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A TIME SERIES ANALYSIS OF REACTOR THERMOCOUPLE DATA

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1.0 SUMMARY AND CONCLUSIONS

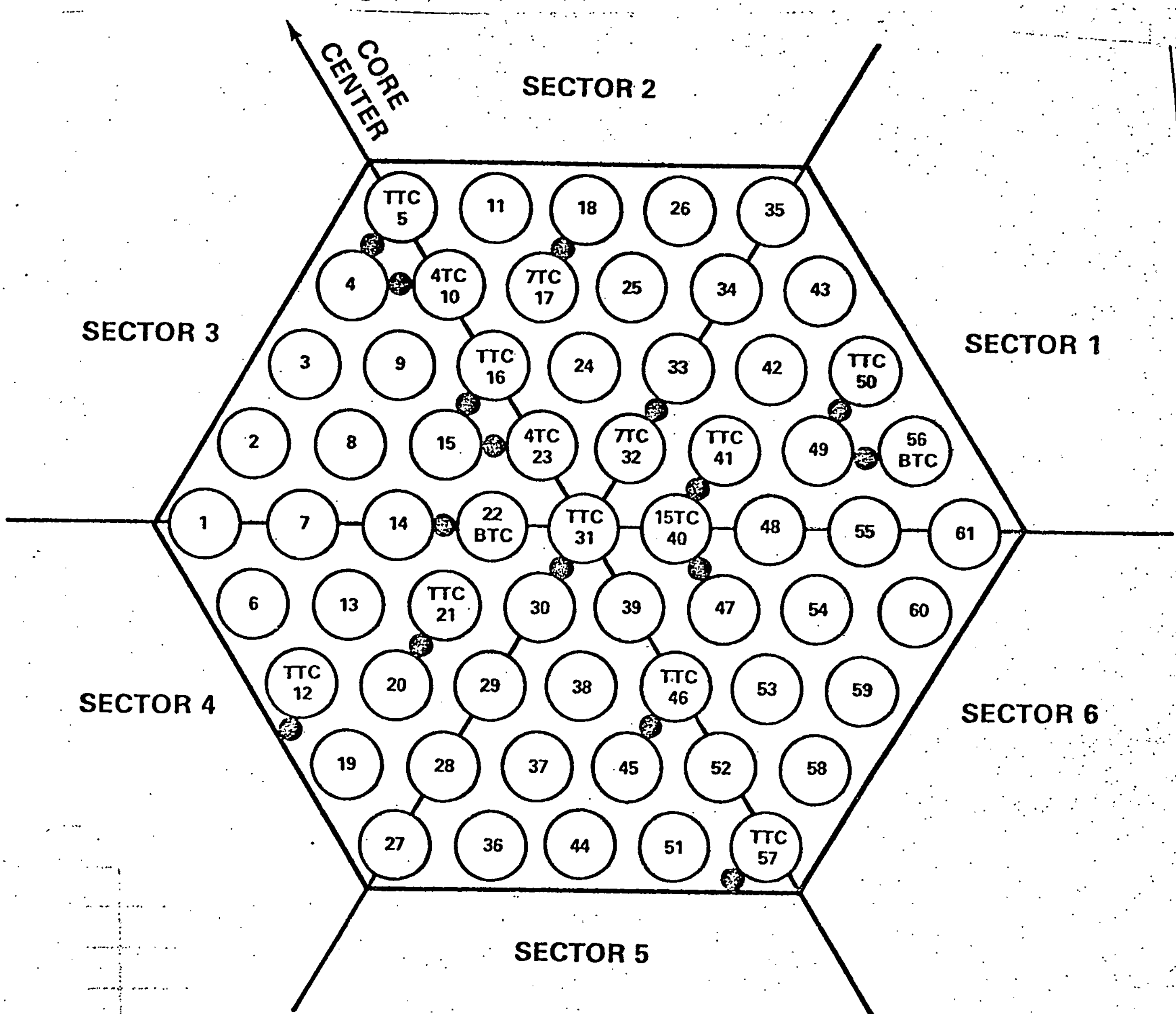
Time-series analysis techniques are applied to nuclear reactor thermocouple data to investigate coolant temperatures measured within the fueled test assembly. The coolant temperature distribution within a fuel assembly affects the length of time a fuel assembly may be operated in a power reactor and, therefore, is an important economic consideration in the design of reactor fuel systems. Frequency-domain signal conditioning techniques were used to reveal the smoothly varying thermocouple signals from the "noisy" digital data. Examination of the cross-correlation function for thermocouple pairs suggested an alternate surging and ebbing of coolant flow within certain zones of the fuel assembly. These zones corresponded to thermocouples which experienced higher or lower than predicted coolant temperatures. This time-series analysis contributed greatly toward the understanding of fuel assembly thermal hydraulics.

2.0 INTRODUCTION

This report describes time-series analyses performed on nuclear reactor thermocouple data to investigate coolant temperatures measured within a fueled test assembly. The coolant temperature distribution within a fuel assembly affects the length of time a fuel assembly may be operated in a power reactor and, therefore, is an important economic consideration in the design of reactor fuel systems.

The thermocouple data originated from the Argonne National Laboratory (ANL) test, XX08. The XX08 test is one of a series of ANL instrumented assemblies that have been irradiated in the EBR-II reactor. It is both fueled and equipped with extensive flow and temperature monitors. We shall be concerned with the 16 spacer-wire coolant thermocouples located at various axial and radial positions within the 61 pin bundle (Figure 1).

During full power, steady state reactor operation the XX08 thermocouples exhibited a skewed coolant temperature distribution compared to the nominal calculations of thermal hydraulic codes. Significant signal variability was observed in several of the "hottest" thermocouples. This phenomenon is assumed to be the result of an abnormal subchannel coolant flow distribution. Time-series analyses were performed on the XX08 thermocouple data to more thoroughly understand this phenomenon.



● = THERMOCOUPLE LOCATION
BTC = CORE BOTTOM LEVEL
4TC = 5.4 INCHES ABOVE CORE BOTTOM LEVEL
7TC = 9.5 INCHES ABOVE CORE BOTTOM LEVEL
TTC = 12.7 INCHES ABOVE CORE BOTTOM LEVEL
15TC = 20.2 INCHES ABOVE CORE BOTTOM LEVEL

FIGURE 1. Location of XX08 Fuel Pin Bundle Thermocouples.

