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

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ABSTRACT

Instrumentation difficulties encountered in the previous reporting period were addressed early in this reporting period, resulting in a new instrumentation configuration that appears to be free of the noise issues found previously. This permitted the collection of flow calibration data to begin. The first issues in question are the effects of the type and location of the transducer mount. Data were collected for 15 different transducer positions (upstream and downstream of an elbow in the pipe), with both a stud mount and a magnetic transducer mount, for each of seven combinations of air and coal flow. Analysis of these data shows that the effects of the transducer mount type and location on the resulting dynamics are complicated, and not easily captured in a single analysis. To maximize the practical value of the calibration data, further detailed calibration data will be collected with both the magnetic and stud mounts, but at a single mounting location just downstream of a pipe elbow. This testing will be performed in the Coal Flow Test Facility in the next reporting period. The program progress in this reporting period was sufficient to put us essentially back on schedule.

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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 will be obtained using a Coal Flow Test Facility built and operated by our subcontractor, Airflow Sciences Corporation, in support of an EPRI program. In the last reporting period, the test facility became operational, and the first shakedown tests with our instrumentation package were performed. Sample data from these tests proved to be problematic, with cascades of oscillatory behaviors present in the data. Calibration testing could not be undertaken until this was resolved.

Early in this reporting period, a Foster-Miller engineer visited the Coal Flow Test Facility to perform hands-on debugging of the instrumentation package. This effort discovered a combination of issues that produced the observed problems. In order for the accelerometer to be electrically isolated from the coal pipe, it must be mounted on the pipe using an insulating stud. Instead, it was found that a plain steel stud had been used, causing the transducer to respond to any electrical interference that is present on the pipe. This improved the signal response significantly, but not to the desired degree. The remaining issues were resolved by replacing one accelerometer amplifier with another, and a compact filter/amplifier module with a laboratory filter/amplifier. These changes produced a dramatic improvement in the signal quality, so that calibration testing can be undertaken.

Prior to this program, the bulk of past instrument development testing was performed using transducers mounted on studs just downstream of an elbow. It would be advantageous if the transducer could be mounted on a magnetic base, so it could be used in a portable manner for plant balancing efforts, and mounted on the pipe where convenient, rather than at a particular location that may not be readily accessible in some plants. In order for this to be possible, the effects of the type and location of the transducer mount must be understood. A series of tests was performed in the Coal Flow Test Facility to collect data with both magnetic and stud mounts for 15 mounting locations (upstream and downstream of an elbow in the pipe), for seven flow conditions.

Analysis of the data disclosed a complicated variation of the signal dynamics with different types and locations of transducer mounts. The signature quantities from the Dynamical Instruments analysis do not vary simply or smoothly with different transducer locations or mounts. Consequently, developing a "Rosetta Stone" analysis that relates the transducer mount to the observed flow dynamics would require an extremely extensive database; that is, it should be possible, but would require a great deal of data. Since testing with multiple transducer locations is difficult and time consuming, it was decided that a full set of calibration data will be collected with a single mounting location with both stud and magnetic transducer mounts. This calibration testing is scheduled for the next reporting period, with full analysis to be completed in the following period.

The progress in this reporting period returns the program to a comfortable schedule position.

EXPERIMENTAL

The preliminary testing by Airflow Sciences of the instrumentation package in the Coal Flow Test Facility in the last reporting period disclosed issues related to electrical noise. These issues could not be resolved through long-distance consultation of Foster-Miller and Airflow Sciences personnel, so a Foster-Miller engineer, Bruce Barck, traveled to the test facility (in Livonia, MI) to perform hands-on debugging.

Figure 1 schematically illustrates the instrumentation package and the changes that were made. The most crucial issue proved to be the transducer mount: the accelerometer must be electrically isolated from the pipe using an insulated mounting stud, yet a plain steel stud had been used. Stray electrical currents are a common problem in coal piping, because of the tendency of the coal particles to become electrically charged. Consequently, coal piping systems are electrically bonded to reduce the likelihood of a dangerous buildup of electrical charge. With a plain steel mounting stud, any residual electrical currents would affect the output of the transducer directly. By replacing the steel stud with an insulated stud, the main source of noise was eliminated.

