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REAL-TIME LMR CONTROL PARAMETER GENERATION USING ADVANCED ADAPTIVE SYNTHESIS*

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Snowbird, Utah

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REAL-TIME LMR CONTROL PARAMETER GENERATION USING ADVANCED ADAPTIVE SYNTHESIS*

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ABSTRACT

The reactor "delta T", the difference between the average core inlet and outlet temperatures, for the liquid-sodium-cooled Experimental Breeder Reactor II is empirically synthesized in real time from a multitude of examples of past reactor operation. The real-time empirical synthesis is based on system state analysis (SSA) technology embodied in software on the EBR II data acquisition computer. Before the real-time system is put into operation, a selection of reactor plant measurements is made which is predictable over long time periods encompassing plant shutdowns, core reconfigurations, core load changes, and plant startups. A serial data link to a personal computer containing SSA software allows the rapid verification of the predictability of these plant measurements via graphical means. After the selection is made, the real-time synthesis provides a fault-tolerant estimate of the reactor delta T accurate to +/-1%.

* Work supported by the U.S. Department of Energy, Reactor Systems, Development, and Technology, under Contract No. W-31-109-ENG-38.

INTRODUCTION

The Facility -

EBR II is a liquid-sodium-cooled nuclear power plant that has been operating since 1964 producing 20 MW of electrical power. During this time period many instruments have failed in locations which make replacement difficult or impossible. Many of these instruments supply information which is necessary for control of the power plant. In particular the differential between the mixed mean inlet and outlet temperatures, the reactor "delta T", is a major control parameter which has become increasingly difficult to estimate over the years and is now being synthesized by System State Analyzer (SSA) technology as a prelude to possible incorporation into control room activities.

EBR II has the reactor core coolant piped to an intermediate heat exchanger (IHX) via a primary sodium heat transport system (HTS), and has the IHX linked to the steam generators via a secondary sodium HTS as illustrated in Figure 1. The symbols in the figure refer to various temperatures, pressures, flows, etc. Both the core and IHX are in a large sodium pool. In operation the EBR II power plant is started with primary pumps set to full flow and the sodium in the primary HTS is isothermal at 700 degrees F. One control room operator pulls the reactor control assemblies and a second operator controls the secondary sodium HTS flow. The control assemblies are first withdrawn slightly from the core to expand the reactor delta T. Then the secondary HTS flow is increased to prevent the reactor inlet temperature from rising. This procedure is sequentially repeated, expanding the reactor delta T and maintaining the reactor inlet temperature at a constant level, with stationary plateaus periodically encountered as plant parameters are validated. The startup process is complete when the reactor delta T reaches 180 degrees F. Figure 2 illustrates the reactor thermal power level during a recent startup.

The Problem -

Historically the reactor delta T has been directly measured by thermocouples in the reactor inlet and outlet at locations indicative of mixed mean temperatures. Unfortunately the non-replaceable thermocouples in the reactor outlet pipe have either failed or become unreliable so that other methods to calculate the reactor delta T have been investigated over the last several years. This paper concentrates only on an analysis of the current estimation algorithm although several different previous calculations have also been evaluated.

The current delta T determination is based on a dynamic power-to-flow calculation. Initially the power-to-flow calculation included a dynamic flow measurement but unfortunately this measurement also became unreliable and directly affected the reliability of the reactor delta T estimate. Because the primary sodium flow is normally set at 100%, the algorithm was modified to employ a constant primary flow term rather than the measured primary flow. This algorithm now constitutes the current method of determining the reactor delta T for the control room operators. However there are still failure modes of this reactor delta T calculation that occur in the reactor heat balance. When these failures occur the reactor control assemblies and consequently the reactor power can be improperly set.

The purpose of the present work is to determine a diverse, reliable, alternative on-line estimate of the delta T measurement which can be installed in the control room so that if a discrepancy occurs between the current calculation and alternative estimate, the operators will be alerted to investigate the discrepancy. In this sense the present work is aimed only at signal validation. However because of the manner in which the SSA technology provides signal validation it can also be used as a synthetic replacement for the current delta T calculation.

The Solution -

The approach of the present work to this problem has been to assemble historical data including the current reactor delta T, and then to link the delta T to other related plant measurements so that these other measurements can be used to infer the current reactor delta T. These other measurements include pressure, flow, and temperature measurements in the primary HTS, secondary HTS, and steam systems. The links between and among all these measurements are provided by the SSA technology which has been previously described in the References. The SSA technology provides both the links and the observational tools necessary to evaluate the correlations, predictabilities, and accuracies of all the plant measurements. These evaluations in turn allow the choice of plant measurements which perform best in terms of stable links which do not change with time and are applicable across plant shutdowns, core reconfigurations, core reloads, and plant startups.