3.0 MATHEMATICAL PRELIMINARIES

During the full power steady-state operation of EBR-II, the observed (i.e., noise contaminated) XX08 thermocouple signals are assumed to be the finite sample paths of a Guassian, N-dimensional, stationary stochastic process, $[x_i(t)]_{i=1}^{N}$: $0 \leq t \leq T$. (N = number of XX08 thermocouples, T = observation period length). The mean values and bivariate covariance structure determine the distribution of such a process.

Parameter	Sample Path Estimate
mean value = m_i = $E[x_i(t)]$	$\overline{x_i(t)}$
covariance = $C_{ij}(d)$ = $E[(x_i(t)-m_i)(x_j(t+d)-m_j)]$	$\overline{(x_i(t)-\overline{x_i(t)})(x_j(t+d)-\overline{x_j(t)})}$

E( ) denotes the expected value, d the lag time, and the "overbar" the time(t)-averaged value.

The covariance is an indication of the "memory" of a stationary process; $C_{ij}(d)$ being large for a lag time d, indicates a high positive or negative correlation between the ith and jth signal components, d units in time apart. The auto- and cross-covariance are defined by $C_{ij}(d)$ with $i = j$ and $i \neq j$, respectively.

The distribution of a stationary process is also completely determined by its power spectrum, $P_{ij}(f)$, defined to be the Fourier transform of the covariance function and evaluated at frequency, f. $P_{ij}(f)$ measures the tendency of the ith and jth signal components to oscillate at frequency, f. The autopower and cross-power spectra are defined by $P_{ij}(f)$ with $i = j$ and $i \neq j$, respectively.

These statistical parameters were estimated from the digitized thermocouple data using subroutines from the International Mathematical and Science Libraries.[1] For a complete discussion of stationary stochastic processes, consult Reference 2.

Another concept required for these analyses is that of a linear filter. In the continuous time domain an input signal, i(t), is transformed or convoluted into the response function, r(t), by a "filtering" or "smoothing" function, h(t).

$$r(t) = i*h(t) = \int_{-\infty}^{+} h(s)i(t - s)ds \tag{3.1}$$

Fourier transforming both sides of equation (3.1) yields the relationship between the Fourier transforms of the input and response functions.

$$I(f)H(f) = R(f) \tag{3.2}$$

(The upper case letter indicates the Fourier transform.) H(f) is known as the frequency response or transfer function of the linear filter. The breakpoint of a linear filter is that frequency, f_o, such that

$$H(f_o)^2 = 1/2 \tag{3.3}$$

A linear filter whose frequency response is given by

$$H(f) = \begin{cases} 1, & -f_c \le f \le f_c \\ 0, & f > f_c \text{ or } f < -f_c \end{cases} \tag{3.4}$$

is known as an ideal low pass filter with cutoff frequency, f_c. Such a filter is given by

$$h(t) = \begin{cases} \sin(2f_c t)/\ t & , t \neq 0 \\ 2f_c & , t = 0 \end{cases} \qquad (3.5)$$

The observed XX08 thermocouple signal was assumed to be given by

$$x(t) = s(t) + n(t) \qquad (3.6)$$

where s(t) is the actual thermocouple signal and n(t) is a noise component. The actual thermocouple signal, s(t), is a "smoothed" or filtered value of the measured coolant temperature, T(t). The actual thermocouple signal and measured coolant temperature are related by the following first order linear differential equation

$$\frac{ds}{dt}(t) + s(t) = T(t) \qquad (3.7)$$

where τ is the $(1 - 1/e) = 63\%$ response time of the thermocouple. This corresponds to the convolution,

$$s(t) = T*h(t) \qquad (3.8)$$

where h is given by

$$h(t) = \begin{matrix} 1/\tau \ \exp -t/\tau & , t \geq 0 \\ 0 & , t < 0 \end{matrix} \qquad (3.9)$$

Digital versions of the low-pass filter, (3.4), and the exponential filter, (3.8), are utilized in Section 4.0 for noise removal and the determination of the actual measured coolant temperature.

4.0 DATA ANALYSIS

Examination of XX08 thermocouple data from EBR-II Run 90B revealed a skewed coolant temperature distribution compared to the nominal thermal-hydraulic code calculations (i.e. assuming as designed power levels, fuel bundle geometry, flow splits, etc.). Several of the "hottest" reading thermocouples also showed a great deal of signal variability. Table 1 lists the CLUSTER thermal hydraulic code predictions of internal assembly coolant temperatures versus the mean values of the thermocouple signals. (CLUSTER is an ANL thermal-hydraulic code.) Figure 2 displays the observed-thermocouple minus CLUSTER-predicted coolant temperatures in the assembly. Notice that the observed coolant temperatures in subchannels nearest the core center (Sectors 2 and 3) are higher than predicted and those in Sectors 1 and 6 tend to be lower than predicted. Figure 3 contains the 10 hour sample path plots (6 observations/hour) of two thermocouples, each located 5.4 inches above the bottom of the fuel column. The signal variability of 4TC10, a thermocouple which operated 100°F higher than predicted, was significantly larger than the signal variability of 4TC23, a thermocouple which operated within 10F° of the predicted value.

The signal variability and the skewed coolant temperature distribution are assumed to be the result of an abnormal subchannel coolant flow distribution. One hypothesis is that flow separation occurs in the inlet diffuser of the fuel assembly causing a vortex action resulting in coolant temperature fluctuations. The thermocouples located at the bottom of the fuel column, BTC22 and BTC56, read higher than expected throughout the test (Run 90B-706°F and 702°F, Run 95-726°F and 722°F, Run 97-722°F and 721°F while the reactor inlet temperature is 700°F). This further supports the hypothesis of an inlet flow anomaly.

To further investigate these singular thermal hydraulic phenomena, higher sampling-frequency data were examined. Analysis of Run 95 thermocouple data recorded at two observations/second revealed an interesting cross-correlation pattern between thermocouples at lag time equal to zero ($C_{ij}(0)$, $i \neq j$, see

TABLE I

COMPARISON OF XX08 THERMOCOUPLE WITH THE CLUSTER THERMAL HYDRAULIC CODE PREDICTIONS FOR RUN 90B

Thermocouple	Observed Temperature (°F)	CLUSTER Predicted Temperature (°F)
BTC22	706	700
BTC56	702	700
4TC10	933	832
4TC23	852	842
7TC17	1008	923
7TC32	944	948
15TC	978	1035
TTC5	988	942
TCC12	907	874
TTC16	1055	1020
TCC21	1036	1010
TTC31	989	1030
TCC41	981	1020
TTC46	975	1008
TTC50	953	980
TTC57	871	875

