CONF-890673--4

# RECENT ADVANCES IN CONTROL AND DIAGNOSTICS DEVELOPMENT AND APPLICATION*

CONF-890673--4

DE89 015133

by

L. R. Monson, R. W. King, R. W. Lindsay, J. D. Staffon
Argonne National Laboratory
Idaho Falls, Idaho 83403

Submitted to the IAEA/IWGFR for presentation
at the
Specialists Meeting on Advanced Control
for Fast Reactors
Argonne, USA
June 20-22, 1989





*Work supported by the U.S. Department of Energy, Reactor Systems, Development, and Technology, under Contract W-31-109-Eng-38.

**Recent Advances in Control and Diagnostics Development and Application**

## Introduction:

The power industry is undergoing rapid technological advances and cultural changes. Technologies are advancing and evolving so rapidly that the industry is hard pressed to keep up and take full advantage of the many developments now in progress. Recent advances in state-of-the-art computer technology are making in-roads in the form of advanced computer control, expert systems, on-line performance monitoring and diagnostics. Validation and verification schemes are being developed which provide increased confidence in the correctness and reliability of both computer hardware and software. Our challenge in the nuclear community is to effectively apply these new technologies to improve the operation, safety, and reliability of our plants.

This presentation discusses two areas of development that are essential to advanced control strategies: application of diagnostic systems to improve fault-tolerance, and model-based graphic displays.

## Fault Tolerant Diagnostic Systems

In order for a process operator or automatic control system to take appropriate control action or decide to take no action in response to an indicated abnormality in process operation, there must be assurance that the indication being received does, in fact, represent actual process or equipment conditions. This implies that a distinction must be made between readings from faulted and unfaulted instruments, and that an accurate determination of the value of a critical parameter must be provided even though the sensor measuring that parameter may have failed or degraded. In other words, the system must have a high degree of tolerance to faulted instrumentation including single and multiple faults. If the operator does not have a high degree of assurance that the indicated reading is correct, he has to make a decision on whether to take the action that is called for if the indication is correct, or assume the indication is incorrect. Since the action that may be called for in response to an indicated reading may be somewhat drastic, the operator may be hesitant to take that action until some other evidence is available regarding the validity of the indication. His decision about the validity of the indication, if incorrect, could have serious consequences.

The importance of providing a validated indication to the operator is extremely important to enable him to take immediate action without hesitation due to uncertainty about the validity of the indication. If the sensor providing the information has failed or degraded, an alternate means of providing the correct information to the operator must be provided in order to enable him to take appropriate action. Thus the system, in order to be tolerant of sensor/instrumentation faults, must be able not only to identify faulted instrumentation, but also provide a valid sensor value even under faulted conditions.

Much work is currently being performed to investigate ways to achieve fault-tolerance in diagnostic systems, particularly in the area of fault detection and sensor validation. Notable work being done in this area includes the integration of parallel diverse signal processing modules, each of which incorporates a different signal processing technique; single and multiple variable consistency checking; process empirical modeling; signal anomaly detection; analytic redundancy; sensor data relationship; heuristics; and several other techniques.

One of the techniques currently in use and undergoing further development and testing at EBR-II is based on pattern-recognition, state determination methods. This system is called the System State Analyzer (SSA). In general terms, the SSA is related to many of the above mentioned techniques, and it has some characteristics that are similar to neural networks.

The SSA(1,2), in different forms, is in various stages of development, testing, and application at EBR-II. The SSA has been developed specifically to be tolerant of instrumentation faults by being able to identify faulted instruments and provide a reasonably accurate estimated value for that instrument reading. This estimated value is based on previously learned pattern relationships with readings from other instruments that are similarly related to and define the process being monitored. The SSA has demonstrated a high degree of tolerance to sensor faults during plant tests and during normal plant operational surveillance. The SSA was also developed to be able to detect a change in the operational state of the process and provide information about the characteristics of the new state and the cause of the state change. This may be a change to a different valid operational state or to a faulted state.

