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"Sensor for Individual Burner Control of Firing Rate, Fuel-Air Ratio, and Coal Fineness Correlation"

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ABSTRACT

Additional calibration data were collected in the Coal Flow Test Facility early in this reporting period. These data comprised a total of 181 tests for stud and magnetic accelerometer mounts, with two mounting locations relative to two different pipe elbows, and including some tests with out-of-plane elbows upstream of the test section to produce coal "roping". The results found in analyzing these new data were somewhat disappointing: correlations for coal flow rate for a given mount type and mounting location were less accurate than desired, and degraded badly when data from other locations were included in the same analysis. Reviewing all of the data files (from both the earlier testing and recent calibration testing) disclosed a significant fraction of cases with several forms of noise. Eliminating these cases improved the correlations somewhat, but the number of cases that remained did not permit general conclusions to be drawn. It was finally learned that yet another type of noise is present in some data files, producing a strong effect on the correlation accuracy. The cases not subject to this noise correlated very well. It would be desirable to collect additional data in the Coal Flow Test Facility prior to moving on to field data collection, a change in program direction that would require a no-cost time extension.

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EXECUTIVE SUMMARY

The project's overall objective is to develop a commercially viable sensing system to infer the flow rate and fineness of pulverized coal flows using the dynamic signature from a pipe-mounted accelerometer. The preliminary calibration data for this effort are to be obtained using a Coal Flow Test Facility built and operated by our subcontractor, Airflow Sciences Corporation, in support of an EPRI program. Additional operational data are to be collected in field testing at coal-fired power plants to fine-tune the calibration.

In previous reporting periods, preliminary data were obtained examining the effects of transducer mounting type and location on the observed flow dynamics. These tests disclosed a complex interplay of transducer mount type, location, and coal flow parameters that render a highly general instrument calibration difficult to achieve. Such a calibration should be feasible, but would require a very extensive set of experimental data. As a result, it was decided to limit the scope of the calibration effort to consider a single mounting location (at the outlet of a pipe elbow) and using both stud and magnetic transducer mounts.

Additional calibration data were to be collected and analyzed in this reporting period before moving on to plant testing. This testing was performed early in the reporting period, producing 181 data files for a range of coal and air flow rates. The tests examined both stud and magnetic sensor mounts at the outlets of two separate pipe elbows and points 8 pipe diameters further downstream. In some cases, out-of-plane elbows upstream of the test elbow were used to produce "roping" conditions, in which the coal particles tend to collect in a coherent structure.

Analysis of the data produced disappointing results. The correlations achieved with a given transducer mount and mounting location were not as good as expected, and including data for other locations or mounts degraded the correlation significantly. The principal investigator of this project, Dr. Wayne Hill, presented these results at an EPRI meeting at the Coal Flow Test Facility. Interestingly enough, these results were as good as or better than those obtained with commercially available instruments tested in the facility.

Further analysis of the data disclosed that some of the data files contained one or more forms of noise. Consequently, each of the 390 data files collected to date was examined individually to identify the bad cases. This effort found that 28 files from the first round of 209 cases and 38 files from the 181 cases collected in the current reporting period had readily identifiable noise. When these cases were eliminated from the analysis, the results generally improved, but not to the extent that was desired.

By sheer accident, it was discovered that a still-unidentified form of noise was present in some data files. The data files not subject to this noise correlated very well, but the noisy cases were essentially uncorrelated. This appears to explain the results found so far, but indicates that additional data will be needed to obtain a desirable instrument calibration. Consequently, it would be desirable to collect additional data at the Coal Flow Test Facility before moving on to the plant testing. Since EPRI testing is planned for the facility in the near future, this testing

could be accommodated at little cost to the program. By the same token, the delay to the program schedule would require a contract extension to permit completing all contract milestones. Consequently, it was decided to request a no-cost time extension to permit performing the additional testing. If this extension is not granted, the scope of program results will be limited.

EXPERIMENTAL

Testing in the previous reporting period was performed at the Coal Flow Test Facility by our subcontractor, Airflow Sciences Corp. The purpose of this testing was to examine the effects of the accelerometer mounting method (using either a rigid mounting stud or a magnetic mount) and the location of the transducer on the dynamics observed for a given flow condition. Figure 1, below, illustrates the 15 transducer mounting locations examined in that testing, beginning 5 pipe diameters upstream of the elbow and ending 9 diameters downstream. The results of the analysis of that data were complicated: there was no simple relationship between the dynamics observed with one mount or the other, or between the dynamics observed at one location and another. While such a relationship must exist, it appeared that a great deal of experimental data would be required to understand these behaviors in detail, so that it was decided to limit the scope of further testing. In particular, it was decided that:

- It is of great interest to be able to use either a stud mount, for permanent instrument installations, or a magnetic mount, for temporary installations.
- The outlet of an elbow offers a reliable means of obtaining a strong signal, but is not always readily available in a power plant. Thus, both the outlet of an elbow and a point well downstream of the elbow were selected as suitable measurement points (illustrated with red dots in Figure 1).