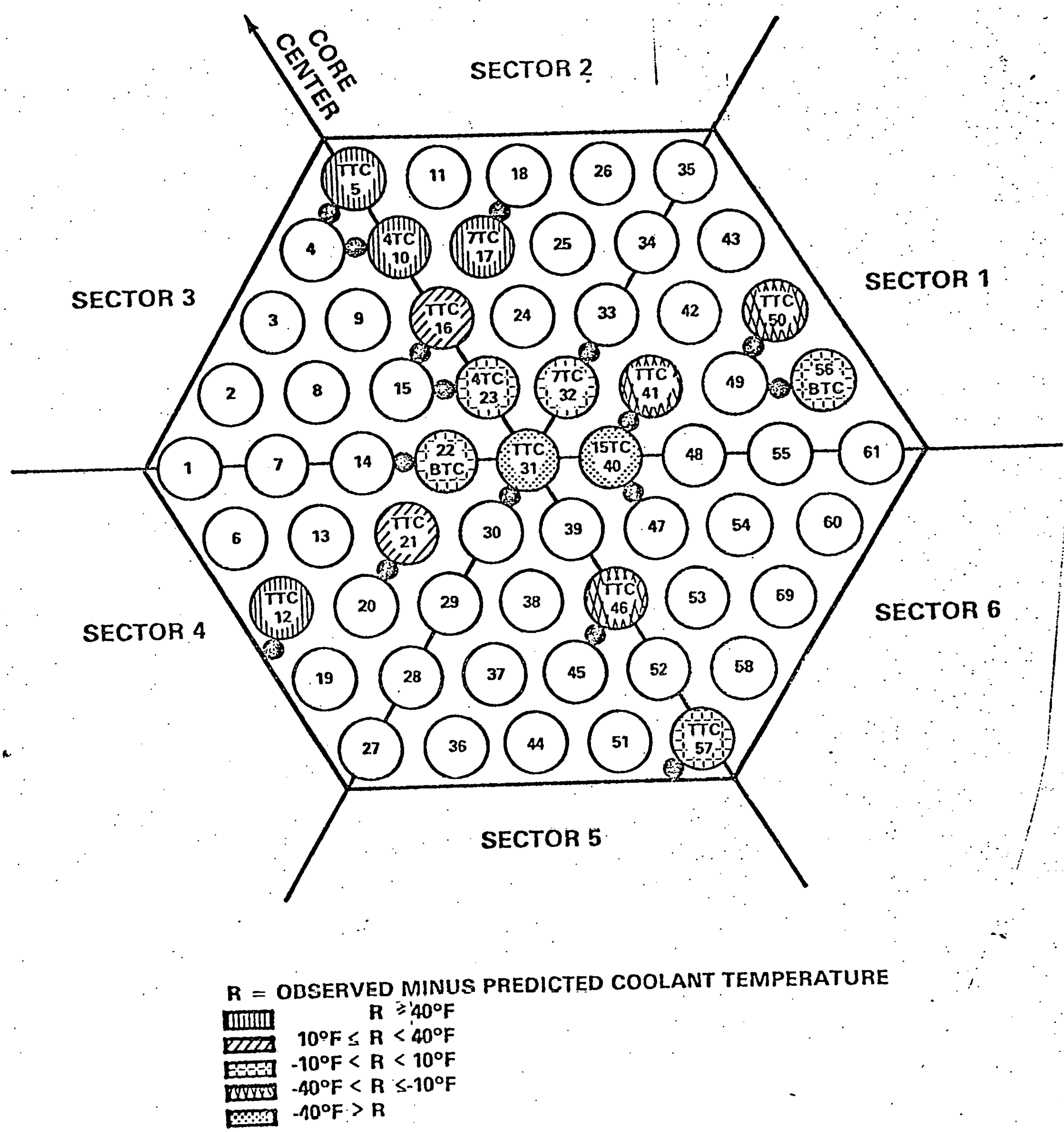


FIGURE 2. Observed Minus CLUSTER Predicted Coolant Temperatures, Run 90B.

