to the application programs (figure 5), the entire DISYS nodal network data base has been externalized in a much larger 2nd shared memory segment as shown in figure 7. Also as shown in figure 7, the operator's graphics interface to the diagnostic data base has been developed in the X Window-11 environment and is contained in yet another separate program which also accesses the externalized DISYS nodal network

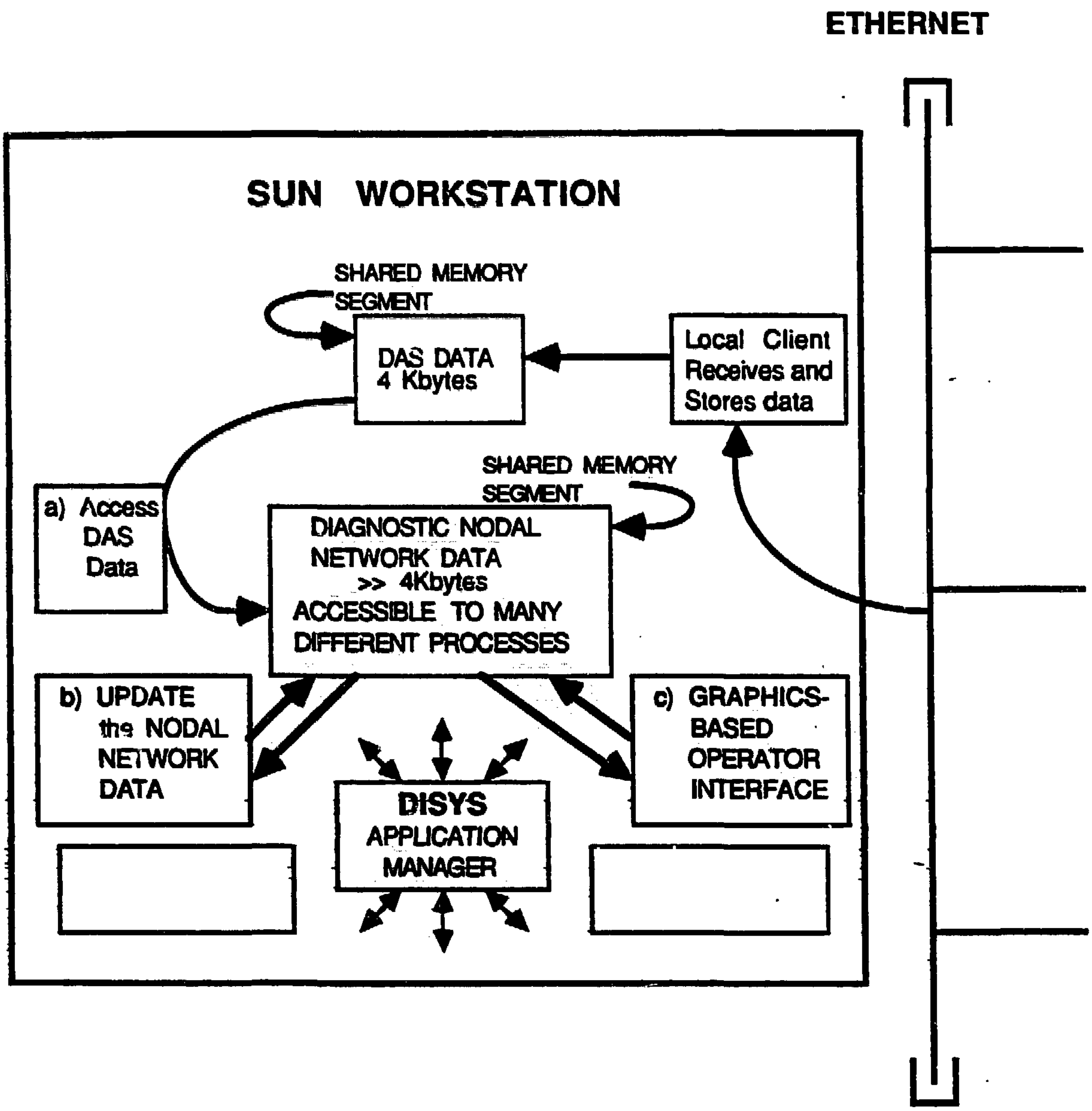

FIGURE 7: DISYS ORGANIZATION WITH EXTERNALIZED NODAL NETWORK IN A LARGE SHARED MEMORY SEGMENT

knowledge base.