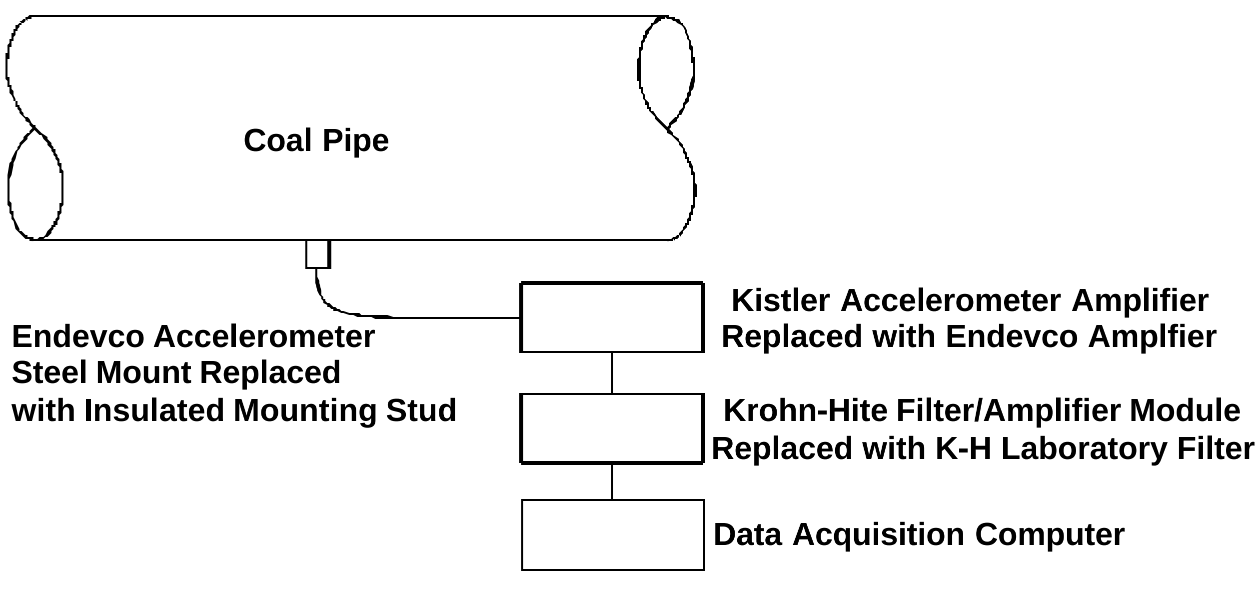

Figure 1. Instrumentation schematic

With the opportunity to test the instrumentation in the operating environment, Mr. Barck examined the performance of each of the other instrumentation subsystems. He found that the noise level of the Kistler Model 504E amplifier was higher than that of an Endevco 133 amplifier he had brought along, so he replaced the Kistler unit with the Endevco one. He also found that the input gain of the compact Krohn-Hite filter/amplifier module was effectively amplifying the noise floor of the accelerometer signal. He remedied this by replacing the filter/amplifier module with a Krohn-Hite Model 2284 filter, a laboratory bench instrument. This instrument was set to have filtering characteristics identical to those of the compact module it replaced, but with input and output gains set to unity. This did not produce any problems, because the noise output of the Endevco amplifier appears to be essentially independent of its own gain. Thus, raising the gain of the Endevco amplifier compensates for the reduced gain of the filter box without raising the noise level. No changes to the data acquisition computer were needed.

The result of these modifications is shown in the power spectrum graph of Figure 2. The red trace in this figure is the power spectrum of no-flow data from the initial shakedown testing from the previous reporting period. The blue trace is the power spectrum of no-flow data after the instrumentation was modified. Both traces reflect data collected with the blower inverter power supply turned on, so the principle likely source of electrical noise was present. As the two traces show, the signal is now quite a bit cleaner than previously. The strong variation in the red trace at low frequencies, which probably reflected amplifier noise, is now greatly diminished. In particular, there is essentially no component of 60 Hz and its harmonics. In addition, the strong lines at higher frequencies are nearly gone.

