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# *Time-Series Investigation of Anomalous Thermocouple Responses in a Liquid-Metal-Cooled Reactor*

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# *Time-Series Investigation of Anomalous Thermocouple Responses in a Liquid-Metal-Cooled Reactor*

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## ABSTRACT

A study was undertaken using SAS software to investigate the origin of anomalous temperature measurements recorded by thermocouples (TCs) in an instrumented fuel assembly in a liquid-metal-cooled nuclear reactor. SAS macros that implement univariate and bivariate spectral decomposition techniques were employed to analyze data recorded during a series of experiments conducted at full reactor power. For each experiment, data from physical sensors in the test assembly were digitized at a sampling rate of 2/s and recorded on magnetic tapes for subsequent interactive processing with CMS SAS. Results from spectral and cross-correlation analyses led to the identification of a flowrate-dependent electromotive force (EMF) phenomenon as the origin of the anomalous TC readings. Knowledge of the physical mechanism responsible for the discrepant TC signals enabled us to devise and justify a simple correction factor to be applied to future readings.

## Introduction

Experimental Breeder Reactor No. II (EBR-II) is a liquid-metal-cooled reactor (LMR) operated for the U. S. Department of Energy by Argonne National Laboratory near Idaho Falls, Idaho. It is currently the only operating electrical-power-producing LMR in the U. S.

EBR-II recently designed and installed an instrumented experimental fuel assembly, designated XX09. This assembly differs from the reactor's ordinary fuel assemblies in that the instrumented assembly contains two flowmeters and several thermocouples (TCs). The instruments provide researchers with continuous, online readings of the flowrate and temperature of the coolant as it flows upward through spaces separating the individual fuel elements that comprise the nuclear fuel assembly. Each flowmeter in the instrumented assembly has its own TC. The flowmeter TCs are designated FM TC 1 and FM TC 2. There are four other TCs in each assembly which are located at positions away from the flowmeters, and are designated TC 1 through TC 4.

During early operation with XX09 in the core, discrepancies were observed in the temperature readings obtained from the flowmeter TCs. This paper describes the spectral decomposition and cross correlation analyses that were conducted using SAS to explore and characterize the anomalous TC readings, and to test hypotheses advanced to explain their origin. The SAS-system macros developed as part of this investigation are quite general and can be applied with only minor modifications to explore and characterize any experimental time series that are suspected to contain periodic components.

## Experimental Data

A sequence of flow-change experiments was performed to provide data used for this investigation. During the flow-change experiments the values of some 800 plant parameters monitored by the EBR-II data-acquisition system were recorded on dedicated magnetic tapes at a sampling frequency of 2/s. For this investigation, data were retrieved from archive tapes, assembled into a master data base, and stored in direct-access memory to facilitate subsequent interactive processing with SAS software tools in VM/CMS. In building the master data base, raw data for all parameters of interest were first scanned and edited using PROC MEANS, PROC PLOT, and PROC EDITOR. After all scanning and editing operations were performed, summary statistics were computed, and plots were provided for all parameters incorporated into the master data base. Figure 1 plots the reactor coolant flowrate (in percent of full nominal flow) and the TC responses for the six TCs in XX09. The figure shows that the response of TCs 1-4 is inversly related to coolant flowrate. This behavior is expected on physical grounds: as the flowrate increases, the rate of heat removal from the fuel assembly increases, and assembly TC response should indicate a drop in temperature. Reverse behavior should be observed as the flowrate decreases.

The bottom subplot in Fig. 1 reveals that the response of the flowmeter TCs in assembly XX09 following changes in coolant velocity is exaxtly opposite of that which we would expect from heat-transfer considerations. Figure 2, which plots 0.5-s averages of the flowmeter TC readings as a function of coolant flowrate, reveals that there is a strong positive correlation between flowrate and FM TC response over the entire range of coolant velocities. The disparity in response characteristics between the FM TCs and the other four assembly TCs is made more clearly apparent in Fig. 3, which tabulates the correlation coefficients computed by application of PROC REG to the raw (unlagged) data plotted in Fig. 1.

