ELECTRIC POWER RESEARCH INSTITUTE

EPRI Coal-Flow Loop

Addendum to Assessment of On-Line Coal-Flow Measurement Technologies

Technical Report

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PRODUCT DESCRIPTION

Power boilers fueled by pulverized coal are known to encounter fuel distribution challenges during normal operation. One of these challenges is the uniform delivery of air and pulverized coal to individual burners. Optimum combustion in a boiler requires careful control of coal and air flow to individual burners. However, measuring the mass flow rate of pneumatically conveyed pulverized coal in burner feed pipes, either by conventional extractive methods or by more recent online *in situ* approaches, is challenging and has been an area of considerable research for more than a decade. This addendum report presents results for two more online *in situ* instruments in addition to a brief summary of the findings from EPRI report 1010318 (December 2005) as part of Phase I of air and coal flow measurement studies at the EPRI Coal Flow Loop (CFL).

Results & Findings

Five online technologies participated in Phase I of this study: ABB's PfMaster™, MIC's mic One, TR-Tech's ECT Star, AMC's PfFlo III, and SWR's SolidFlow. Results of this study have helped to clarify how these online coal-flow measurement technologies respond under controlled test conditions. These technologies provide an indication of coal-mass flow while contending with the complexities inherent to the transport of pulverized coal by pneumatic systems This study found that the participant technologies bear unique responses under similar test conditions, and most exhibited a range of measurement uncertainties dependent on either transport velocity changes, distance from flow disturbances, or changes in air temperature.

Challenges & Objective(s)

This report is designed for plant personnel responsible for coal-flow measurement and mill balancing who are using or are considering the use of *in situ*, real-time measurement technologies. The challenge for users of these systems is to interpret observed instrument output and to gain confidence in their accuracy. The main objective of this study is to increase understanding of the online instruments' performance when these are subjected to carefully controlled conditions.

Applications, Values & Use

By clarifying the response of online instruments to various conditions encountered at power plants, this report helps engineers and operators understand how certain plant conditions affect the response of these technologies. The selection of a particular technology for a specific power plant application can be better assessed when the strengths and limitations of technologies are known. Since coal piping design and physical operating conditions are often unique to each power plant, operators can use the information in this report as a tool for better assessing the applicability of these measurement devices at their plants.

EPRI Perspective

Boiler performance and emissions control are highly dependent on burner-to-burner fuel balancing. However, most investigations of online coal-flow measurement, at actual power plants, have been performed with limited knowledge of the measurement uncertainty surrounding these tests. Results of these field tests have often been ambiguous or inconclusive. In addition, as technology evolves and improves, companies offer new measurement products to the industry, and the challenge to determine their measurement accuracy is always important. EPRI's Coal-Flow Measurement and Control Laboratory, or Coal-Flow Loop (CFL), was built to provide a controlled environment where technologies to measure and control pulverized-coal flow could be assessed with confidence.

Approach

CFL was constructed and commissioned in early 2004. Assessments of both manual extractive and online measurement technologies have been carried out over the last two years to elucidate the primary conditions that may influence their performance. This effort completes Phase I of a study to evaluate pulverized-coal-flow measurement methods, including extractive techniques and online *in situ* instrumentation, and adds material to that presented in EPRI report 1010318.

Keywords

Coal-flow measurement
Coal-flow control
Pulverized coal
Pneumatic conveying
Online measurement
In situ measurement

ABSTRACT

This report is targeted at plant personnel responsible for coal-flow measurement and mill balancing that are using or are considering the use of online, *in situ* measurement technologies. Optimum combustion in a boiler requires careful control of coal and air flow to individual burners. Measuring in near real-time the mass flow rate of pneumatically conveyed pulverized coal in burner feed pipes is a critical element of such control. This report summarizes the findings for two online coal-flow instruments tested at EPRI's Coal-Flow Loop (CFL). Study results have helped clarify the response of various instruments that are currently offered to the power industry. Online or real-time measurement technologies attempt to provide an indication of coal-mass flow while contending with the complexities associated with pulverized-coal transport. This study found that the technologies exhibit a range of measurement uncertainties dependent on either transport velocity changes, distance from flow disturbances, or changes in air temperature. This effort is part of the first phase of a study assessing pneumatically conveyed pulverized-coal-flow measurement methods, including extractive techniques and online *in situ* instrumentation. Five online technologies participated in Phase I of this study: ABB's PfMaster™, MIC's mic One, TR-Tech's ECT Star, AMC's PfFlo III, and SWR's SolidFlow.

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Instrument Vendor	Participant(s)
Foster Wheeler North America	Mr. John Grusha and Mr. Tony Mosca
TR-Tech Oy	Dr. Tomas Rosin
SWR Engineering Messtechnik GmbH	Dr. Ralf Schmedt and Mr. Bernhard Poole

PREFACE

This report summarizes the results of tests conducted at the EPRI Coal-Flow Measurement and Control Laboratory or Coal-Flow Loop (CFL). The tests were conducted in cooperation with industry vendors of technologies offered to the power industry to measure pneumatically conveyed pulverized coal. Representatives from various organizations assisted in the review of the early drafts. Instrument suppliers were given the opportunity to comment on the drafts for their respective instrument. Supplier comments, if submitted, are presented in their original form in each respective instrument appendix.

The information in the report is intended for planning purposes only and it is not intended to be comparative assessment of competing technologies. The inclusion or exclusion of equipment suppliers or vendors in this effort is not intended to be an endorsement or disapproval of any one technology, respectively.

In spite of best efforts to design experiments that simulate power plant conditions through execution of a robust test matrix, differences between the simulated conditions and actual power plants were sometimes inevitable. Therefore, actual power plant experience with any of these instruments may depend on plant specific factors.

EXECUTIVE SUMMARY

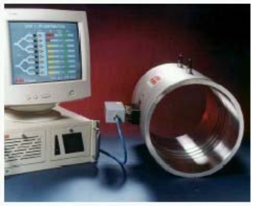
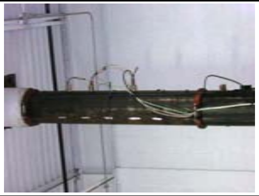
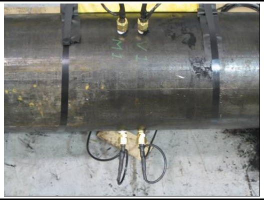
Achieving optimum combustion within a boiler requires careful control of coal and air flow to individual burners. A critical element of such control is the ability to measure, in near real time, the mass flow rate of pneumatically conveyed pulverized coal in the coal pipes feeding the burners. The measurement of pneumatically conveyed pulverized fuel (Pf) is challenging, and has been the subject of considerable research for more than a decade. Several instruments have recently been introduced to the power boiler market for this purpose. EPRI and its members have traditionally conducted tests of such technologies at host power plants. However, the ambiguous results from these studies have pointed toward the assessment of these technologies under better known and controlled conditions. To address this need, EPRI built the Coal-Flow Measurement and Control Laboratory or Coal-Flow Loop (CFL). This state-of-the-art facility can simulate pulverized coal transport under known conditions. In combination with tailored test matrices designed to encompass a range of primary conditions typically found in power plants, the CFL offers the capability to precisely assess measurement technologies. The CFL's capabilities are summarized in Section 2 of this report and detailed further in EPRI Technical Report 1004743, *Coal-Flow Loop: System Description and Commissioning.*

The results for the first three instruments assessed under this program were summarized in report 1010318 (December 2005). This report presents the results two more on-line coal flow instruments: the ECT PFflow™ by TR-Tech that is supplied by Foster Wheeler Corporation and the SolidFlow PF that is supplied by German Company SWR Engineering Messtechnik GmbH. As in the past study, the goals of this effort were to assess instrument performance under a wide range of conditions encountered in typical power plant applications such as instrument installation location, changes in air and/or coal flow rate, changes in air temperature, and proximity to an orifice.

Study Approach

Each of the coal flow meters was evaluated with a similar test program (with differences noted in the specific chapter for each instrument). The baseline test matrix measured three principal parameters to quantify instrument performance: (1) the effect changes in air transport velocity, (2) the effect to changes in air to coal ratio, and (3) the effect of instrument installation location. The baseline tests were followed by tests to assess other factors present in power plants such as the effects of upstream and downstream orifices, and the effect of air temperature changes. The test matrix included 12 test conditions which enveloped a combination of air to coal ratios and three air transport velocities. Details of the test matrix are presented in Section 3. A brief description of each technology is summarized in Table ES-1. Detailed descriptions are provided on each instrument section.

Table ES-1
Summary of instruments that participated in EPRI study

Name	Photo	Description	Contact:
PFMaster		One electrostatic ring sensor spool customized to pipe diameter. Pre-calibrated at factory	Mr. Steven McCaffrey Greenbank Energy Solutions, Inc 185 Plumpton Ave Washington, PA 15301 724 794-3300 Fax: 724 794-3400 Greenbankenergy@aol.com
MIC One		Three microwave sensors positioned 120 degrees apart. Non-instrusive but requires three ½" (15mm) holes in pipe for mounting. Field calibration procedure	Alan Jensen MIC USA LLC 330 904-6750 alan.jensen@earthlink.net
PfFlo III		2 – 4 microwave sensors positioned over 4 pipe diameters as per vendor specification. Intrusive probes and sensor rods Field calibration procedure	Dean DeBaun, President Air Monitor Corp. 1050 Hopper Ave Santa Rosa, CA 95403 707 544-2706 ddebaun@airmonitor.com
ECT		3-6 electrostatic Intrusive antennae 5/8" holes in pipe required for mounting Field calibration procedure	John Grusha Foster Wheeler Corp Perryville Corporate Park Clinton, NJ 08809 908 713-2270 John_Grusha@fwc.com
SolidFlow		Three microwave sensors positioned 120 deg apart on a pipe plane Non-instrusive but requires special welded mount coupling Field calibration procedure	Ralf Schmedt SWR Engineering Messtechnik GmbH Mittlerer Weg 22 D - 79424 Auggen Fon ++49 7631 10 50 1 schmedt@swr-engineering.com

Study Results

In order to present a generalized summary of the instrument performance, the following metric parameters were used throughout this study: Uncertainty, sensitivity and normalized sensitivity and are defined as follows:

Uncertainty: a measure of how well an instrument output fits a best-fit-straight-line (BFSL) calculated for all the test matrix data points for a single test location. A value of zero uncertainty means that all points fall exactly on a BFSL.

Sensitivity: an indicator of the impact on instrument output from measurement at different test locations. Sensitivity is the slope of the BFSL (determined for uncertainty) at a given location. If sensitivity changes with location, the instrument output and actual coal flow linear relation between different locations may not be equivalent.

Normalized Sensitivity: This parameter is used to determine the impact of instrument location. It is found by dividing the sensitivity at each location by the sensitivity calculated at the location with most uniform air and coal profiles (1V15 first vertical leg, 15 diameters from downstream 90 degree bend).

These metrics are presented in tabular form for each instrument at each test location. In light of the observed behavior from most of the instruments, and for the interest of the reader, statistical results are presented with and without the results of the low range air velocity of 75 ft/s (23 m/s). In addition to the TR-Tech and SWR instrument results, summaries from the ABB, MIC and Air Monitor instruments are presented as well.

ES.1 ABB/Greenbank PfMaster™ Results

For the PfMaster assessment, the vendor supplied two instruments one which was fixed at location 1V15 and the other which was moved around to different locations. Thus, this test enabled the comparison of one instrument to the other under the same test run. The PfMaster calculated sensitivity and uncertainty results are summarized in Table ES-2. A left to Right ratio is also presented in the table and represents the signal ratio from the “mobile” sensor to the one fixed at 1V15. From this table and the other matrix tests, the system was found to have the following performance characteristics:

- The instrument output is sensitive to installation location and proximity to bends. Output signal could be up to 38% lower and up to 262% higher than at the 1V15 Location.
- The output signal is highly sensitive to transport velocity. This appears to be the primary reason for the high measurement uncertainty which ranged from ±23% to ±42%. Omitting the 75 ft/s (23 m/s) air velocity tests, uncertainty is significantly reduced for most locations.
- The output is highly sensitive to the presence of an upstream orifice but not sensitive to a typical downstream orifice.
- The output is somewhat sensitive to a 25°F (14°C) change in air temperature.

One notable point from this assessment was the upward signal drift over time observed during commissioning. The drift increase was on the order of 1% per day until a steady state was reached after several days. In spite of arduous efforts by ASC and EPRI, the cause of this observed behavior remains unknown.

Table ES-2
PfMaster Sensitivity and Uncertainty Summary

	All Velocities				75 ft/s (23 m/s) Omitted			
Location	**Sensitivity**	**Normalized Sensitivity**	**Uncertainty**	**Right/Left Ratio**	**Sensitivity**	**Normalized Sensitivity**	**Uncertainty**	**Right/Left Ratio**
1V15	2.99E-03	1.00	30.5%	1.04	2.56E-03	1.00	19.7%	1.01
1V11	3.85E-03	1.29	26.9%	1.09	3.44E-03	1.34	20.7%	1.10
1V7	4.98E-03	1.67	25.2%	1.52	4.75E-03	1.86	15.6%	1.57
1V3	6.14E-03	2.05	23.5%	1.95	5.73E-03	2.24	13.6%	1.99
3V15	4.17E-03	1.39	42.6%	1.23	3.29E-03	1.29	18.0%	1.15
3V7	5.29E-03	1.77	28.5%	1.69	4.65E-03	1.82	17.7%	1.61
3V3	7.83E-03	2.62	29.3%	2.35	7.12E-03	2.78	16.4%	2.33
1H55	1.84E-03	0.62	23.3%	0.49	1.78E-03	0.70	21.5%	0.52
1H33	2.51E-03	0.84	37.2%	0.74	2.06E-03	0.80	16.3%	0.73

ES.2 Mic *One* Mobile Results

Mic *one* mobile sensitivity and uncertainty results are summarized in Table ES-3. As only one MIC system was tested, the sensitivity values calculated in reference to Location 1V15. The following performance characteristics were observed:

- The instrument is sensitive to installation location. Instrument output ranged from 33% lower to 80% higher than at Location 1V15 as indicated by the Normalized sensitivity range.
- The instrument shows some sensitivity to air transport velocity. Uncertainty values ranged from ±12% to ±23% and improved slightly when the lower velocity tests were not taken into account.
- The instrument output was not affected by a 25°F (14°C) increase in air temperature at Location 1V15 but did experience an 8% drop in output at the more stratified coal flow location.
- The instrument is sensitive to the presence of an upstream orifice but is not affected by a downstream orifice.