The SSA process begins with identification of system operational states over a learning period of system operation. The SSA then compares new observed data with the learned state patterns. The SSA then establishes an estimated state based on the similarities with previously learned states. The estimated state is "built" using a weighted combination of learned states, the weighting value being determined by the degree of pattern overlap with each learned state. The estimated state contains a new estimated value for every parameter being monitored, including estimated values for sensors that have degraded or failed, assuming sensor data was available during the learning process. Because the estimated signal values are based on actual established relationships with the values of all the sensor signals in the signal group representing the process, the failure or degradation of any sensor has an insignificant effect on the SSA estimated value for that sensor signal.

The pattern-recognition methodology gives the SSA the property of essentially ignoring faults in individual signals during the system state estimation process. The estimation for the faulty signal is essentially unaffected because it is based primarily on the other signals in the signal group and the previously learned pattern relationships. The SSA methodology involves no fitting and no convergence criteria. The SSA uses a single-pass equation which is always solvable, thus making it fast and robust.

An important feature of the SSA is the output display which provides to the operator or engineer the diagnostic information being generated by the SSA algorithm. Figure 1 is an example of an SSA output display called a signature plot which shows the distribution of actual system signals at a point in time, relative to the SSA estimated values which are represented by a horizontal line through the center of the plot. The vertical bars above the line to the left represent signals that are higher than the estimated values, and those below the horizontal line to the right represent signals that are lower than estimated. The signal deviations from estimated values are shown normalized to the average signal deviation for the entire group of signals, so that the height of a vertical bar indicates a multiple or a fraction of the average percent deviation for the group.

The average signal deviation from estimated values for the signal group at that point in time is shown at the top center of the graph. This value is important for detecting process state changes, for differentiating between signal failures and process state changes, and for determining if the process is operating within the learned domain. The distribution of signals is shown as an ordered list from left to right showing in descending order those signals that deviate most in the positive direction on the far left, crossing over the horizontal line near the center indicating signals that are close to or right on estimated values, and continuing to the right with signals that are lower than estimated. The "X"s and the curve drawn through them are overlaid as an indication of an expected normal distribution of signal deviations as a multiple from 0 to 3 times the average deviation. Two vertical lists of numbers on the far left and far right sides of the plot indicate those signals that are three average deviations or more above or below the estimated values.

Another type of SSA output display is the individual signal plot as shown in Fig. 2. This type of plot is a time history plot that shows a DAS channel value plotted over time, the SSA estimated value for the same DAS channel plotted over the same time period, and an upper and lower "uncertainty boundary" above and below the SSA estimated signal trace representing relative uncertainty of the estimate based on how well the current data patterns are fitting into the learned domain.

The SSA has been undergoing performance and operational testing in various forms at EBR-II for the past three years. The most significant results have been achieved using the "on-line" SSA software (in FORTRAN) that has been installed on the EBR-II Data Acquisition System (DAS) computer and runs in the background while the DAS performs its primary function of data collection, display, and storage. This version of the SSA uses one-minute signal averages from the DAS data log. The signal group being monitored consists of 115 signals representing the heat generation and transfer process from the reactor core to the primary, secondary, and steam systems. Many of the signals come from key plant parameter sensors measuring sodium flow rates, core inlet and outlet temperatures, and neutron flux.

The tests were designed to investigate the ability of the SSA to detect and characterize minor plant state changes simulating a faulted process, and then the ability to detect a faulted signal condition and provide a "correct" estimated value for the faulted signal. The tests include slight power level changes, secondary flow changes, primary pump speed changes, and multiple signal failures.

The tests indicated that the SSA could detect and characte ize a plant state change simulating a process fault, when the magnitude of the change was less than 0.5%. The tests also demonstrated the ability to continue to provide an accurate estimation of a critical sensor value even during the sequential, cumulative failures of over 12% of the sensors in the sensor group being monitored.