Several hypotheses were advanced to explain the anomalous behavior of the FM TCs. One conjecture is based upon Faraday's law of induced voltage. As a conducting liquid (in this case liquid sodium) flows through a stable magnetic field, an electromotive force (EMF) is developed at right angles to the field. This EMF is proportional to the volumetric flowrate of the liquid and the magnetic flux density. Each of the flowmeters in XX09 contains a small permanent magnet. It is therefore plausible that the FM TC junctions are sufficiently close to the magnetic fields of the FM permanent magnets that the induced EMF is affecting TC output. If this could be proven to be the case, then we could justify a simple linear correction factor that could be applied to the FM TC readings, and no physical modifications to the assembly instrumentation would be necessary.

Alternative hypotheses included the possibility of interference effects from electrical machinery--most likely the large motors that drive the primary-system mechanical pumps; and the possibility of interference effects in the data-acquisition or signal conditioning instrumentation.

The following sections describe how we were able to rule out the latter two hypotheses and conclusively demonstrate the presence of an EMF phenomenon by application of SAS/ETS and base SAS software tools.

## Univariate Spectral-Decomposition Analysis

Univariate spectral-decomposition analysis of the raw data recorded during steady-state portions of the flow-change experiments was performed using PROC SPECTRA, which is part of the SAS/ETS software. Output from PROC SPECTRA for univariate analyses is provided in the form of periodograms and spectrograms, which plot the power spectral density (PSD) for the time series as a function of period, P, or frequency, w, respectively. A physical interpretation of the PSD function is that f(w)dw represents the contribution to variance of components with frequencies in the range (w,w+dw). When the spectrum is plotted, the total area under the curve is equal to the variance (i.e. square of the standard deviation) of the time series. A peak in the spectrum indicates an important contribution to variance at frequencies in the appropriate region.

PROC SPECTRA with the CROSS option was employed in bivariate spectral-decomposition analyses of the flow and TC signals from the steady-state portion of the test. In bivariate analysis the objective is to compute a cross power spectral density (CPSD) function, whose plot in either the time domain or the frequency domain is similar in appearance and interpretation to the univariate PSD function used above. Basically, the CPSD function computed from two time series shows whether frequency components in one series are associated with large or small amplitudes at the same frequency in the other series. If we divide the CPSD function by the product of the means of the respective time series, we obtain the normalized cross power spectral density (NCPSD). Time domain analysis using PROC CORR will be presented in the following section.