Table ES-3
Mic one mobile Sensitivity and Uncertainty Summary

	All Velocities			75 ft/s(23 m/s) Omitted		
Location	**Sensitivity**	**Normalized Sensitivity**	**Uncertainty**	**Sensitivity**	**Normalized Sensitivity**	**Uncertainty**
1V15	1.54E-02	1.00	13.0%	1.60E-02	1.00	12.3%
1V11	1.38E-02	0.90	12.1%	1.37E-02	0.86	14.3%
1V7	2.21E-02	1.44	17.5%	2.41E-02	1.51	10.7%
1V3	2.77E-02	1.80	20.1%	3.06E-02	1.91	11.0%
3V15	1.69E-02	1.10	18.8%	1.61E-02	1.01	16.3%
3V7	2.45E-02	1.59	23.7%	2.50E-02	1.56	26.7%
3V3	1.38E-02	0.90	12.5%	1.37E-02	0.86	11.6%
1H56	1.03E-02	0.67	22.8%	1.12E-02	0.70	12.3%
1H33	1.38E-02	0.90	12.1%	1.37E-02	0.86	13.8%

ES.3 Air Monitor Pf-*FLO*-III Results

Table ES-4 summarizes the sensitivity and uncertainty values for this instrument. Only one Pf-*FLO* III system was tested thus the sensitivity values are calculated in reference to Location 1V15. Based on these results, the system was found to have the following performance characteristics:

- The mass flow output is sensitive to installation location as evidenced by the observed sensitivities. Under highly stratified conditions, the instrument output nearly doubled.
- The mass flow output signal shows some sensitivity to air velocity. The uncertainty range spans from +/-15.4% to +/-34% when all three air velocities are compared. Excluding all of the 75 ft/s (23 m/s) data greatly improves the instrument uncertainty in the range of +/-3.3% to +/-36.4%.
- Due to environmental constraints, the effect of air temperature test was not completed.
- The output is only slightly sensitive to the presence of an upstream orifice and not sensitive to a downstream orifice.

The Pf-*FLO* III system indicated a layout condition during some of tests at the horizontal locations. Therefore, the data for those tests is highly affected and is not accounted during the statistical analysis.

Table ES-4
Pf-FLO III mobile Sensitivity and Uncertainty Summary

	All Velocities			75 ft/s (23 m/s) Omitted		
Location	Sensitivity	Normalized Sensitivity	Uncertainty	Sensitivity	Normalized Sensitivity	Uncertainty
1V10.5	4.61E-03	1.00	21.7%	4.21E-03	1.00	4.7%
1V6.5	4.86E-03	1.06	22.0%	4.37E-03	1.04	3.3%
1V2.5	5.34E-03	1.16	15.4%	4.96E-03	1.18	6.1%
3V10.5	5.54E-03	1.20	26.6%	5.11E-03	1.22	15.0%
3V6.5	6.21E-03	1.35	34.4%	5.82E-03	1.38	36.4%
3V2.5	9.50E-03	2.06	27.6%	8.65E-03	2.06	21.7%
1H47	9.01E-03	1.96	74.9%	5.55E-03	1.32	10.0%
1H29	7.42E-03	1.61	74.7%	4.93E-03	1.17	5.8%

ES.4 Foster Wheeler / TR-Tech ECT Star Results

Table ES-5 summarizes the calculated performance values for this system. The following observations are offered:

- The instrument output is sensitive to installation location. This is shown in the sensitivity values of Table ES-4. In addition, since the ECT was calibrated to provide an absolute measurement indication a unity value is expected for optimum sensitivity. Evaluating the instrument on that basis, the instrument reads 36% lower and 11% higher than the coal loop indication depending on location.
- The coal mass flow output signal is slightly affected by a change in air velocity. While the effect is negligible at the locations in the first vertical (1V), at the locations in the third vertical (3V) the instrument output at 75 ft/s (23 m/s) is lower than the output at the other velocities. The uncertainty of the instrument from all tested locations ranges from +/-7.1% to +/-16.0%. Note that omitting the lower velocity is not possible in this instance because this velocity was one of the two instrument calibration points.
- The tests to evaluate the influence of an orifice were inconclusive due to calibration and procedural inconsistencies.
- A 25°F (14°C) increase in air temperature yielded an 11% decrease in output at Location 1V15 and 27% drop in output at the more stratified double bend location.

Table ES-5
ECT Star System Sensitivity and Uncertainty Summary

	All Velocities		
Location	**Sensitivity**	**Normalized Sensitivity**	**Uncertainty**
1V15	0.684	1.00	13.3
1V11	0.667	0.97	8.5
1V7	0.707	1.03	9.5
1V3	1.000	1.46	7.1
3V15	0.730	1.07	16.0
3V11	0.641	0.94	13.3
3V7	na	na	na
3V3	1.112	1.62	9.2
1H50	na	na	na
1H20	na	na	na

na = data not available

ES.5 SWR Engineering SolidFlow Results

Two sets of data pertaining to the SWR instrument are presented in this report. The first set was collected using the typical calibration method, as advised by SWR, and the second set was collected using an alternative calibration method.

Typical Calibration Method Conclusions

Based on the data reduction for tests conducted using the standard or most typically used calibration procedure, the following observations of the performance characteristics can be made:

- Sensitivity and Normalized Sensitivity are also summarized in Table ES-6. Normalized sensitivity ranges from 0.69 to 6.33 for all tested locations. The data suggests that the instrument is highly sensitive to installation location. For example, the instrument indicated readings 6.33 times higher at Location 3V3 than for the same test conditions at Location 1V15. Excluding the 75ft/s data, sensitivity values improve at some locations while becoming worse at others.
- The coal mass flow output signal is affected by changes in air velocity. While the general trend seems to indicate higher velocities result in lower instrument output, there are some instances where this trend does not hold up. Uncertainties, for all tested locations, range from +/-14.8% to +/-31.3%. Little improvement was observed by omitting low velocity data.

- The tests to evaluate the influence of a downstream orifice were inconclusive. It appears that the presence of an orifice does affect the instrument output, but there is no data to give insight as to how far away the orifice must be placed such that it does not affect the instrument signal.
- The change in air temperature test indicated little influence in the SolidFlow output, thus no significant effect of air temperature can be expected.

Table ES-6
Summary of Uncertainty and Sensitivity Values for All Tested Locations Using Standard Calibration Method

	All Velocities			75 ft/s Omitted		
	Sensitivity	Normalized Sensitivity	Uncertainty	Sensitivity	Normalized Sensitivity	Uncertainty
1V15	0.00057	1.00	17.7%	0.00054	1.00	15.8%
1V3	0.00208	3.65	14.8%	0.00194	3.62	11.2%
3V15	0.00160	2.82	29.4%	0.00148	2.76	20.6%
3V7	0.00319	5.60	31.3%	0.00327	6.09	31.3%
3V3	0.00360	6.33	24.6%	0.00343	6.40	24.7%
1H50	0.00039	0.69	29.6%	0.00040	0.75	24.4%

<u>Alternate Calibration Method (Extractive Approach) Conclusions</u>

In lieu of conducting extractive testing to determine actual coal flow rate, the CFL instrumentation coal flow rate was used to set-up the lower and upper calibration points for the SWR instrument. The following observations as summarized from these results:

- The SolidFlow output is less sensitive to installation location when using this calibration approach. This is shown in the normalized sensitivity values of summary Table ES-7. In particular, Location 1V15 demonstrates a slightly higher input (~0.1%) than Locations 1V7, 1V3, and 3V3. The latter sensitivities are very close to one another (within +/-0.05%).
- The coal mass flow output signal is, in many cases, significantly affected by changes in air velocity. In general higher velocities result in lower instrument output. The uncertainty of the instrument from all tested locations ranges from +/-15.4% to +/-28.2%. Also presenting an instance where some improvement is observed compared to the other calibration approach. Improvement is also observed when the 75 ft/s (23 m/s) data is omitted from the analysis.
- No temperature tests were conducted for this method based on the first test results.
- The tests to evaluate the influence of an upstream orifice were inconclusive. Since the baseline test and the repeat of that baseline test bracket all of the other tests, it is difficult to draw a conclusion on how an upstream orifice affects the SolidFlow's output.

Table ES-7
Summary of Uncertainty and Sensitivity Values for All Tested Locations Using the Extractive Calibration Method

	All Velocities			75 ft/s Omitted		
	Sensitivity	Normalized Sensitivity	Uncertainty	Sensitivity	Normalized Sensitivity	Uncertainty
1V15	0.00420	1.00	28.2%	0.00374	1.00	22.5%
1V7	0.00385	0.92	15.4%	0.00370	0.99	16.7%
1V3	0.00379	0.90	17.5%	0.00361	0.96	13.9%
3V3	0.00360	0.86	24.6%	0.00343	0.92	24.7%

ES. 6 Other Factors Affecting Coal-Flow Measurement

Although some technologies effectively monitor pulverized coal flow within a pipe under steady conditions, there are some factors that can influence the instrument output and thus introduce additional error to the accuracy of the measurement. Some of these factors include:

- Holdup of coal within the pipe
- Build-up of deposits on probes
- Humidity of the transport air
- Pipe deformation
- Equivalent Location

Although none of these parameters were part of the study during the course of testing, their influences were apparent and suggest the need for further investigation. The following comments were derived from the various experiences during this test campaign.

ES.6.1 Holdup of Coal within a Pipe

Because the actual amount of coal within the measurement region of an instrument is quite small, if coal holdup is present—such as coal recirculation on eddies (reflux condition), or layout as may occur in a horizontal section—instrument output will be affected. This is not a fault of any one instrument, but is a condition for which most systems were not designed. Thus, this behavior may account for the higher uncertainties observed at the 3V locations, where high roping conditions exist, and at the horizontal locations where some layout (<3%) is known to occur at low velocities and high coal flows. Based on the assessments at the CFL, some instruments indicate higher readings than the actual coal flow when coal layout is present in the horizontal sections. For the AMC Pf-*FLO* instrument, the layout condition is easily discernable, and although the instrument output is affected, it is in fact a very good detector of layout conditions. For other instruments, similar test conditions seem to increase the data scatter and affect uncertainty and sensitivity.

ES 6.2 Build-up of Deposits from Coal Streams

There is currently no definitive answer on the propensity for deposit formation, either on the instrument sensor or within a coal pipe. If the deposits formed on a sensing probe are stable, then a recalibration factor may be developed in some instances. However, if the deposits are not stable, i.e., change with time or break off, then the effect on instrument response will be transient and recalibration may not compensate for the presence of deposits. Based on this study and more recent field experience, the formation of deposits on probes that are inserted into a pulverized coal stream appear to be a function of coal type, coal loading, degree of stratification, and moisture content. As the response from the AMC instrument states, EPRI has only one documented account of the hard but brittle deposit buildup that occurred in the field. That deposit occurred with a normally operating ball mill application and only appeared on two of the 12 coal pipes instrumented. During that project, there were variations in the data that may have been related to deposit levels changing or holdup within the pipe. Other more recent studies have shown the propensity of soft deposits to form under some high moisture conditions even when placed at long vertical runs. However, it should be very easy to determine if deposits may occur in a given installation location by inserting an operating probe into a coal pipe and making periodic inspections.

ES.6.3 Humidity of the Transport Air

Although examining moisture or humidity effects was not part of the test matrix, it became apparent that there was a strong sensitivity to moisture when a new batch of coal was used. It is inferred that an equilibrium moisture level had not been reached at the test facility. Evaluating relative mass flow measurement between coal pipes from any one mill would likely be unaffected by moisture level. However, there are two scenarios where humidity could pose a concern. The first scenario illustrates the case where the relative flows between two or more mills are compared. If the drying efficiencies or the coal moisture levels are different for each mill, then moisture levels for each instrument will be different. If each instrument is not calibrated for the same condition there will be a difference in output that may not be representative of the coal flow. In addition, placement of the instrument at different locations may also affect the humidity conditions within a pipe. If the instruments are located in pipe sections subjected to more cooling than at other locations, the possibility exists that some condensation or change in air moisture level may occur. The second scenario addresses the instrument calibration. Some instruments require that the calibration “zero” reading be conducted with clean air going through a mill. However, when coal is introduced in the mill, a significant amount of moisture is released. Therefore, the “zero” reading will shift in each pipe because of the added moisture. The absolute shift will likely be the same for all pipes from the mill, but the relative shift will depend on the density of the coal in each pipe. However, since we have not tested this parameter at the levels that exist in actual coal pipes, no definitive conclusion can be drawn. Additional work is needed in this area.

ES.6.4 Pipe Deformation

For some coal flow instrumentation, the coal pipe serves as a waveguide for signal propagation. During evaluation of a jig to aid in the movement of pipe sections in the loop, the static output of one microwave instrument changed. More specifically, the behavior was observed when a U-bolt and a cross-bar jig were used to clamp onto the center of the pipe where the instrument was installed. When the jig was tightened down, thereby deforming the pipe slightly (by about 0.045 inches, or 1.14 mm), the instrument reading measurement increased to high levels. It is also inferred that in a power plant environment, this behavior may occur as a result thermal or mechanical cycling due to mill operation changes. At this point, it is unknown to what extent this type of pipe deformation occurs in a power plant. Further research is needed to assess if this condition affects all technologies that use the coal pipe as a waveguide.

ES.6.5 Equivalent Location

Since many of the results suggest that for installations in multi-pipe systems, the instruments should be placed at "equivalent positions" in each pipe, an effort was made to determine what exactly defines two positions to be equivalent. From a measurement standpoint, two locations are equivalent if air and coal flow profiles at the sampling plane are similar. Results from a joint study to characterize extractive measurement methods (Report 1010319) can provide some insights into this quest. In order to characterize the air and coal flow profiles of each test location, a detailed 180-point, extractive test was performed at five different air and coal flow rates. These tests were then analyzed to determine the air flow and coal flow profile non-uniformity or skewness of the test cross-section. A skewness factor was determined by dividing the standard deviation of the 180 air or coal measured values by the average of the 180 air or coal values for each respective test. These values are then expressed as a percentage such that a perfectly uniform profile has a skewness factor of 0%, while a profile derived from a roping condition results in a relatively large skewness factor. For example, Location 3V3 in the CFL, the location where the most severe roping occurs, has a coal non-uniformity of 180%. While statistically the discussed method assigns a similar degree of non-uniformity to similar flow profiles, it is generally not true that locations with a similar degree of non-uniformity will have exactly the same profile or, for that matter, will necessarily be read exactly the same by a given instrument. For instance, taking the 180 samples from one profile and then randomly reassigning them to different locations within the same pipe cross-section will result in a profile that is different from the original but will have the same statistical description as far as standard deviation and average value, and will hence have the same skewness factor. Regardless, the degree of skewness is still a valuable measuring stick as to how two profiles and hence two pipe locations compare to one another.

ES.7 Summary of Observed Sensitivities and Uncertainties

Figure ES–1 shows the sensitivity of the tested on-line instruments versus the degree of coal flow profile skewness or "roping" (the air flow profile skewness is generally small regardless of location or test condition). The degree of coal profile skewness (with respect to Location 1V15), indicated on the y-axes, is the average value from the five air and coal flow rates tested at each location (1V15, 1V11, 1V7, 1V3, 3V15, 3V7, 3V3, and 1H50). The normalized sensitivity of each instrument (also with respect to Location 1V15), presented on the x-axes, is derived from the slope of the line for each test location. For an ideal instrument, the normalized sensitivity should be equal to one under all test conditions and should lie on the vertical turquoise line in Figure ES-1. Based on this plot, the influence of coal profile skewness is observed for all instruments. Worthy of note is the relationship indicated by the SWR instrument which shows a strong influence of roping when calibrated using traditional method (Calibration 1) versus when calibrated based on extractive techniques (Calibration 2). In the latter instance, data lie in close proximity to the ideal line at all skewness levels. For all other instruments, sensitivity values tend to diverge from the ideal line as coal skewness increases. In some instances with low coal profile skewness, instruments exhibited sensitivities less than one (to the left of the ideal line). These data points originated from the horizontal test locations. Because of this inconsistency, a similar plot is presented by omitting the horizontal data. Under these circumstances, the impact of coal profile skewness is more evident.