Use of the SSA as an engineering surveillance tool for periodic monitoring of EBR-II plant conditions has resulted in some interesting observations during normal plant operations. In several instances, the SSA has detected signal problems. These have ranged from instrument drift to sensor failures. The most notable of these occurrences was observed in 1988 with the degradation of a thermocouple (TC) measuring mixed-mean reactor coolant temperature in the reactor outlet pipe. This measurement provides the basis for the reactor core $\Delta T$ determination and is used by the reactor operator as a control parameter. TC degradation resulted in a drop in the indicated outlet temperature, resulting in a drop in indicated core $\Delta T$ of about seven degrees over a period of about 40 minutes beginning with a one degree drop, then continuing down on a jagged decline. Over this same time period, the SSA estimated value for this core $\Delta T$ channel increased about one-half degree shortly after the drop in indicated $\Delta T$, and then held steady. Later analysis indicated that the reactor operator, observing an indicated drop in core $\Delta T$, raised reactor power very slightly to compensate. He then observed that the indicated core $\Delta T$ was not responding to his action and switched to other core $\Delta T$ indicators for plant control and held the plant steady. The SSA estimated value continued to provide an accurate estimate of the $\Delta T$ value during the TC failure and responded properly to the slight power increase (3).

## Model-Based Displays for Plant Control and Diagnostics

A reduction in the time and effort required by nuclear plant operators to accurately determine the condition of the plant, especially in off-normal events, is a must. At the Experimental Breeder Reactor II (EBR-II), a display system was devised, based on the early work of Beltracchi (4), which provides a thermodynamic model-based, real-time display of the plant processes. This display provides the operator with the information needed to make rapid, correct decisions. The main display, Figure 3 is based on the Rankine thermodynamic cycle. The display system includes other, lower-level displays which are directly related to the main display.

The display approach was devised in an effort to provide for a much better presentation of plant information to the operators. Several considerations and assumptions were made to assist in the formulation of the display approach. For example, it is assumed that a "typical" operator, no matter how much formal education he or she has, cannot integrate hundreds of individual pieces of information and synthesize a correct mental model of the plant state except when the plant is stable. It is when the plant is not stable that it is desirable for the operator to know exactly what is going on and what effect any control action initiated by the operator may have on the plant.

There is some question whether it is humanly possible for an operator to have a correct mental model of a plant when the plant is in a transient condition. It has been observed that most people have difficulty remembering a seven digit telephone numbers long enough to dial (without rechecking the number once or twice). Remembering 30 to 100 pieces of data and determining a "model" from the information is probably impossible. An additional concern is that it is nearly impossible that any normal human would have the steam tables (or curves) committed to memory such that determination could be made of a plant state whenever the plant was out of the known realm of memorized operational or procedural information (as in the TMI accident for example).

The receipt of plant data by an operator and making logical connections that results in formation of a mental concept of plant state may be referred to as "preprocessing". Preprocessing of data has as its objective the mapping of separate data into coherent relationships that can then be examined, and, if necessary, acted upon. Preprocessing of data need not be (and we believe should not be) done by the human now that sufficient computer power is available. The preprocessing of data by the computer may be done in several ways. One way is to process plant data, using a computer, into a display that will represent plant state to the operator. The shortcoming of methods that have been investigated may be illustrated by the following. If the plant signals are mapped into a computer generated display such that some arbitrary geometric figure represents plant state, by pattern recognition, the operator can readily determine when the plant is not in the desired state. A problem with this approach is that the operator must determine the cause of the distortion of the geometric figure, determine what the plant state really is, and then determine the appropriate action to be taken. In addition, there is a potential for multiple simultaneous plant problems, which distort the geometric figure, such that the operator cannot readily determine the source of the problem. Thus valuable time may be wasted while searching for the wrong information.

Processing plant data (the "preprocessing" step) into a graphic figure that represents an accepted model of the plant state can obviate the need for mental preprocessing. The term "accepted", when referring to the plant model, means a model that is universally accepted and which conveys more total information than the sum of the incoming plant signals used to generate the model.

An example of such a model is the Rankine Cycle using a temperature-entropy curve to represent the steam-system at EBR-II. A temperature-entropy curve not only provides temperature information to the operator, but information as to subcooling, saturation, and superheat status. Such information is not available from any plant input parameter directly. It is the kind of information needed whenever there is an off-normal condition that results in a pressure-temperature relationship that is not well known by the operator.

The model-based display as used at EBR-II also provides the capability to determine instrument failure by inspection. For example, one of the thermocouples failed that is used in providing an averaged temperature for the secondary sodium entering the superheaters. The failure resulted in a low reading on the display of that averaged value, and simply by noting that the sodium inlet to the superheaters was cooler than the superheated steam out of the superheaters, the correct and obvious conclusion was made that an instrument had failed.

