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PATTERN-RECOGNITION SYSTEM APPLICATION

TO

EBR-II PLANT-LIFE EXTENSION*

by

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ABSTRACT

A computer-based pattern-recognition system, the System State Analyzer (SSA), is being used as part of the EBR-II plant-life extension program for detection of degradation and other abnormalities in plant systems. The SSA is used for surveillance of the EBR-II primary system instrumentation, primary sodium pumps, and plant heat balances. Early results of this surveillance indicate that the SSA can detect instrumentation degradation and system performance degradation over varying time intervals, and can provide derived signal values to replace signals from failed critical sensors. These results are being used in planning for extended-life operation of EBR-II.

INTRODUCTION

As Experimental Breeder Reactor-II (EBR-II) continues to play an important role in the development and demonstration of the liquid-metal-cooled, metal-fueled reactor and integral fuel-cycle concept, it is also serving as a national test bed for advanced control and diagnostics concepts. These and other missions require EBR-II to extend its planned operating lifetime to forty years, a significant increase over the originally intended lifespan of about ten years.(1) EBR-II is a complete power plant operated by Argonne National Laboratory for the U. S. Department of Energy. It started power operation in 1964. As an electrical power producer as well as experimental facility, plant capacity factor is important. In 1987, the plant capacity factor was 81.3 % even while supporting extensive tests and experiments that reduce capacity factor.

The EBR-II plant-life extension program has as one important element the development and implementation of advanced methods for monitoring and diagnosing changes in plant and critical component operation and performance which could be indicative of

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aging or other degradation phenomena.(1) This is also consistent with EBR-II's role as a test bed for advanced diagnostics concepts. The System State Analyzer (SSA) is an advanced diagnostics system incorporating pattern-recognition techniques to detect abnormalities in the plant. The SSA has proven to be both useful and flexible in application. This paper describes the System State Analyzer, provides results of current applications at EBR-II, and describes its application in support of EBR-II plant-life extension.

SYSTEM STATE ANALYZER DESCRIPTION

The System State Analyzer (SSA) is a software-based pattern-recognition system that uses previously established relationships of signals from the plant data acquisition system to compare with relationships of current signals.(2) This comparison is used to detect inconsistencies, compared to earlier data, in the signal patterns representing a particular area of focus in the plant. The SSA software learns patterns from a selected group of sensor signals that have been determined to be representative of the system or component to be monitored. It uses the learned patterns or relationships to monitor new data and detect variations from the expected relationships over the period of time specified by the user. The SSA identifies system or component states that occur over the learned period and identifies the learned states that the new data patterns most closely match. The SSA then establishes a new estimated state that takes into account the similarities with previously learned states. The estimated state contains a new estimated value for every parameter being monitored. It also provides estimated values for sensors that have degraded or failed, assuming the sensor was available during the learning process.

Figures 1 and 2 show examples of SSA output graphs. Figure No. 1 is a signature plot showing the distribution of actual system signals at a specific time, relative to the SSA estimated values normalized to a horizontal line through the center of the plot. The vertical bars above the line on the left side indicate signals that are higher than the estimated values, and those on the right side indicate signals that are lower than estimated. The distribution 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 average signal deviation from estimation is printed just above the graph in the center. The "X"s are overlaid as an indication of an expected normal distribution of signal deviations as a multiple from 0 to 3 times the average deviation. The two vertical lists of numbers indicate those signals that are three average deviations or more above or below the estimated values.

Figure No. 2 is a time-based plot of an individual plant signal as shown on an SSA display. The SSA estimated values for that signal are plotted along with the actual measured values. On the actual computer display of this plot, the plotted lines are each a different color. For this paper, the actual signal taken from the data acquisition system is labeled on the plot as well as the SSA estimated signal value. Upper and lower uncertainty boundaries are also called out which represent the degree of uncertainty for the SSA analysis at every data point. When the actual value is within the range represented by these boundaries then the parameter is consistent with the patterns that the SSA has previously learned. When the signal value deviates from estimated ranges, especially in overall trend, then that is an indication that there is a potential problem developing in the parameter being measured or that the sensor signal is degrading, and further investigation is required.