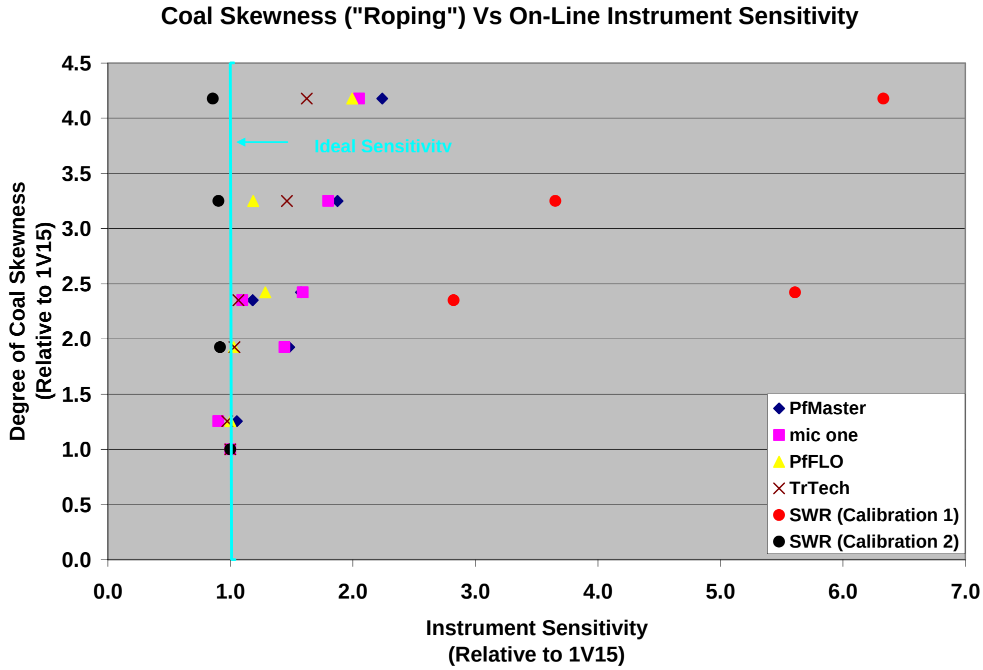


Figure ES-1
Relationship between Coal Profile Skewness and Instrument Sensitivities.

Figure ES-2 presents the results of the instrument uncertainty versus the normalized degree of coal skewness for all the tested on-line instruments. There does not appear to be any clear correlation between instrument uncertainty and degree of coal skewness. The overall range of instrument uncertainties varies from 5% to 45%. However, not all the high coal skewness levels

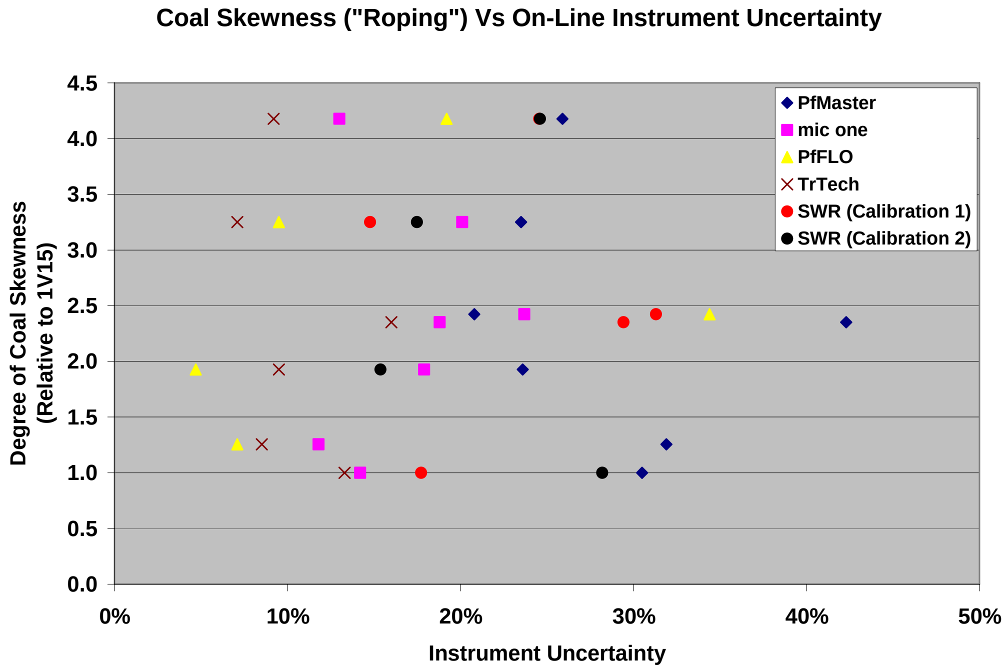


Figure ES-2
Plot of Coal Skewness versus Instrument Uncertainty for all Instruments.

ES.8 Recommendations

Based on the findings from this study, operators considering the use of these technologies at their plants are encouraged to follow up these guidelines:

1.0 Although many of these technologies respond linearly to increases in coal flow, the output signal is affected by operating parameters that may vary over time during normal plant operation. Coal moisture, particle fineness, air to coal ratio, air velocity and air temperature fall within this type of variables. Therefore, the operator should establish the range of operating conditions experienced by the plant fuel delivery lines before installing any on-line system.

2.0 Install sensor probes or antennae at coal pipe locations that can be readily accessible such that verification of probe conditions can be efficiently monitored.

3.0 Considering items 1 and 2, the instruments should be installed at locations where the coal flow profiles will be the most uniform, i.e., avoid long horizontal runs, or locations in close proximity to flow obstructions such as elbows. Results from this study suggest a minimum of seven diameters away from obstructions in order to reduce those effects.

4.0 Consider establishing a verification test plan. Traditional methods to measure coal flow could be used to both calibrate and assess the output of these instruments. Guidelines for improved extractive techniques are discussed in EPRI report 1010319 (October 2006).

Although advancements in technology will foster more opportunities to improve the current state-of-the art for coal measurement, the ultimate objective is to use a reliable measurement indication such that active control scheme can be adopted and real-time boiler fine tuning can be achieved.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

Cost-effective compliance with NO_x emission restrictions usually requires a combination of well-balanced firing among the burners within a boiler and overfire air for staged combustion. Optimization of heat rate and avoidance of operational issues, such as slagging or excessive waterwall tube corrosion, often also require precise burner tuning. Even when post combustion NO_x controls are required, such systems can be applied most cost-effectively when NO_x emissions from the combustion zone are made as low as practical from low-NO_x burners, combustion staging, and overall low excess air operation.

Achieving "well balanced" combustion within a burner elevation requires careful control of coal and air flow to individual burners. A critical element of such control is the ability to measure, in near real time, the mass flow rate of pneumatically conveyed pulverized coal in the coal pipes feeding the burners. This is not an easy task, and has been the subject of considerable research for more than a decade.

However, several instruments have recently been introduced to the power boiler market for this purpose. EPRI and power generators have traditionally conducted collaborative tests of such boiler instrumentation. The ambiguous results from demonstrations at power plants have pointed toward the assessment of these technologies under better known and controlled conditions. To address this need, EPRI built the Coal-Flow Measurement and Control Laboratory (CFL) for performance verification testing and parametric studies. This state-of-the-art facility can transport pulverized coal under known conditions. In combination with a test matrix designed to test a range of primary conditions typically found in power plants, the CFL offers a precise assessment of the various measurement technologies. The CFL's capabilities are summarized in Section 2 of this report and detailed further in EPRI Technical Report 1004743, *Coal-Flow Loop: System Description and Commissioning.*

Assessments for three commercially available on-line coal-flow measurement devices have been conducted at the CFL. Results from those tests were summarized in the recently published EPRI report 1010318 (December 2005). In this report, assessment of a fourth and fifth on-line coal flow instruments tested at the CFL: the ECT by Foster Wheeler and TR-Tech are presented. The goals of this test were to assess the instrument performance under a wide range of conditions including installation location, coal flow rate, air flow rate, air temperature, and proximity to an orifice.

2 THE CFL FACILITY

The coal flow instruments were tested in EPRI's Coal-Flow Measurement and Control Laboratory (CFL), which was designed for this purpose. The CFL, or coal loop, closely replicates the scale, piping, and flow conditions found in a typical coal-fired power plant. Unlike an operating plant, however, the coal loop is able to provide precisely known and controlled air and coal flow rates and temperature to serve as a reference for evaluating Coal-Flow Measurement instruments. The coal loop operates in a continuous, closed-loop mode. Both air and coal are continuously recycled through the loop.

This section summarizes the basic design and operating characteristics of the CFL. Additional information on the CFL can be found in EPRI Technical Report 1004743, *Coal-Flow Loop: System Description and Commissioning.*

Figure 2-1
EPRI's CFL facility was expressly designed to measure the mass flow rate of pneumatically transported pulverized coal. This exterior photo shows the filter/receiver, storage hopper, and cleaned carrier gas outlet.

Figure 2-2
The coal loop closely replicates the scale and flow conditions of a typical coal plant.

2.1 Air Measurement

The air flow rate through the loop is measured with a Hershel-type low-loss venturi. The venturi was calibrated over the Reynolds number operating range of the coal loop. The calibration was performed at Alden Research Laboratory of Holden, Massachusetts. The calibration is NIST-traceable with an uncertainty of 0.25%. The air flow calculation takes into account the effects of Reynolds number, compressibility, air density, and thermal expansion. Air properties are calculated using real air correlations supplied by Techware Engineering. Air properties are calculated as a function of pressure, temperature, oxygen concentration, and relative humidity. Calculated air properties include density, molecular weight, specific heat, viscosity, and dew point. Air flow control is maintained through feedback control between the venturi differential pressure (DP) and the variable- frequency drive controlling the fan. The loop can operate at line velocities up to 135 ft/s (41 m/s). In order to control the explosion potential of pulverized coal, the coal loop operates with a reduced-oxygen atmosphere. Oxygen levels in the loop can be maintained within ±2% under most coal loading conditions.

2.2 Coal Measurement

The coal flow rate through the loop is measured using a loss-in-weight gravimetric feeding system. An isolated weigh hopper with a capacity of 800 lb (363 kg) is suspended from load cells and the coal flow rate is calculated from the loss in weight of the hopper over time. The weighing system has a static accuracy of 0.08 lb (0.036 kg). The hopper is refilled as needed from the coal stored above in the filter/receiver. During the refill process, the feeder operates in volumetric feeding mode. The coal flow rate is controlled by a variable-speed rotary feeder at the bottom of the hopper. Coal flow rates up to 20,000 lbm/h (9100 kg/h) can be achieved. The rotary feeder is connected to a vibratory feeder which functions to smooth out the dumping action of the rotary feeder. The vibratory feeder then feeds the material into the pipe. A dedicated computer continuously monitors and logs the coal feeding process. A steady, known feed of coal can be maintained within ±2% under most coal loading conditions.

2.3 Temperature Control

The coal loop has a tube-and-shell-type heat exchanger for heating the transport air. The service medium is water and propylene glycol heated with a 50-kW electric heater. The air temperature is maintained through feedback control between the test section RTD temperature probe and a proportioning water flow control valve. Temperature can be maintained within +/- 2°F (1.1°C) and the loop can operate at temperatures up to 180°F (82°C).

2.4 Particle Size

The coal used in the loop is a Pittsburgh seam coal, pulverized to ~75% less than 200 mesh. The coal was provided by Consol Energy and pulverized at their facility in South Park, Pennsylvania. Because the coal is continuously recycled through the loop, the coal particle size has a tendency to decrease slightly over time. As part of the test procedure, coal samples were taken immediately before, during, and immediately after the instrument was evaluated. A portion of these samples were sent to a laboratory for size analysis and the remainder of the samples is archived for future reference.

2.5 Controls

The coal loop is controlled with a Siemens PLC and a PC-based human-machine interface (HMI). The control system manages flow set points, alarms, and data logging. Data logging occurs every 15 seconds.

2.6 Loop Test Sections

The test section piping of the loop is composed of 12-in (30.5-cm) schedule 40 steel pipe connected with Victaulic-type grooved pipe fittings. The pipe is cut grooved. The test section contains the piping configurations most commonly found in a power plant. The test section consists of a long horizontal run, a vertical upflow run, a vertical downflow run, a short horizontal run, and a vertical upflow run with a double-bend (out-of-plane) inlet. The double-bend inlet results in a substantially higher degree of roping than the single-bend inlet.

2.7 Instrument Installation Locations

In general, there is a preferred installation location for a particular instrument. However, it is quite common that in a power plant the preferred location either does not exist or is inaccessible. For this reason, each instrument was tested at a range of locations. As detailed in Figure 2-1, the testing can be performed at up to ten locations, including two locations in a horizontal pipe, four locations in a vertical upflow pipe with a single-bend inlet, and four locations in a vertical upflow pipe with a double-bend inlet.

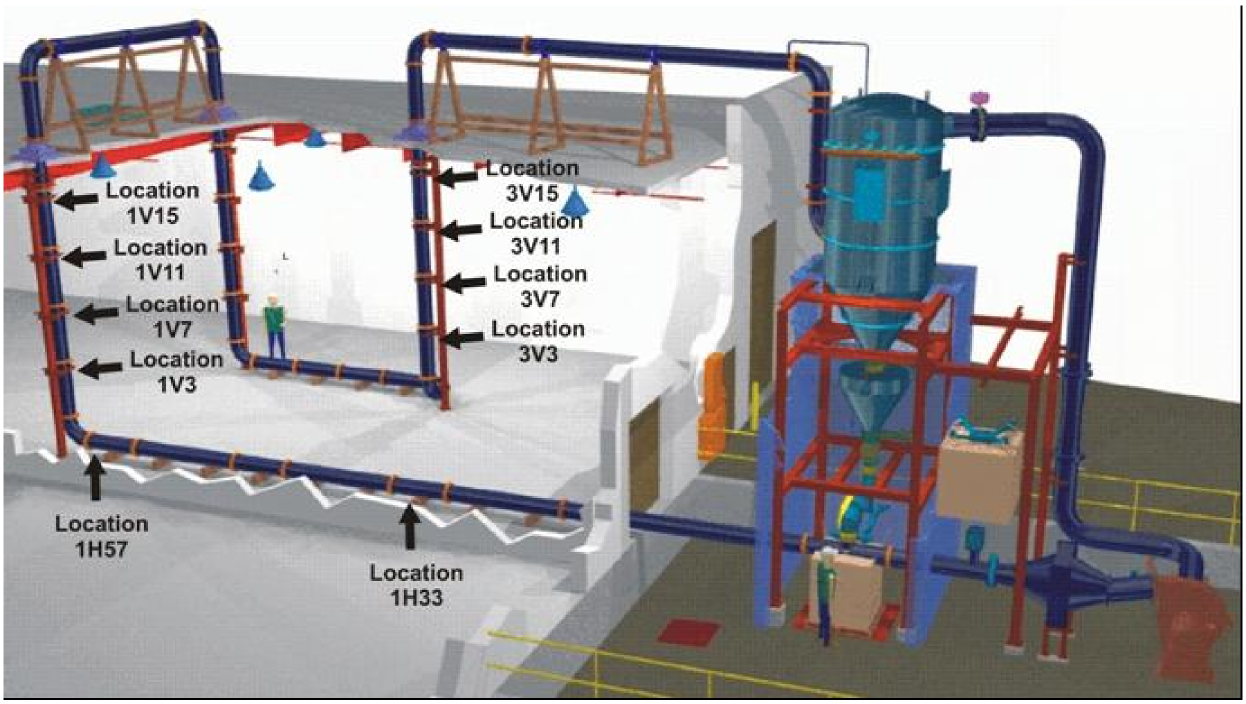


Figure 2-3
Schematic of testing locations. The in-feed junction is located below filter/receiver, just outside the small bay door.