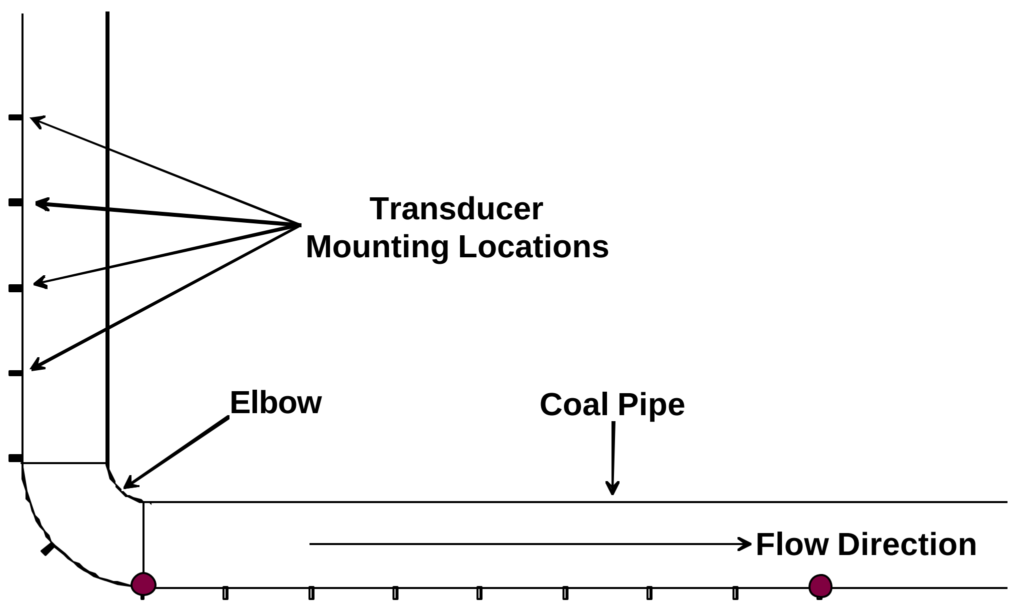

Figure 1. Schematic illustration of transducer mounting locations

The calibration testing was performed using 2 elbows, one turning a vertical downward flow to horizontal and the other turning a horizontal flow upward. For the horizontal-to-vertical elbow, some tests were performed with an additional horizontal elbow installed immediately upstream. This induces swirl in the flow, which tends to cause the coal particles to "rope" together into a coherent structure in the middle of the pipe (an issue of considerable concern to plant operators). Tables 1-3 below summarize the flow conditions that were visited in this testing. For the vertical-to-horizontal elbow, each flow condition typically represents four data files, including two mounting types and the two locations relative to the elbow. For the other two elbows, the mount type used is listed in the last column, so that each row in the table typically corresponds to two data files (for the two mounting locations). Overall, this testing produced 181 data files, including:

- Stud-mounted transducers in 95 tests.
- Magnetically-mounted transducers in 86 tests.
- Transducers mounted at the elbow outlet in 91 tests.
- Transducers mounted 8 diameters downstream of the elbow in 90 tests.

Table 1. Conditions Visited in Downflow-to-Horizontal Configuration

Air Flow (lb/hr, kg/sec)		Coal Flow (lb/hr, kg/sec)		Air/Fuel Ratio
16284	2.052	0	0.000	NA
12933	1.630	4263	0.537	3.0
16141	2.034	4736	0.597	3.4
19298	2.432	4802	0.605	4.0
16075	2.025	6314	0.796	2.5
19209	2.420	6339	0.799	3.0
12876	1.622	6370	0.803	2.0
19123	2.409	7481	0.943	2.6
16135	2.033	7722	0.973	2.1
12814	1.615	8428	1.062	1.5
18315	2.308	9351	1.178	2.0
15896	2.003	10223	1.288	1.6
12694	1.599	12167	1.533	1.0
15865	1.999	10335	1.302	1.5
16322	2.057	0	0.000	NA
19112	2.408	7566	0.953	2.5
16146	2.034	7747	0.976	2.1
16166	2.037	4675	0.589	3.5
16065	2.024	6391	0.805	2.5

Table 2. Conditions Visited for Horizontal-to-Upflow Configuration

Air Flow (lb/hr, kg/sec)		Coal Flow (lb/hr, kg/sec)		Air/Fuel Ratio	Transducer Mount
12767	1.609	12168	1.533	1.0	Magnetic
12769	1.609	21604	2.722	0.6	Stud
12844	1.618	8656	1.091	1.5	Stud
12858	1.620	8468	1.067	1.5	Magnetic
12895	1.625	6352	0.800	2.0	Magnetic
12938	1.630	6595	0.831	2.0	Stud
12953	1.632	4353	0.548	3.0	Magnetic
13002	1.638	4434	0.559	2.9	Stud
15970	2.012	10069	1.269	1.6	Magnetic
16035	2.020	7799	0.983	2.1	Magnetic
16077	2.026	10421	1.313	1.5	Stud
16122	2.031	6326	0.797	2.5	Magnetic
16168	2.037	8230	1.037	2.0	Stud
16182	2.039	7827	0.986	2.1	Magnetic
16228	2.045	4618	0.582	3.5	Magnetic
16257	2.048	6136	0.773	2.6	Stud
16266	2.050	7409	0.934	2.2	Stud
16318	2.056	4453	0.561	3.7	Stud
16349	2.060	0	0.000	NA	Magnetic
16448	2.072	0	0.000	NA	Stud
18500	2.331	9282	1.170	2.0	Magnetic
18675	2.353	6306	0.795	3.0	Magnetic
18749	2.362	4869	0.613	3.9	Magnetic
18786	2.367	7513	0.947	2.5	Magnetic
18930	2.385	9505	1.198	2.0	Stud
19396	2.444	7752	0.977	2.5	Stud
19493	2.456	6747	0.850	2.9	Stud
19580	2.467	4833	0.609	4.1	Stud