For the six months from October 1989 to April 1990, which includes five plant startups and shutdowns, the present work has been successful in establishing stable links of over forty plant measurements with the reactor delta T, and this has been done in a rapid, highly efficient, productive manner. Future work will include a study of operations from 1985 through 1989. A fundamental benefit of the present approach is that it is extremely fault tolerant to failures in any of the linked measurements, so much so that multiple failures of the real plant measurements can occur without a material effect on the estimates of any of the linked measurements including the reactor delta T.

Previous attempts to solve this problem involved the development of analytic expressions to provide the links. The development of the analytic expressions was a labor-intensive approach requiring a high level of expertise. Operation required constant adjustment of parameters in the analytic expressions because of the continual changes in core configuration and fuel loading. Additionally the analytic expressions were not tolerant of failures in the plant measurements. By contrast the SSA technology employs empirical redundancy which can be rapidly applied on personal computers after a short training program and is extremely fault-tolerant.

DESCRIPTION

The Overall System -

The overall system hardware at EBR II includes the Perkin-Elmer data acquisition system (DAS) computer and a selection of personal computers linked to the DAS computer by 9600 BAUD serial links. The DAS computer accepts up to 1024 channels of plant measurements 10 times per second and then averages these measurements over half-second, five-second, one-minute, and three-hour intervals and places the results into buffers and disk files. Once per week the one-minute disk files are archived into a tape storage system. The DAS computer is available to a variety of monochrome and color terminals via a network.

The system software includes the SSA kernel in a program on the DAS computer which accesses the half-second average buffer and produces a screen display which is updated as often as once per second. This program is available to any user on the network and displays the current measurements of the reactor delta T paralleling that used by the operators in the control room, the SSA-based delta T, and the uncertainty in the SSA-based delta T.

Auxiliary software to support the SSA kernel program on the DAS computer includes a program to read archive tapes and extract desired signals for a file of plant states according to a control file identifying the desired signals. A catalog of plant state files is maintained which can be subsequently accessed to build a custom library of plant states appropriate for particular plant conditions and configurations. For example, separate libraries might be created for startup, for partial power operation, for full power operation, and for shutdown.

Personal-computer (PC) software containing similar programs to the DAS computer are also used in a typical application. To use these programs, the plant state files are first downloaded to the PC via standard communications programs over a serial link. Once the plant state files are resident on the PC then library formation and management programs, off-line SSA kernel analysis programs, and graphics programs are available for a rapid determination of the characteristics of the system being analyzed. These characteristics include observations of signal correlations and predictability. The exercise of the PC programs is essential for a rapid understanding of how to set up the DAS computer files which control the real-time analysis.

Initial Selection of Measurements -

The initial selection of measurements for this work was made by engineering personnel familiar with the plant. They selected measurements which were known to be correlated with the reactor delta T both from observation and engineering judgement. The measurements totaled 69 in number and included measurements of most of the parameters shown in Figure 1 plus related measurements. The related measurements included many above-core temperature-measuring devices. Although such measurements are related to the reactor delta T the relations are quite subtle. This is so because there is an above-core temperature profile and flow profile which is affected by core configuration, core loading, blanket configuration, and control assembly positions. While these 69 measurements may be related to the reactor delta T there is no easy a-priori way of determining their interrelations with a high degree of accuracy.

OPERATION

Application of the SSA technology to the stated problem is quite simple once the appropriate hardware and software is in place. A reasonable spectrum of plant states is first obtained on the DAS computer and immediately downloaded to a PC. An SSA analysis is then performed with all initially selected measurements in the system. On a high-end PC this takes only a few minutes. Plant state history plots are then reviewed for predictability and the file controlling the signals used in the analysis is modified to include only predictable signals. The analysis is then repeated with the predictable signals to reduce estimation errors and identify a highly-robust, fault-tolerant, tightly-coupled signal set for use on the DAS computer.

The difference between predictability and correlation is very important here. Correlation means that changes in one measurement occur with changes in another measurement with no requirement on the magnitudes of the measurements. Predictability as employed here adds the requirement that the magnitude of the synthesized measurement is the same as the real measurement within a specified discrepancy over a defined region of interest.

In operation the SSA technology takes a real-time observation of a system and uses pattern-matching techniques to withdraw a set of states from a library. Then via a patented process it again uses pattern-recognition techniques to synthesize, from the set of states, a single state which lies close to the real-time state. The library is formulated and managed to have no defects. Because the set of states withdrawn from the library has no defects the synthesized state has no defects. This is true even if the real-time state has defects such as drifting or failing signals. The real-time state and all the measurements in it are validated by comparisons with SSA estimates.

Initial Analysis -

Plant states were obtained from archive tapes for three startups in October, November, and December, 1989. These plant states totaled 90 in number and were one-minute-average snapshots of the 69 plant variables taken approximately every 15 minutes. Another 90 states of one-minute-average snapshots every 5 minutes were obtained from a late January, 1990 startup. These latter 90 states were treated as if they were real-time measurements.

A typical well-predicted signal history is illustrated in Figure 3. A typical well-correlated but not well-predicted signal history is illustrated in Figure 4. In these graphs the solid line represents the real-time signal value while the dashed line represents the SSA estimate.

