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INSTRUMENT RESPONSE DURING OVERPOWER TRANSIENTS AT TREAT

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ABSTRACT

A program to empirically analyze data residuals or noise to determine instrument response that occurs during in-pile transient tests is outlined. As an example, thermocouple response in the Mark III loop during a severe overpower transient in TREAT is studied both in frequency space and in real-time. Time intervals studied included both constant power and burst portions of the power transient. Thermocouple time constants were computed. Benefits and limitations of the method are discussed.

INTRODUCTION

Instrumentation on tests performed in-pile is characteristically much more limited than on corresponding tests performed out-of-pile. Destructive in-pile testing of liquid-metal fast breeder reactor (LMFBR) fuel at the Transient Reactor Test Facility (TREAT) at Argonne National Laboratory subjects test instrumentation such as thermocouples, flowmeters, and pressure transducers to a hostile environment of extreme and rapidly-varying temperature and neutron/gamma-radiation fields. On the face of it, the response of even the limited available instrument data during rapid transients could be suspect. Predictions, even if possible theoretically, of the impact of the test environment on instrument response would likely be regarded as an arcane art that would have little meaning outside a circle of experts. The way out of this dilemma is to scrutinize test data in as many ways as possible. Instrument readings whenever possible are taken redundantly and checked for self-consistency. A previously-determined reactor-to-test-fuel power coupling is used in conjunction with thermal-hydraulic computations to correlate reactor power, sodium flow rate, and measured temperatures. Observed instrument responses during transient tests in TREAT have been partly validated by a series of instrument response tests (IRT-series) performed and reported in 1975-76. These tests subjected thermocouples, flowmeters and pressure transducers to a wide variety of transient thermal conditions both out of pile[1] and in-pile[2]. The in-pile tests in this series were set up in the TREAT Mark-II loop similar to destructive transient tests except that dummy reactor fuel pins were used. The IRT series of tests has proved useful not only in confirming the validity of instrument readings but also in identifying areas where transient response problems existed.

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This paper describes an additional method of assessing instrument responses that occur during transient tests with reactor fuel. Application is made to experiments in the new Mark III series of test loop. The method applies a statistical analysis of instrument "noise" or data residuals left over after the signal's main trend is removed. A key feature of this method involves the Fourier transformation of the time-dependent data residuals into frequency space. There, for example, a high frequency component of the noise can simply be thrown away by observing that it cannot possibly represent the response of the particular instrument. Typically, the result of this filtering is a much-smoother signal whose remaining residuals reflect the quality of the instrument response. The treatment here follows closely the analysis presented by Doerner, Meek, Hurt and Pekarsky[4] who first applied these methods in an extensive analysis of in-pile tests in the Mark II loop.

The theoretical basis and the analysis method will be briefly described. Unlike Ref. 4, emphasis here is placed on analyses that do not require an exacting theory of instrument noise or its origins. The aim is to find straightforward, empirical techniques that may be applied routinely to test data. For example, the concept of a fall-off of measured instrument response with increasing frequency is readily transformed into a non-zero instrument time response. Apart from absolute values, the presence or absence of trends in time responses as the time-interval under consideration advances in the transient provides an additional form of data validation. Furthermore, if an instrument response function is identified or postulated, the instrument data, including the main trend of interest, may be corrected to yield an improved estimate of the applied signal. By way of example, these techniques were applied to test data taken during a severe transient overpower simulation at TREAT in the Mark III test loop. Emphasis was placed on analysis of thermocouple data, with studies of residuals of the data from theoretically fast-responding flowmeters and pressure transducers performed for comparison. Time intervals that were studied included both constant-power portions of the irradiation as well as the rapid overpower burst to ~20 times nominal power. These results, when they are included with other means of data qualification, illustrate uses as well as limitations of these methods. During the overpower burst, the significance of correcting the readings of fast-rising outlet thermocouples for non-zero time response is illustrated.

THEORY AND METHOD

The statistical method of Ref. 4 is designed to draw information from data residuals or "noise" left over after a main trend or smooth fit is subtracted. References 5 and 6 provide basic theoretical discussions. In this paper all analysis is performed on digitized data in both time and frequency domains.