Table 3. Conditions Visited for Horizontal-to-Upflow Elbow, Roping Configuration

Air Flow (lb/hr, kg/sec)		Coal Flow (lb/hr, kg/sec)		Air/Fuel Ratio	Transducer Mount
12788	1.611	11790	1.486	1.1	Stud
12851	1.619	7713	0.972	1.7	Stud
12928	1.629	6016	0.758	2.1	Stud
12990	1.637	4327	0.545	3.0	Stud
15965	2.012	6374	0.803	2.5	Magnetic
16064	2.024	10247	1.291	1.6	Magnetic
16072	2.025	10537	1.328	1.5	Stud
16149	2.035	7696	0.970	2.1	Stud
16216	2.043	8118	1.023	2.0	Stud
16238	2.046	6715	0.846	2.4	Stud
16294	2.053	7480	0.942	2.2	Magnetic
16298	2.054	4976	0.627	3.3	Stud
16399	2.066	0	0.000	NA	Stud
16400	2.066	0	0.000	NA	Magnetic
18622	2.346	9332	1.176	2.0	Magnetic
18781	2.366	7574	0.954	2.5	Magnetic
18817	2.371	6329	0.797	3.0	Magnetic
18913	2.383	4844	0.610	3.9	Magnetic
18962	2.389	9128	1.150	2.1	Stud
19305	2.432	4690	0.591	4.1	Magnetic
19356	2.439	7900	0.995	2.5	Stud
19446	2.450	6753	0.851	2.9	Stud
19569	2.466	5058	0.637	3.9	Stud

RESULTS AND DISCUSSION

The data analysis was performed using the procedure described in the last report: each data file was digitally filtered to eliminate behaviors above 100 kHz, then broken up into 30 1-second snippets of data. A dynamic signature was calculated for each snippet, and then the median value was found for each of the signature quantities over the 30 snippets. This procedure greatly reduces the influence of noise spikes that have been found to be common in both laboratory and plant data. The median dynamic signatures for a given group of test conditions were assembled into arrays. These arrays considered data from various combinations of transducer mounting types and one transducer mounting location, and often included data for different elbows and data from the earlier scoping tests and the current calibration tests. The signature arrays were then analyzed using Particle Swarm Optimization to identify correlations between the flow dynamics and the coal flow rate.

Figure 2 is a typical result that was obtained for a stud-mounted transducer located at the outlet of the vertical-to-horizontal elbow. An ideal result would place all points on the diagonal line, producing a correlation coefficient, r^2, of one. The actual correlation coefficient was 0.946 in this case, which is not a bad result but does not represent a high-precision instrument.

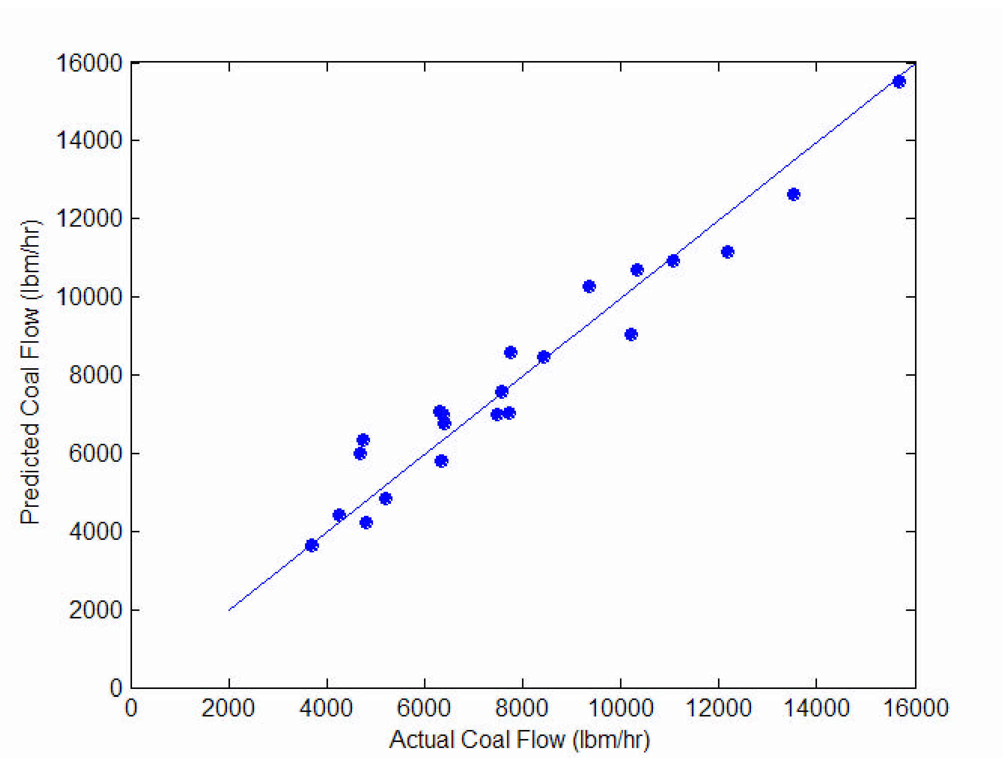

Figure 2. Typical result for stud-mounted transducer for a specific elbow mount

The results for the magnetic mount were not as favorable, as illustrated in Figure 3. In this case, a correlation coefficient of 0.875 was obtained, a significant reduction in accuracy compared to the result in Figure 2. It is not clear whether or not the near-horizontal behavior for predicted flow rates just under 6000 lb/hr is significant.