Reduced Number of Measurements -

A review of all 69 candidate signals showed that only 45 were well-predicted after the plant had reached full power at the end of the startup. A re-analysis was then performed using only these 45 signals to form the basis of the results in the next section of this paper. The reactor delta T measurement that is the focus of this investigation was fortunately one of the well-predicted signals and this fact will be discussed in the conclusions.

RESULTS

Stability -

Figure 5 shows the reactor delta T over the full range of plant startup. The predictability of this late January 1990 startup from learned states in October, November, and December 1989 is so good that the real-time solid line and the SSA estimation dashed line are virtually identical. Figure 5 indicates that the particular 45 signals used are very stable over changing core configurations and core loads.

Accuracy -

Figure 6 shows the delta T with uncertainties in the final steady state portion of the startup. In this figure the upper and lower dashed lines indicate a +/- one standard deviation uncertainty on the SSA estimation. The average uncertainty in this region is approximately +/-1% and the difference between the real-time signal value and the SSA estimation is approximately 0.15%.

Speed -

The 45 signal set allows the SSA kernel program on the DAS computer to analyze the real-time buffer once per second.

Fault Tolerance -

Figure 7 shows the effect of a downward drift in the real-time delta T during the steady state portion at the end of the startup. The SSA estimation is virtually unaffected by this artificial failure in the real-time signal. A real failure similar to this actually occurred at EBR II and initially prompted the operator to pull a control assembly slightly in order to expand the reactor delta T. Shortly thereafter, the operator's experience enabled him to determine the true situation. If the SSA estimate of the reactor delta T had been present in the control room, the operator may have recognized the instrument failure more quickly.

CONCLUSIONS

The work presented in this paper shows that it is easy to find a set of stable, predictable signals in a complex system if appropriate data acquisition hardware and software are present to accommodate the SSA technology. These stable, predictable signals allow the estimation of each one of them over long time periods during real-time observations with high accuracy. Defects in the real-time observations have virtually no effect on the SSA estimates so that the SSA estimates can be simultaneously used for signal validation and for replacement of failed or drifting signals.

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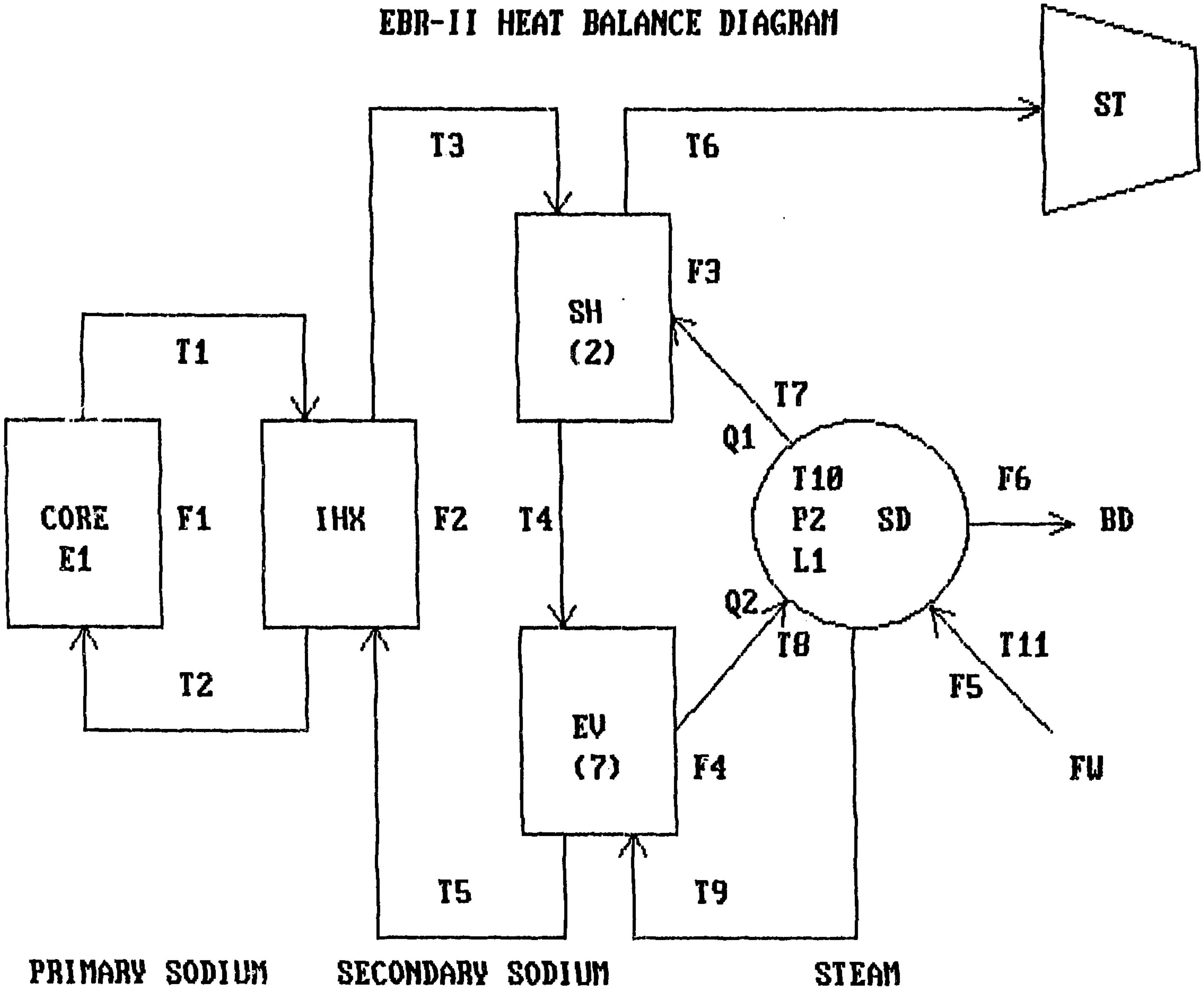