Experience with using the SSA at EBR-II has shown that the normal plant signal pattern characteristics identified by the SSA during steady-state operation are very repeatable during a reactor run. When a sensor signal drifts or when a change in the plant occurs such as a slight adjustment in reactor power level, the current observed pattern no longer matches the previously learned patterns as closely. The SSA determines the "closeness" of the new pattern match and provides a quantitative measure of how close the current state is to the previously learned patterns. It also identifies the signals which, in effect, are causing the pattern mismatch. The SSA algorithms also provide estimates of what each signal value would need to be in order for the currently observed pattern to be consistent with the patterns previously observed. This feature of the SSA provides signal validation capability similar to analytic redundancy techniques, and opens up the possibility of replacing the signal from a failed or degraded sensor with a validated estimate of the signal value.

DESCRIPTION OF SSA PLANT-LIFE EXTENSION APPLICATIONS

For plant-life extension and reactor aging applications, the detection of long-term degradation of critical components and sensors is important. The emphasis typically is on detection of gradual, long-term degradation that may not be recognized in its early stages, or may not be easily measured. The SSA provides the capability to compare plant or system operational patterns over any time interval chosen by the user. Thus, it can be applied to observe and diagnose short-term degradation or failures, and it can be applied on a long-term basis looking for changes that may only be observable over long time periods. Used in this manner, the SSA can establish base-line data on performance of systems and components that can then be used for comparison on a periodic basis to detect and analyze degradation trends, or verify lack of degradation. This information is valuable for long-range planning for repair, replacement or refurbishment of major components, and for qualification of the aging plant for extended life operation.

Two applications at EBR-II that make use of different features of the SSA technology to address reactor aging/life extension concerns, are described below.

Failed Critical Sensor Signal Replacement

Over the 24 years of EBR-II operation, most of the sodium flow sensors in the primary flow circuit, and all of the temperature sensors in the reactor outlet pipe to the intermediate heat exchanger, have failed. These sensors are inaccessible for repair or replacement. The signals from these sensors are important to the long-term operability of the plant. Various options such as special replaceable instrumentation probes, mathematical combinations of related signals, and analytic modeling have been used with varying degrees of success to accommodate the loss of these sensors. The recent failure of the last remaining thermocouple providing a direct measurement of mixed-mean reactor outlet temperature caused additional concern. The signal from this thermocouple was used for determination of primary sodium temperature rise across the core which is used by the reactor operator as a control parameter. This thermocouple is inaccessible, and to install a new thermocouple to provide the same measurement capability would be difficult, expensive, and with some associated installation uncertainty.

As an alternative, a special dedicated version of the SSA is undergoing testing leading to eventual qualification for providing an on-line estimated value of the reactor core coolant temperature rise displayed to the reactor operator that can be used by the operator for reactor control purposes. The capability of the SSA to provide a reliable, accurate estimation of this parameter was initially demonstrated at the time of the failure of the thermocouple in question. The SSA was being used for routine plant surveillance at that time. Figure 2 shows an SSA signal plot of reactor core temperature rise based on the installed thermocouple, along with the SSA estimated value and an estimation uncertainty band. As can be seen during the initial point of sensor degradation between -216 and -200 minutes, the SSA estimated value increases slightly while the sensor-based value has decreased. The increase was traced to the response of the reactor operator who slightly increased power to compensate for what he thought was a drop in reactor temperature rise based on this sensor. The SSA estimated value responded appropriately while the sensor-based signal did not.

The sensor performance, although appearing to recover to normal at about -30 minutes, subsequently degraded further and is assumed to have failed. For the remainder of that reactor run, the indicated sensor-based temperature rise across the core remained at about 150 degrees F, while the SSA estimated the temperature rise to be about 180 degrees F. The core temperature rise measured and calculated from other plant sensors during that time was within one degree of the SSA value.