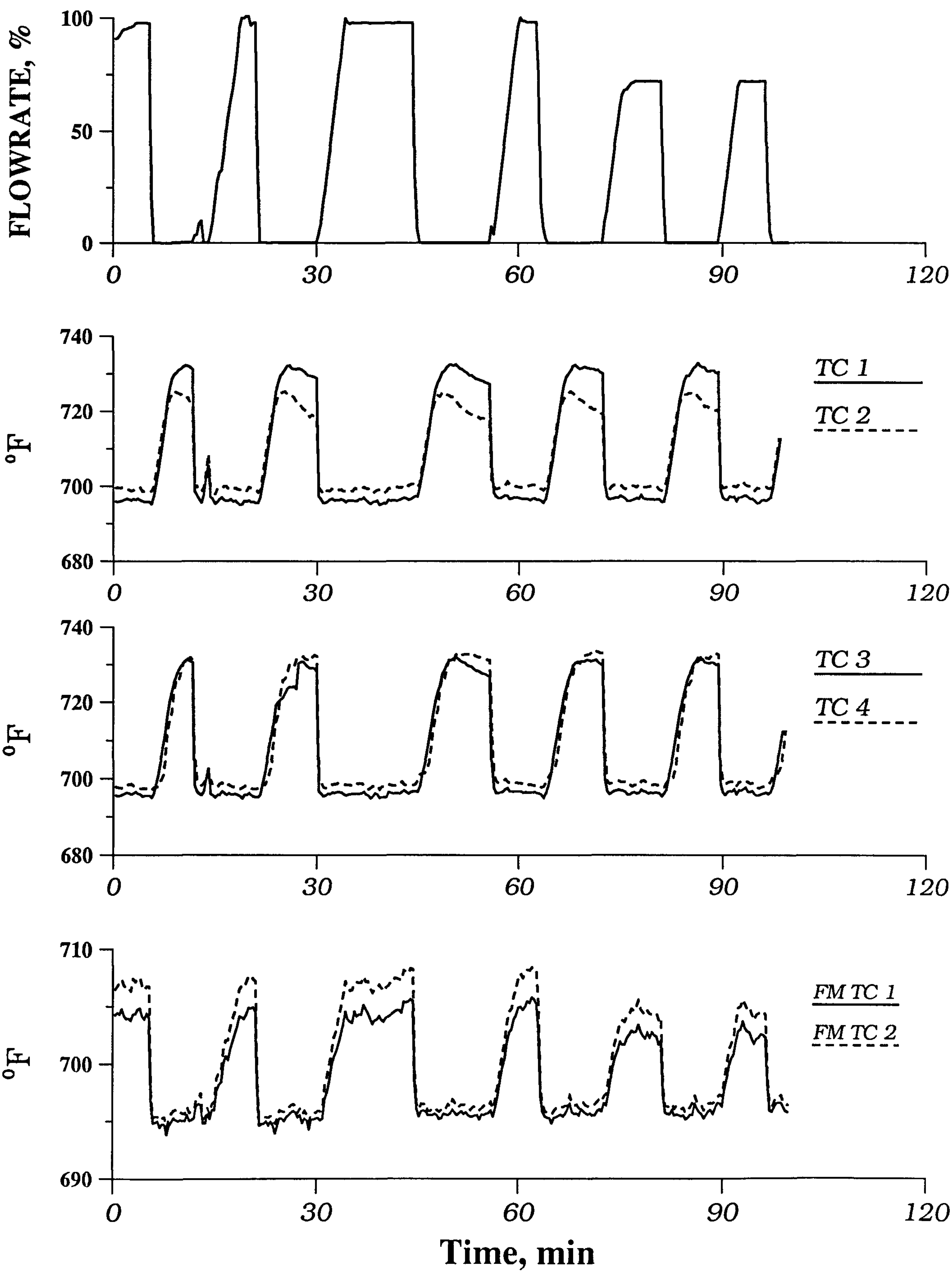
It is not physically possible for a small-amplitude variation in local temperature to produce a variation in flow rate. Also, we know from other experimental data that no high-frequency variations exist at the location of the primary system pumps. This latter fact has been confirmed by spectral analysis of primary pump parameters (current, pump power, shaft RPM) and of global flow rate signals. It can therefore be concluded that the periodic flow variations observed with XX09 sensors are a local phenomenon arising in the assembly itself and, moreover, that the temperature variations either result from the flow flow variations, or possibly arise from a common-cause electrical disturbance in the data-acquisition or signal-conditioning equipment. To eliminate the possible of an electrical disturbance, lagged correlation analyses are applied in the following section.