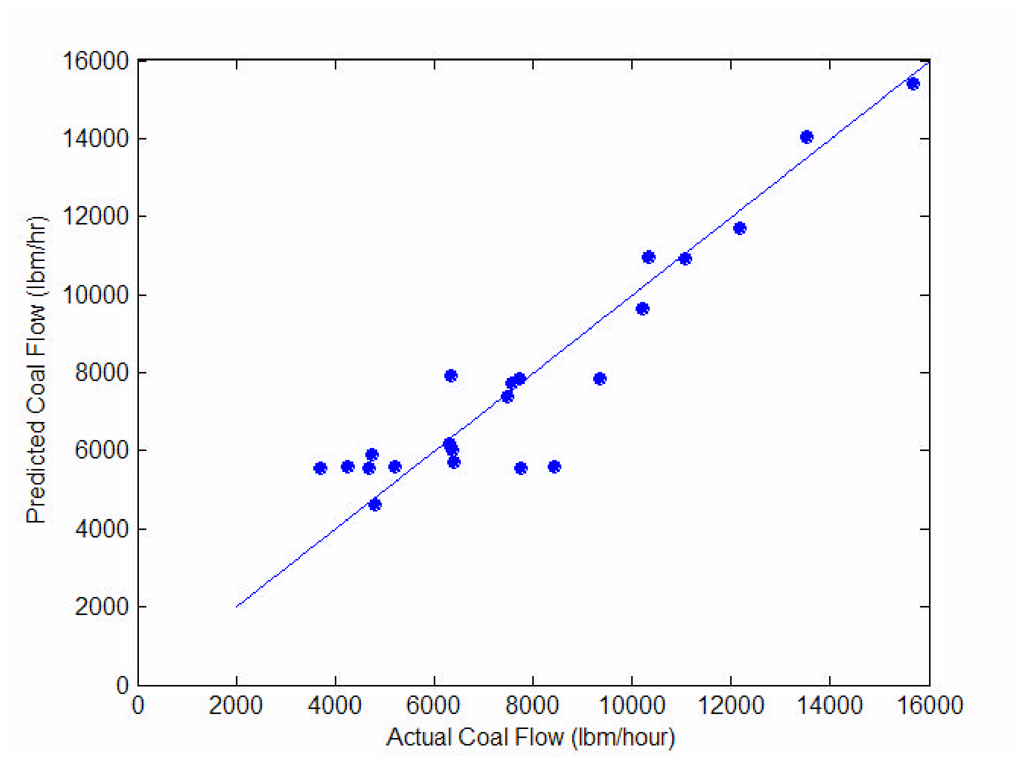

Figure 3. Typical result for magnetically-mounted transducer for a specific mounting location

The results degrade even more markedly when data for the different elbows are combined in one correlation, illustrated in Figure 4. In this case, the correlation considers data for stud-mounted transducers in all 3 mounting situations, including the vertical-to-horizontal elbow, the horizontal-to-vertical elbow, and the horizontal-to-vertical elbow with a roping configuration. The correlation coefficient here is 0.677, far below the level one would consider acceptable in a commercial instrument.

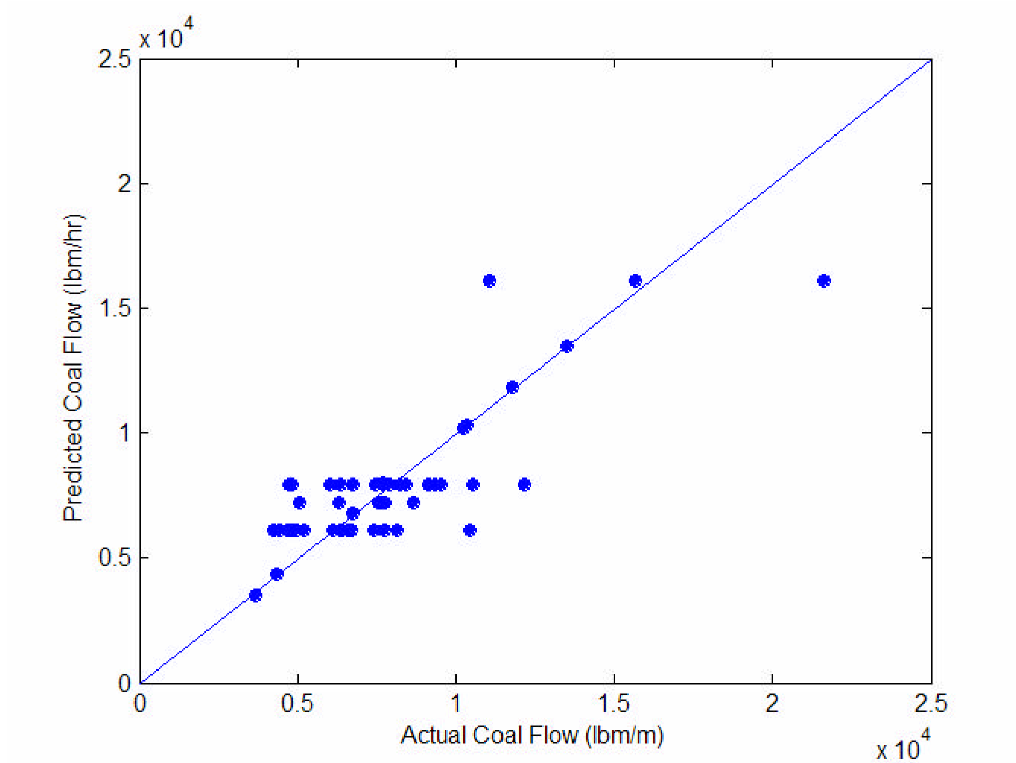

Figure 4. Typical results for a stud-mounted transducer for all elbow mounts

In support of the EPRI program that is co-funding this program, the principal investigator, Dr. Wayne Hill, attended a progress meeting at the Coal Flow Test Facility in Livonia, MI. At this meeting, the overall progress of testing at the facility was presented, including the results presented above and results obtained with two commercial coal flow meters. Amazingly, neither of the commercial instruments fared significantly better in testing than the analysis presented above.