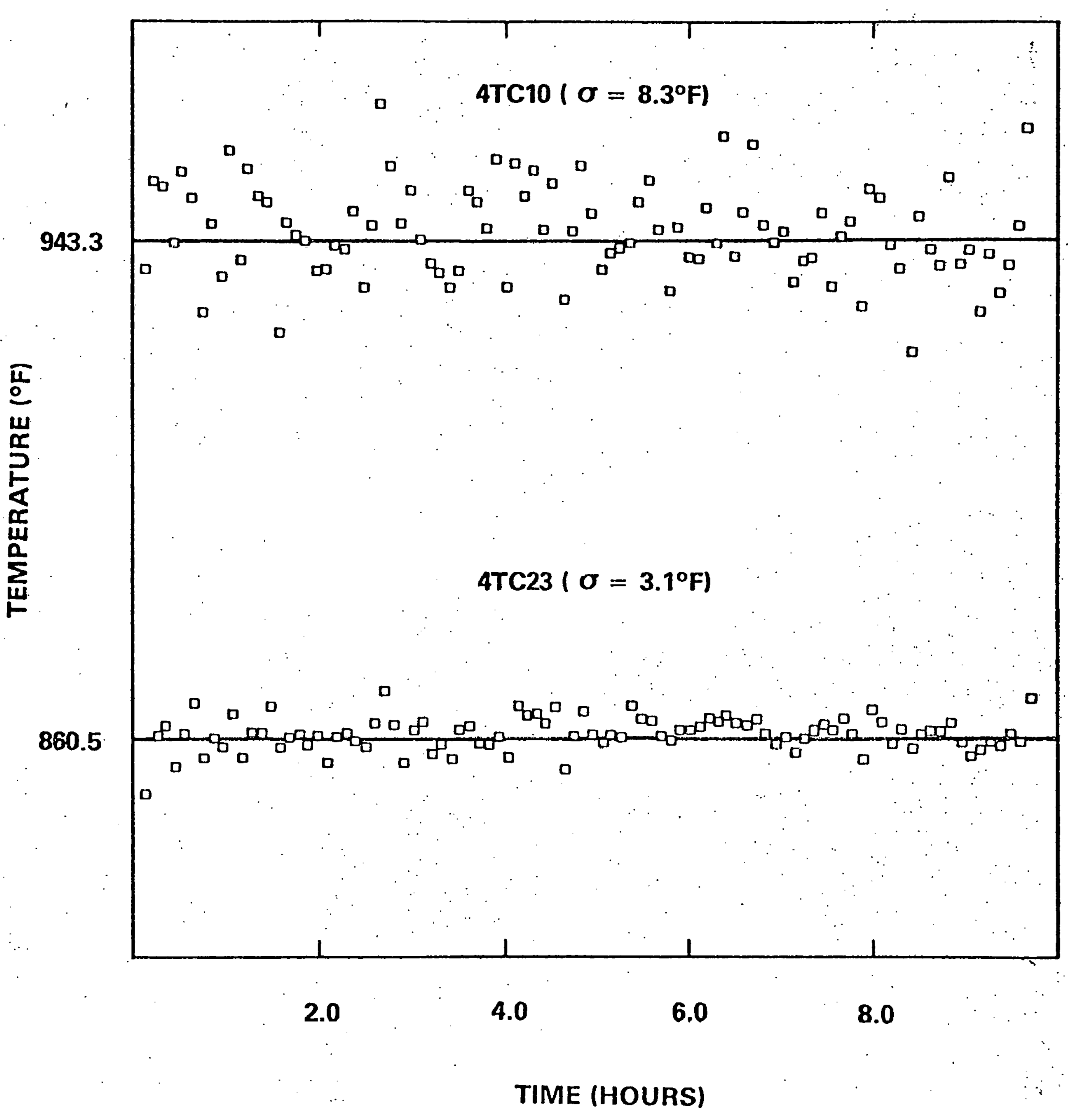


FIGURE 3. 4TC-Thermocouple Data, 10 Observations/Hour, Run 90B.

Section 3). The signal fluctuations of thermocouples located within the "hot" zone (Sectors 2 and 3 of Figure 2) or within the "cold" zone (Sectors 1 and 6) tended to be highly positively correlated. Signal fluctuations from thermocouples where one is located in the "hot" zone and the other in the "cold" zone tended to be quite negatively correlated. Figures 4 and 5 indicate the cross-correlation patterns of two thermocouples, 4TC10 from the "hot" zone and TTC50 from the "cold" zone. Notice the strong similarity of the cross-correlation plots to the temperature plots of Figure 2. This suggested that the coolant is alternately surging and ebbing from the hot zone to the cold zone.

To further investigate this cross-correlation pattern a second data set recorded at 100 observations/second was created during reactor Run 97. The analog thermocouple signals were passed through a 100 Hz breakpoint linear filter and then digitized in creating the data record. These relatively unfiltered thermocouple signals were assumed to be given by

$$x(t) = s(t) + n(t) \tag{4.1}$$

where s(t) is the actual thermocouple signal, and n(t) is a noise component. Figure 6 contains 10 seconds of data for several different XX08 thermocouples. Examination of this data, cf. 4TC10, suggested a "white" noise component superimposed upon a low frequency (<1 Hz) harmonic. ("White" noise is a stationary process with a constant auto-power spectrum function.) Figure 7 contains the same 10 seconds of thermocouple data from Figure 6 after digitizing at the more tractable rate of 10 observations per second and 1.5 Hz low-pass noise filtering. This filtering is entirely comparable to that used by the EBR-II data acquisition system in creating the previously discussed Run 90B and 95 data sets. Notice the reduction in signal standard deviation from Figure 6 to Figure 7 and the continuous smooth sample paths of Figure 7 as evidence of noise removal.

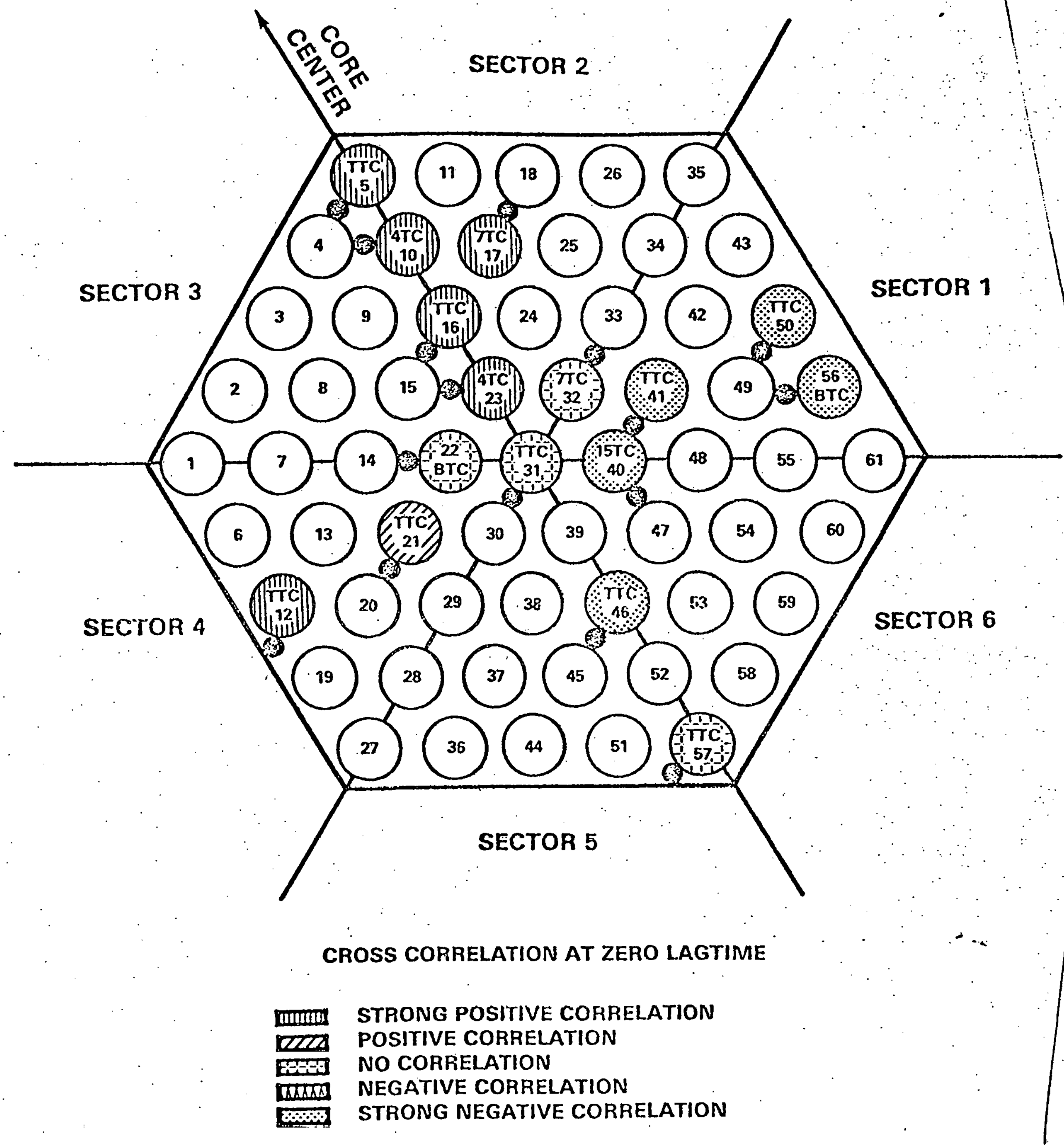


FIGURE 4. 4TC10 Cross-Correlation Pattern, Run 95.