## Cross-Correlation Analysis for Time-of-Flight Determination

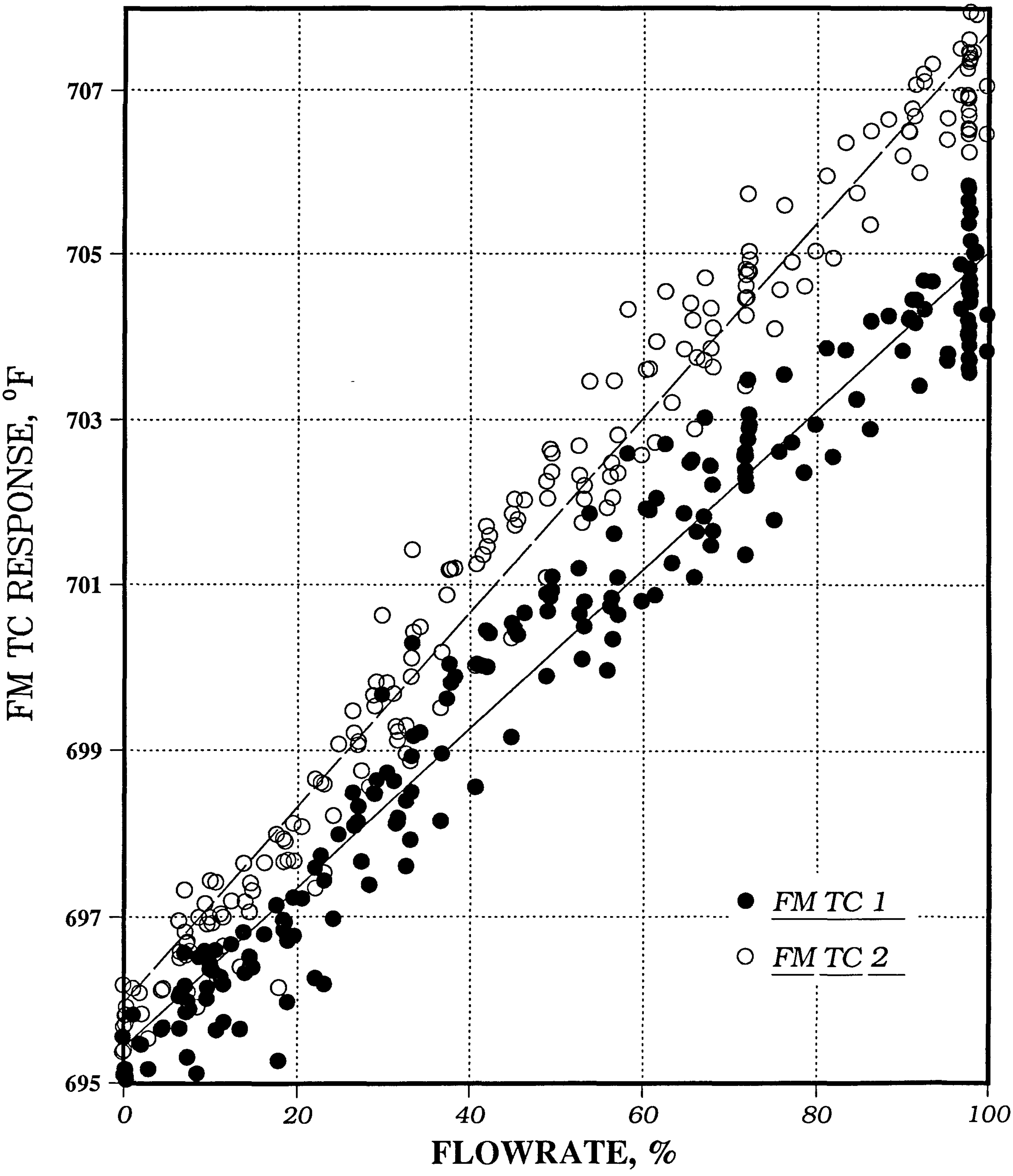
Bivariate cross-correlation analyses were performed using the inlet flowmeter signals and TC signals to compute the total transit time from the flowmeters to each respective TC location. The inlet flowmeter signals were selected for this calculation on the basis of their superior statistical quality as evidenced from the spectral analyses presented above. To compute the transit time to the TCs a correlogram is generated by recursive application of a regression algorithm that computes a coefficient of correlation between two time series as a function of lag time. The lag time is treated as an adjustable independent variable. A peak in the correlogram defines the optimal estimate of the sodium transport-delay time.

The algorithm devised to compute correlograms from successive pairs of time series has been incorporated into the SAS macro LAGCOR. Results of applying LAGCOR to data from XX09 flowmeter 1 and TC 2 are plotted in Fig. 5. For comparison, the best estimate of the transport time from flowmeter 1 to TC 2 based on pressure-drop and transport-geometry considerations is 5.8 +/- 0.5 s. Fig. 6 reveals that the lag time computed from the LAGCOR macro is 5.9 s. The transport time to TC 3, which is as a higher location in the assembly (and hence farther from the inlet at the bottom) is found to be 6.8 s. This value also agrees well with independent hydrolic calculations. In contrast, the correlogram for FM TC 2 was found to have a sharp negative peak at zero lag time. The physical interpretation of this result is that the effects of flowrate on FM TC 2 output are instantaneous. The same results are obtained from LAGCOR calculations using XX10 data as input. These findings add further support to the hypothesis that the anomalous TC responses in the vicinity of the flowmeters are attributable to a flow-enduced EMF phenomena, which affects the FM TCs with zero lag time.