It was discovered in analyzing one of the data files that not all of the noise had been eliminated from the data through the debugging effort early in testing. The first type that was identified is a relatively large amplitude, low-frequency behavior, such as that shown in Figure 5. Assuming that it is simply additive to the otherwise correctly sampled dynamics, this type of noise can be eliminated by digitally high-pass filtering the data. Consequently, it was decided to high-pass filter data files to suppress behaviors below 20 kHz in calculating dynamic signatures for the remaining analysis.

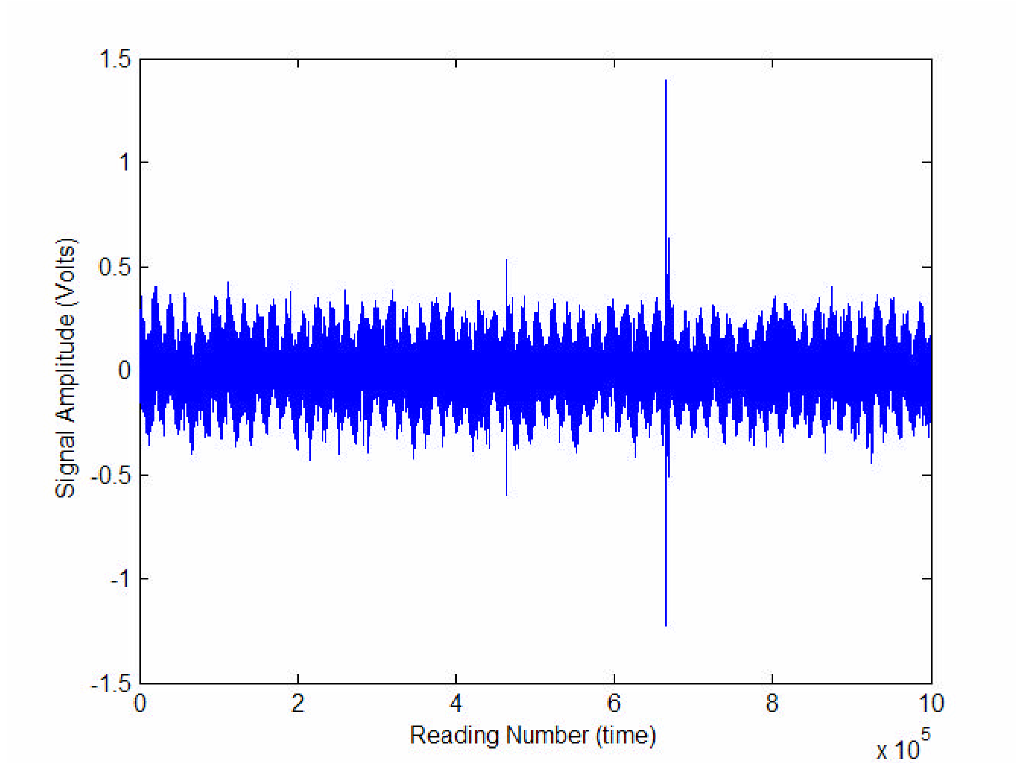

Figure 5. Typical data with low-frequency noise

This example led us to perform an exhaustive examination of all of the data obtained to date. We had not performed this screening earlier because of the sheer volume of data. In this process, each data file was opened, graphed at two different time resolutions, and its power spectrum graphed. Figure 5 above is the result of graphing the first 100,000 data points, comprising a mere 1/3 of a second of data. A second kind of noise is found in graphing the entire data set, shown in Figure 6. The central section of the data has an amplitude that has proven to be typical of the bulk of the "good" data sets. The earlier and later sections presumably suffer from additive noise. When a data file like the one shown in Figure 6 was encountered, the range of data that displayed "normal" amplitude was noted, and signatures calculated for the limited window.