DATA QUALIFICATION

After a time interval is chosen, the data trend is determined by a smooth polynomial fit. This smooth fit is subtracted from the data. Time intervals studied need to be long enough to obtain sufficient statistical data on residuals (weak stationarity) but, during transients, not so long that the character of the residual undergoes significant change. Taken as a whole, the residuals should be normally distributed. In the present analysis program, the residuals' first four statistical moments are computed. The residuals' second moment σ^2, where σ is the root-mean-square value of the residuals, is used as an indicator of significant qualitative change (such as instrument failure) as attention moves from one time interval to another. The third and fourth moments (skewness and kurtosis) provide a check on the hypothesis of a normal distribution. Present programs process either 512 or 1024 data points. Current examples use data digitized at intervals of 1 ms so time intervals under consideration are about 0.5 to 1.0 s in duration.

FREQUENCY SPACE

Turning attention now toward the time dependence of residuals, considerable advantage is to be had by Fourier transformation into frequency space. First of all, no data information is lost in such a transformation. More importantly, the significance of the noise is more easily assessed in frequency space. For example a thermocouple such as used in TREAT tests is an instrument with a response time to environmental temperature changes of order ~20 ms. Noise components of frequencies $\lesssim$ 20 Hz may represent a thermocouple response to a real thermal fluctuation. Noise components of frequency $\gtrsim$ 20 Hz represent something else, most likely electronically-created noise arising somewhere in the process of signal generation, transmission, recording and/or digitization. The high frequency noise components may then be filtered out without fear of distorting our perception of any real temperature signal. As will be seen later, filtering the data in such a fashion greatly enhances the quality of the observed signal. Additional information may now be gleaned from the frequency dependence of the data that remains.

When the residuals are Fourier transformed, their absolute square, as a function of frequency, is termed the power spectral density or PSD. When the PSD is integrated over all frequencies, the result is proportional to σ^2 of the real-time data. If unwanted high-frequency noise has been removed by a low-pass filter, σ can be significantly reduced. For a representative test instrument, the behavior of the PSD with increasing frequency may show initially slow variation followed by a sharp drop-off (before the cut-off artificially imposed by the filter). If the instrument in question receives signal fluctuations that are typically slowly varying in frequency space, i.e., white noise, then the relative drop-off of an instrument's PSD with frequency measures the absolute square of the degradation of that instrument's response.

REAL TIME

Information in real time may be recovered from the frequency dependence of the filtered PSD. The inverse Fourier transform of the PSD is proportional to the time-varying auto-covariance function. The auto-covariance at time t represents the correlation of all residuals separated in time by an amount t. For reference, its value at $t = 0$ is proportional to σ^2. Under the above assumption of incident white noise, the value of the auto-covariance for time t, normalized by its time-zero value, represents the memory of the instrument. Specifically, this memory is that fraction of the signal from the variable time t in the past that persists to the present. Averaging the value of t weighted by the autocovariance yields the instrument response time.

If desired, knowledge of the instrument's measured response time may be used to correct the observed data. Representing the normalized autocovariance with the form exp $(-t/\tau)$, where τ is the response time, suggests a multiplicative correction of the form $1 + i\omega\tau$ to the instrument data in frequency space. (ω is the angular frequency and $i = \sqrt{-1}$). This correction is to be applied to the data as a whole, not just to residuals, and serves to correct the degradation observed in the high frequency response of the instrument.

As demonstrated in Ref. 4, other calculations may be performed on filtered data residuals to explore other aspects of instrument response. Fluctuations in the response of different instruments may be easily correlated one to another as a function of an arbitrary delay time. Such techniques may be used to discover cross-talk among instruments or may be used to infer that different instruments are actually seeing the same fluctuation, with perhaps a time delay. Examples of cross-correlation of Mark III loop instrumentation will be deferred to future reports.