The SSA performance demonstrated in this example was the result of the use of a general SSA signal map used for overall surveillance of the whole plant. In order to provide a higher degree of confidence in the estimation of this specific parameter, a modified signal map has been developed that is smaller and more focused on parameters related to reactor power generation and heat transfer. This version of the SSA is being tested and evaluated during normal plant operation, and a series of special plant tests is planned for validation of the response of the SSA estimated parameter to various off-normal plant conditions. In practical application, the SSA will provide a direct digital display of the estimated value with an indication of degree of certainty to the reactor operator at the operating console.

Long-term Degradation Surveillance of Primary Pumps

The ability of the SSA to detect relatively short-term abnormal or degraded system performance in the EBR-II plant has been demonstrated.(2) The two EBR-II primary sodium pumps are examples of major critical components that are essential for continued long-term availability of the EBR-II plant, and therefore have been selected for application of the SSA for long-term degradation monitoring important to plant-life extension concerns. These pumps were made by the Byron Jackson Company specifically for use in EBR-II in a high-temperature sodium environment. They are centrifugal pumps each capable of circulating 5500 gpm of sodium at a head of 74.6 psi. They are driven by 350 hp motors. The pump assembly is submerged in sodium in the primary tank. Both pumps have operated well over the life of the plant after overcoming initial startup problems early in life. Since the time the early problems were resolved, the pump shaft and impeller assembly has been replaced once in each pump.

Because the design of the pumps is unique to EBR-II, and the pumps were designed and built nearly thirty years ago, major spare parts are not readily available. As the plant ages, the importance of long-term degradation detection of the pumps becomes increasingly important to long-term plant availability. In addition to the general surveillance version of the SSA that monitors all major plant parameters, a special version of the SSA has been set up to monitor pump-related parameters. This particular application is a typical example of how the SSA can be used for long-term surveillance of critical plant systems or components.

The SSA was first set up to begin monitoring the primary pumps in May 1987. A dedicated pump signal map was established that includes pump parameters directly related to pump performance such as power draw of the pumps and pump rpm, as well as total primary system flow and pressure in the outlet plenum of the reactor. Because of the small number of original surviving flow and pressure sensors in the primary system, and the common suction and discharge volumes of the pumps, the parameters of both pumps were grouped together in the SSA signal map. A total of 27 parameters were included in the signal map for the pumps compared to 130 in the general surveillance version.

Pump surveillance with the SSA is performed in an off-line mode using a personal-computer(PC)-based version of the SSA. Data is captured periodically on the plant data acquisition system and transferred to the PC over a network link. This data is stored on disk and then used for SSA analysis by comparison of the signal patterns established at this time with the patterns of the signals captured at a later time. This off-line mode is a different mode of SSA operation than the on-line SSA application described above although the analysis done by the SSA is basically the same.

The SSA signature plot provides an indication of which signals in the map are higher and which are lower than the SSA estimated values, and displays the average deviation of the whole signal group from their estimated values. Refer to Fig. 1 for an example of the signature plot. The information provided by this plot is used by noting which key parameters, such as pump power, are flagged as being higher than the estimated values, or when a particular combination of high and low signals occurs that has been identified as an indication of a specified problem. Each individual signal value can be plotted out on a signal plot along with the SSA estimated value at each time step plotted. The signal plots are similar to that discussed above for the on-line version. Figure 3 is an example of a signal plot from the off-line version showing pump No. 1 power draw in kilowatts, along with the SSA estimated values over the same time period based on patterns learned by the SSA several months previously.