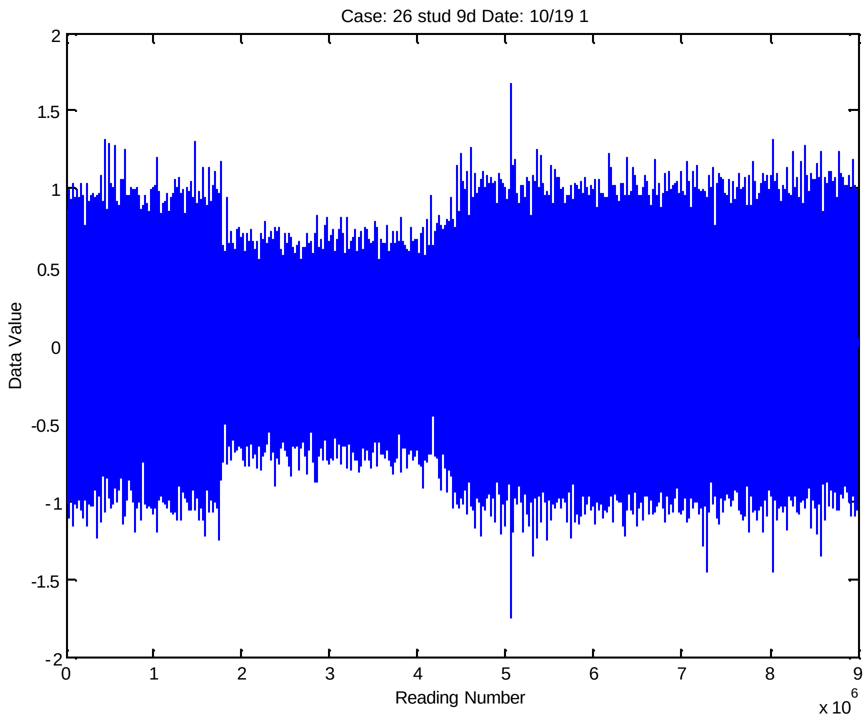

Figure 6. Noise producing a varying signal amplitude

Another form of noise visible in full-file graphs is shown in Figure 7. It is not at all clear what combination of instrumentation, data acquisition, and/or system conditions could produce such a bizarre behavior, but it clearly is not representative of flow dynamics. Such files were discarded out of hand.

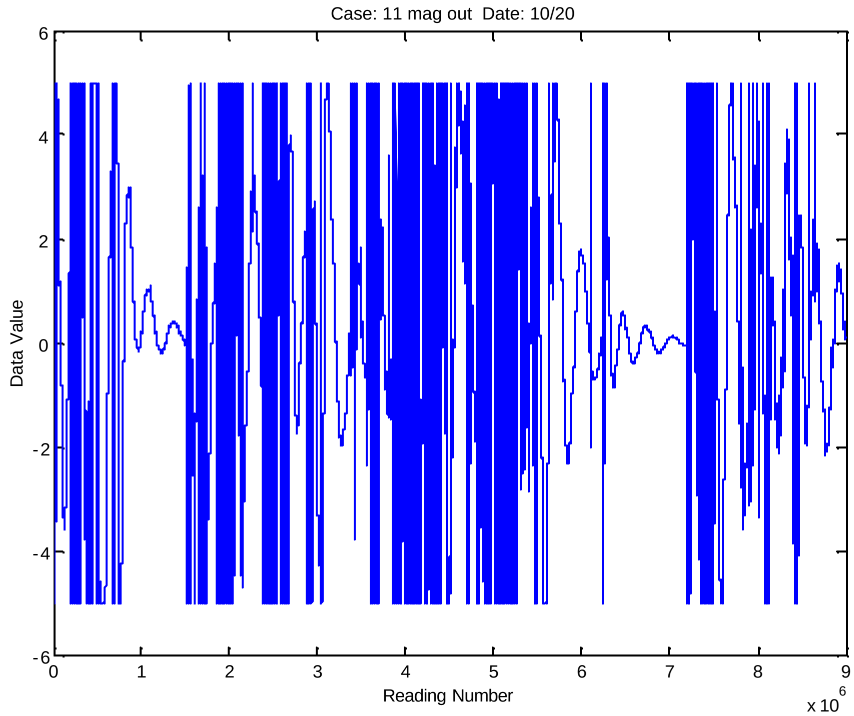

Figure 7. Over-the-top noise

Yet another form of noise can be seen in a power spectrum of a data file, as shown in Figure 8. In this case, the power spectrum is essentially flat from DC up to the roll-off produced by the hardware low-pass filter in the instrumentation package. Such a behavior represents pure white noise, a behavior never encountered in previous Dynamical Instruments development efforts. Again, it is not clear what combination of instrumentation, data acquisition, and/or system conditions could produce such a behavior, so these cases were discarded.

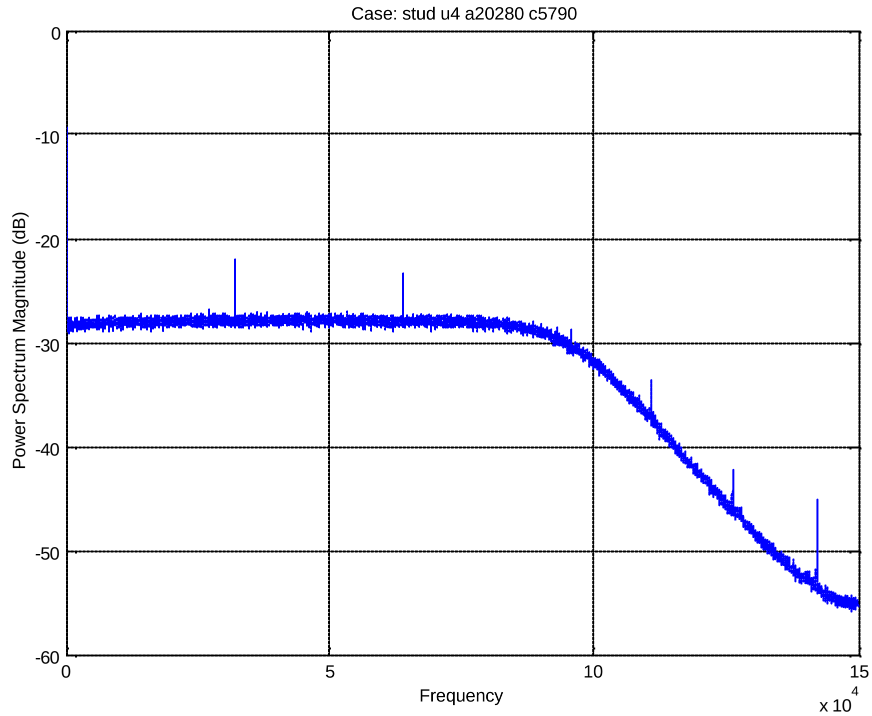

Figure 8. Noise producing a flat power spectrum

A significant number of files were discarded through this screening process. Of the 209 data files in the original scoping data, 28 cases were discarded. Of the 181 files in the more recent calibration set, 38 were discarded. In general, the cases with magnetic mounts tended to be noisier than with the stud mounts: of the 95 stud mount cases in the calibration data, only 12 were discarded, while 26 of the 86 magnetic mount cases were discarded.