COMPLICATIONS

Since the data used in the analysis are digital and the time-length of the data tracks considered are finite, some care must be taken in the manipulations and interpretations described above. The time-length T of the data tracks is limited both by the time constants of transient phenomena under study and by the memory capacity of the digital computer. Clearly, time correlations of residuals are to be restricted to times much less than T. In addition, a finite value of T imposes a frequency resolution limit of ~ 1/T in Fourier analysis. In the present calculations, a Hanning (4,5,6) smoothing function is employed to eliminate small, but anomalous, frequency peaks introduced by this nonzero frequency resolution.

In the analysis of transient phenomena, the subtraction of a smooth fit to the raw data unavoidably removes some of the desired low-frequency components of the residual data as well as the data trend. Thus, some weak dependence of computed instrument response time on the order of the polynomial fit to the data is to be expected.

The finite digitization interval δt places an upper limit of $1/(2\delta t)$ on frequencies that may be resolved or considered according to the Nyquist Criterion. In our present examples, $\delta t = 1$ ms imposes a frequency limit of 500 Hz. If the data being digitized contain noise of frequencies higher than 500 Hz, these higher-frequency components can appear in computed lower-frequency noise components by the phenomenon of aliasing.(5,6) Filtering the residual digitized data in frequency space will not eliminate the problem. In our present example, the presence of very-high-frequency noise and possible contamination of low-frequency Fourier coefficients cannot be absolutely ruled out. Analog time averaging of data before digitization would eliminate the appearance of very high frequencies in any form and would be most helpful.

RESULTS

The above methods have been applied to thermocouples mounted in a variety of configurations during a severe transient overpower simulation at TREAT in the Mark III integral loop. The thermocouples were all grounded-junction, magnesia-insulated, chromel-alumel type sheathed in 1.0-mm O.D. stainless steel. They were mounted in three configurations. Inlet thermocouples TC1 and TC2 (below the test fuel) and outlet thermocouples TC12 and TC13 (above the test fuel) were immersed in a flowing sodium stream. Thermocouples TC3 through TC11 were attached to the exterior of the thin (0.9-mm thick) flowtube around the test pin bundle: TC3 through TC8 were strapped intact against the flowtube surface, whereas with TC9 through TC11 the individual chromel and alumel wires were spot-welded to the flowtube wall in close proximity to one another. Thermocouples both in and out of TREAT core during irradiation were studied. Some of the thermocouples leads passed through the core, while others did not.

The test consisted of a constant power flattop of about 4 s duration followed by a very rapid burst to roughly 20 times the test fuel's nominal power in about 0.5 s. Fuel failure occurred resulting in molten fuel release, considerable flow disruption and failure of thermocouples mounted on the flowtube. Data tracks of about 0.5 s duration were used in the Fourier analysis of residuals. PSD's were averaged over several overlapping time intervals so that any quoted result encompasses a time interval of about 1 s. The power burst is studied with a single time-interval that covers the end of the flattop and the part of the burst up to but not including fuel failure.

INSTRUMENT PSD AND MEMORY

Fig. 1 shows the unfiltered PSD computed for inlet thermocouple TC2 at the beginning of the power flattop as a typical result for a thermocouple. Evident here is a prominent 60 Hz line signal and white noise all the way out to the maximum resolvable frequency of 500 Hz. As frequency drops below 60 Hz, there is a dip in the noise spectrum followed by low frequency peaks. As discussed earlier, noise can be either thermal or electronic in origin. It is asserted that the low frequency structure represents, at least in part, the response of the instrument to real, thermal fluctuations. At higher frequencies electronic noise takes over, independently of the response of the thermocouple to an applied signal. In support of this assertion analogous PSD's of fast-responding pressure transducers and flowmeters show no such dip in the noise spectrum below 60 Hz.