To assist in the surveillance and determination of potential degradation of the pumps, a detailed degradation mode and sensitivity analysis was done to identify various pump degradation modes, and to identify the pump and primary flow system parameters that would be affected by the various types of potential pump degradation. By observing which signals are flagged by SSA analysis as being high and low in various combinations and comparing these with the degradation and sensitivity matrix, a judgement can be made about the condition of each pump relative to its condition at the time the learned domain was established. Additionally, since the key pump parameter involved in most of the degradation mode scenarios is pump motor power draw, this parameter can be monitored with the SSA and compared with the estimated value for pump power. By comparing the actual pump power draw with the SSA estimate, developing trends can be detected wherein power draw for either pump continues to be higher or lower than estimated over a period of time. In Fig. 3 the indicated pump kilowatt draw is very close to the values estimated by the SSA. By observing the differences between measured and estimated values over different time periods, changes in the performance characteristics of the pumps can be identified.

Because of the large number of possible signal combinations related to potential degradation modes of the pumps, the information contained in the degradation mode and parameter sensitivity matrix has been captured in a simple pump expert system developed using a PC-based commercial expert system shell. Using the SSA to determine which pump parameters are higher and which are lower than estimated, and to what relative degree, the engineer inputs this information into the expert system. The expert system then outputs the type of degradation mode, if any, that most closely matches the parameter patterns input to the system. This pump expert system is a prototype for more extensive expert systems that will be built at a later time; it is in an evaluation mode by the engineers responsible for pump surveillance and SSA applications at EBR-II.

The surveillance of the EBR-II primary pumps with the SSA to date has indicated no evidence of long-term degradation of either pump over the one year period that the SSA has been used in this application. Because of a short-duration shaft-binding incident occurring in March of 1987, one of the pumps was removed from the primary tank for inspection during the April/May 1988 long maintenance shutdown. No evidence of long-term degradation of pump components was observed. This, of course, supports the SSA findings. Although the SSA has not been in use for pump surveillance for a sufficient length of time to make a valid assessment of its performance in this application, demonstrated capabilities of the SSA in other applications have indicated that the SSA should perform well for long-term pump surveillance.

FUTURE DEVELOPMENT AND APPLICATIONS

Further development and application of the SSA technology is a priority effort in the EBR-II Engineering Department. In addition to further work to be done in the areas described in this paper, we plan to institute long-term surveillance programs for the intermediate heat exchanger and the steam generating system using the SSA in support of EBR-II plant-life extension. Within the next year, we also plan to run a series of plant tests to test, demonstrate, and validate the response and sensitivity of SSA to specific changes in the plant. This will lead to more applications in the area of on-line signal validation and on-line plant diagnostics, and as an operator aid for adjusting the plant to match previous conditions during startup as well as full-power operation. As part of the advanced control and diagnostics work at EBR-II, the SSA will continue to be developed for use as a plant state identifier, signal validator, and alarm filter in support of high level, real-time graphical displays of plant processes.

SUMMARY

The pattern-recognition techniques embodied by the SSA continue to be exploited for use in the EBR-II plant-life extension work and well as in other applications. The SSA has been applied at EBR-II in two specific areas related to plant-life extension. One application is the substitution of the on-line SSA calculated estimate of the temperature rise of the primary coolant across the reactor core, to replace the signal from a failed, inaccessible thermocouple in the reactor outlet pipe used previously as a control parameter. Because much of the originally installed primary system instrumentation has failed and is inaccessible for replacement, the capability to replace key parameter sensor signals with validated calculated signal values is important to continued long-term availability of EBR-II. The other application is the use of the SSA for long-term degradation monitoring of the EBR-II primary pumps which are critical to extended-life operation of EBR-II.

Although both of these applications are in their early stages, the initial results together with the results of other SSA applications in EBR-II, have indicated that pattern-recognition techniques can be very useful in plant diagnostics and surveillance to support different aspects of a plant-life extension program.