A small specialized program (Application Manager) coordinates the execution of the DISYS diagnostic calculation and the separate graphics user interface program. Compartmentalization of the diagnostic functions into these separate programs is movement in the direction of producing a diagnostic in object oriented programming format[17]. The use of the UNIX shared memory as a common data area for the objects is a form of "black-boarding" described in the AI literature. The specialized Application Manager approaches the coordination problem pursued in Distributed Artificial Intelligent (DAI)[18] research in the subject area of multiple cooperating intelligent agents.

Another program to be added to the diagnostic system as part of the current research activity is to provide an automatic learn mode. For a new application on an existing power plant system where the user has identified the components and sensors involved in diagnosis, the automatic learn mode will simply observe acceptable system operation and create the necessary MAP node functional relationships that create an acceptable diagnostic output. It is expected that this initial set of mappings will be tighter than necessary because it is not likely that the observed system performance will be generated over the possible extremes of acceptable operating conditions. The learn mode mappings will be based on observed statistical variations and are simply an initial starting point for further refinement by the plant operating staff. This learn mode is being explored to alleviate some of the developmental effort required of a new application and can be viewed as one element of automated knowledge acquisition.

PLANNED REAL-TIME DIAGNOSTIC DEVELOPMENT

The DISYS diagnostic system seems to be ideally suited for further modularization and implementation in a proposed distributed control environment[19]. A recently announced NSF equipment grant (ECS-8905917) will provide a state-of-the-art microprocessor based control system which will be interfaced with other computers and networks at Penn State to establish what we have named the "Intelligent Distributed Controls Research Laboratory". The microprocessor based control system is a Bailey NETWORK 90 system compatible with Bailey equipment currently installed at the Experimental Breeder Reactor. A block diagram of the major elements of the system is shown in figure 8. Two process control units (PCUs) will be configured such that they can be operated together or split into separate operations as research needs may dictate. When operated together they will be interfaced through the Bailey Plant Control loop which performs communication by exception reporting. The COM03 controller (in PCU #2) and the MFC03 multifunction controller (in PCU #1) can be easily moved from one PCU to another. Controllers in the same PCU can communicate through a module bus which has an ethernet like communications protocol. The COM03 controller is based on a 6809 microprocessor and executes a control strategy defined by the user in terms of standard control functions such as Proportional Integral Derivative (PID) feedback. The controller can take 3 digital and 4 analog inputs and generate 4 digital and 2 analog outputs, thus permitting control of two process loops. The MFC03 multifunction controller is based on a powerful 68020 microprocessor. To execute a control strategy, it permits the user to select 50 times the number standard control functions than is possible with the simpler COM03 controller. The MFC03 controller can interface to a process through up to 64 slave modules for handling input and output. A typical slave module can handle 16 points (analog and/or digital). The processor can also integrate 5000 lines of user