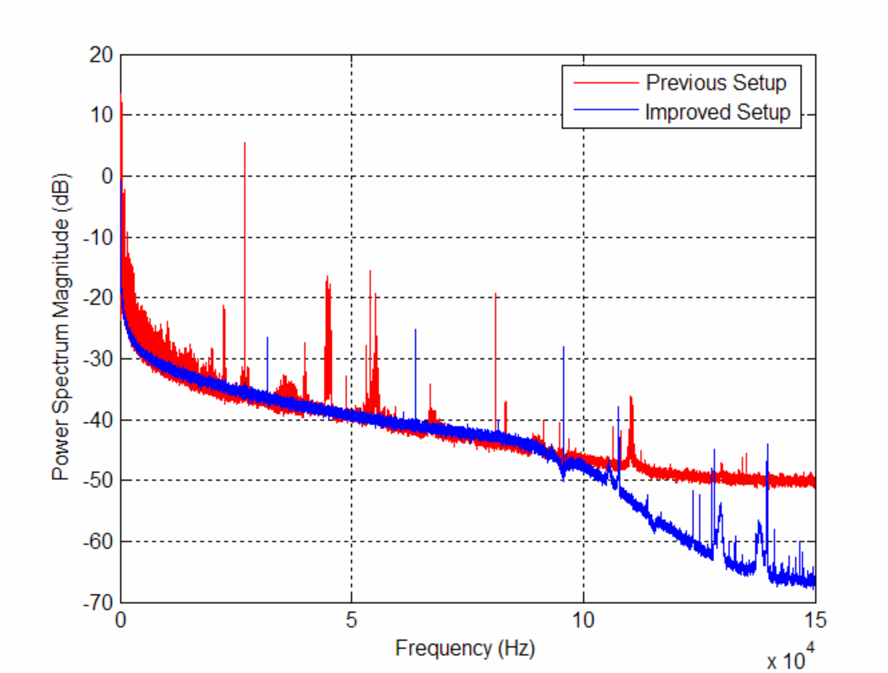

Figure 2. Power spectra of no-flow data before and after improvements

The improvement is just as clear when flow is present in the pipe, as shown in Figure 3. In this case, the flow conditions for the two data files are similar. The characters of the two signals are quite different. With the improved instrument setup, the low-frequency noise seen with the previous setup is strongly suppressed, and the numerous strong frequency lines are essentially absent. With this major improvement to the instrumentation setup, collection of calibration data could begin in earnest.

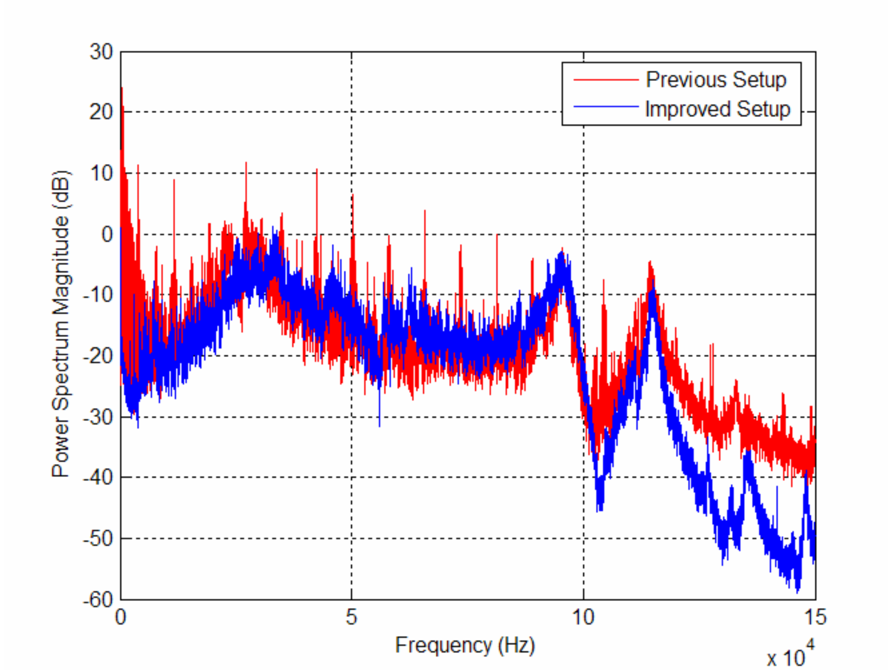

Figure 3. Power spectra of data with flow before and after improvements

One of the issues of this instrument approach that has remained unsettled for the entire development effort (approximately 10 years) is how the type and location of the transducer mount affects the dynamics of the data and how the instrument calibration can accommodate this. The transducer has historically been mounted just downstream of an elbow, on the outside of the bend, using a stud threaded into the pipe wall. This has always worked well, but there are two reasons to consider alternative mounts:

- Although elbows are commonplace in coal piping systems, an elbow is not always situated in a readily accessible location. Thus, it would be advantageous if the transducer could be mounted in other locations without loss of accuracy.
- Although a stud mount is suitable for a permanent instrument installation, one market of great interest is for portable instruments, either to be used by plant personnel or by contractors who do plant balancing. For a portable instrument, a magnetic transducer mount would be highly advantageous.