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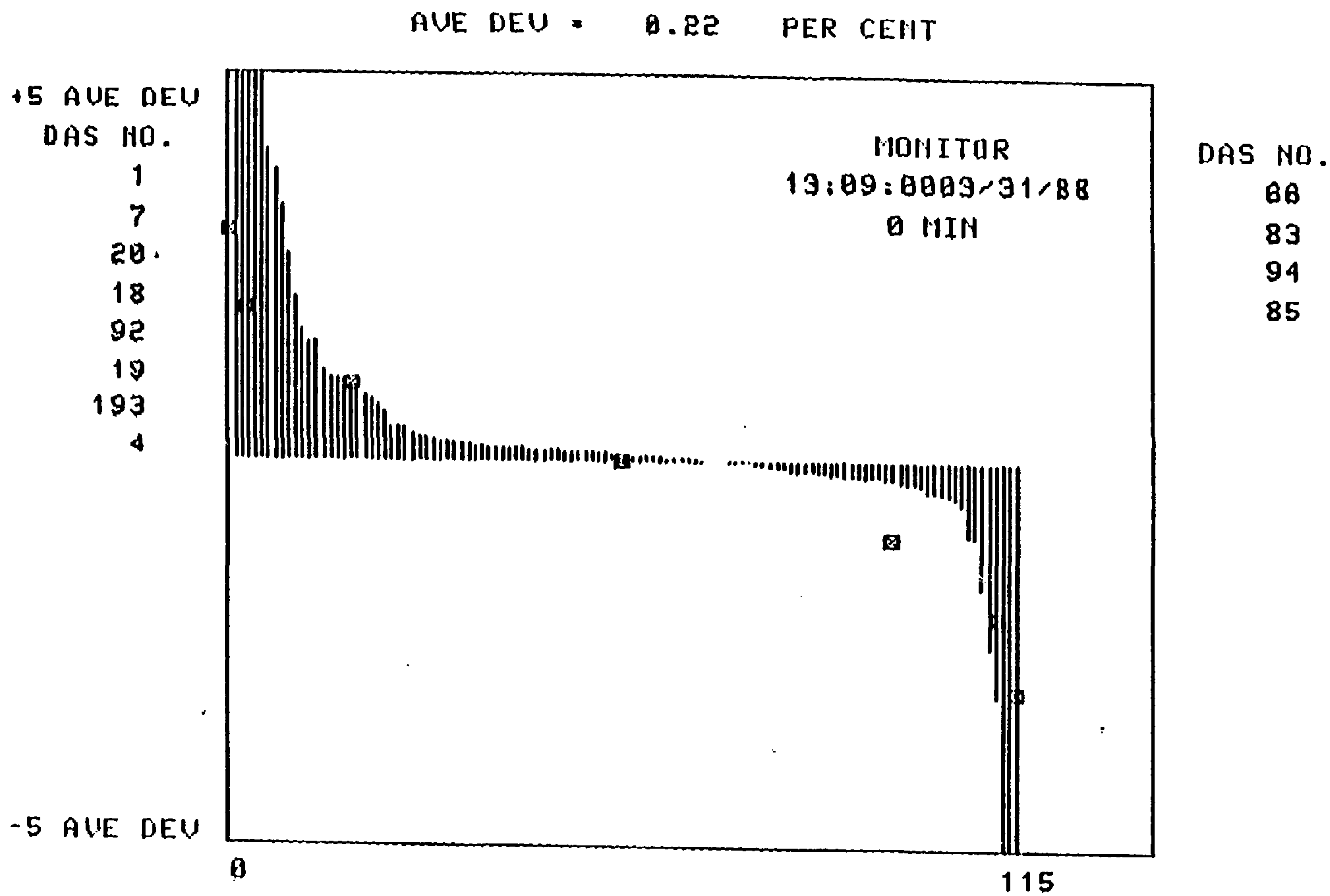