EBR-II HEAT BALANCE DIAGRAM
ST
T3
T6
F3
SH
(2)
T1
T7
Q1
CORE
E1
F1
IHX
F2
T4
T10
P2
L1
SD
F6
BD
Q2
T8
T11
T2
F5
EV
(7)
F4
FW
T5
T9
PRIMARY SODIUM
SECONDARY SODIUM
STEAM

Fig. 1

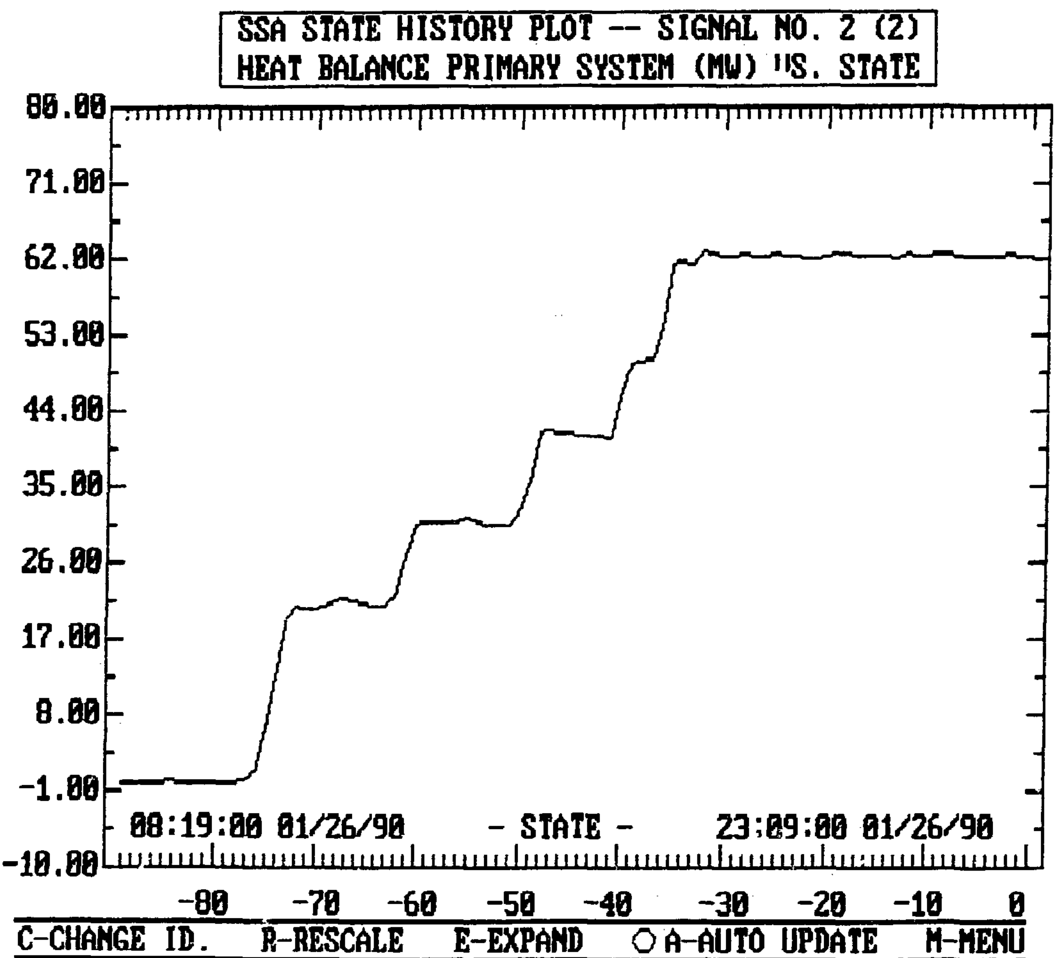

SSA STATE HISTORY PLOT -- SIGNAL NO. 2 (2)
HEAT BALANCE PRIMARY SYSTEM (MW) VS. STATE
80.00
71.00
62.00
53.00
44.00
35.00
26.00
17.00
8.00
-1.00
-10.00
08:19:00 01/26/90
- STATE -
23:09:00 01/26/90
-80
-70
-60
-50
-40
-30
-20
-10
0
C-CHANGE ID.
R-RESCALE
E-EXPAND
A-AUTO UPDATE
M-MENU