As the model-based display has been developed, there are a number of other important benefits that have become evident. During plant transients, the relationships of all systems in a thermodynamic sense are readily apparent. The display clearly shows the thermal inertia inherent in the system during a plant scram or other rapid transient. This provides a better understanding and feel for the dynamics of the system than previously available. As the operator views the display, operating in real-time, he or she is constantly aware and reminded of system thermodynamic relationships.

Viewing the actual thermodynamic performance of the nuclear plant during operation is of special benefit to the operator from a training perspective. In today's systems, the operator reviews thermodynamics as a basis for requalification exams. The use of model-based displays for plant control then invites the use of the same displays in plant simulators for training.

control then invites the use of the same displays in plant simulators for training.

The rationale in providing the thermodynamic model is that the operator in a conventional control room has little hope of integrating enough information mentally in a real-time situation to make correct decisions and act accordingly if the decision requires the synthesis of a high-level "model" of the actual plant conditions.

The following provides a brief description of the model-based display development effort at ANL.

The displays used are updated once a second with new data from the EBR-II Data Acquisition System (DAS) via an Ethernet. The network is currently comprised of four (4) SUN-3 Series color workstations, a VAX 11/750 and a Concurrent (Perkin/Elmer) 3210. The SUN computers consist of a File Server and (3) "diskless" clients, all of which run SUN/OS, a version of UNIX. The data communication software on the SUNs and VAX utilize standard UNIX internet sockets with both TCP/IP and UDP/IP protocols. The Concurrent 3210 uses third party software to provide the user to network link.

The Concurrent computer (DAS) sends approximately 1000 signal values at one second intervals to the SUN File Server where they are converted and stored in Shared Memory. The File Server then sends a subset of this data to clients running graphics applications.

Figure 3 is a high level display that shows the entire process of EBR-II. This display represents three major systems. Figure 4 is a simplified version of Figure 3 and clearly shows the three main systems: 1) The primary sodium system, 2) the secondary sodium system and 3) the steam system. The primary system in figure 4 has 4 dynamic points that control the shape of the polygon representing this system. Point 1 is the sodium inlet temperature to the reactor core, point 2 is the sodium outlet temperature of the reactor core, point 3 is the sodium inlet temperature to the primary side of the Intermediate Heat Exchanger (IHX), and point 4 is the sodium outlet temperature of the primary side of the IHX. Each corner of the polygon is driven by the DAS channel value assigned to it and is plotted in accordance with the temperature scale to the left of the display. As the temperatures within the primary system change, the polygon changes shape appropriately. The secondary system follows the same scenario as the primary system except that it has 6 dynamic points controlling its shape.

Since the steam system represents more than one fluid phase, it is overlayed on top of a temperature entropy diagram. Point 5 represents the sub-cooled water from the feed water heaters entering the steam drum and evaporators. The path from point 5 to point 6 represents the change from subcooled feedwater to saturated steam accomplished by transferring energy from the secondary sodium system in the evaporators. Point 6 is where the saturated steam enters the superheaters and receives additional energy from the secondary system and becomes super heated steam. Between points 7 and 8 the energy is dissipated through the steam turbine-generator. The cycle continues, from the hot well, point 9, and up through the feed water heaters, point 10.

Since EBR-II is tightly coupled between the three major systems, minor changes in the plant cause significant changes in the overall patterns displayed on the screen. This gives the operator advanced warning of potential problems while displaying the overall process.

**SUMMARY**

The development and use of a pattern-recognition, state-determination methodology as the basis for fault-tolerant diagnostic systems has been very successful in tests and initial applications at the EBR-II reactor facility. The SSA algorithm is inherently fast and can therefore be incorporated into systems requiring near real-time diagnosis, and it is robust in the sense that it will always provide an answer and an indication of the degree of uncertainty of the answer, even when multiple input failures have occurred. It is these features that are important to the development and application of fault-tolerant diagnostic systems. The SSA technology is generic to the extent that many different types of applications are being developed with little or no change required in the basic SSA algorithm.