In order to study thermocouple response at low frequencies, PSD's were filtered by multiplication with a gaussian function of frequency that is unity at zero frequency and falls to 0.5 at 20 Hz. For consistency in the analysis, this same filter was applied to all thermocouples. As is shown below in Table I, the gross effect of the filter is evident in all cases by the large reduction in the residual, root-mean-square, σ. A fourth order polynomial fit was used in each case to de-trend the data. Examples of filtered PSD's are shown in Figs. 2-4. A variety of patterns

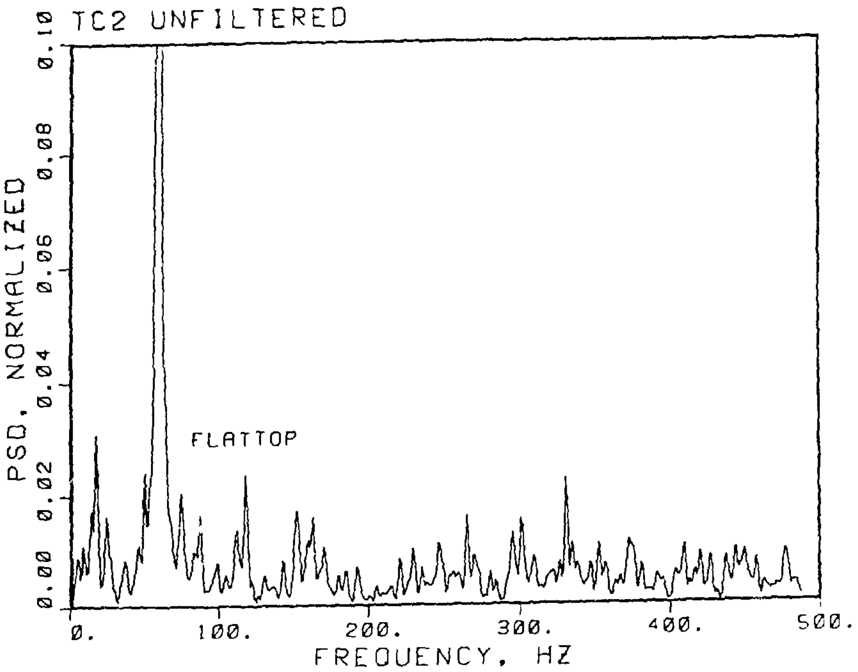

Fig. 1. Unfiltered Power Spectral Density (PSD) for inlet thermocouple, TC2 at Constant reactor power.

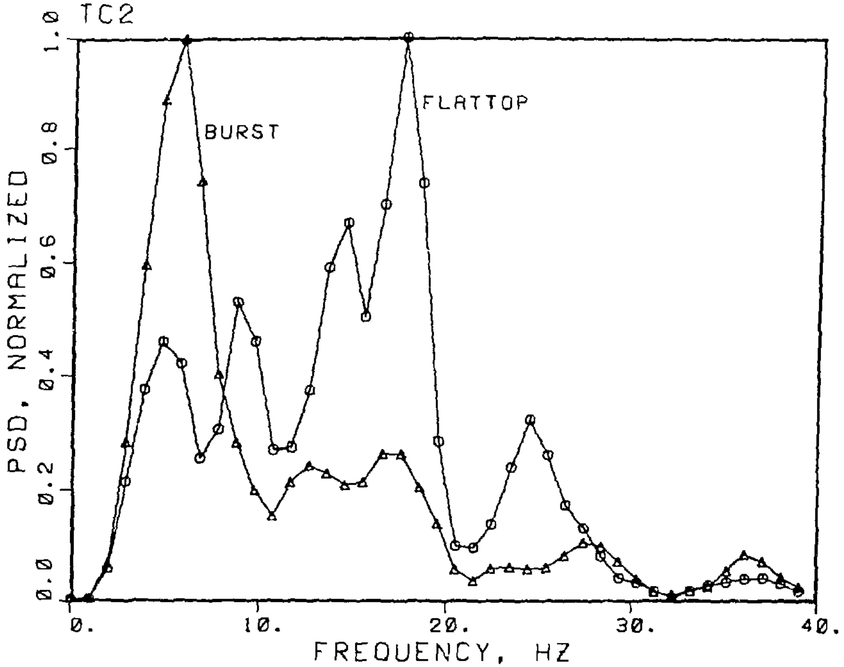

Fig. 2. Filtered PSD for inlet thermocouple TC2 during constant power and burst portions of the transient.