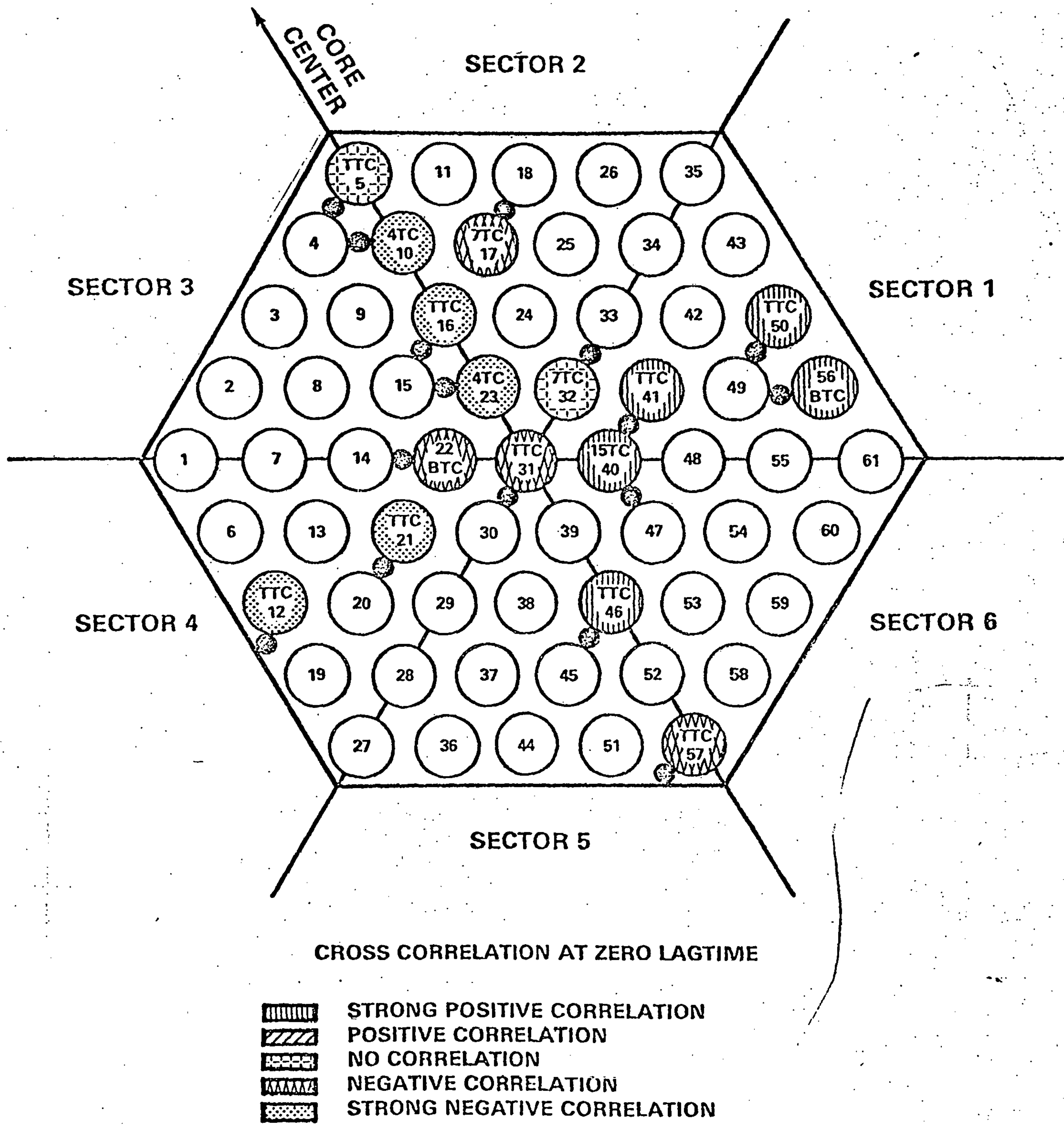


FIGURE 5. TTC50 Cross-Correlation Pattern, Run 95.