Fig. 2

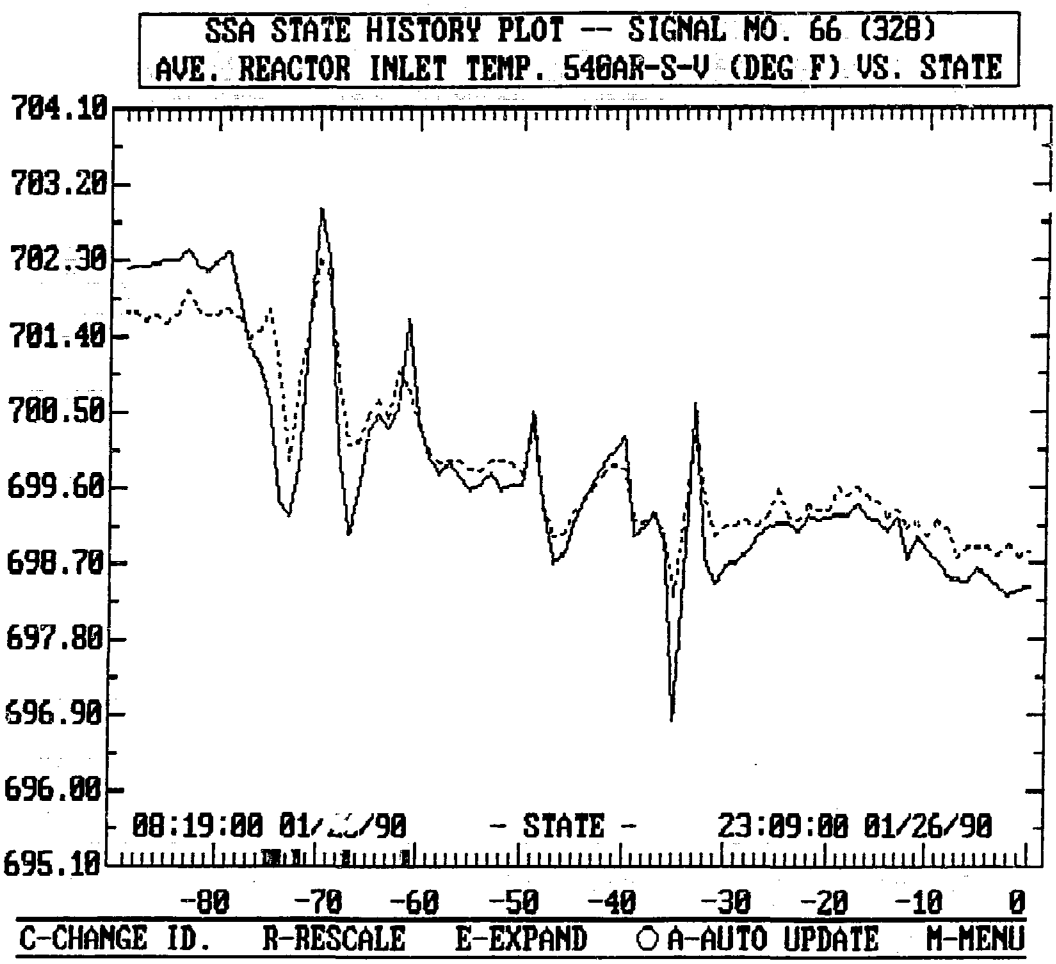

SSA STATE HISTORY PLOT -- SIGNAL NO. 66 (328)
AVE. REACTOR INLET TEMP. 540AR-S-V (DEG F) VS. STATE
704.10
703.20
702.30
701.40
700.50
699.60
698.70
697.80
696.90
696.00
695.10
08:19:00
- STATE -
23:09:00 01/26/90
-80
-70
-60
-50
-40
-30
-20
-10
0
C-CHANGE ID.
R-RESCALE
E-EXPAND
A-AUTO UPDATE
M-MENU