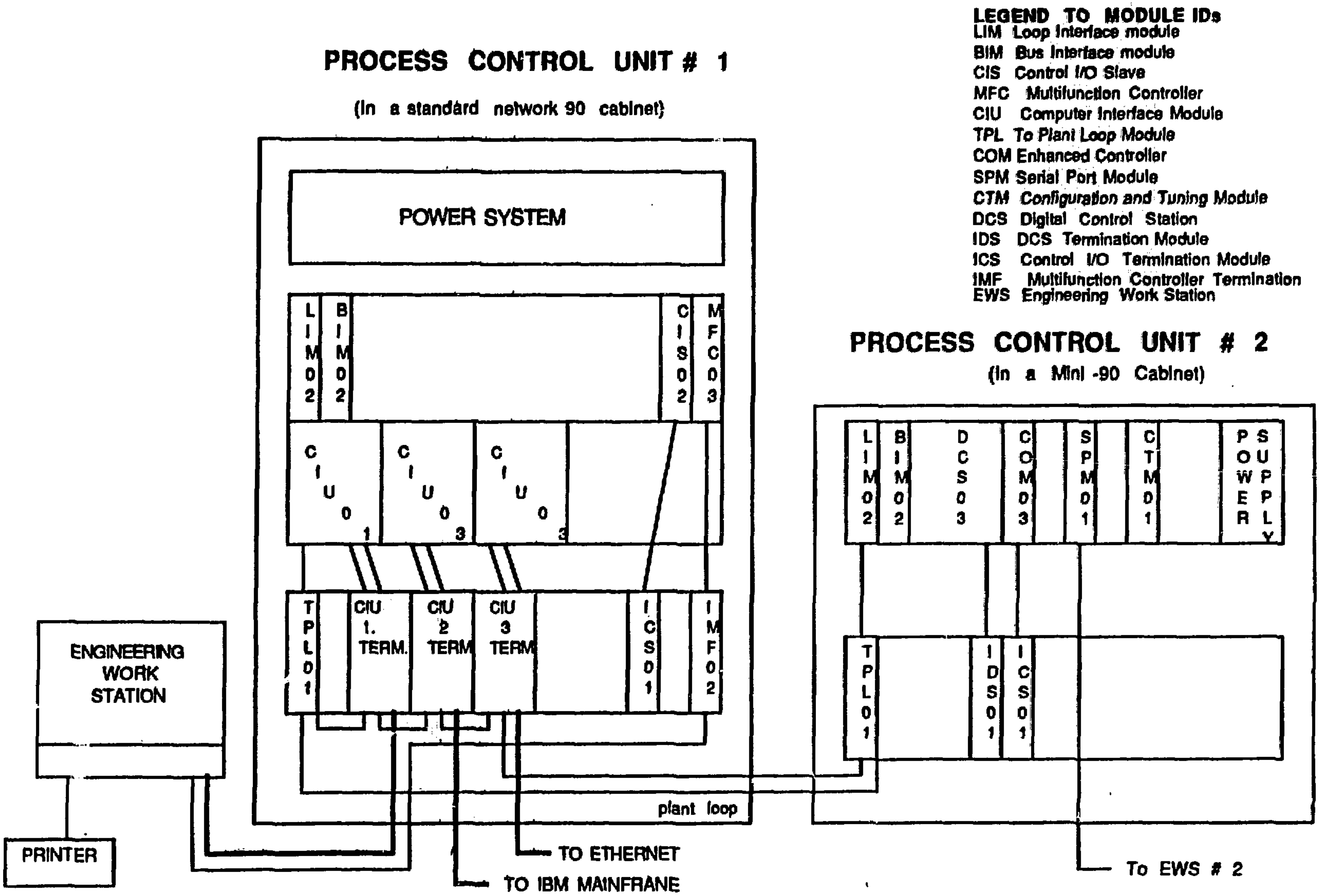

FIGURE 8: BAILEY NETWORK 90 SYSTEM FOR INTELLIGENT DISTRIBUTED CONTROL LAB

defined C language code with the standard control functions to produce intelligent control at the microprocessor level. Generation of the C language code is accomplished in an engineering workstation and down-loaded to the controller through a computer interface unit. The C language programming capability of the multifunction controller is already being used for process control expert systems[20] now offered by the manufacturer. The dedicated engineering workstation indicated in figure 8 includes a 386 based computer which also permits generation of standard control strategies, display of process variables, plant schematics, and hard copy documentation of controller programming in a computer aided design (CAD) format. An existing COMPAQ 386 computer at the Penn State TRIGA research reactor facility will be upgraded to permit operation of a second engineering workstation for research activities which can use the smaller PCU #2 in a stand alone environment. Three computer interface units will be included in the system. One computer interface unit will be used with the dedicated engineering workstation, the second to effect a communication link with an ethernet system of computers, and the third to interface with the IBM mainframe computer.

Another research grant has also been recently awarded by the DOE and will provide 3 years of research funding to develop a prototype demonstration of intelligent distributed control at EBR-II. The EBRII steam cycle power plant subsystem was chosen for the prototype demonstration because it is similar to that used in all power plants and includes turbine, condensor, feedwater, and steam generation systems. Results from the research project will thus be readily adaptable to most power plants. The project has identifiable yearly milestones. During the first year, a diagnostic data base for the EBR-II steam cycle power plant will be developed and tested on a dynamic simulation which is also to be finalized in the first year. The first year milestone is to demonstrate the steam cycle diagnostic operating in a single SUN computer on-line at EBR-II. The second year of the project will develop a distributed diagnostic system where the low level functions of the diagnostic evaluation are executed in microprocessor based controllers and interfaced with the remaining higher level diagnostic functions in the SUN computer network. The second year milestone is to demonstrate the distributed diagnostic operating on-line at EBR-II. A first-cut at distributing diagnostic functions will be to incorporate everything needed for component diagnosis in the microprocessor based controller that is executing the low level control algorithms for the component. For example, deaerator component diagnostics could be incorporated in the controller executing the deaerator level control algorithms and its evaluation would be sent across the ETHERNET network to the higher level diagnostic analysis in a UNIX based workstation. The third year of the project will explore closing the control loop by using the output of the diagnostics to automatically effect changes in control.