A full color, model based display system based on the Rankine thermodynamic cycle has been developed for use at the Experimental Breeder Reactor II by plant operators, engineers, and experimenters. The displays generate a real time thermodynamic model of the plant processes on computer screens to provide a direct indication of the plant performance.

Initial introduction of the displays to the plant operators has been met with enthusiasm and ready acceptance. The displays have been active in the control room since October of 1987 and were used extensively during the Inherent Safety and Operability Testing of EBR-II during November 1987 and through 1988. It is significant that the display readily shows thermal "decoupling" during plant transients, and it has also shown several instrument calibration drift errors or failures. During dynamic plant maneuvers such as startups, changing power, etc. it is simple to track the thermal wave from the reactor (heat source) through the power plant (heat sink).

If further use and testing support preliminary findings, the concept of model-based displays for monitoring and control of heat engines (power plants) will redefine the present thinking in control room panel display design. The implications are broad and include training advantages, a significant step in operator error reduction, and a much better base to build on for plant automation and the incorporation of computer-based expert operator aid systems.

## REFERENCES


1. R. King, R. Singer, "Development and Application of Diagnostic Systems to Achieve Fault Tolerance," Proceedings of the 7th Power Plant Dynamics, Control and Testing Symposium, Vol. I, Knoxville, TN, May 15-17, 1989, pp. 35.01-35.16.

2. J. Mott, R. King, W. Radtke, "A Generalized System State Analyzer for Plant Surveillance," Artificial Intelligence and other Innovative Computer Applications in the Nuclear Industry, Plenum Press, New York and London, pp. 241-249, 1988.

3. R. King, W. Radtke, J. Mott, "Pattern-Recognition System Application to EBR-II Plant-Life Extension," Proceedings of the ANS Topical Meeting on Nuclear Power Plant Life Extension, Vol. II, Snowbird Utah, July 31-August 3, 1988, pp. 512-518.

4. L. Beltracchi, "A Direct Manipulation Interface for Heat Engines Based upon the Rankine Cycle," IEEE Transactions on Systems, Man and Cybernetics, Vol. SMC-17 No. 3, May-June, 1987.