The availability of the Coal Flow Test Facility provides an excellent opportunity to address these issues. As a first step in developing a coal flow instrument calibration, data were collected with many mounting locations and two mount types:

- Fifteen mounting locations (illustrated schematically in Figure 4), beginning 5 pipe diameters upstream of the middle of an elbow, and moving one diameter at a time downstream, ultimately to a point nine diameters downstream of the elbow.
- Two mount types, including a stud threaded into the pipe wall and a magnetic mount.

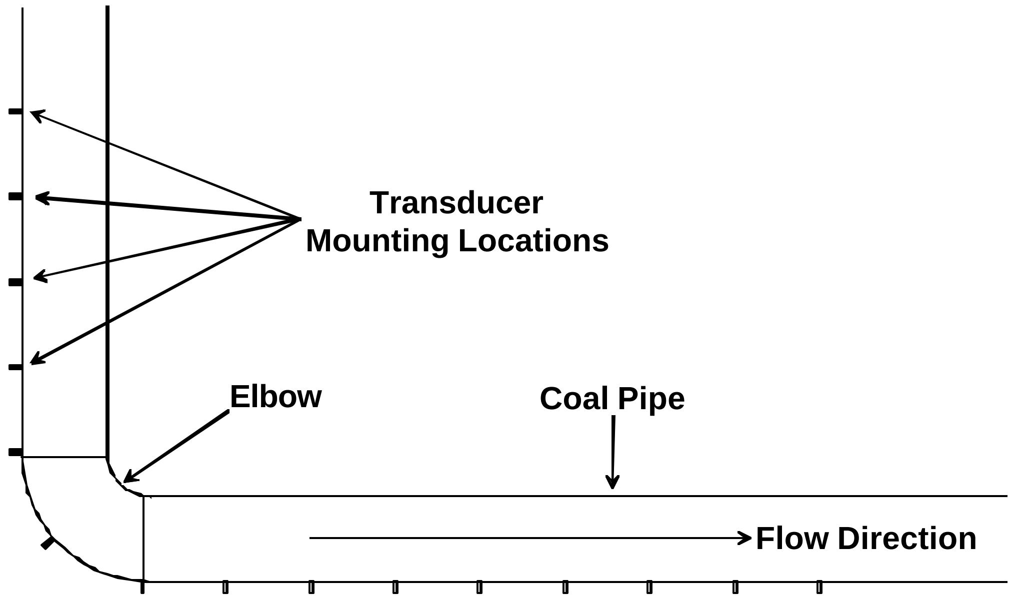

Figure 4. Schematic illustration of transducer mounting locations

Although only 7 flow conditions were visited in this testing, as outlined in Table 1, these conditions covered a broad range of air flow velocities and air/fuel ratios. Thus, although these tests do not fill the operating space, they visit conditions that should include the range of dynamics encountered in practice.

Table 1. Flow Conditions Visited in Scoping Testing

Flow Condition	Air Flow (lb/hr, (kg/s))	Air Velocity (ft/s, (m/s))	Coal Flow (lb/hr, (m/s))	Air/Fuel Ratio
1	11060 (1.394)	52.2 (15.9)	3690 (0.4649)	3.00
2	11060 (1.394)	52.2 (15.9)	11060 (1.394)	1.00
3	15670 (1.974)	73.9 (22.5)	0	inf
4	15670 (1.974)	73.9 (22.5)	5220 (0.6577)	3.00
5	15670 (1.974)	73.9 (22.5)	15670 (1.974)	1.00
6	20280 (2.555)	95.6 (29.2)	5790 (0.7295)	3.50
7	20280 (2.555)	95.6 (29.2)	13520 (1.704)	1.50

The resulting data files, filling 7 compact disks, were sent to Foster-Miller for analysis.