POSSIBLE FUTURE DIRECTIONS IN DIAGNOSTICS

The research funding provided by the NSF and DOE provide a core program for development and demonstration of intelligent distributed control for power plants. There are of course several peripheral research activities which can be initiated that would hopefully produce additional advanced techniques for power plant operations. Two such areas are being examined under start-up funding provided by the Penn State Nuclear Engineering Department's industry affiliates group, FERMI. These areas are in applications of qualitative reasoning and quantitative methods for real-time diagnosis. Both qualitative and quantitative approaches attempt to include the use of known physical laws as part of the assessment of plant condition and both use a mathematical model of the process instead of the difficult to elicit human expert knowledge.

Most of the theories on qualitative reasoning are based on the concept of envisioning by de Kleer[21]. The physical laws that describe each of the processes in the plant are formulated in terms of a qualitative differential equation using qualitative variables. The qualitative variables describe process variables as in quantitative analysis: pressure, temperature, flow rate, etc. Qualitative variables however only take on a small set of possible values such as positive, negative, or zero. Equations that use qualitative variables to describe the physical laws and behavior of power plant components can be formulated and used to automate reasoning about the observed performance of a system. Many applications of qualitative model- based reasoning for process diagnosis are already being pursued by a number of organizations. The recent EPRI conference on Expert Systems Applications for the Electric Power Industry had many papers which discussed the use of model based techniques as part of diagnosis [22 23 24 25 26 27 28 29 30 31].

Research on quantitative approaches to diagnosis has also been conducted[32 33 34]. Unlike expert systems and qualitative reasoning, quantitative approaches use traditional mathematical descriptions in the form of simultaneous (possibly non-linear) differential equations that describe the precise behavior of continuous real variables. Quantitative analysis can be time consuming, particularly if a large number of trial and error runs must be made to identify a fault. A goal of an integrated diagnostic approach that uses quantitative techniques is thus to focus the application of the quantitative analysis to only a few possibilities that need to be evaluated. The possibility of combining expert knowledge and qualitative techniques in an integrated diagnostic system has already been identified and is being pursued[28 30 31]. Operation of a multiechelon real-time diagnostic system including quantitative techniques is conceptualized with the aid of figure 9.