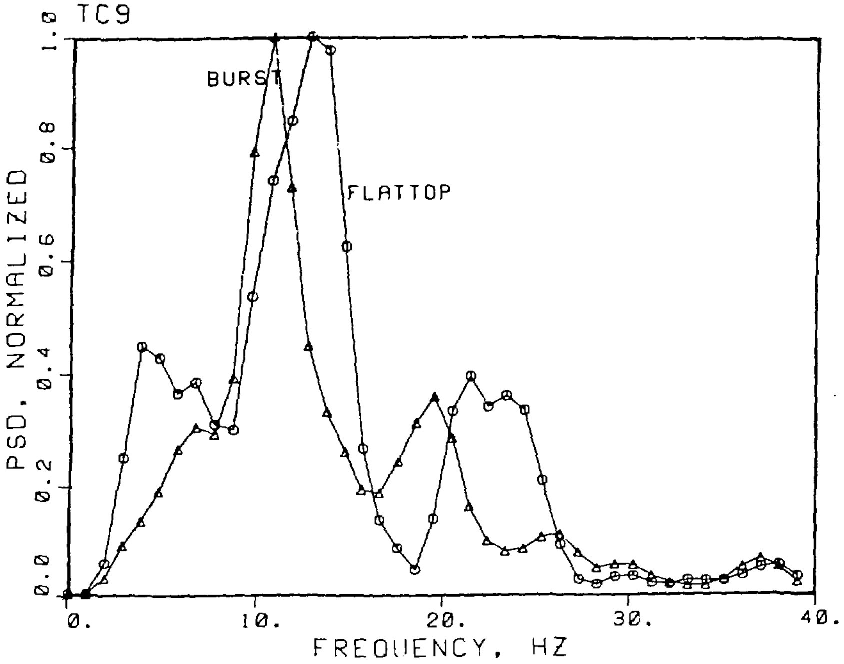

Fig. 3. Same as Fig. 2 for spot-welded, wall thermocouple, TC9.

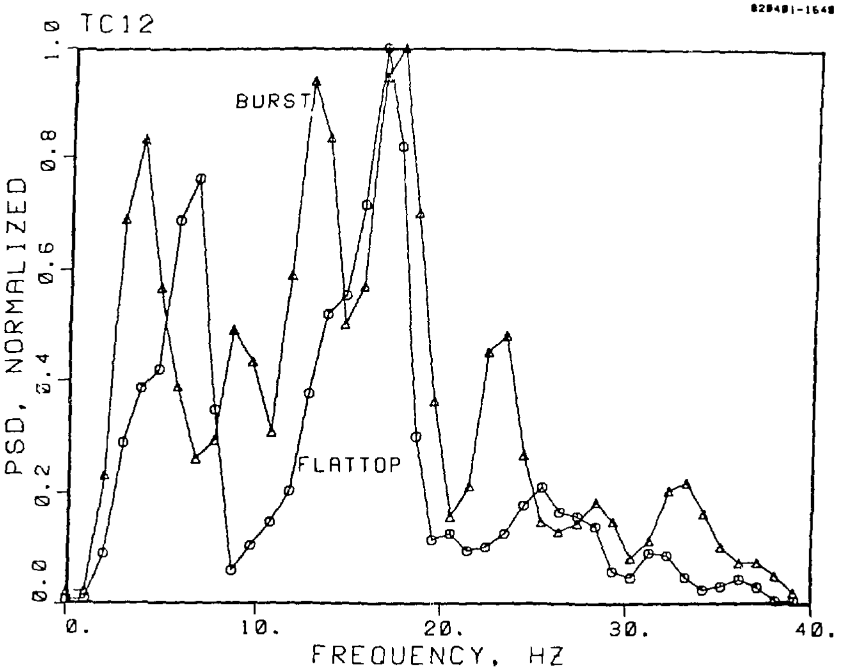

Fig. 4. Same as Fig. 2 for outlet thermocouple, TC12.

appeared in the data studied that could simply demonstrate contamination by electronic noise, but alternatively could show different response characteristics resulting from different conditions of thermocouple mounting. In-sodium thermocouples tended to show multiple prominent peaks. *Spot-welded, flow-tube thermocouples terded to display a single* prominant peak. The thermocouples that were strapped to the flowtube showed a wide variety of multiple and single peaks. In practice, data from the strapped thermocouples have been discounted because of possibly poor thermal contact with the flow tube, so the possibility of a poor, erratic thermal noise signal is very real.