Figure 1

SSA SIGNATURE PLOT

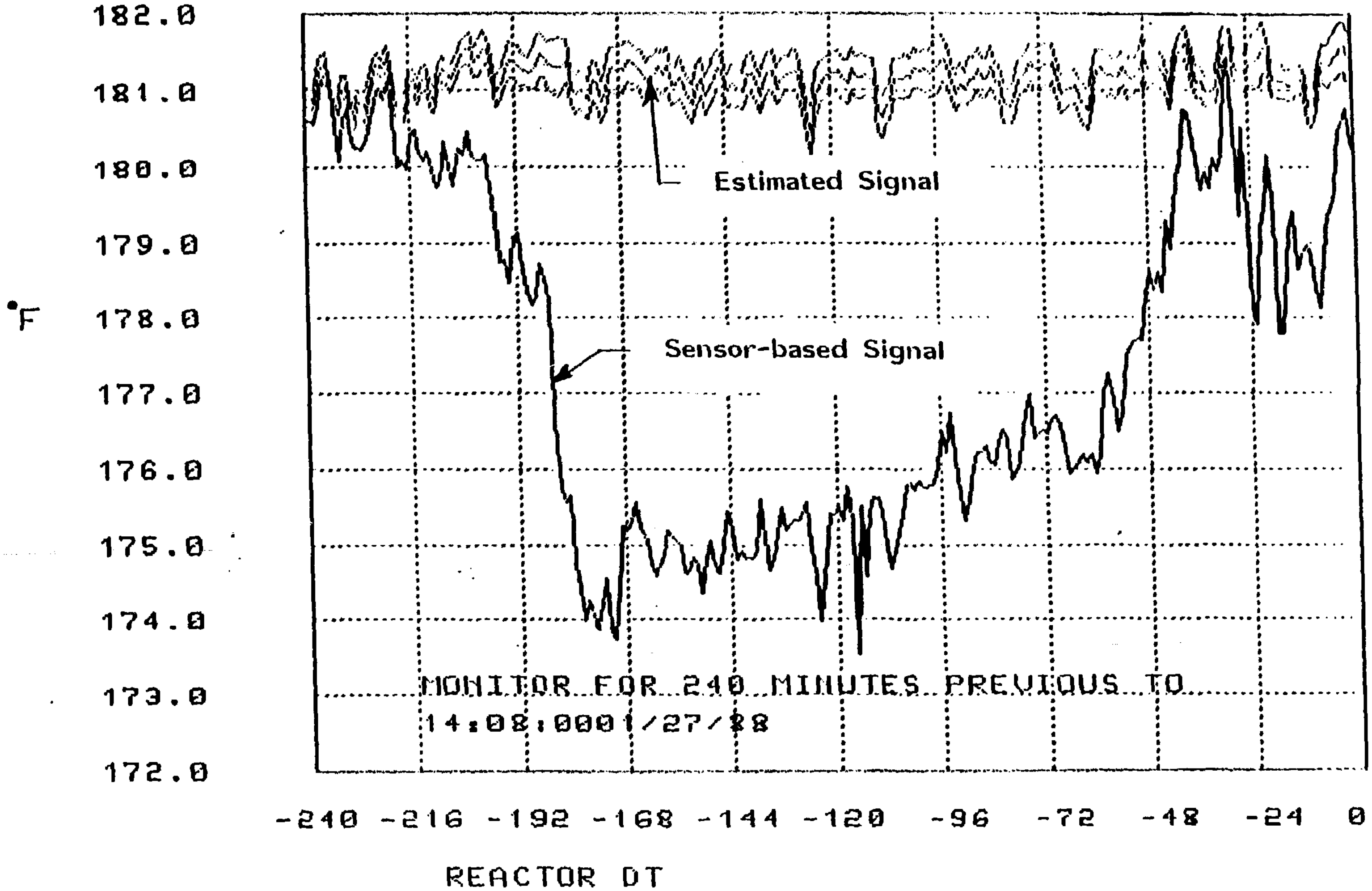

Figure 2
SSA Signal PLOT Showing sensor-based Reactor ΔT Signal and SSA Estimated Signal for Reactor ΔT