Figure 2-3 shows specific test locations along the loop. Location 1H33 is in the first horizontal run and is 33 pipe diameters downstream of the coal in-feed location. Location 1H57 is 57 pipe diameters downstream of the coal in-feed location in the first horizontal run.

In the first vertical upflow pipe, Location 1V3 is 3 pipe diameters downstream of the bend. Similarly, Locations 1V7, 1V11, and 1V15 are 7, 11, and 15 pipe diameters downstream of the bend, respectively.

When the instruments were tested in this first vertical run, a "segmental orifice" was installed in the upstream horizontal run 12 diameters upstream of the bend. The segmental orifice is a straight flat plate blocking the bottom third of the horizontal pipe, leaving a "D" shaped open area in the top two thirds of the pipe (see Figure 2-4). The purpose of the orifice was to “kick” the coal flow off the bottom of the pipe and provide a more uniform coal flow profile at the inlet to the bend. Extractive testing has shown that the orifice reduces the degree of coal stratification (roping) in the first vertical leg. The orifice was added to address the concern that the long horizontal run of pipe (and resulting stratification of coal towards the bottom of the pipe) was causing an unrealistic degree of stratification in the vertical pipe. Because the third vertical pipe run (Locations 3V3, 3V7, and 3V15, described below) is subject to a very high degree of stratification, it was desirable to have the first vertical pipe run with relatively low stratification.

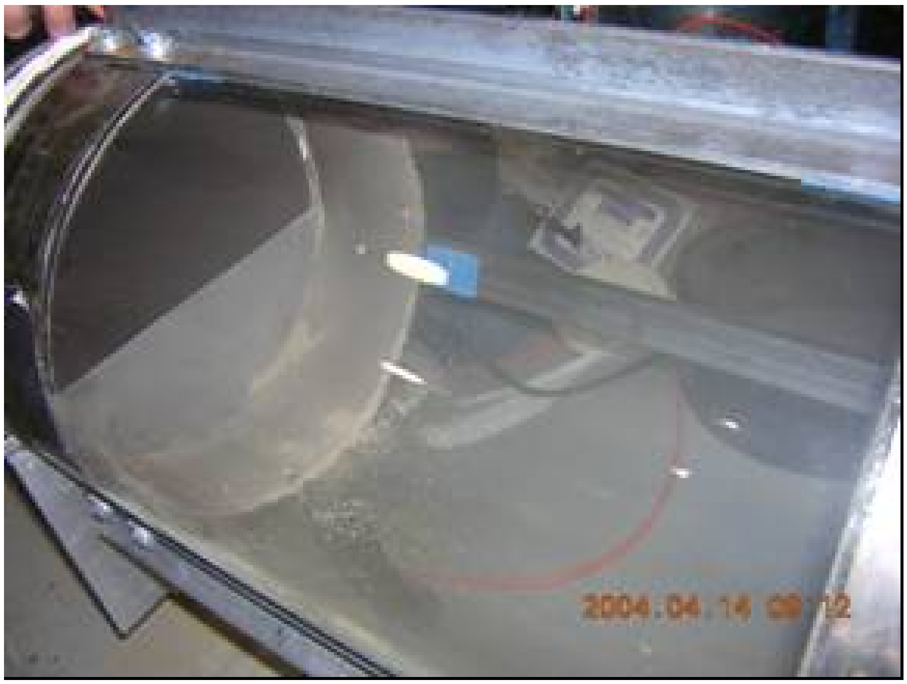


Figure 2-4
Segmental orifice located 12 diameters upstream of single 90-degree elbow

Location 3V3 is 3 pipe diameters downstream of the double bend in the third vertical run. Locations 3V7 and 3V15 are 7 and 15 pipe diameters downstream of this double bend, respectively. The double-bend configuration creates a significant roping condition, as was observed using glass pipe sections while the CFL was operating with a ceramic particulate instead of coal. Figure 2-5 shows the roping phenomenon.

Figure 2-5
Photo of roping flow with ceramic particulate at Location 3V3

3
TEST PROGRAM AND ANALYTICAL APPROACH

Each of the coal flow meters was evaluated with a similar test program (with differences noted in the specific chapter on each instrument). The baseline test matrix measured three parameters to quantify instrument performance: (1) the effect of air velocity, (2) uncertainty, and (3) the effect of location (sensitivity). The baseline tests were followed by tests to assess the effects of upstream and downstream orifices, as well as elevated temperature, upon instrument performance. The complete test program is detailed in Table D-2 of Appendix D.

3.1 Baseline Test Matrix

At each location along the CFL test loop, a series of air velocities and air-to-coal ratios was run and the response of the instrument to various flow rates was examined. Three air velocities, 75, 95, and 115 ft/s (23, 29, and 35 m/s), were run. At 75 ft/s (23 m/s), air-to-coal ratios of 1.0, 1.5, 2.0, and 3.0 were run. At 95 ft/s (29 m/s), air-to-coal ratios of 1.5, 2.0, 2.5, and 3.5 were run. At 115 ft/s, air-to-coal ratios of 2.0, 2.5, 3.0, and 4.0 were run. The baseline test matrix also includes a zero coal flow point at 95 ft/s (29 m/s). This was included to see how the instrument output at zero flow was influenced by location. A matrix of these conditions and the associated air and coal flow rates is shown in Table 3-1. The loop was operated at an air temperature of 150°F (66°C) for the baseline test matrix. Based on laboratory conditions specific to each instrument, minor changes to the test matrix were required during the course of the tests.

Table 3-1
Baseline Test Matrix for On-line Instruments

Air Velocity ft/s (m/s)	**Air/Coal Ratio**							
	1.0	1.5	2.0	2.5	3.0	3.5	4.0	Clean
75 (23)	X	X	X		X			
95 (29)		X	X	X		X		X
115 (35)			X	X	X		X	

Each flow condition was run for 22 minutes: 5 minutes to allow the coal loop and instrument reading to stabilize, 15 minutes during which the instrument reading and coal loop flows were logged for comparison, and an additional 2 minutes at the end of the run to allow for any data logging timing differences between the coal loop and the system being evaluated. The baseline test matrix was run at each test location.

It should be noted that while some of the instruments evaluated included coal velocity as one of their outputs, the coal-flow loop does not have the ability to evaluate the accuracy of this measurement. While the air velocity within the loop is accurately known, the coal velocity may be either higher or lower than the air velocity depending on location.

3.2 Interpreting Baseline Tests

3.2.1 Effect of Air Velocity

The ideal performance of a flow-measuring instrument is that at a given coal flow rate, the instrument will output a single number. If the coal flow rate is held constant, the instrument output should not be affected by changes in other parameters, such as the air velocity. For example, if the coal flow rate is 8,000 lbm/h (3629 kg/h), the instrument should output the same number regardless of whether the air velocity is 75, 95, or 115 ft/s (23, 29, or 35 m/s).

The effect of air velocity on instrument output was evaluated by plotting a best fit straight line (BFSL) through the four coal flow rates of each of the three air velocities. Each of the three BFSLs show the instrument output vs. coal flow rate characteristic at a given velocity. If the instrument is unaffected by air velocity, then these lines will be coincident (having not only the same slope but the same y intercept). More simply, all the data should fall on a single line regardless of air velocity. A BFSL was plotted for each velocity to assess whether there was any systematic effect of air velocity.

3.2.2 Uncertainty

The ideal performance of the instrument is that the instrument output will be linear with coal flow rate. If the instrument output is 5.0 for Pipe A and 10.0 for Pipe B, then the assumption is that Pipe B has twice as much coal flow as Pipe A. *Uncertainty is a simple measure of how well the instrument output fits the BFSL calculated for all the data points at a single location.* (Often, the term accuracy is used interchangeably with uncertainty.) If all the data (coal flow rate vs. instrument output, all air velocities) at a given location fall exactly on a single straight line, then the uncertainty is zero. The uncertainty is calculated using the following procedure:

- For a given location, the twelve data points of the baseline matrix are plotted on a graph of coal flow rate vs. instrument output. If the instrument has a non-zero output at zero coal flow, this constant is subtracted off the data before it is plotted.
- The BFSL through the data points is calculated. Because the instrument output is considered to be proportional to coal flow (instrument output of 5 indicates twice as much coal flow as 10), the BFSL is constrained to pass through the origin.
- For each of the twelve data points, the distance from the point to the BFSL is calculated. The horizontal distance (x-axis, lbm/h [kg/h] coal) is used.
- The standard deviation of these twelve distances is calculated. In order to express the standard deviation as a percentage, it is divided by a "full scale" mass flow rate of 12,000 lbm/h (2,722 kg/h)—slightly higher than the maximum coal flow in the baseline matrix.

- The uncertainty is then expressed as +/- two standard deviations (encompassing 95% of the data points).

For example, suppose that the instrument shows 5.0 in Pipe A and 10.0 in Pipe B. If the instrument uncertainty is +/-20%, then one can be 95% confident that the indicated readings are correct, within an error band of +/-20% (not taking into account changes in output due to location as explained below).

3.2.3 Effect of Location (Sensitivity)

Ideally, an instrument's performance should not change if installed at a different location. *Sensitivity is simply the slope of the BFSL (determined for uncertainty) at a given location.* Sensitivity may also be called the "calibration factor" for the instrument at a given location. Even if the instrument has very low uncertainty at each location, meaning that all twelve data points fall closely on a straight line, the slope of the BFSL may be considerable thus indicating a high instrument dependency on location. Thus, for instruments installed at different locations, an instrument may indicate 5.0 for Pipe A and 10.0 for Pipe B when in fact both pipes have the same coal flow.

3.3 Influence of Orifice Tests

Following the baseline tests, additional tests were performed to evaluate how the instruments responded to the presence of an orifice in the pipe. The effects of an upstream orifice and a downstream orifice were both evaluated. It was hypothesized prior to testing that an orifice upstream of the sensors could potentially influence the sensor output by changing the air and coal flow profile through the sensor and also by directly interacting with the sensor signal. However, a downstream orifice could influence the instruments only by interacting with the sensor signals. All of the orifice tests were run at an air velocity of 95 ft/s (29 m/s) and air-to-coal ratios of 1.5, 2.0, 2.5, and 3.5.

A simple circular square-edged concentric orifice was used for the test. It was fabricated from 0.090-in (2.29-mm) aluminum plate with an open area of 56%. A photo of the orifice installed within the loop is shown in Figure 3-1.

The upstream orifice tests were performed with the instruments installed at the 1V15 location. The orifice was installed at distances of 3 diameters (3D), 7 diameters (7D), and 11 diameters (11D) upstream of the instruments. The orifice was also installed 4 diameters upstream of the bend going into the vertical run.

The downstream orifice tests were performed with the instrument installed at the 1V3 location. The orifice was installed at Locations 1D, 4D, and 8D downstream of the instruments.

Figure 3-1
Photo of a concentric orifice installed just upstream of a bend

3.4 Elevated-Temperature Tests

In order to evaluate how the instruments responded to changes in air temperature, the 95 ft/s (29 m/s) portion of the test matrix was re-run at an elevated temperature of 175°F (79°C). The elevated-temperature tests were performed at selected locations.

3.5 Test Protocol

All instrument tests at the CFL were subject to the following stipulations and guidelines:

1. The instrument representative was allowed to be present during the evaluation.
2. At each test location, the baseline test matrix—both air and coal flows—were performed in random order. Elevated-temperature tests, when performed, were run after the baseline test matrix. The test matrix flows, temperatures, and run times were preprogrammed in the CFL computer. The computer automatically advanced through the matrix once the test was started.
3. The test matrix was performed blind. The order of the test matrix at each location was not disclosed.
4. Data from the instrument were provided by the instrument representative at the completion of each test location.
5. The preferred data logging interval for the instrument was 15 seconds.

6. After each flow rate change, a 5-minute period was given for the CFL and the instrument readings to stabilize. The CFL flows and instrument readings were then compared over the following 15-minute period.
7. No adjustments were made to the instrument during a test run at a particular location.
8. No adjustments were made to the instrument when moving the instrument to a new location unless these adjustments had been discussed and agreed upon prior to the evaluation. “Zeroing” the instrument at each location (zero coal flow) was permitted, as this process can also be easily performed in the field.
9. Coal samples were obtained from the coal feeder at the start of the evaluation and after completion of each test location. The first and last coal samples were sieved to determine any change in fineness during the evaluation. Intermediate samples could also be analyzed.
10. Coal and air flow data were provided to the instrument manufacturer/representative within 30 days of the completion of the evaluation testing.

3.6 Test Quality Control

For each test performed, the CFL operating data was inspected to ensure that the coal feed and air velocities were held sufficiently steady throughout the course of the testing. If for any test the coal feed standard deviation was greater than 6% or the air flow rate standard deviation was greater than 1.5%, those specific tests were omitted from the data analysis.

4
ECT STAR TESTING AND RESULTS

This section describes the results of the TR-Tech's ECT STAR instrument. The ECT STAR is an on-line coal measuring instrument based on an electrostatic measurement principle. The following passage from the pre-evaluation report reflects TR-Tech's description of the instruments functionality.

> "The ECT is a real-time system that measures the electric field created by electrostatic charges present in any two-phase flow application. The measured charge is not dependent on the dispersion of particles and accounts for random coal roping. The ECT system works in accordance with Coulomb's law in which a point charge creates an electric field around itself. Electrostatic charging occurs when two materials come in contact with each other and then separate. In this case, when coal particles impact the conduit wall in transportation, electrons will be transferred from one material to the other. Both materials end up with a net charge, one positive and one negative.
>
> The ECT system measures the voltage produced by changes in this generated electric field. The system does not need a contact between the probe and coal particles. The ECT system determines the mass flow of pulverized coal being transported in a pipe by independently measuring the components of coal velocity and density."

The ECT system is comprised of a number (typically 6) of probes with local junction boxes, ECT node computers, ECT signal conditioning units, an industrial grade computer with software, a 15" flat panel monitor, PS-2 keyboard and mouse, and an Ethernet hub for ECT node-to-server computer communication. Probes are installed in the pipe by means of threaded holes. Three probes are mounted in a plane 120 degrees apart, and three additional probes are mounted 50 mm downstream of the first set. This typical sensor installation arrangement is shown in Figure 4-1 for horizontal pipe test section at the Coal-Flow Loop. Figure 4-2 shows a photo of the ECT system instrumentation used at the CFL. The system uses standard 120V, 60Hz cycle electrical power and does not require any special electrical insulation, grounding or separation. ECT representatives supplied the following information about the system:

> "A suitable probe location should chosen at approximately six (6) pipe diameters downstream and one (1) diameter upstream from any bend, valve, or other internal obstruction. Either horizontal or vertical runs are adequate. Placement should also take account future accessibility."

For a typical installation, Foster Wheeler engineers (Foster Wheeler NA is TR-Tech's North American distributor) connect all wiring to the sensors and connect coaxial cables to the computer at the ECT workstation.