As described earlier, the inverse Fourier transform of the filtered PSD yields the auto-covariance or memory. At small times these curves turn out to be much smoother and more uniform in appearance than do the PSD's, and Fig. 5 shows a typical example. Note that in Fig. 5 the computed memory seems to show a periodic component (not an artifact of the filtering) as well as the decaying amplitude. The conventional parameterization of a single exponential time constant does not provide a particularly good fit. The possibility of a more complex instrument response function should not be overlooked.

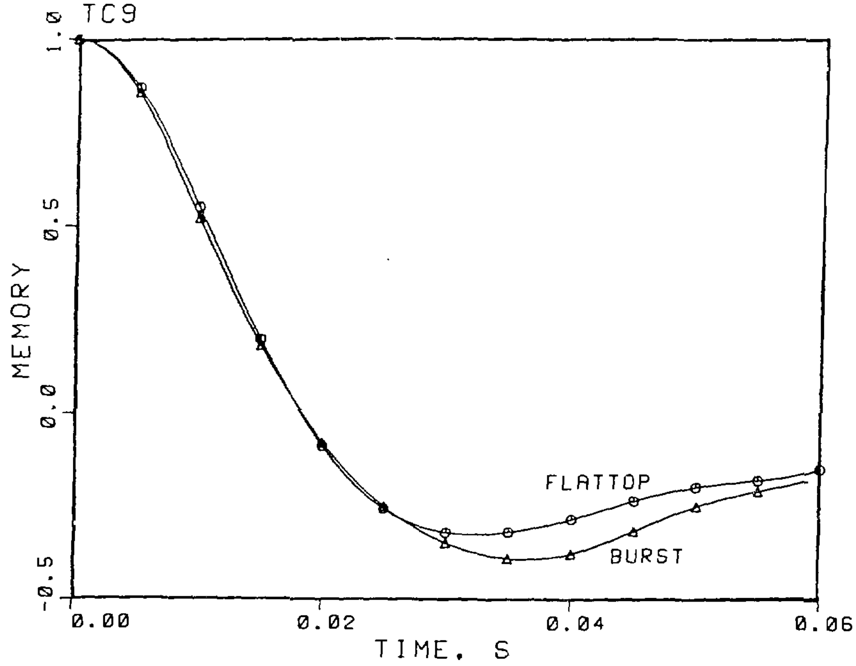

Fig. 5. Auto-covariance or memory of spot-welded, wall thermocouple TC9 during constant power and burst portions of the transient.

INSTRUMENT RESPONSE

The response time τ shown in Table I is the value of time weighted by the memory averaged out to the memory's first zero. Time intervals included the begining of the power flattop and the burst. Most thermocouples yielded response times ~10 ms with little change noted between the flattop and burst. When changes did occur they were in the direction of lengthening the time response. However, these changes should be compared to the variation of response time over time-intervals within the flattop of ~±2 ms. No significant difference related to the mode of mounting was noted. The absolute value of the computed thermocouple time response may be more difficult to interpret. It is appreciably smaller than previously-quoted[1] values (in the range of 20-50 ms) derived from thermocouple response to "dipping" tests. As already noted, the response function itself may be more complicated than a single exponential time constant. For reference, Fig. 6 shows the effect of a postulated single exponential time constant on data from a fast-rising outlet thermocouple during the power burst. Corrected data cover a reasonable range of possible equivalent time constants and is filtered prior to correction. The unfiltered, raw data is also shown for comparison.