RESULTS AND DISCUSSION

The analysis of the data from the transducer mount scoping tests was the first application of the Dynamical Instruments analysis technique in this program. Although a full discussion would be too long to be included in this report, the Dynamical Instruments technique involves calculating a large number of easily computed statistics that characterize the temporal variation of the accelerometer signal. Some of these statistics are rather mundane, such as the standard deviation of the signal, while others seem strangely esoteric, such as the RMS integral of events above the mean plus standard deviation. Each of these statistics is chosen to characterize different aspects of the signal, or a given aspect of the signal in a different way. In all, we commonly use 57 such quantities with signals like that from an accelerometer, but have often augmented these statistics with quite a few others, as seems appropriate for a given new application. These statistics form a candidate population of signal features from which one might select a subset that comprises a "signature" of the dynamics of the signal. Whenever the same flow condition is visited, these same quantities will be encountered, so that one could recognize that condition. Further, as the flow conditions are changed, the signature quantities change in a consistent manner so that various flow conditions can be recognized from the values. This approach is the basis for this instrument development effort, and is the subject of 5 US patents and numerous foreign patents in force or pending.

In analyzing the transducer mount scoping data, we were only interested in the effects of the type and location of the transducer mount on the signal dynamics, as reflected by the signature quantities. Thus, we were not interested at this point in relating the signature quantities for each data file to the flow conditions, but instead were studying the effects of the type and location of the transducer mount on the signature quantities calculated for a given flow condition. If the statistics vary in a relatively simple manner with transducer location, then there is excellent reason to believe that a universal calibration could be found that predicts flow parameters (coal flow, air flow, and coal fineness) irrespective of transducer mounting location. Similarly, if the effect of the transducer mounting type (stud or magnetic mount) on the statistics is relatively simple, then the application of the instrument could be broadened even further.

Our analysis of the scoping data indicates that there are strong effects of the type and location of the transducer mount on the signature quantities. Example results are presented in Figures 5 and 6, from flow condition 5 (equal air and coal flows of 15,670 lb/hr). Figure 5 graphs the standard deviation of the signal as a function of position for both the stud and magnetic mounts. One striking feature of this graph is how different the variation with position is for the two different mounts. For the stud mount, position 6 (corresponding to the outlet of the elbow) produces the strongest signal, with the signal becoming weaker in a manner that is essentially symmetrical for positions upstream and downstream of this location. This behavior can be seen in quite a few of the signature quantities that measure the amplitude of the signal. By contrast, the behavior of the magnetic mount is quite different, with the signal at position 6 being weaker than any other location. The very strong behavior at position 2 may or may not be real, as the signature quantities for this particular run were often anomalous compared with the other cases. Both mounts produce similar results for positions well downstream of the elbow.

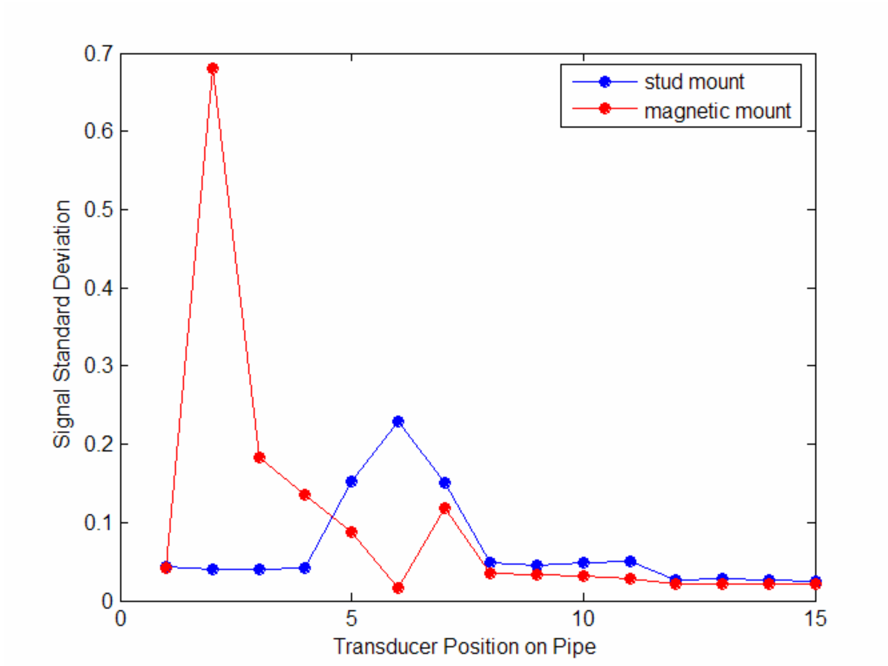

Figure 5. Standard deviation of signals as functions of transducer position and mount