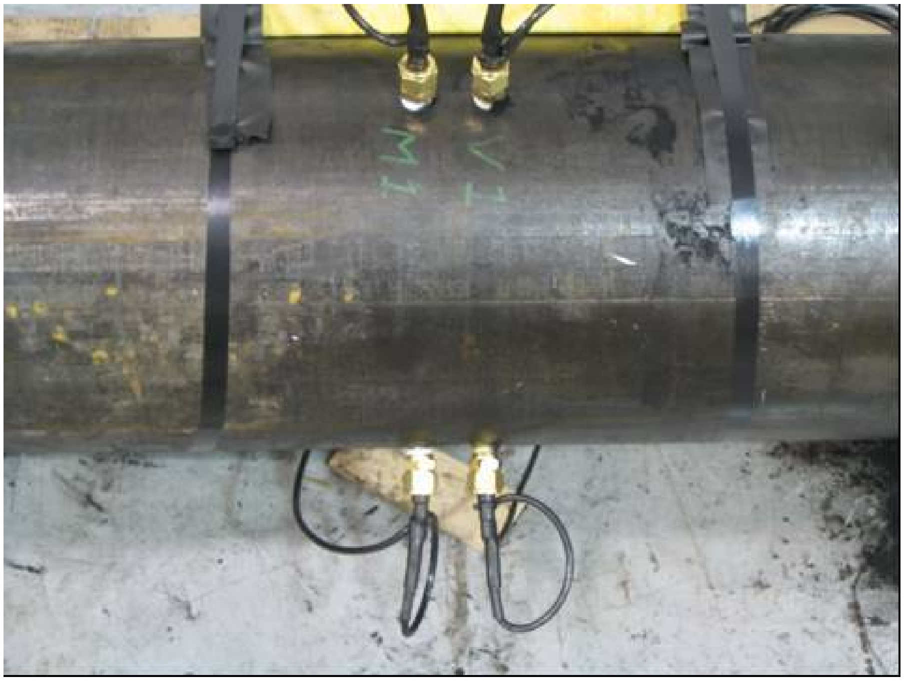


Figure 4-1
ECT Sensors Installed on a Horizontal Pipe at the CFL

Figure 4-2
ECT Instrumentation Workstation Used for the CFL Test

4.1 Commissioning

Foster Wheeler, TR-Tech's North American distributor, provided two instruments for the ECT evaluation at the CFL. The instruments were initially setup and configured on November 20, 2005 at the 1V15 and 3V15 locations, and the evaluation began that day. Foster Wheeler personnel operated the ECT system and were on site for the entire evaluation period.

4.1.1 Calibration

In typical field operation, the ECT system is calibrated at a minimum of two mill loads spanning the range of normal mill operation. No calibration is required for coal velocity measurement. During this calibration, the ECT samples data continuously, while a manual (extractive with Rotoprobe™) test of the coal pipe is performed to measure the actual air and coal flow through the pipe. The ECT system is then calibrated remotely using a communications interface. For the ECT evaluation in the CFL, a modified procedure was used to calibrate the ECT. The following calibration method was agreed to by both EPRI and Foster Wheeler/TR-Tech for evaluating the ECT system. At each location, four air and coal flow combinations were run to simulate the procedure used at actual power plants. The four calibration conditions points included:

- low velocity and low coal flow rate,
- low velocity and high coal flow rate,
- high velocity and low coal flow rate,
- and high velocity and high coal flow rate.

The ECT system sampled each calibration point for 30 minutes and the actual air and coal flow rates, from the CFL instrumentation, corresponding to those tests were reported to TR-Tech engineers. Because of extended time required to process the calibration data points and testing schedule time constraints, the evaluation of the ECT at each location proceeded immediately following the calibration runs and before TR-Tech could process the calibration information. Instead, the raw evaluation data were post-processed by TR-Tech to reflect the appropriate calibration.

4.2 Baseline Test Matrix

The evaluation proceeded by moving the instrument through the locations, flow conditions and tests described in Table 3-1.

4.2.1 Results for Locations 1V15, 1V11, 1V7, and 1V3

The first formal evaluations were performed at the four locations in the first vertical up-flow pipe run after a 90 degree, horizontal to vertical elbow. The sensor was installed 15, 11, 7, and 3 diameters downstream of the elbow at locations 1V15, 1V11, 1V7, and 1V3 respectively. Figure 4-3 indicates the test locations at the first vertical leg. Equivalent locations were tested at the second vertical leg downstream of the double bend.

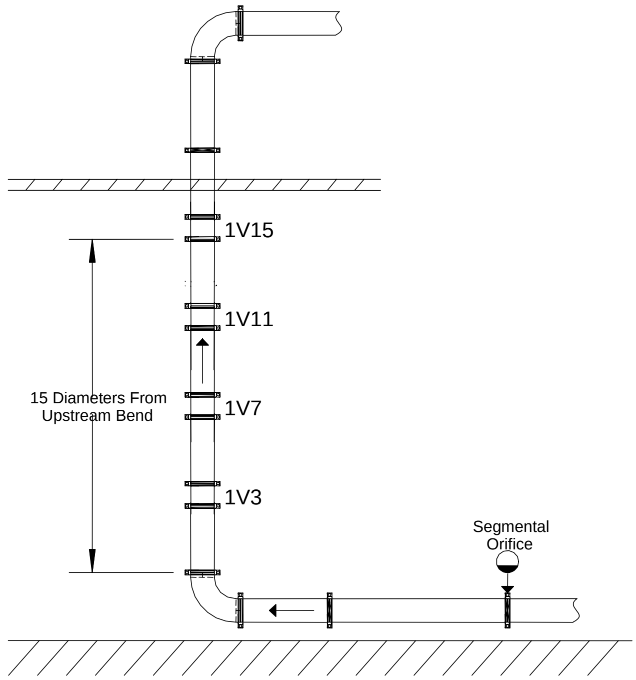


Figure 4-3
ECT Sensor Installation Locations in the first vertical leg

4.2.1.1 Effect of Air Velocity

The results for the effect of air velocity on the instrument performance for Locations 1V15, 1V11, 1V7, and 1V3 are presented in Figures 4-4 through 4-7 respectively. It can be seen that, with the exception of location 1V3, the instrument output has little dependence on air velocity.

4.2.1.2 Uncertainty

The calculated uncertainty for Locations 1V15, 1V11, 1V7, and 1V3 is presented in Figures 4-8 through 4-11. At Location 1V15 the uncertainty is +/- 13.3%. At location 1V11 the uncertainty is +/-8.5%. At location 1V7 the uncertainty is +/- 9.5%. At location 1V3, the location closest to the bend, the uncertainty is +/- 7.1%.