Figures 9 and 10 provide an indication that this screening process is on the right track. Figure 9 plots the signal standard deviation calculated for tests performed at a single flow condition with both mount types and various transducer mounting locations. The data had been filtered to pass frequencies between 20 kHz and 75 kHz (the upper limit being chosen to avoid over-emphasizing behaviors at the transducer's resonance in the neighborhood of 85 kHz). A similar graph was presented as Figure 5 in the last quarterly report. This graph looks the same, but identifies the first four points for the magnetic mount as noisy cases. Ignoring these cases, the variation with position is seen to be much smoother.

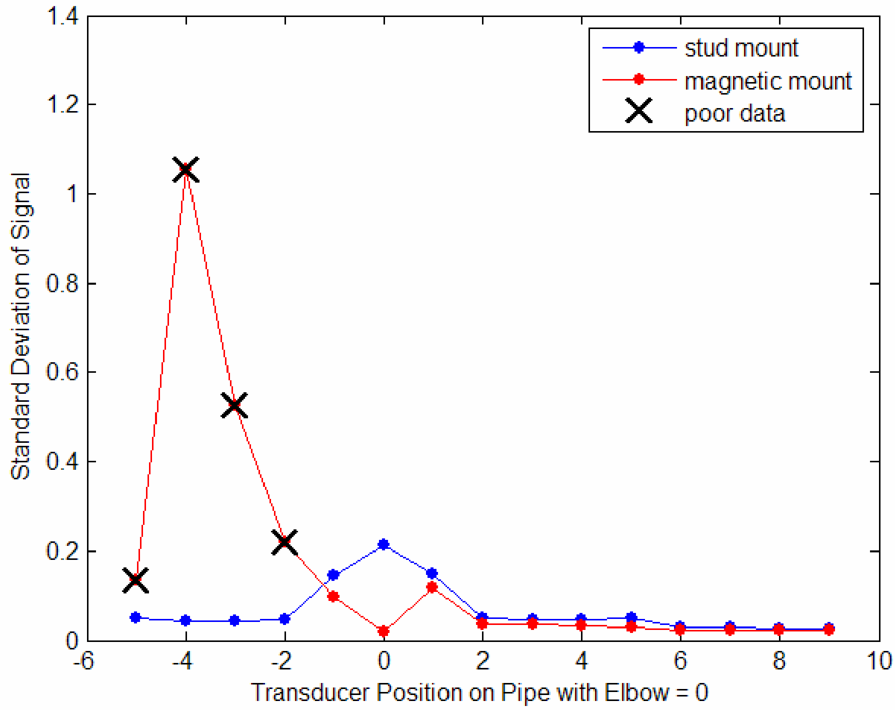

Figure 9. Signal standard deviation as a function of position and mount type

Figure 10 plots the value of another signature quantity as a function of transducer position and mounting type. This figure is similar to Figure 6 from the last quarterly report, but the values of the statistic are now quite different. The reason for this is that filtering the data to eliminate low-frequency behaviors changes the character of the signal. The net result is that, ignoring the four noisy cases, the variation with position is quite smooth.

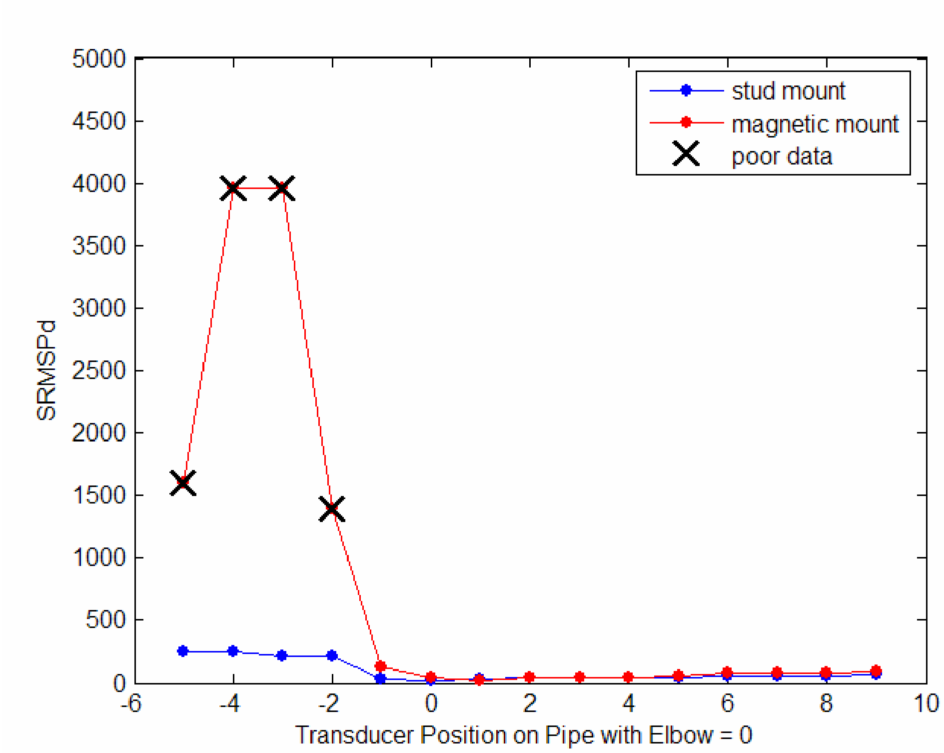

Figure 10. A time measure of the signal dynamics as a function of position and mount type