The signature quantity shown in Figure 6 is a measure of the period for the passage of the largest events in the signal. Larger values for this statistic reflect a longer interval, on average, for the passage of large disturbances. The behaviors for the stud and magnetic mounts are somewhat similar for locations downstream of the elbow, but markedly different for locations upstream of the elbow. The large value of this quantity for the magnetic mount at position 3 is unrelated to the behavior shown in Figure 5 (which was at position 2), and appears to be real.

The results for other flow conditions were generally similar to the results shown in Figures 5 and 6, with quite a bit of variation in the behaviors of some signature quantities with position and mount type. The net result is that there does not appear to be a simple means of identifying the effects of the mount type and position of the transducer on the signal dynamics.

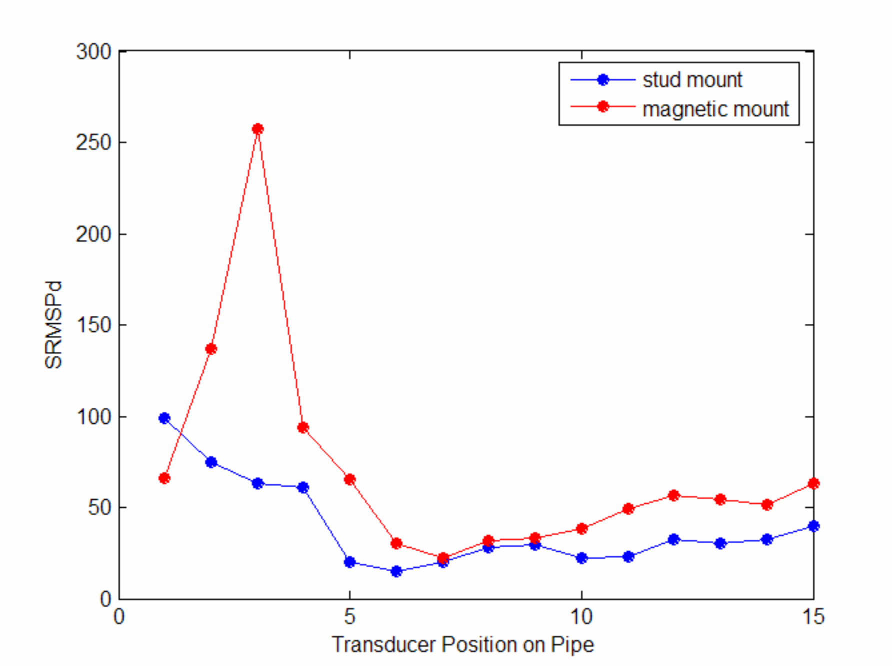

Figure 6. A time measure of the signals as functions of transducer mount and position

CONCLUSIONS

The results of the analysis described above do not indicate that a universal correlation is unachievable. In fact, we are utterly convinced that this is possible. There must be identifiable effects of mounting type and location on the signal dynamics, but there is no requirement that these effects be simple. In principle, given enough experimental data, these effects can be "learned" by a suitable analysis, so that the flow conditions can be determined for any reasonable transducer mounting type and location. The problem is that developing such an analysis could potentially require a very large quantity of data, which cannot be obtained within the constraints of this program. Instead, the objective of the current program is to develop commercially viable instrument systems for both fixed and portable applications, and limiting the transducer installation to specific locations is a reasonable compromise at this point. Experience gained through field use may provide the data required to expand the instrument calibration to different transducer locations, but it appears that the best approach for the current program is to concentrate on the issues that are of greatest interest:

- Given a standard transducer mounting position (at the outlet of an elbow), can we generate an instrument calibration that works favorably for a variety of pipe sizes and coal flows?
- Can both magnetic and stud mounts be accommodated?

To answer these questions, we have directed our subcontractors at Airflow Sciences to collect extensive calibration data for transducers mounted at the outlet of an elbow, with both stud and magnetic mounts. These data will be collected and analyzed in the next reporting period. We will also continue to analyze the data described above to determine whether a universal calibration might be determined without extremely extensive experimentation.