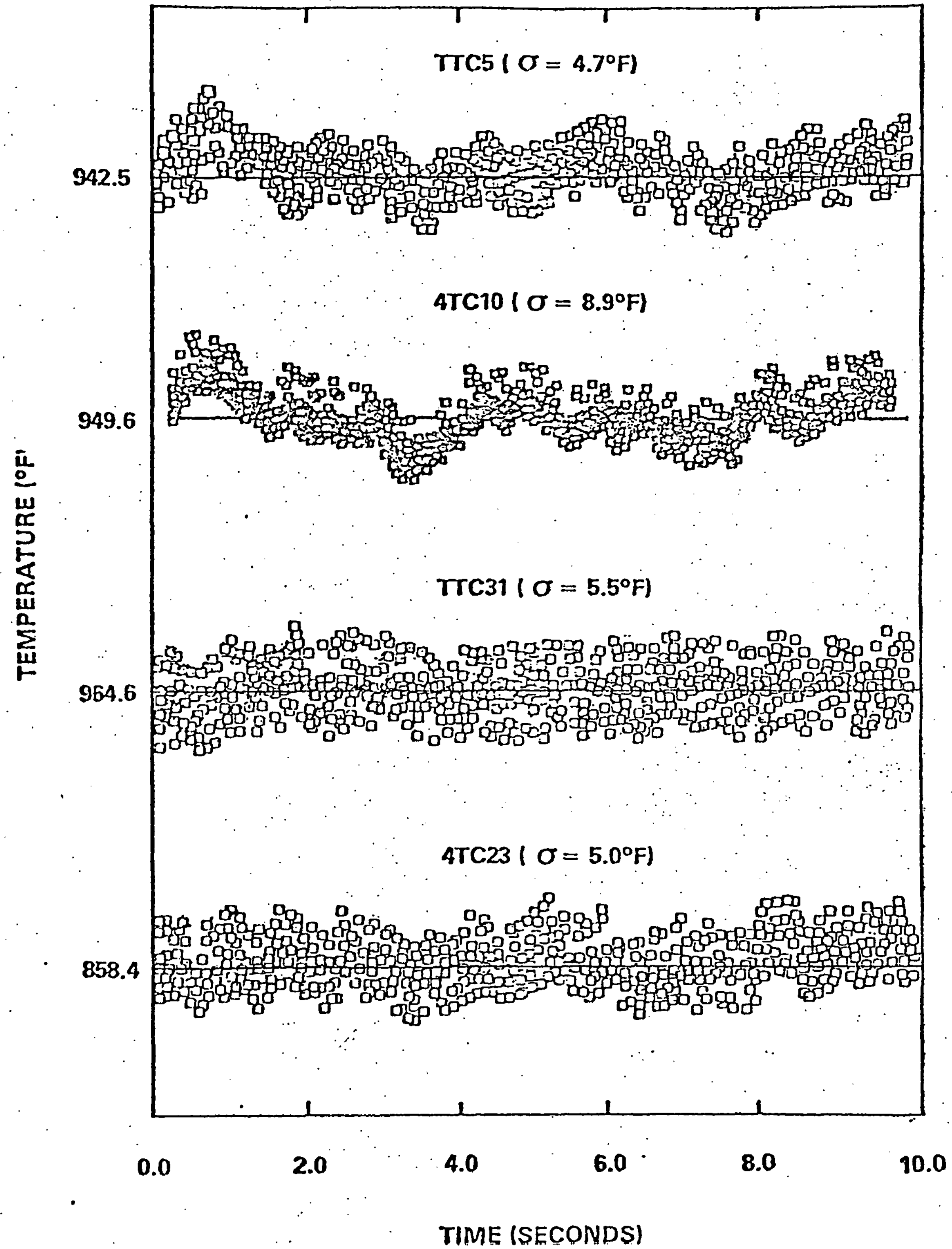


FIGURE 6. XX08 Thermocouple Data, 100 Observations/Second, Run 97.

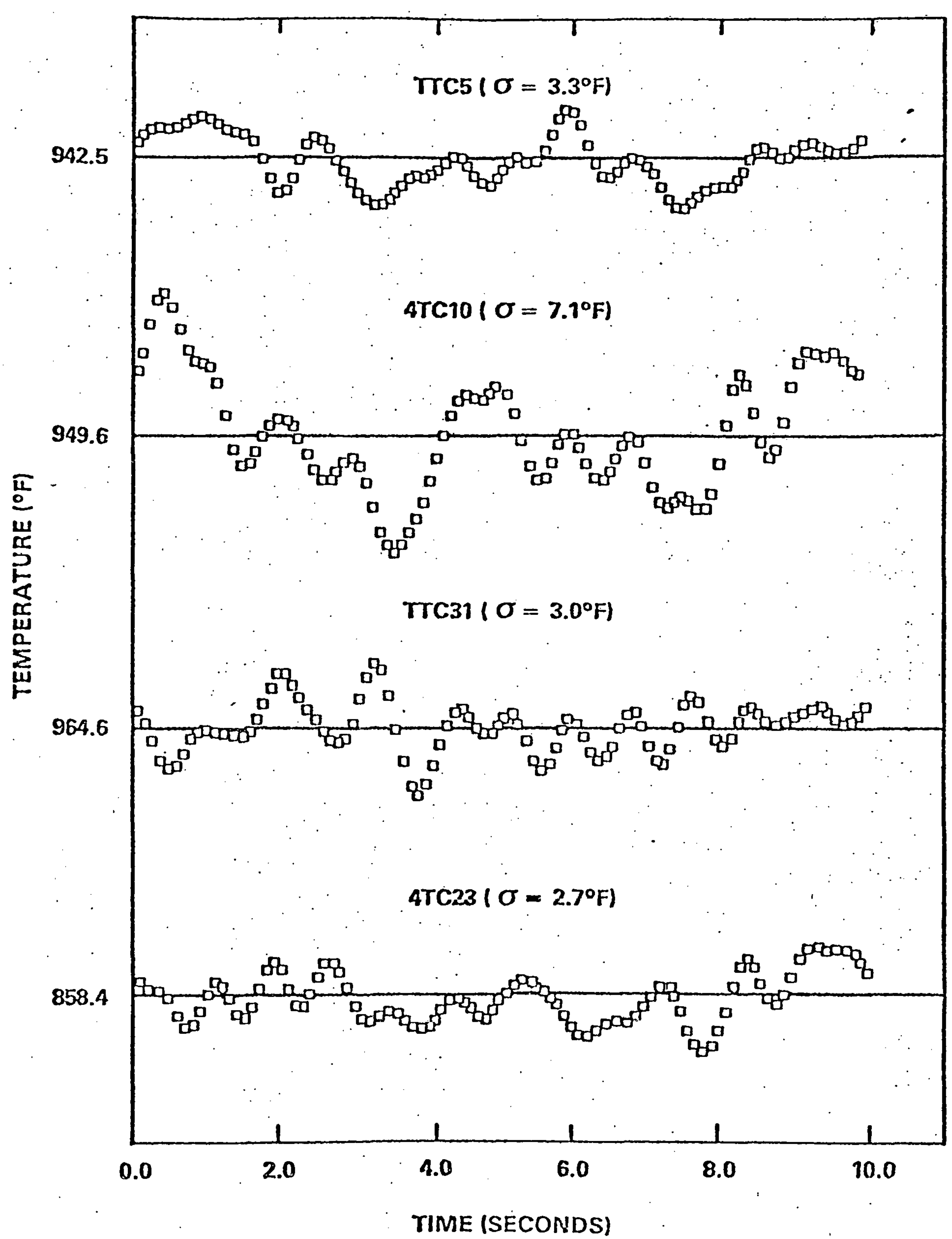


FIGURE 7. XX08 Thermocouple Data, 10 Observations/Second, After 1.5 Hz Low-Pass Noise Filtering, Run 97.

The actual thermocouple signals, s(t), as estimated in Figure 7, are the "smoothed" or filtered values of the measured coolant temperatures, T(t), according to equation (3.8). Because of the "slow" response time of the thermocouples, $\tau = 0.6$ second, this first order linear filter has a break-point frequency of 0.27 Hz. This means considerable damping of coolant temperature oscillations occurs in the thermocouple response at frequencies above 0.27 Hz. Figure 8 contains the sample path plots before and after the amplification or "unfiltering" of thermocouple 4TC10's actual signal, s(t). Notice the increase in signal standard deviation due to the amplification and the smoothly varying harmonic character of the reconstructed coolant temperature, T(t).