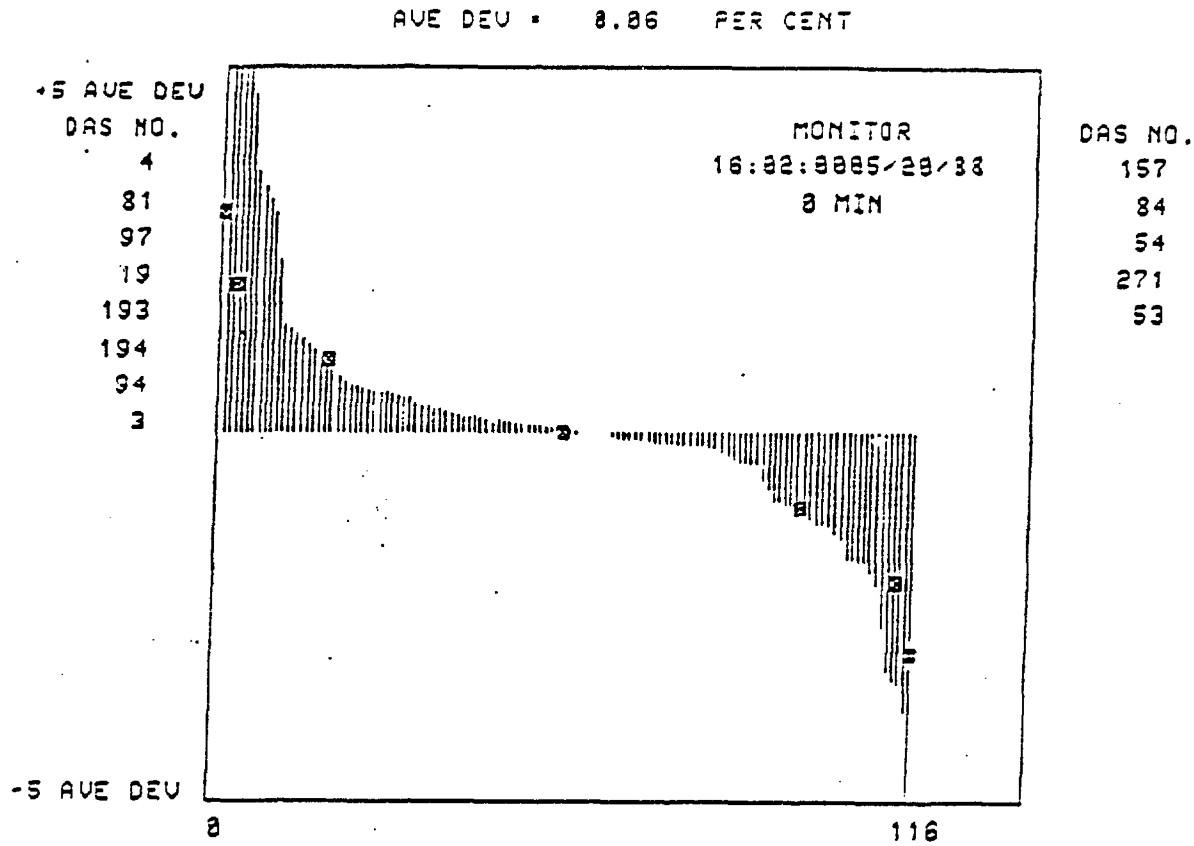


Figure 1. SSA Signature Plot

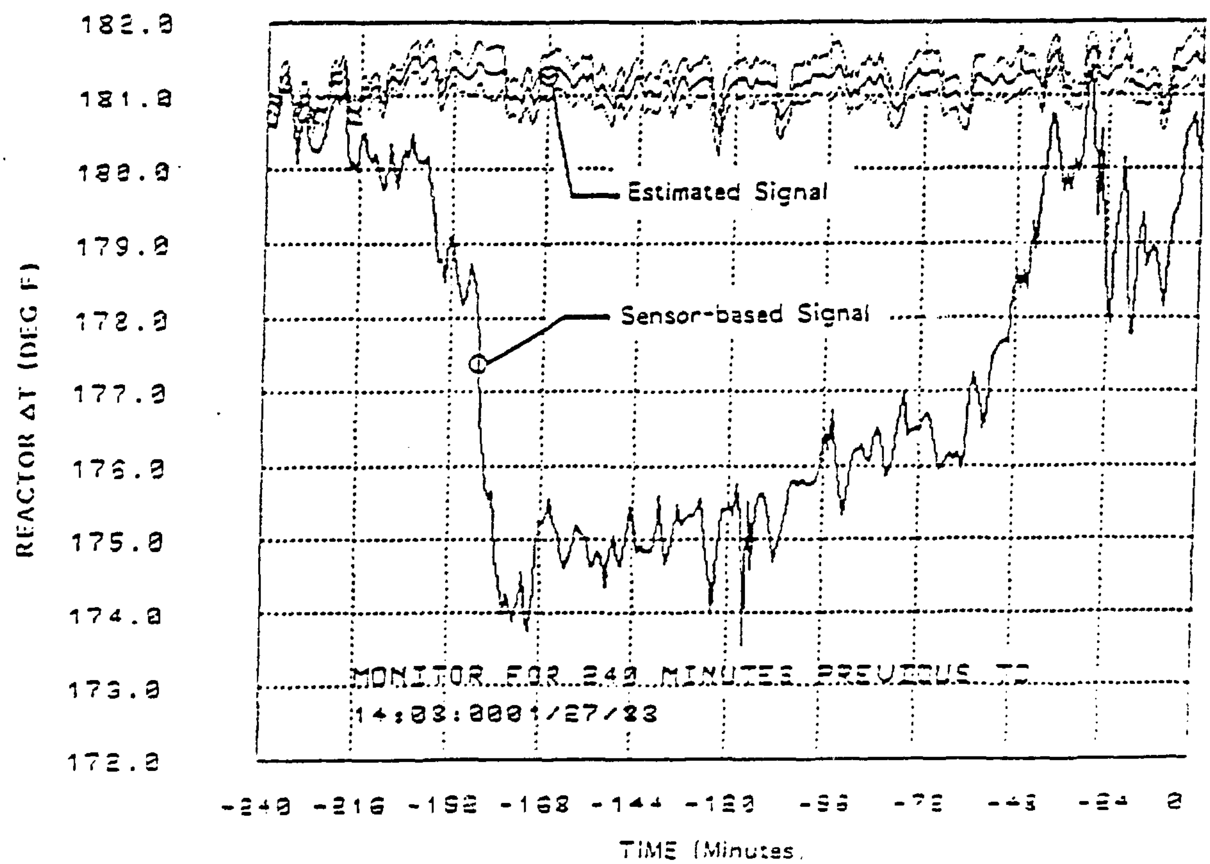