# ASSEMBLY XX09 THERMOCOUPLE RESPONSES DURING FLOW MANEUVER TEST 1

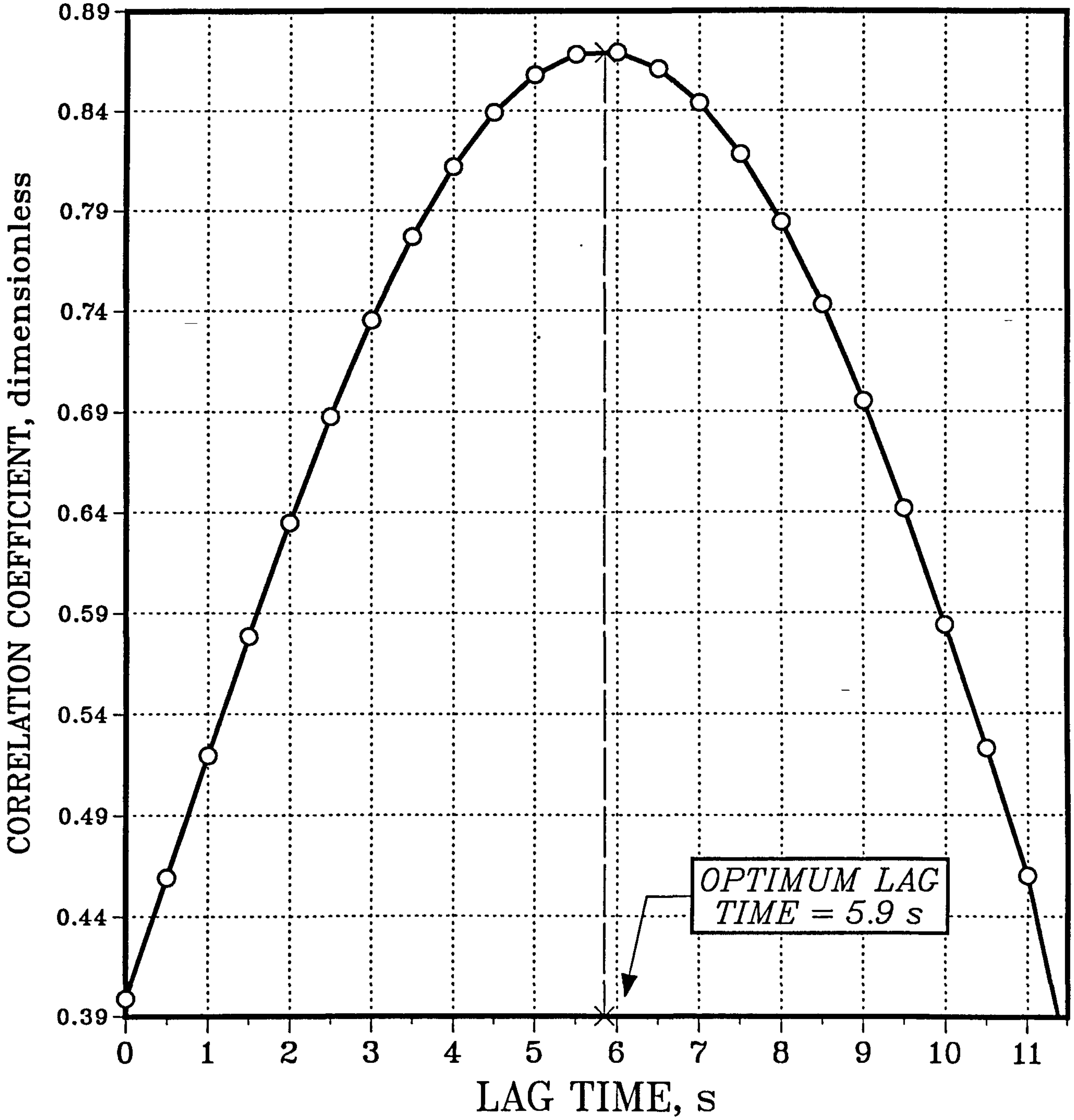


# ASSEMBLY XX09 THERMOCOUPLE RESPONSES AS A FUNCTION OF COOLANT FLOWRATE

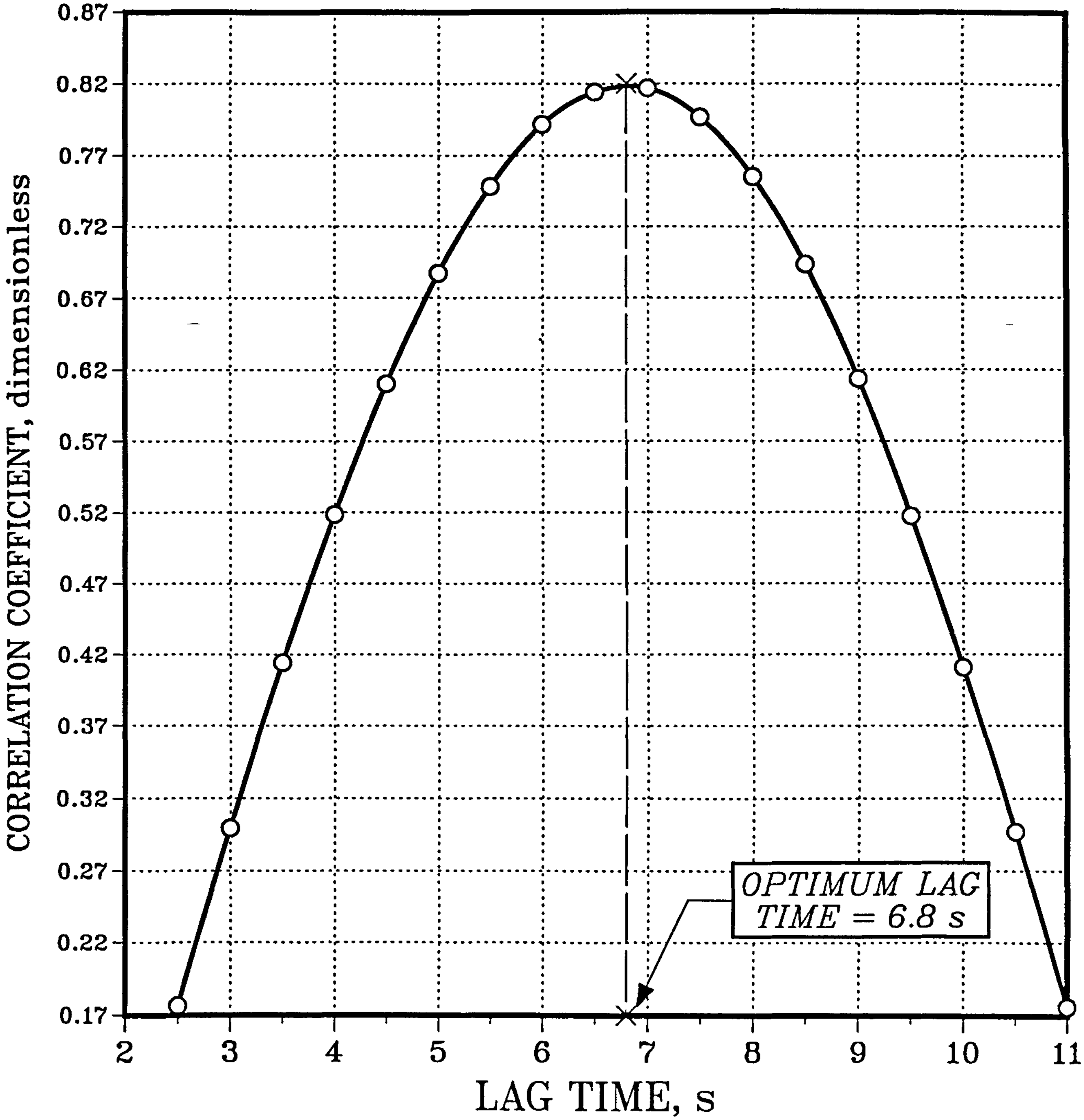


*CROSS-CORRELATION COEFFICIENTS*
*COOLANT FLOWRATE VS. XX10 TC RESPONSES*

| SENSOR | CORR. COEF. |
|---|---|
| TC 1 | -0.66 |
| TC 2 | -0.66 |
| TC 3 | -0.64 |
| TC 4 | -0.56 |
| TC 5 | -0.45 |
| FM TC1 | 0.5 |
| FM TC2 | 0.23 |




Use of LAGCORR Macro to Compute Flow Transport Time from Assembly Inlet to Midplane Thermocouple 2




Use of LAGCORR Macro to Compute Flow Transport Time from Assembly Inlet to Upper Thermocouple 3