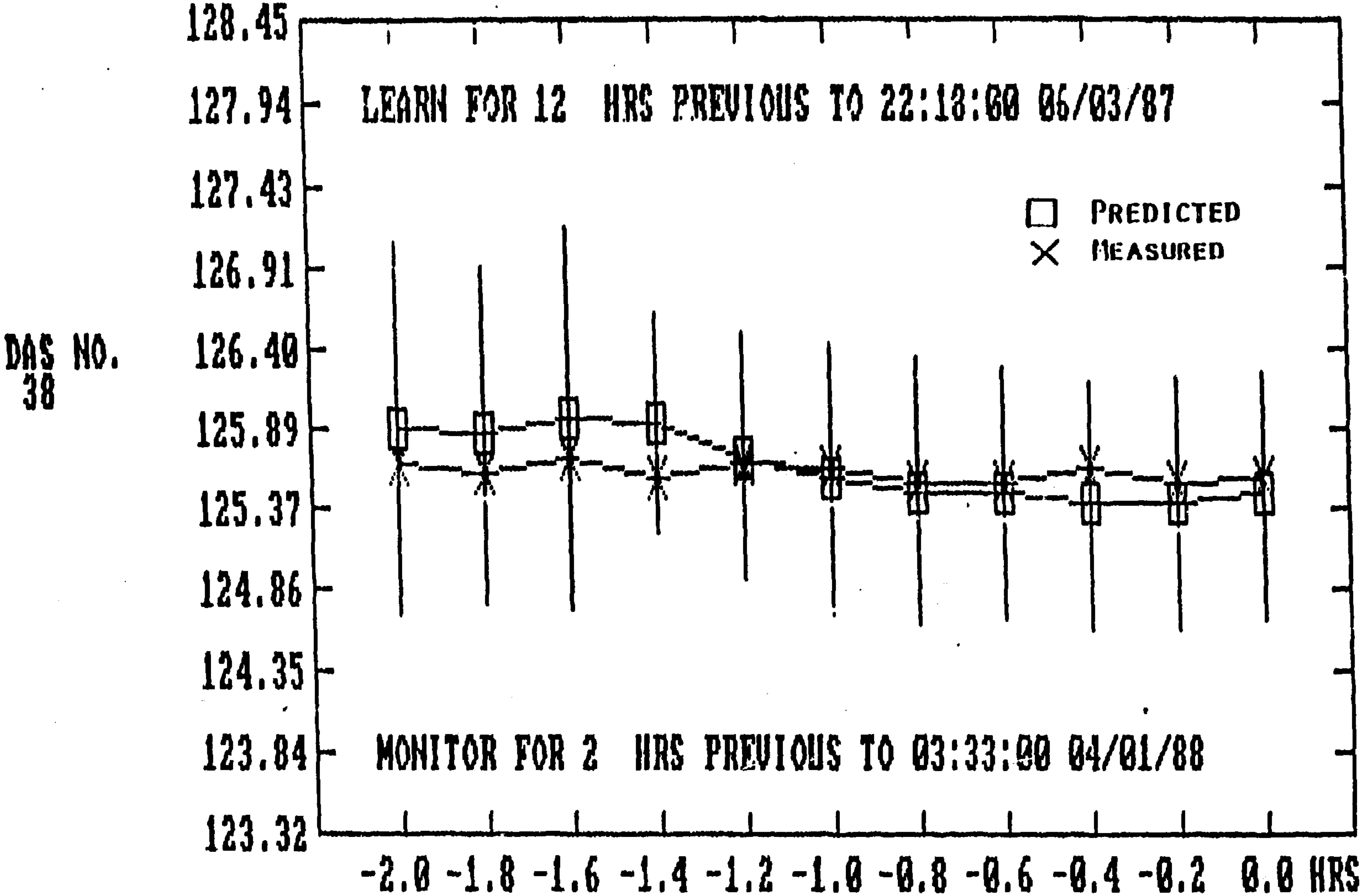

Figure 3
Offline SSA Signal Plot
Showing Primary Pump No. 1
Measured Power Draw and SSA
Estimated Power Draw