Figure 2. SSA Signal Plot Showing Sensor-Based Reactor ΔT and SSA Estimated ΔT

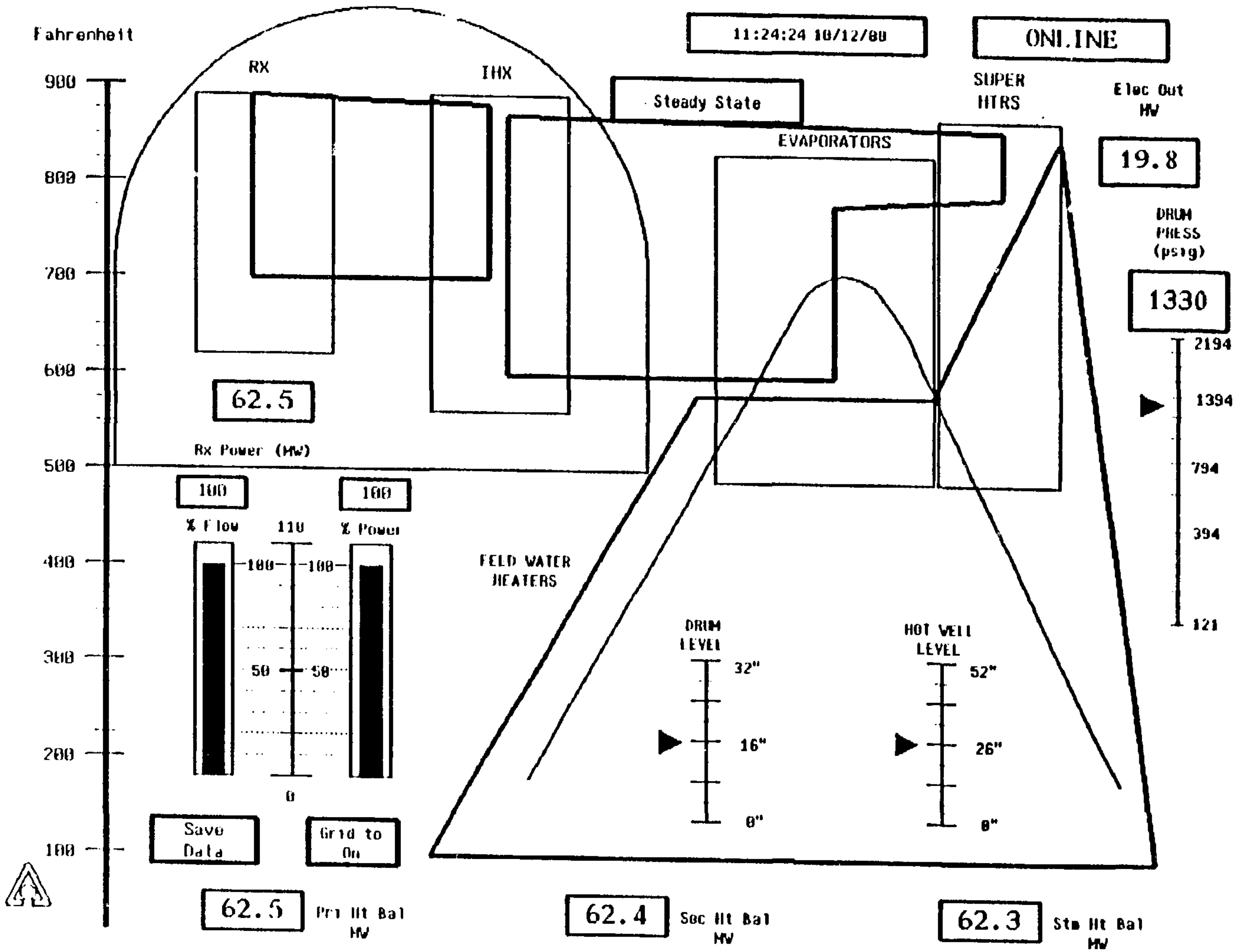