The cross-correlation phenomenon, previously described for Run 95, was again observed in the filtered data of Run 97 (Figure 7). The cross-correlation pattern was obscured by noise in the raw data of Run 97 (Figure 6). This was to be expected since the Run 95 data underwent considerable on-line filtering in the EBR-II data acquisition system. Figures 9 and 10 indicate the cross-correlation pattern of thermocouples, 4TC10 and TTC57. A slight change in the flow pattern appeared to be present in the Run 97 data. Thermocouples TTC31 and 4TC10 have increased their mean temperatures while all other thermocouples have decreased mean temperatures (as expected) since Run 95.

In conclusion it is thought that the thermocouple signal fluctuations and the cross-correlation phenomenon are real and correspond to an abnormal coolant flow distribution in the fuel pin bundle. These time series analyses disclosed data patterns previously obscured by noise and helped to explain the thermal hydraulic performance of the XX08 test.

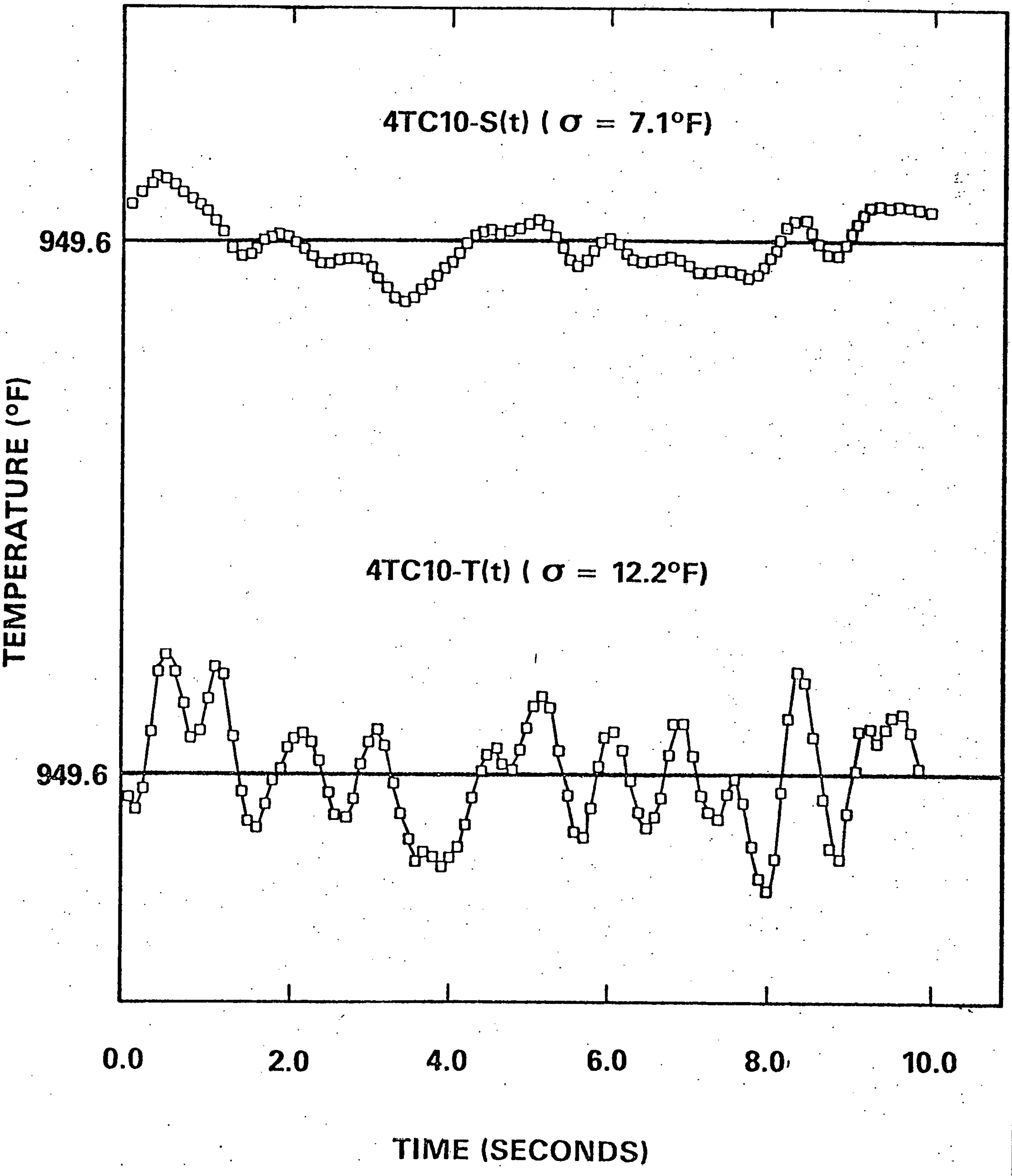


FIGURE 8. 4TC10 Thermocouple Data, 10 Observations/Second, After 1.5 Hz Low-Pass Noise Filtering (above), and After 1.5 Hz Low-Pass Noise Filtering and Amplification (below), Run 97.