Fig. 3

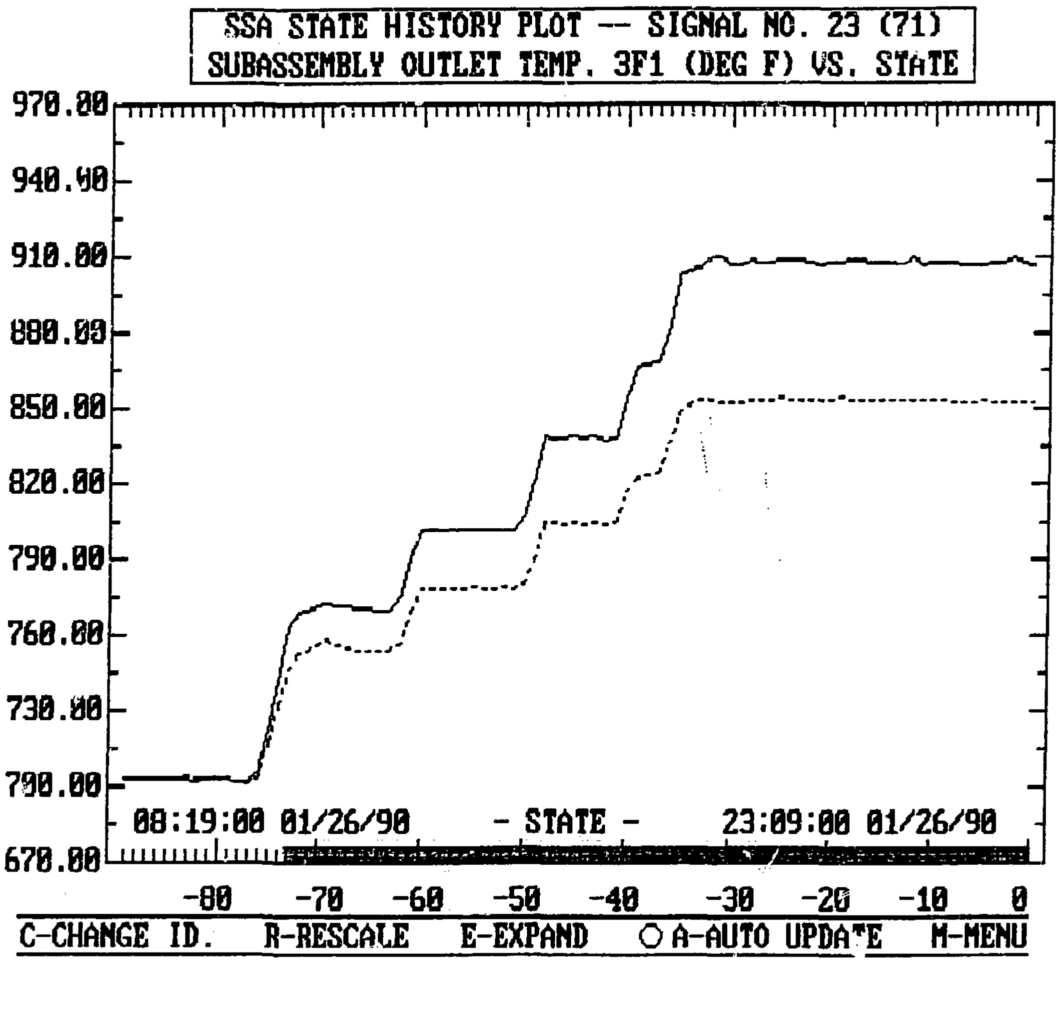
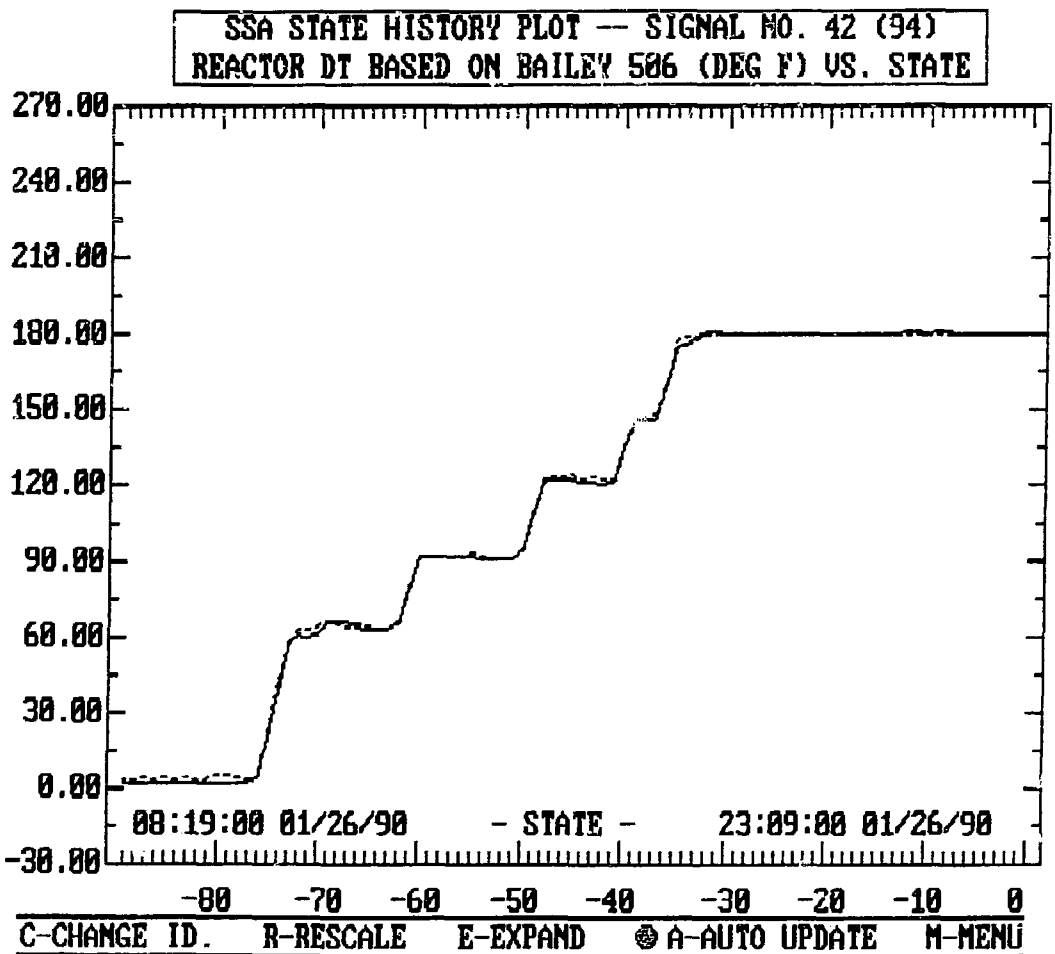