After eliminating the cases identified as noisy, an attempt was made to correlate all of the magnetically-mounted cases where the transducer was mounted at an elbow outlet. The procedure was repeated numerous times to ensure that the best result was obtained. The analysis typically produced correlation coefficients in the general range of 0.75. This was better than the previous results of less than 0.7, but not to the extent that was hoped for. This was surprising, since there was no particular reason to believe that any of the remaining cases were noisy. It was by sheer accident that one particular correlation was graphed, with the extraordinary result shown in Figure 11. In this case, the overall correlation coefficient was 0.78, but the graph clearly shows that there are 2 separate behaviors. One subset of the cases has an excellent correlation coefficient of 0.994, while the other is essentially uncorrelated (r^2 = 0.014). The well-correlated cases, approximately half of the total, indicate that at least some cases sensitively disclose dynamics that are related to coal flow. The fact that roughly the other half of the cases do not share the same dynamics indicates that there is yet another, as yet unidentified form of noise in some cases. Fortunately, since the uncorrelated cases all fall within a narrow band of predicted flow, it should be possible to discern cases with normal dynamics from those with noisy dynamics.

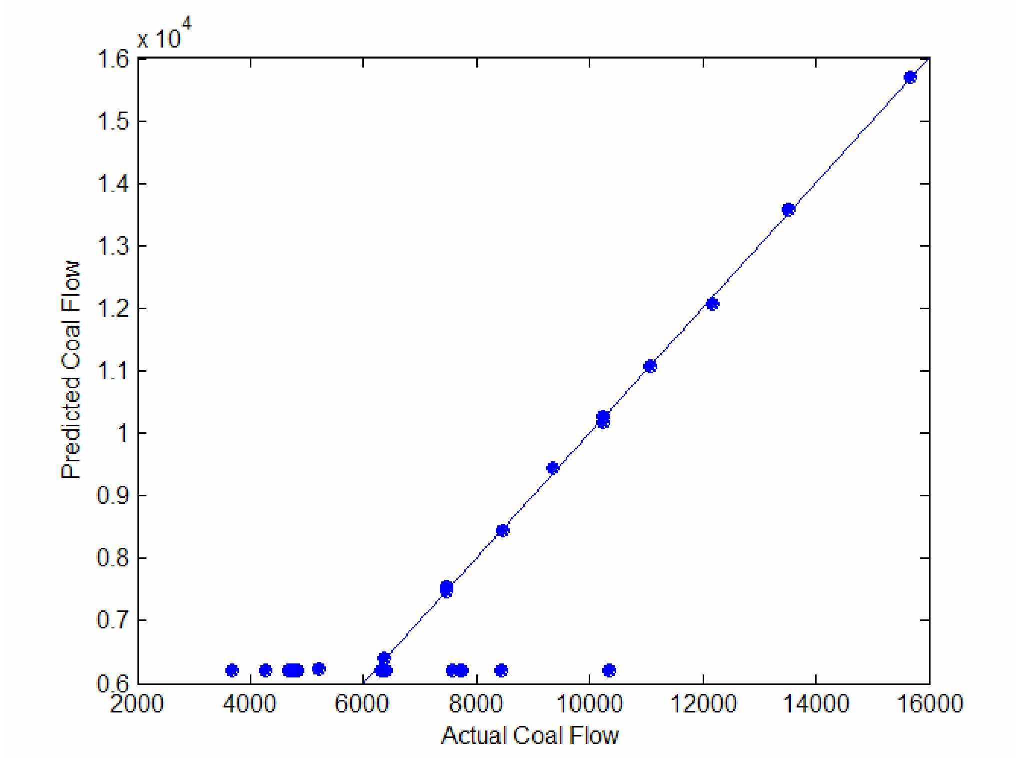

Figure 11. Bimodal correlation obtained with all elbow-outlet magnetically mounted cases after removing identifiably noisy cases

The well-correlated data points in Figure 9 comprise the best result we have encountered with coal flow data in the many data sets we have collected over numerous test efforts, confirming that observed dynamics should be sensitively related to flow. This correlation accuracy is typical of the results we have obtained with the Dynamical Instruments technique in other flow measurement applications.

CONCLUSIONS

The noise identified in the data this reporting period explains a great deal of the trouble that has been encountered in analyzing the data collected to date. The noise can be identified, either by direct analysis of the time series or by comparison of the signal dynamics to non-noisy cases. Still, this does not explain where the noise originates. In addition, the data left after eliminating noisy cases is of such a modest quantity that it is not sufficient to produce a reliable instrument calibration.

Consequently, we feel that additional data should be collected in the Coal Flow Test Facility to complete the instrument calibration before plant testing is undertaken. By piggy-backing on planned EPRI testing at the Test Facility, this testing can be performed at very little cost to the program, but will require an extension to the program schedule. We will pursue a request for an extension in the next reporting period.