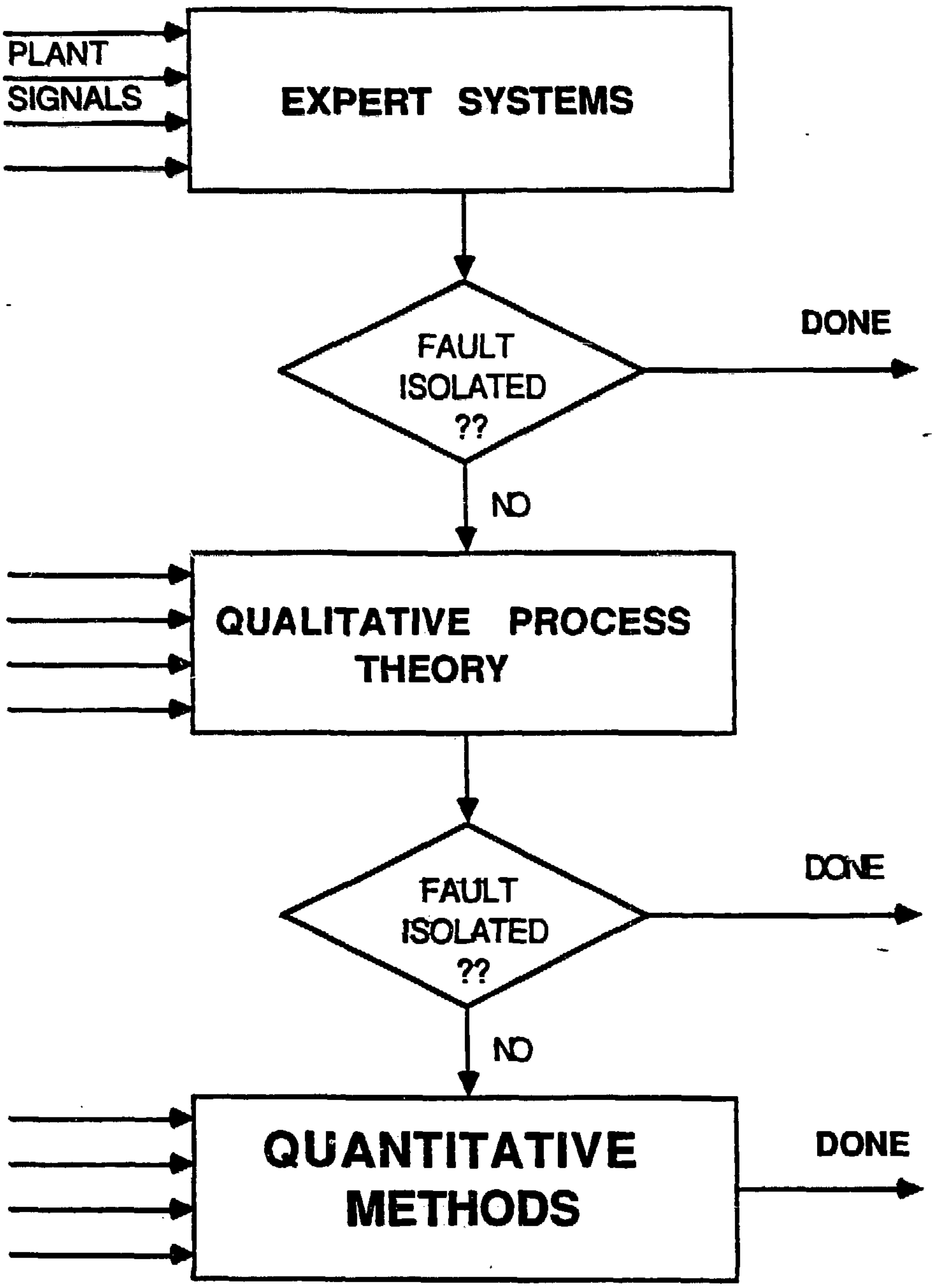

FIGURE 9:

MULTI-ECHELON REAL-TIME DIAGNOSTIC CONCEPT

A simple real-time expert system monitors plant signals at a high priority. Normal operation and some faults may not require any further use of alternate methods and the routine diagnostic monitoring would then be complete and rescheduled for execution. If the expert system cannot unambiguously identify a fault, a focused qualitative reasoning process would be scheduled to attempt to resolve the situation. If, in turn, the qualitative technique cannot unambiguously identify a fault, then a tightly focused analysis using quantitative methods would be initiated.

An example of a quantitative method for resolving the fault unambiguously is to use modern optimization techniques such as Pontryagin's maximum principle[33]. In this method an objective functional is calculated quickly to identify the fault. The objective functional is a sum of differences between measured and calculated state variables integrated over time; when these calculated and measured state variables become nearly equal, the objective functional goes to a minimum and the fault is identified. The state variables are key variables which when appropriately chosen resolve the fault. This quantitative technique should only be used when the expert system and/or the qualitative reasoning process have narrowed the fault between two or three possible malfunctions, because the method must simulate the plant response for each postulated malfunction. In addition switching functions must be determined and used to evaluate the objective functional. Other modern optimal control techniques may be employed but they will evaluate the objective functional and state variables at points in time rather than integrating them over time. Use of these quantitative techniques may be expedited through parallel processing of two or more simulated faults.

The distributed power plant computer and control system is considered to be the best environment to unify a variety of diagnostic techniques into an integrated approach for real-time application as suggested in figure 9. A distributed system such as a network of UNIX based computers (figure 6), microprocessor based controllers (figure 8) and a mainframe computer (figure 3) can provide a fluid environment where various jobs are simpler to initiate, monitor, and cancel as conditions in a plant change.

SUMMARY AND CONCLUSIONS

Real-time diagnostics based on an expert systems approach has been installed and operated on-line at the Experimental Breeder reactor in Idaho, USA. A program of testing advanced applications using real-time dynamic simulation and real-time playback of actual plant data has been developed at Penn State and was used in the diagnostic system development and testing for the EBR-II installation. A graphics interface for diagnostics is being developed in the X-Window 11 environment.

The NSF and DOE have also recently established an Intelligent Distributed Controls research program at Penn State for power plant operations. The research program is interdisciplinary with participation of researchers from several Penn State engineering departments. Mr. Robert M. Edwards, Professors E.H. Klevans, E.S. Kenney, M.A. Schultz and S.H. Levine from the Nuclear Engineering Department are involved along with Professors Kwang Y. Lee (Electrical Engineering), Asok Ray (Mechanical Engineering), and Soundar Kumara (Industrial Engineering).

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