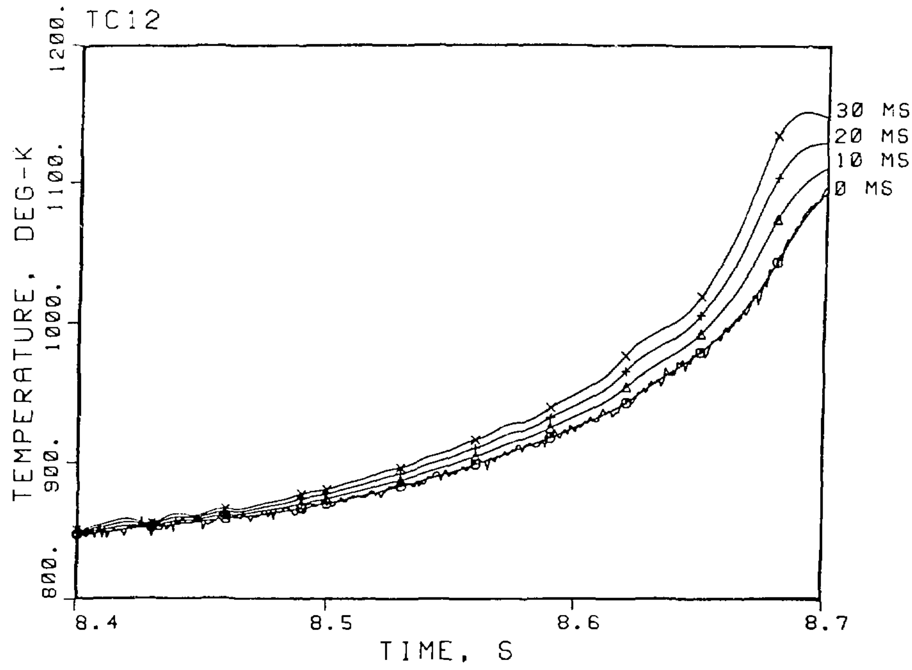

Fig. 6. Data of outlet thermocouple TC12 during the power burst-raw, filtered, and "corrected" for various plausible response times.

CONCLUSIONS

A program for analysis of data residuals has been set up to study thermocouple response during actual transient tests. Time constants computed are shorter than those previously reported from bench tests on thermocouples of the present type. Evidence may exist for thermocouple response more complex than a single exponential time constant. Studies of fast-rising thermocouples during transient tests indicate that the magnitude of a correction applied for time response can be important. No large changes in instrument response times during the rapid power burst were noted.

Major drawbacks in the method stem from uncertainty as to the true nature of the instrument noise spectrum and the difficulty of separating electronic noise from the instrument response to true fluctuations. Poor thermocouple performance, such as by those strapped to the flowtube, was not detected by this analysis method. Despite these limitations, the fact that instruments are studied under actual in-pile test conditions makes these results potentially superior to any out-of-pile laboratory simulation.

TABLE I THERMOCOUPLE RESIDUALS AND COMPUTED RESPONSE TIMES

Thermocouple	σ - raw (deg-k)		σ-filtered (deg-K)		response time, τ(ms)	
	Flattop	Burst	Flattop	Burst	Flattop	Burst
In Inlet Flow stream						
TC1	4.0	4.3	0.7	0.7	10	10
TC2	3.3	3.2	0.6	0.4	10	13
Strapped to Flowtube						
TC3	2.4	2.3	0.3	0.4	7	12
TC4	1.8	1.7	0.5	0.5	11	11
TC5	2.5	2.6	0.4	0.5	9	9
TC6	5.1	5.1	0.3	0.4	9	9
TC7	1.8	1.8	0.6	0.6	11	11
TC8	2.2	2.5	0.4	0.4	8	10
Spot-welded to flowtube						
TC9	2.0	2.6	0.5	0.4	11	11
TC10	1.8	1.8	0.4	0.5	10	11
TC11	2.4	2.5	0.3	0.4	11	12
In Outlet Flowstream						
TC12	2.6	2.4	0.5	0.3	10	10
TC13	2.7	3.1	0.4	0.6	8	11

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