Figure 3
Main Iconic View of EBR-II

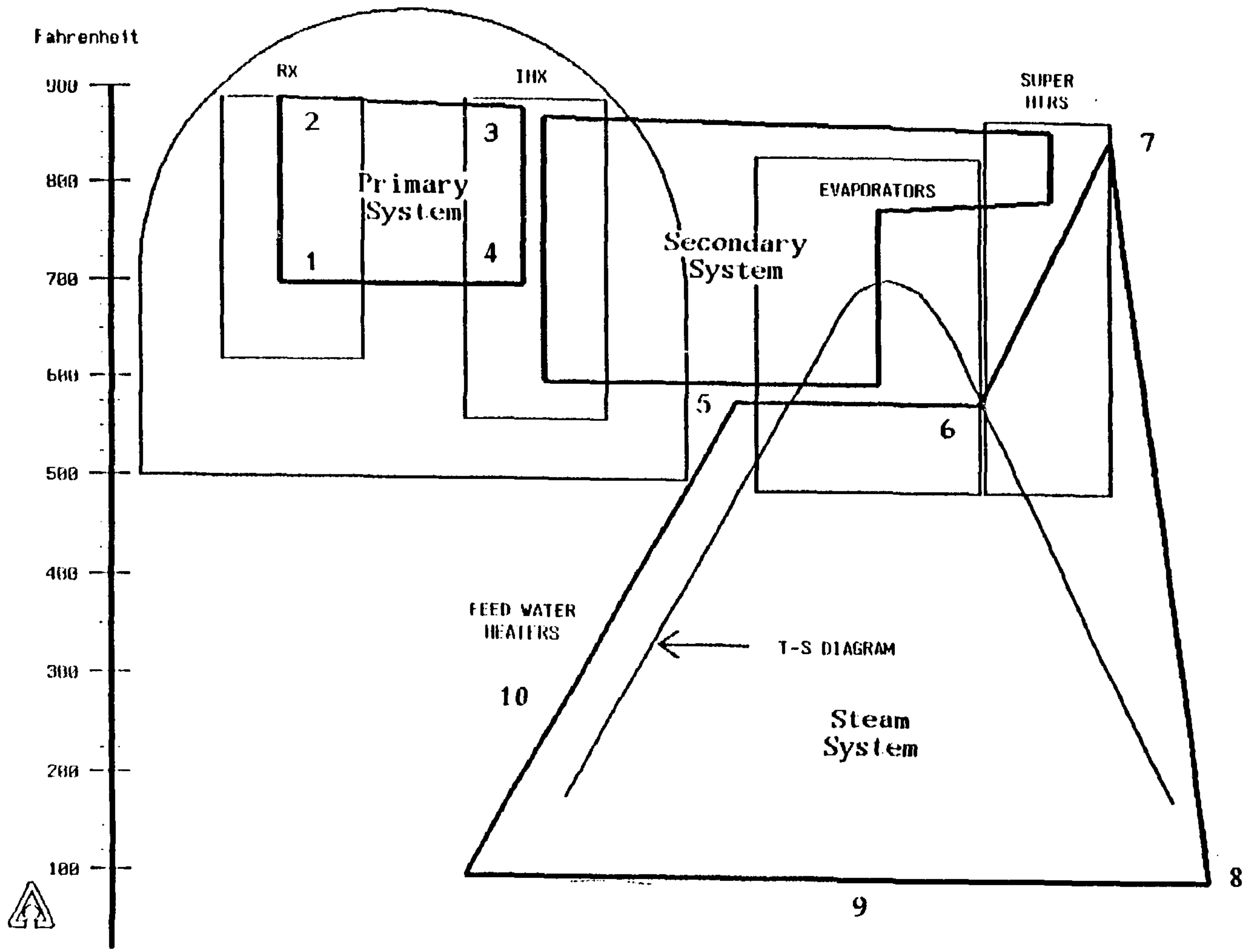


Figure 4
EBR-II Systems Description