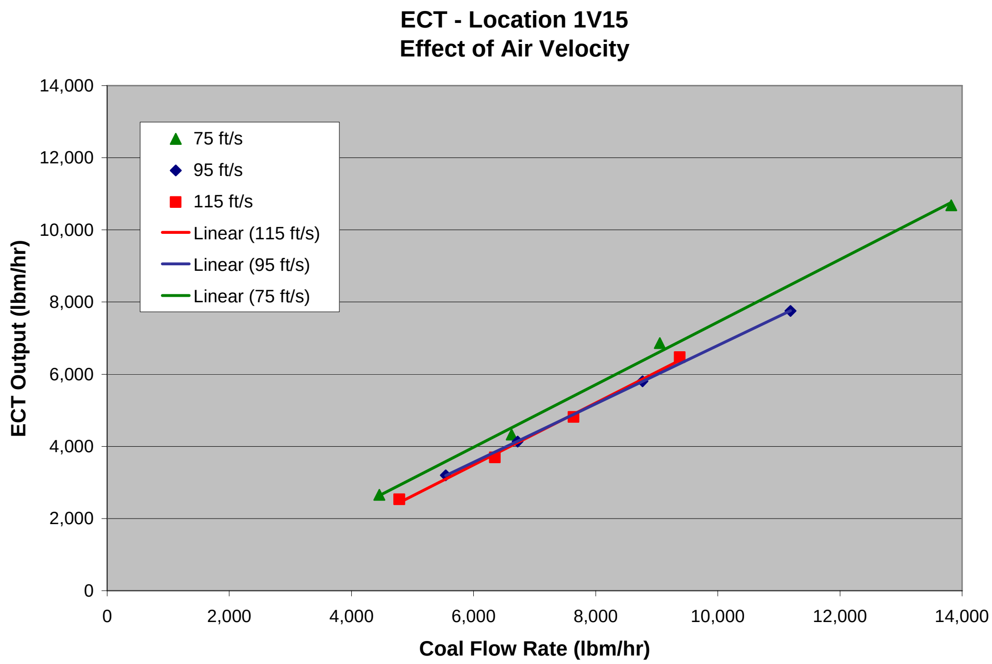


Figure 4-4
Effect of Air Velocity at 1V15

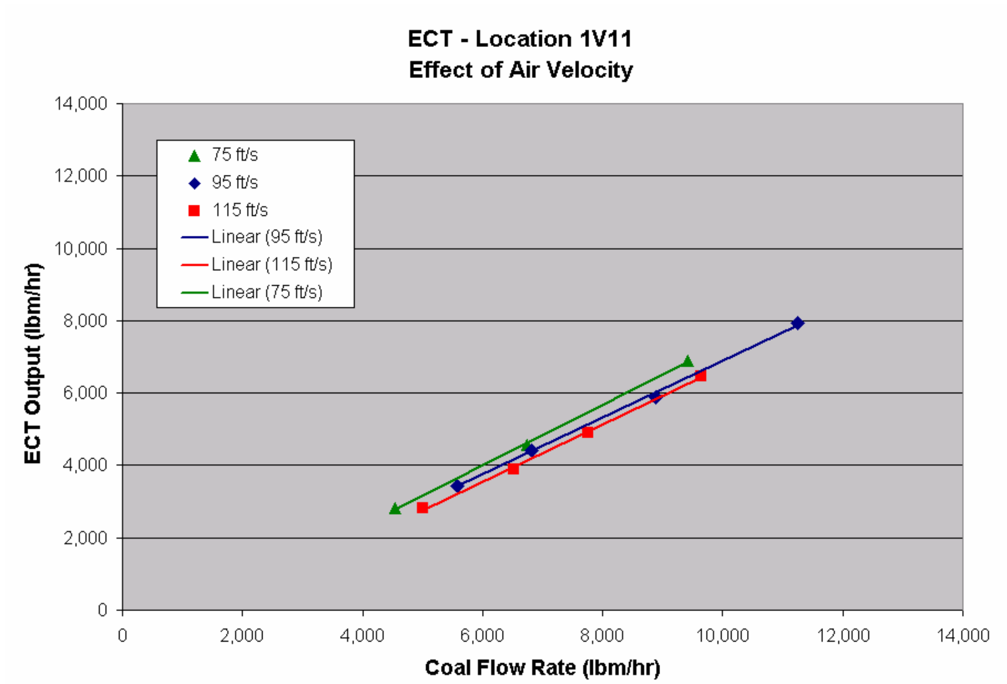


Figure 4-5
Effect of Air Velocity at 1V11

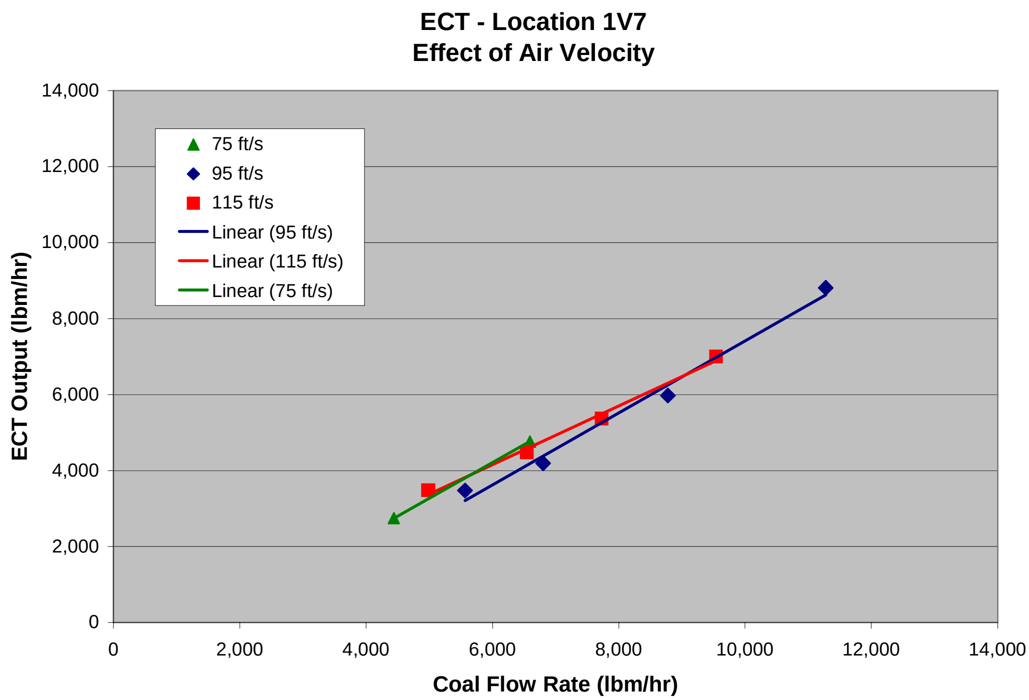


Figure 4-6
Effect of Air Velocity at Location 1V7

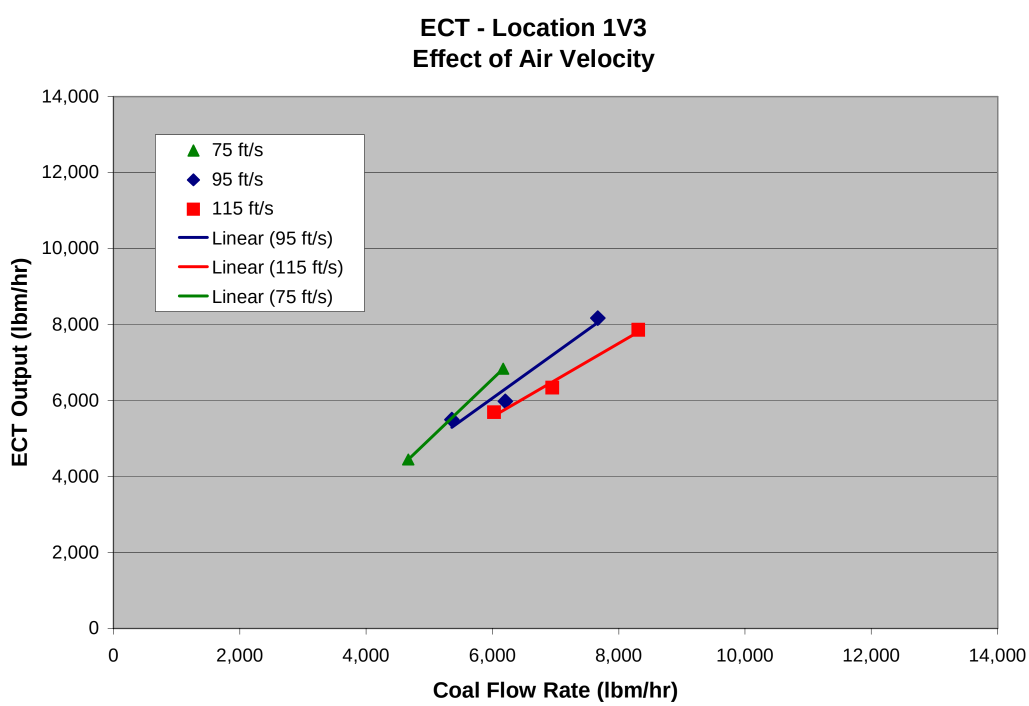


Figure 4-7
Effect of Air Velocity at Location 1V3

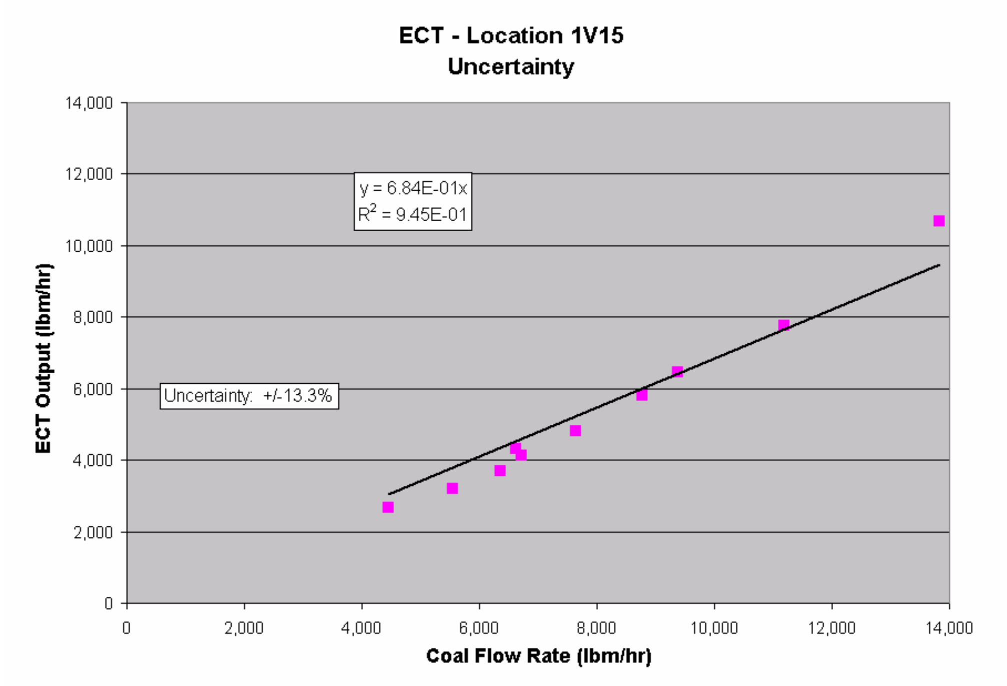


Figure 4-8
Uncertainty at Location 1V15

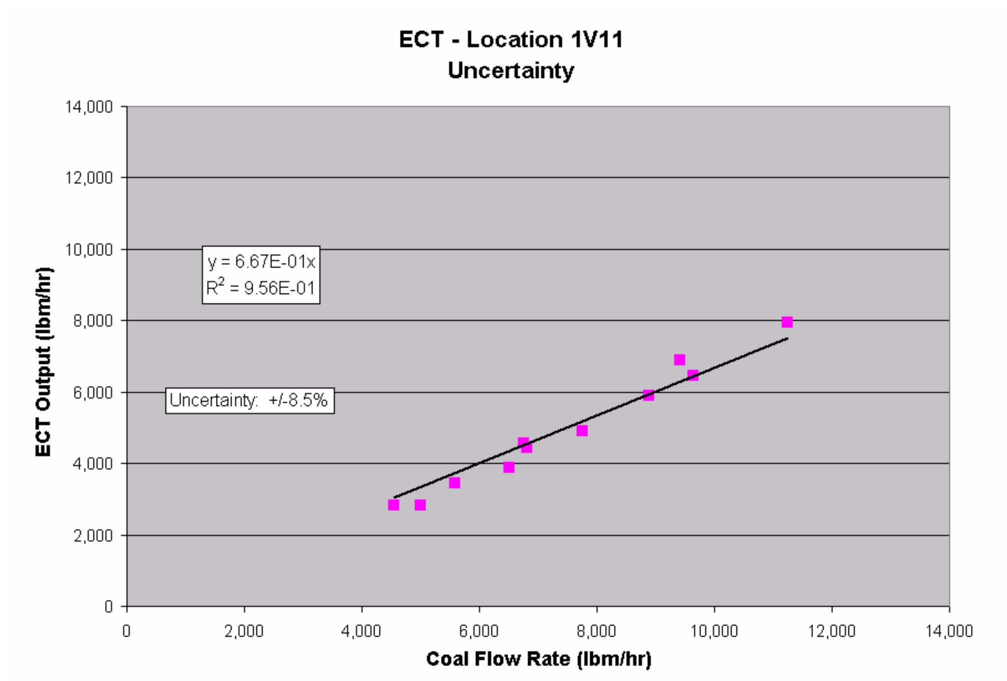


Figure 4-9
Uncertainty at Location 1V11

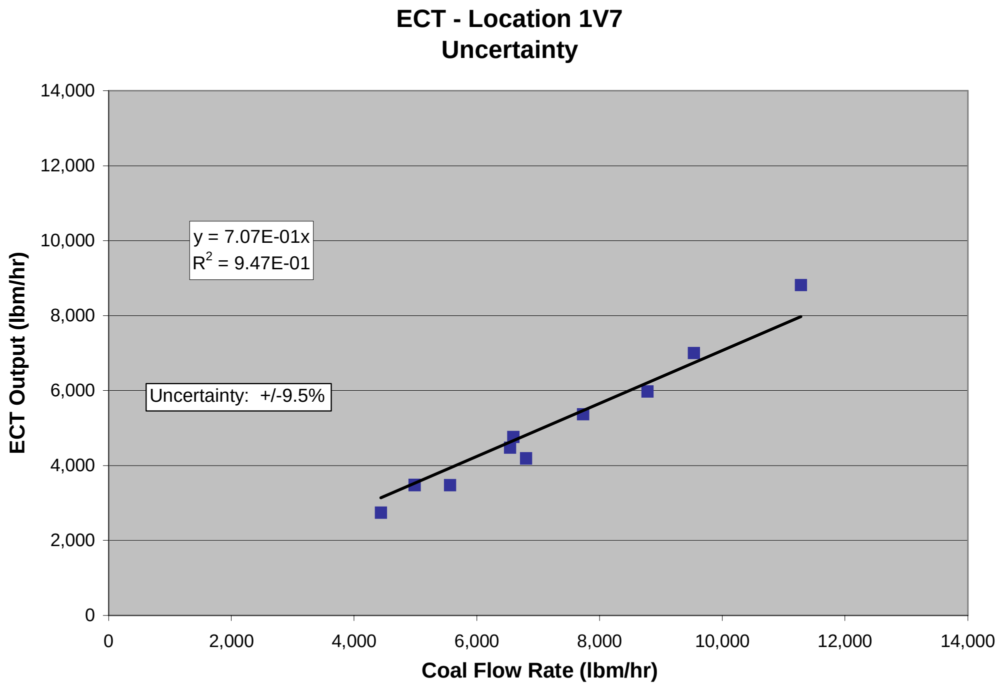


Figure 4-10
Uncertainty at Location 1V7

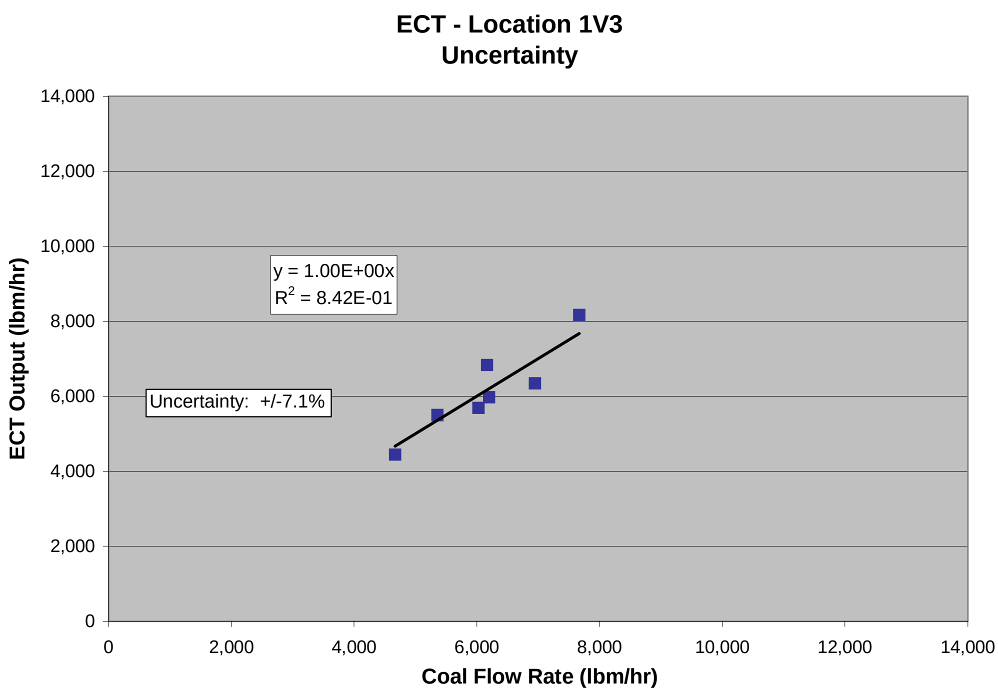


Figure 4-11
Uncertainty at Location 1V3

4.2.1.3 Effect of Location (Sensitivity)

The effect of instrument installation (location) was examined for all locations in the first vertical upflow run, and is detailed below in Table 4-1. Qualitative visual analysis and extractive testing to date has indicated that Location 1V15 has the most uniform air and coal profiles. Therefore, the sensitivity at all locations will be compared to the sensitivity at 1V15. The normalized sensitivity then, is found by dividing the sensitivity at a particular location by the sensitivity at 1V15. These results will then be used to determine the effect of location on sensor output. In this case, the normalized sensitivity ranges from 0.97 at 1V11, to 1.46 at 1V3. Taking this into account, it can be seen that the instrument output is 3% low at Location 1V11, 3% high at 1V7, and 46% high at 1V3 as compared to Location 1V15. However, when viewing the ECT system output as an indicator of absolute coal-mass flow, the output for 1V15 reads 32% lower than actual coal flow, the output at 1V11 is 33% lower than the actual coal flow, the output at 1V7 is 25% lower than the actual coal flow, and the output at 1V3 is equivalent to the actual coal flow

Table 4-1
ECT System Effect of Installation Location – First Vertical Run

Location	Sensitivity	Normalized Sensitivity	Uncertainty
1V15	0.684	1.00	13.3%
1V11	0.667	0.97	8.5%
1V7	0.707	1.03	9.5%
1V3	1.000	1.46	7.1%

4.2.2 Results for Locations 3V15, 3V7 and 3V3

The effect of air velocity, uncertainty and effect of instrument location were examined at the vertical upflow run downstream of the double 90 degree out of plane double-bend, i.e., at locations 3V15, 3V11, 3V7 and 3V3. Qualitative visual analysis and extractive tests conducted to date indicate that a stronger coal stratification profile is formed downstream of the double bend (3V) than after the single bend (1V). This high degree of stratification has been observed through a glass-pipe section at location 3V3 while the loop operated with ceramic particulate. At this location, a high concentration of particles followed a spiral motion along the periphery of the pipe walls, whereas downstream of the single bend, stratification was concentrated towards the outside wall. Due to sensor malfunctions during the course of testing, the data collected at location 3V7 has been deemed unusable and hence has been omitted from the data analysis.

4.2.2.1 Effect of Air Velocity

The effect of air velocity at 3V15, 3V11, and 3V3 is illustrated below in Figures 4-12 through Figure 4-15. From the plots, a general trend can be observed between lower air velocities and higher instrument output. Another interesting observation can be noted from the linear behavior of the 75 ft/s (23 m/s) data with the exception of the highest coal flow. In that instance, the ECT output drops considerably at all locations. It should be noted that the 75 ft/s (23 m/s) data at test location 3V15 are omitted from the plot because TR-Tech encountered a sensor malfunction while post-processing the data.

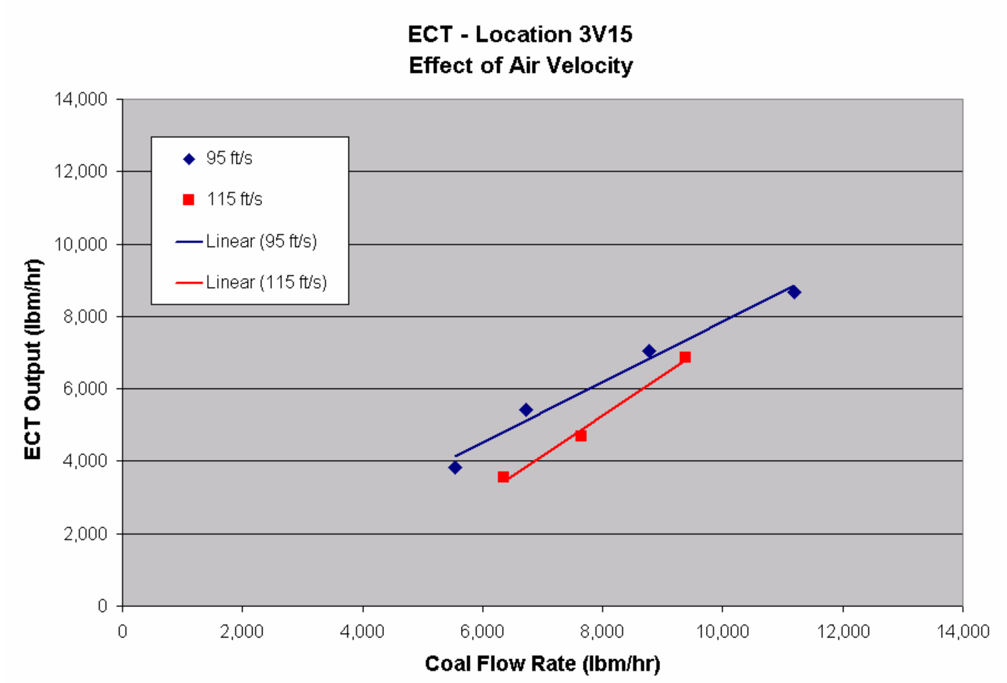


Figure 4-12
Effect of Air Velocity at Location 3V15 – 75 ft/s (23 m/s) data omitted