SSA STATE HISTORY PLOT -- SIGNAL NO. 23 (71)
SUBASSEMBLY OUTLET TEMP. 3F1 (DEG F) VS. STATE
970.00
940.00
910.00
880.00
850.00
820.00
790.00
760.00
730.00
700.00
670.00
08:19:00 01/26/90
- STATE -
23:09:00 01/26/90
-80
-70
-60
-50
-40
-30
-20
-10
0
C-CHANGE ID.
R-RESCALE
E-EXPAND
A-AUTO UPDATE
M-MENU

Fig. 4



SSA STATE HISTORY PLOT — SIGNAL NO. 42 (94)
REACTOR DT BASED ON BAILEY 506 (DEG F) VS. STATE
270.00
240.00
210.00
180.00
150.00
120.00
90.00
60.00
30.00
0.00
-30.00
08:19:00 01/26/90
- STATE -
23:09:00 01/26/90
-80
-70
-60
-50
-40
-30
-20
-10
0
C-CHANGE ID.
R-RESCALE
E-EXPAND
A-AUTO UPDATE
M-MENU

Fig. 5

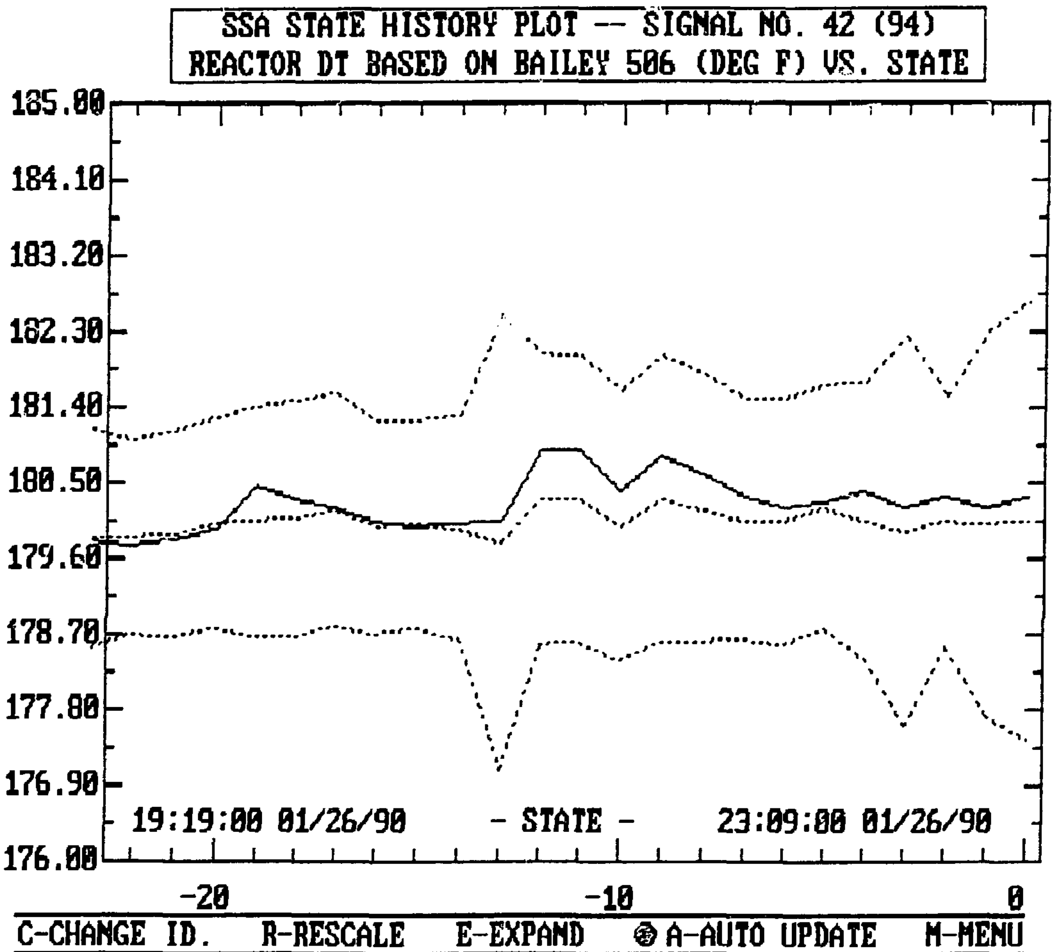

SSA STATE HISTORY PLOT -- SIGNAL NO. 42 (94)
REACTOR DT BASED ON BAILEY 506 (DEG F) VS. STATE
185.00
184.10
183.20
182.30
181.40
180.50
179.60
178.70
177.80
176.90
176.00
19:19:00 01/26/90
- STATE -
23:09:00 01/26/90
-20
-10
0
C-CHANGE ID.
R-RESCALE
E-EXPAND
A-AUTO UPDATE
M-MENU

Fig. 6

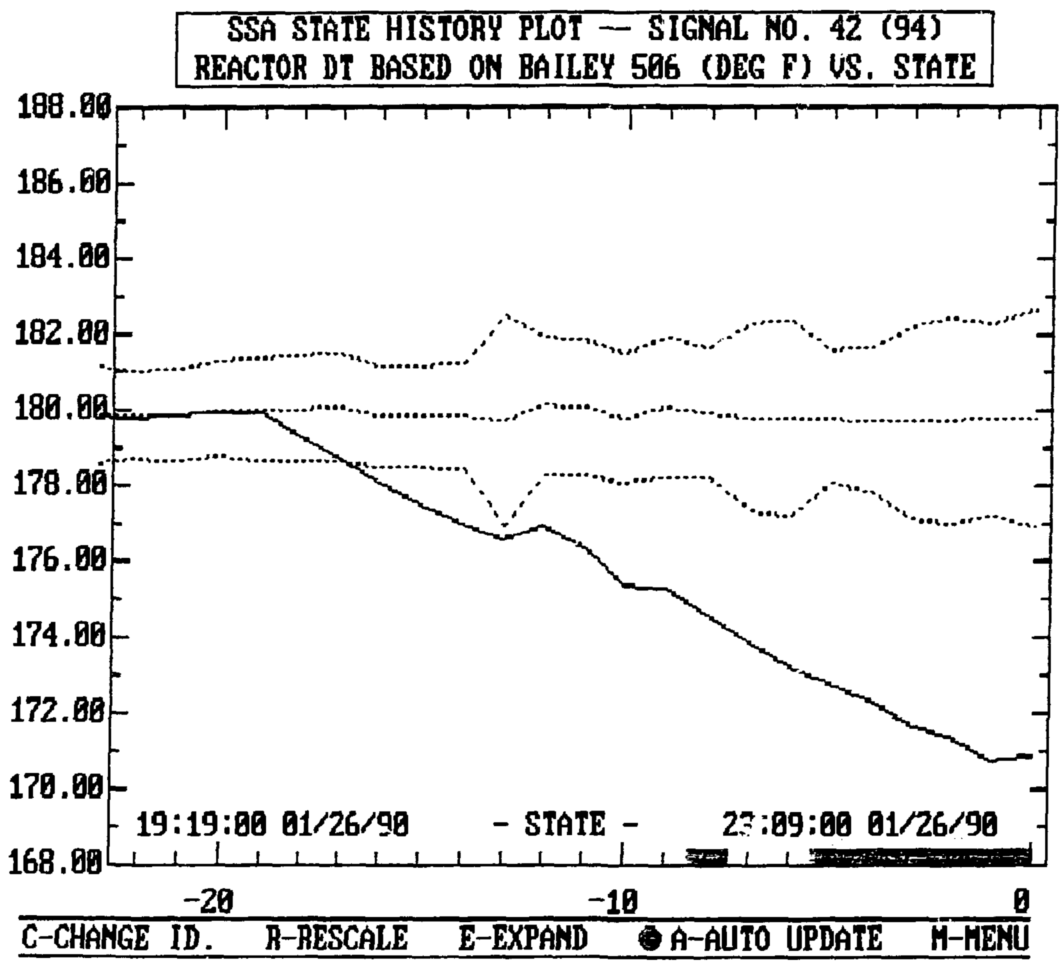

SSA STATE HISTORY PLOT — SIGNAL NO. 42 (94)
REACTOR DT BASED ON BAILEY 506 (DEG F) VS. STATE
188.00
186.00
184.00
182.00
180.00
178.00
176.00
174.00
172.00
170.00
168.00
19:19:00 01/26/90
- STATE -
-20
-10
0
C-CHANGE ID.
R-RESCALE
E-EXPAND
A-AUTO UPDATE
M-MENU

Fig. 7