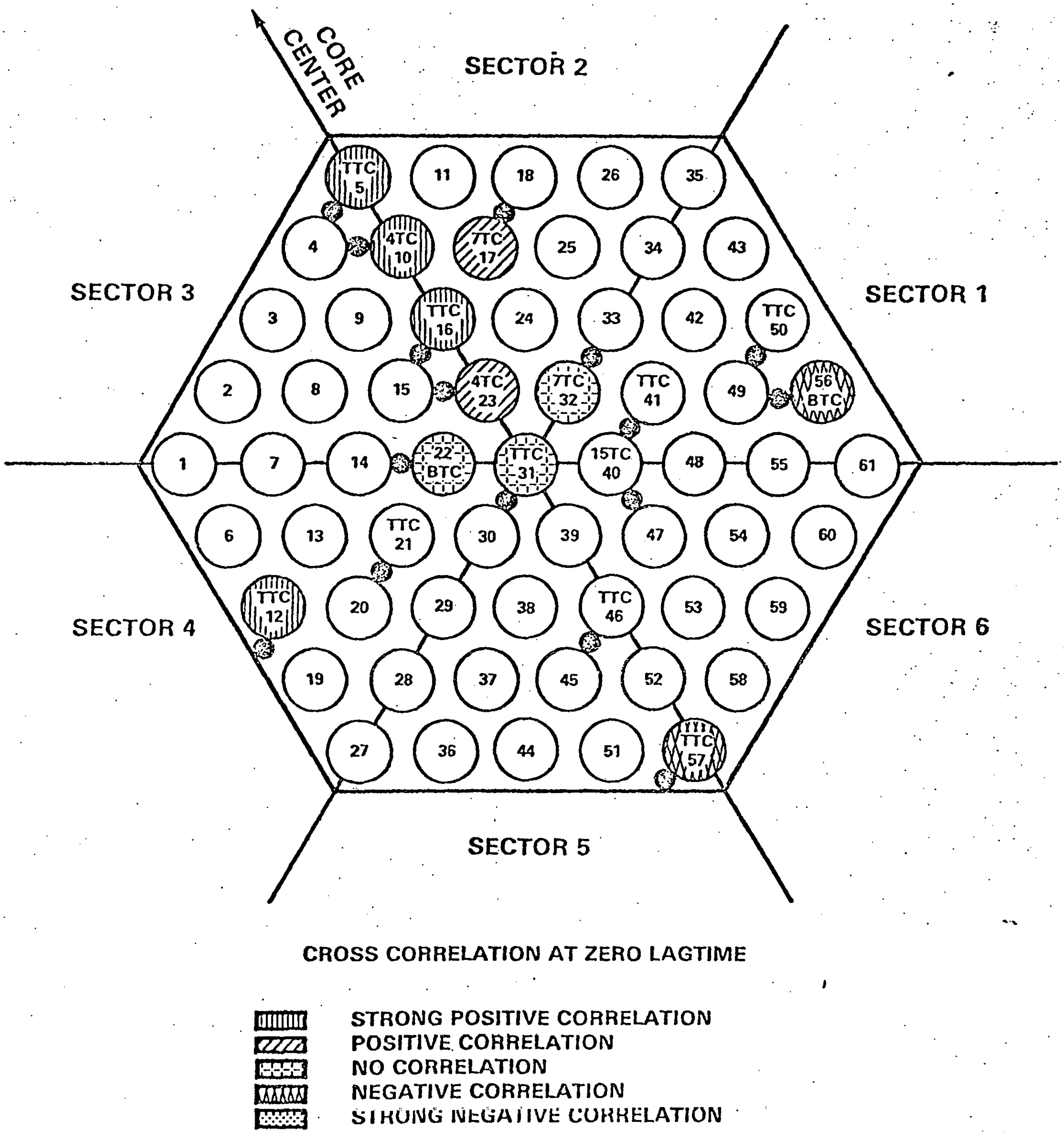


FIGURE 9. 4TC10 Cross-Correlation Pattern, Run 97.

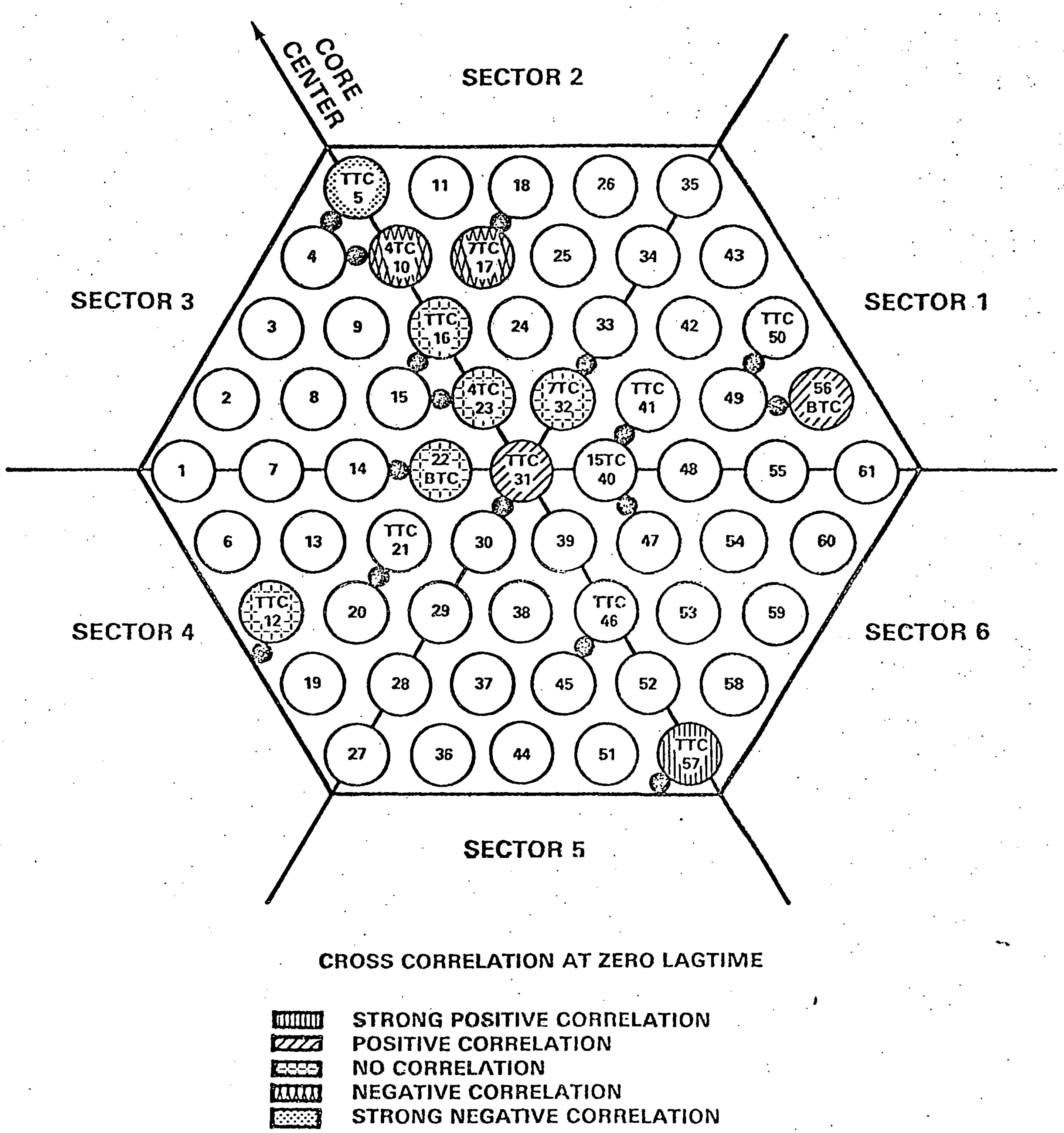


FIGURE 10. TTC57 Cross-Correlation Pattern, Run 97.

5.0 REFERENCES

1. International Mathematical and Science Libraries, Library 2, Sixth Edition, Houston, TX, 1977.

2. Parzen, E., Stochastic Processes, Chapter 3, Holden-Day Inc., San Francisco, 1962.