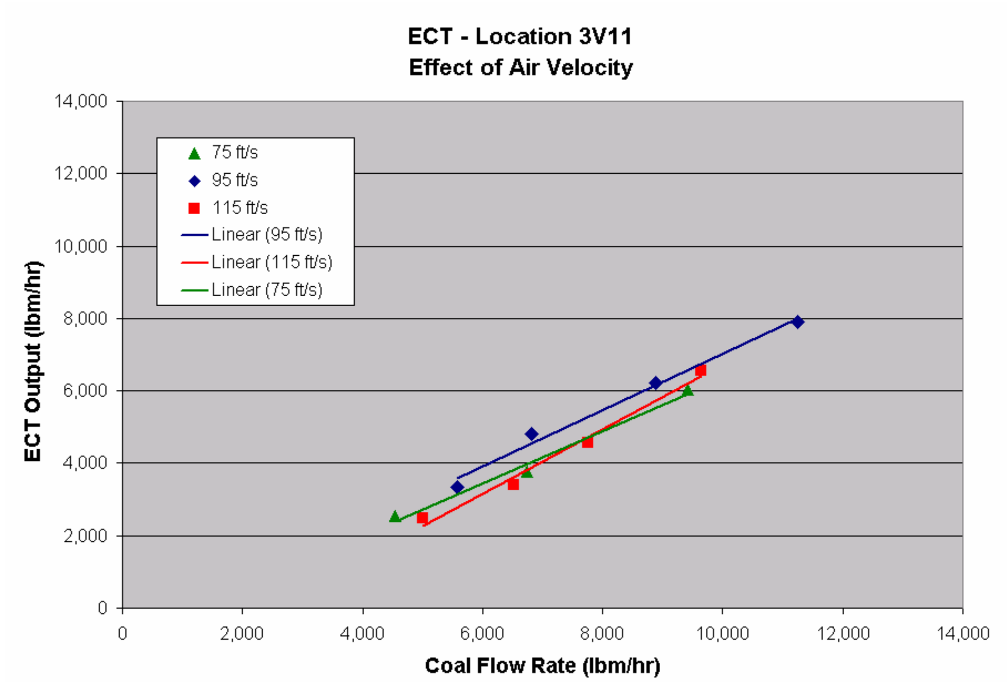


Figure 4-13
Effect of Air Velocity at Location 3V11

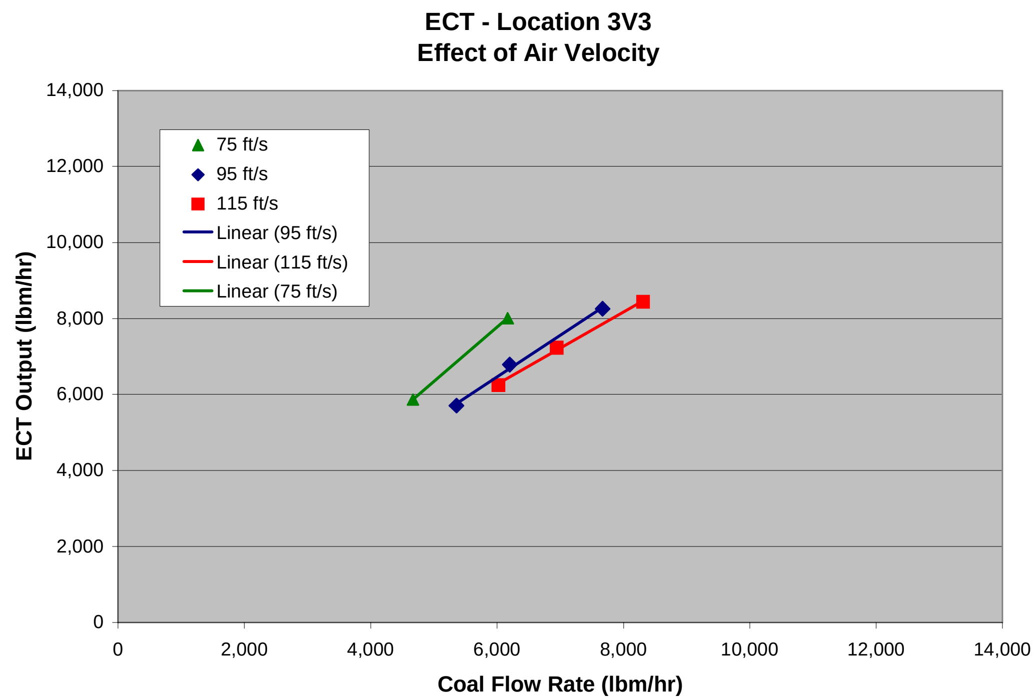


Figure 4-14
Effect of Air Velocity at Location 3V3

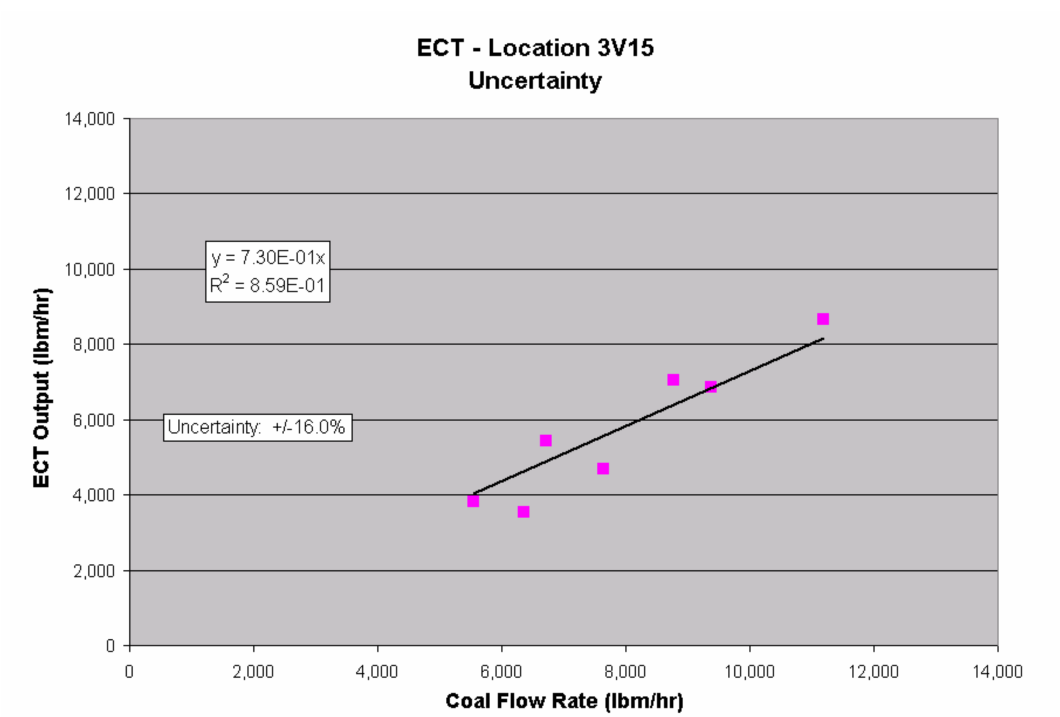


Figure 4-15
Uncertainty at Location 3V15

4.2.2.2 Uncertainty

The calculated uncertainties for Locations 3V15, 3V11, 3V7 and 3V3 are presented below in Figure 4-16 through Figure 4-19. At Location 3V15, where the 75ft/s was unavailable, the uncertainty is +/- 16.3%. At location 3V11 the uncertainty is +/-26.9%. At location 3V7 the uncertainty is +/- 31.8%. At location 3V3, the location closest to the bend, the uncertainty is +/-15.8%. Extractive testing has confirmed that coal flow stratification (roping) increases dramatically closer to the bend. The expectation would be that the instrument uncertainty increases as its proximity to the bend decreases. This trend was not fully observed here as Uncertainty differed from location to location.

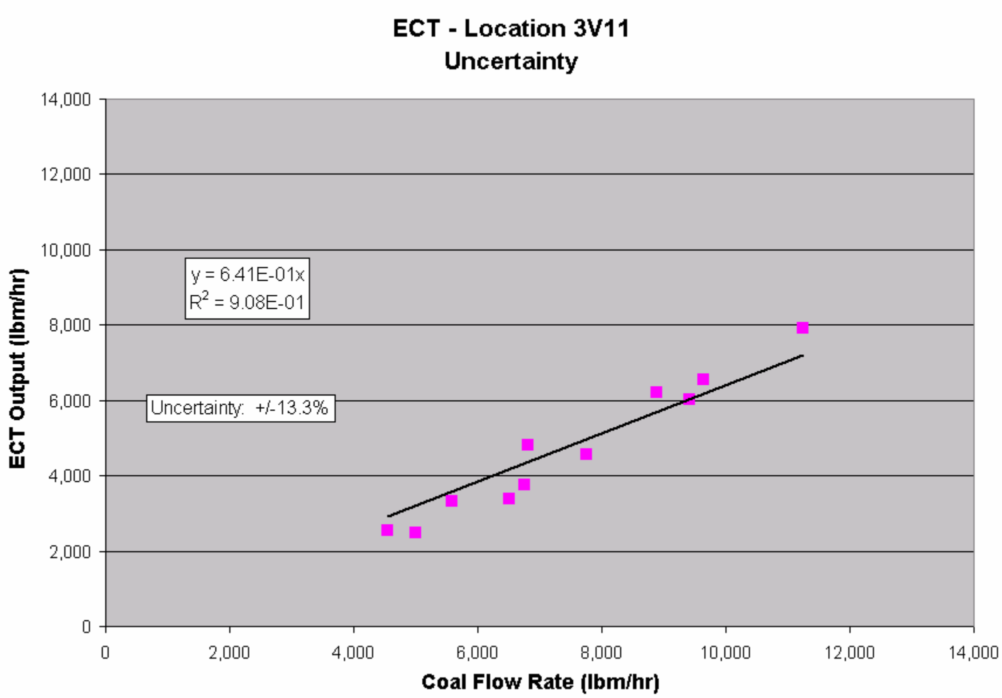


Figure 4-16
Uncertainty at Location 3V11

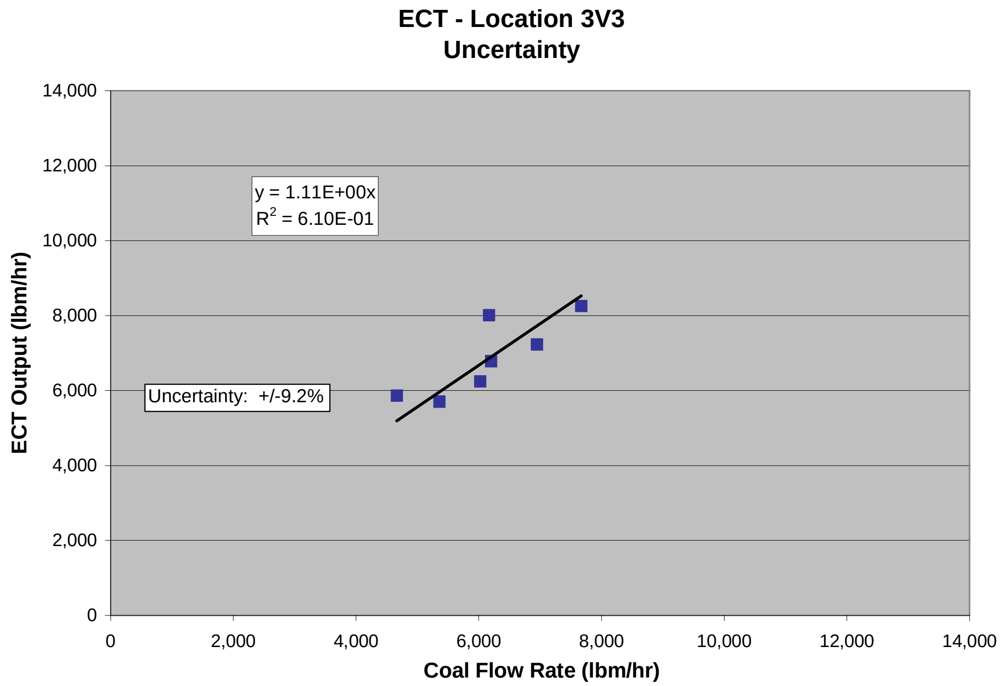


Figure 4-17
Uncertainty at Location 3V3

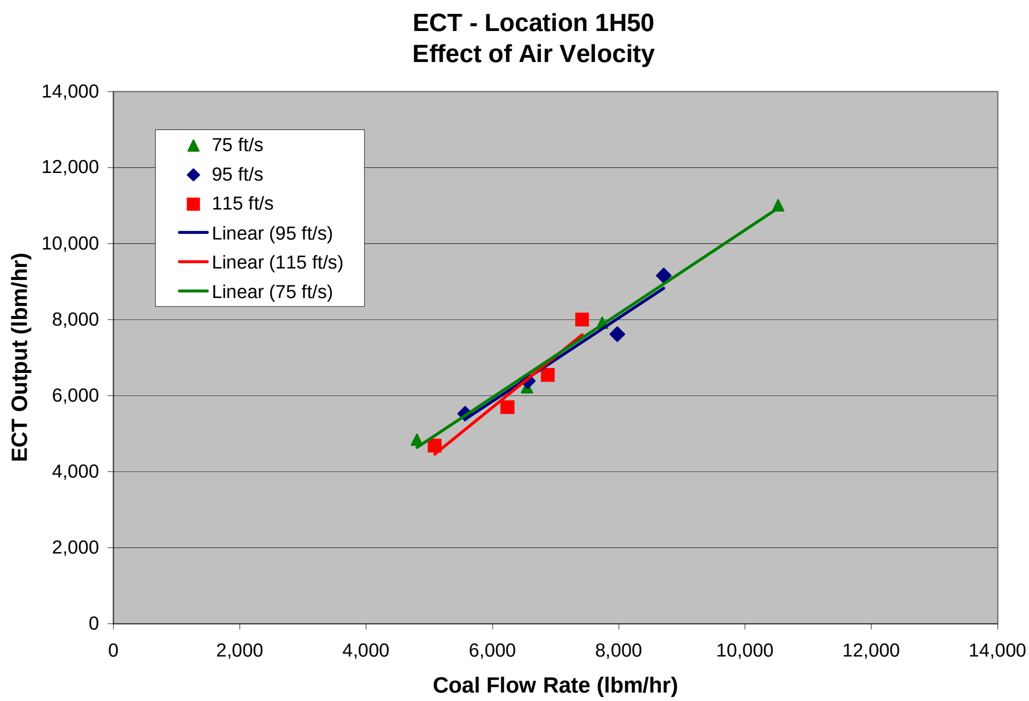


Figure 4-18
Effect of Air Velocity at Location 1H50

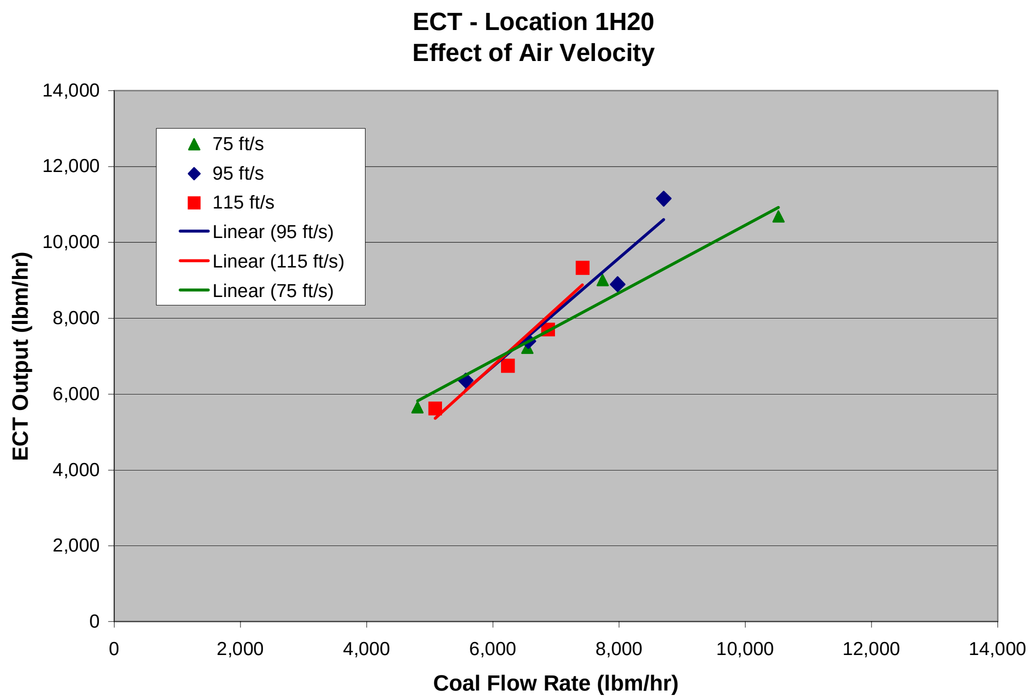


Figure 4-19
Effect of Air Velocity at Location 1H20

4.2.2.3 Effect of Location (Sensitivity)

The effect of location on the instrument sensitivity was more pronounced at the 3V locations than at the 1V locations. Table 4-2 summarizes each location's sensitivity and normalized sensitivity. Viewing the data on a relative basis (comparing the output to location 1V15), the ECT instrument output was 7% high at 3V15, 6% low at 3V11, and 62% high at 3V3. In addition, when viewing the ECT as an absolute instrument, the output is 27% low at 3V15, 36% low at 3V11, and 11% high at 3V3.

Table 4-2
Effect of Installation Location – Double Bend Vertical Run

Location	Sensitivity	Normalized Sensitivity	Uncertainty
3V15	0.730	1.07	16.0%*
3V11	0.641	0.94	13.3%
3V3	1.112	1.62	9.2%

* 75 ft/s (23 m/s) data omitted from calculation

4.2.3 Results for Locations 1H50 and 1H20

The final locations analyzed were in the first horizontal run between the coal in-feed section and the first vertical upflow run of pipe. As stated in the data quality control Section 3.6, if the CFL coal feed exceeded a standard deviation of greater than 6% during any time, those tests would be omitted from the data reduction procedure. In this instance, all of the tests conducted at both Locations 1H50 and 1H20 were affected by larger than desired coal feed steadiness. Because of this constraint for data quality, the data collected at these locations was deemed invalid. However, for the interest of the reader, data are presented in this section

4.2.3.1 Effect of Air Velocity – Questionable Coal Feed Deviation

The effect of air velocity at 1H50 and 1H20 is illustrated below in Figures 4-18 through 4-19. In spite of the known fluctuations in coal steadiness during these tests, It can be seen that ECT output is largely unaffected by changes in air velocity. This is notably the main reason for presenting the air velocity plots.

4.2.3.2 Uncertainty – Questionable Coal Feed Deviation

Disregarding the unusually high coal feed steadiness fluctuation and conducting the standard data reduction for these two locations, the uncertainty values for locations 1H50 and 1H20 are presented in Figures 4-20 and 4-21. At Location 1H50 the uncertainty is +/-6.1% and at location 1H20 the uncertainty is +/-8.8%. In spite of the known coal flow fluctuations, these values represent the lowest observed results in the entire test matrix.

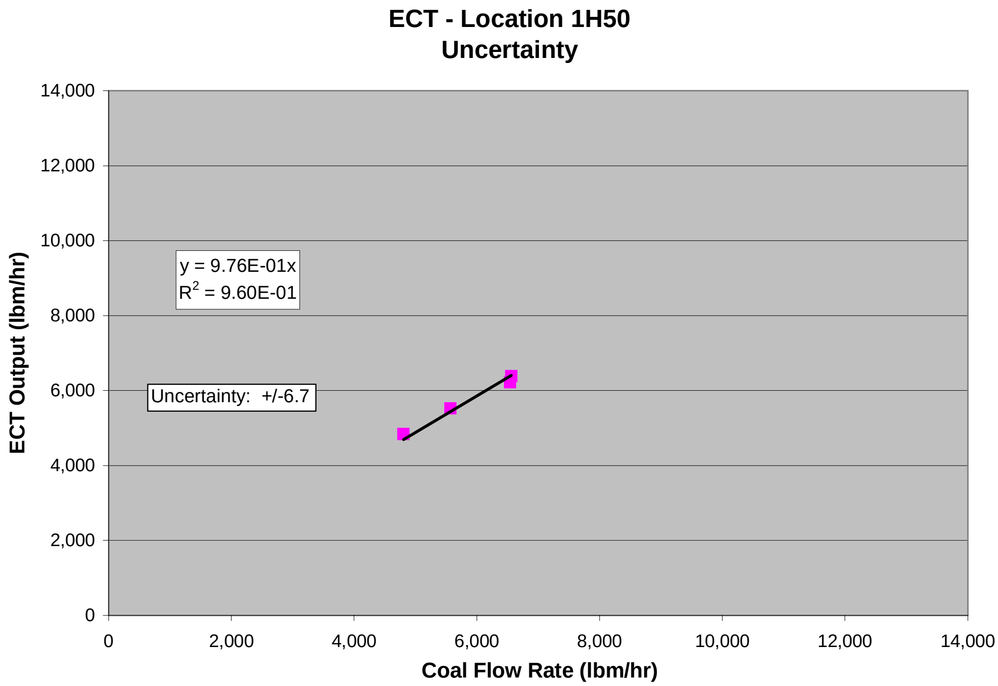


Figure 4-20
Uncertainty at Location 1H50

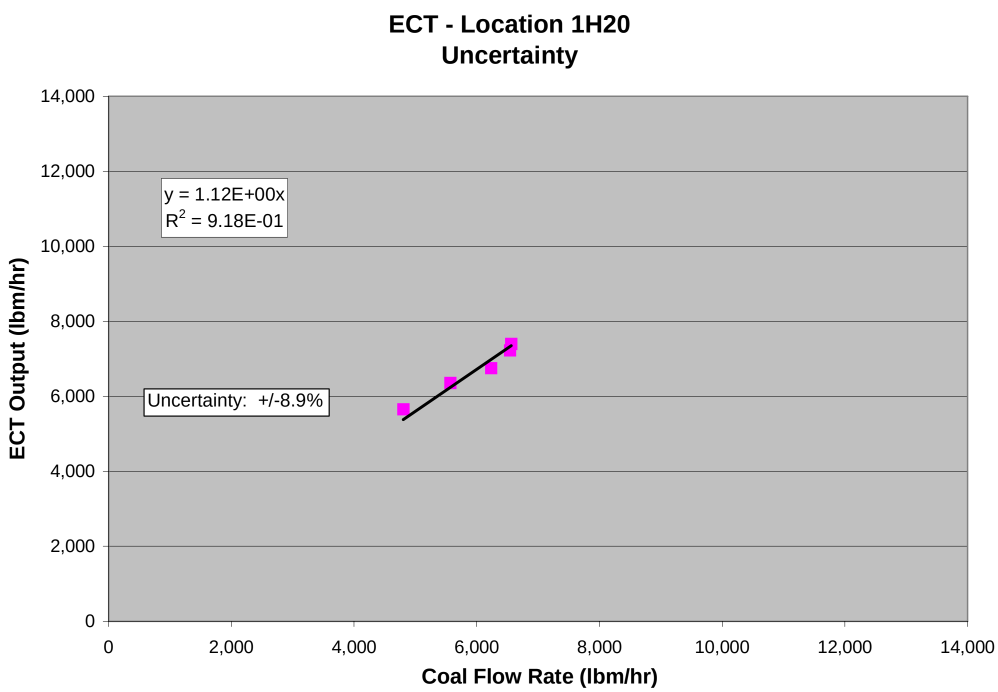


Figure 4-21
Uncertainty at Location 1H20

4.2.3.3 Effect of Location – Large CFL Coal Feed Deviation

The ECT sensitivity at Locations 1H50 and 1H20 is presented in Table 4-3. The normalized sensitivities at these locations are 1.46 at 1H50 and 1.65 at 1H20. This comparison to Location 1V15 indicates that the instrument reads 46% high at 1H50, and 65% high. When viewing the instrument on an absolute basis, the instrument has little error at location 1H50, and reads 14% high at 1H20.

Table 4-3
Effect of Installation Location – Horizontal Run

Location	Sensitivity	Normalized Sensitivity	Uncertainty
1H20	1.002	1.46	6.1%
1H50	1.136	1.65	8.8%

4.3 Effect of Orifices

A series of tests was performed to determine the effect of upstream and downstream orifices at varying distances from the instrument. For this investigation, a 56% open concentric circular orifice, fabricated from 0.090" aluminum, was used. A reduced test matrix was used at each location, consisting of four coal flows and a nominal air velocity of 95 ft/s (29 m/s). In addition, for the reduced test matrix, a two-point calibration matrix was used: low coal flow and high coal flow, both at 95 ft/s (29 m/s). This reduced calibration matrix had some unintended consequences that will be addressed shortly.

4.3.1 Upstream Orifice

For the upstream orifice evaluation the instrument was located at Location 1V15. Three different upstream orifice distances were tested at each flow condition. As shown in Figure 4-24, the orifices were installed at 0.5, 4.5, and 8.5 diameters in the upstream direction and a case was also run where the orifice was installed in the horizontal pipe 4 diameters upstream of the horizontal-to-vertical bend.

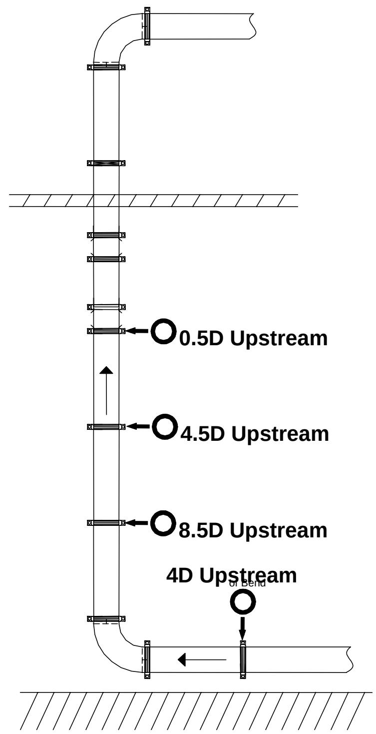


Figure 4-22
Position of Orifice Relative to the 1V15 Location

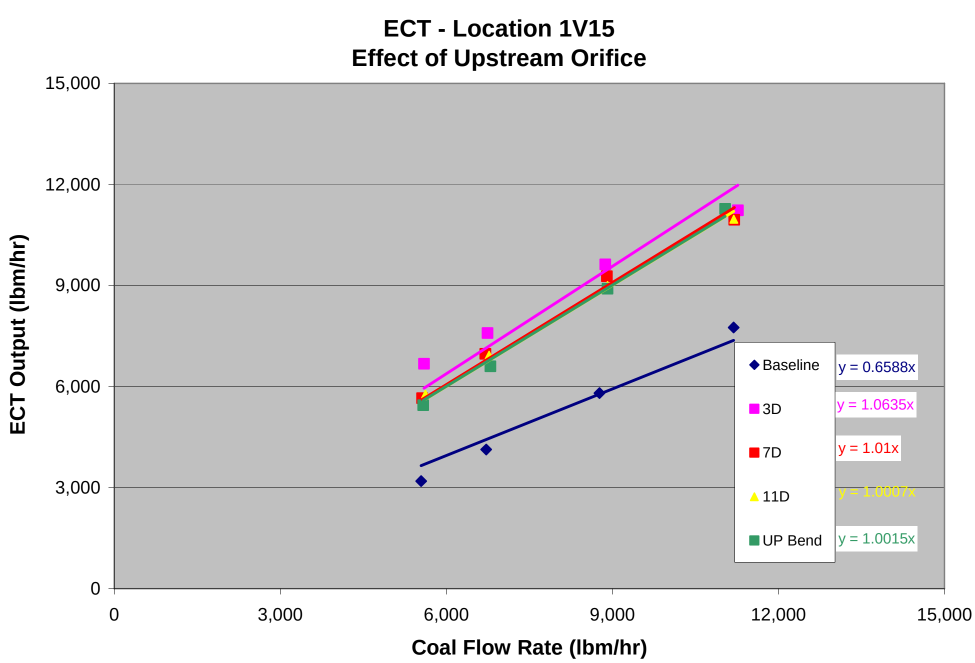


Figure 4-23
ECT Output with Orifice Upstream

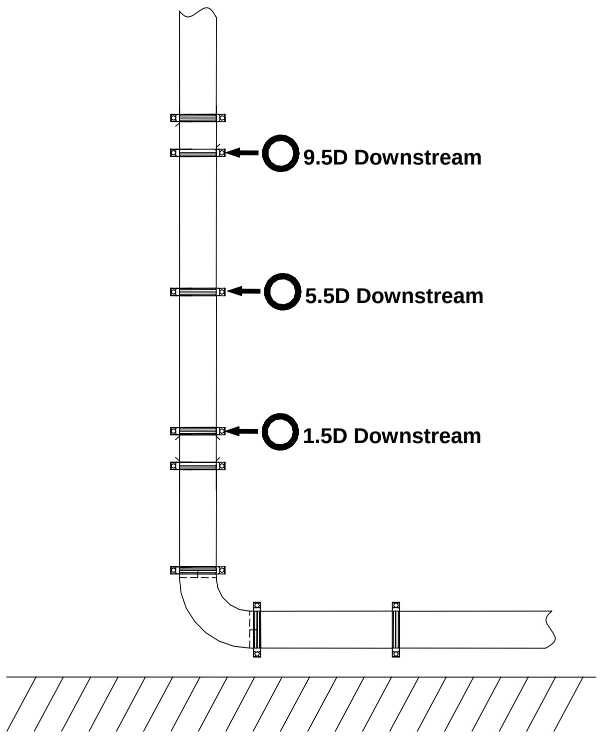


Figure 4-24
Downstream Orifice Locations

The results of the upstream orifice tests are summarized in Figure 4-25 where the ECT output versus actual coal flow rate, at the various upstream orifice distances, are plotted. The results indicate that presence of an upstream orifice does affect the sensor output, but the proximity of the orifice to the sensor is inconsequential. This result seemed highly unlikely, and further investigation of the data was performed. Upon closer investigation, it was determined that the procedure used to calibrate the sensor for the upstream orifice runs accounted for the seemingly strange result. For each upstream orifice location, an instrument calibration was performed. However, since the tests were only to be run at 1 velocity (95 ft/s), the calibration procedure for these tests was reduced from four points (low coal – low velocity, low coal – high velocity, high coal – low velocity, and high coal – high velocity) to two points, low and high coal flow rates at 95 ft/s (29 m/s). It appears that the calibration was so effective for these tests that it was able to completely compensate for the influence of the upstream orifice. It is speculated that the reason the baseline data stands out as different from the tests where the orifice was present is that the baseline data is a subset of a larger test matrix where a different calibration procedure was used. The baseline case is derived from the full test at 1V15, which was calibrated at four points (none of which include 95 ft/s as the velocity). While the full test at 1V15 consisted of 3 velocities (75, 95, and 115 ft/s) and 4 coal flows at each velocity, only the 95 ft/s (29 m/s) data taken at that location was used as the baseline for the upstream orifice tests (This was done in order to be consistent with the tests where the orifice was present that were only run at 95 ft/s). It is believed that, if a dedicated test was run for the baseline, following exactly the same procedure as the tests that were run with the orifice present, that the baseline results would fall in line with the data with the orifice present.

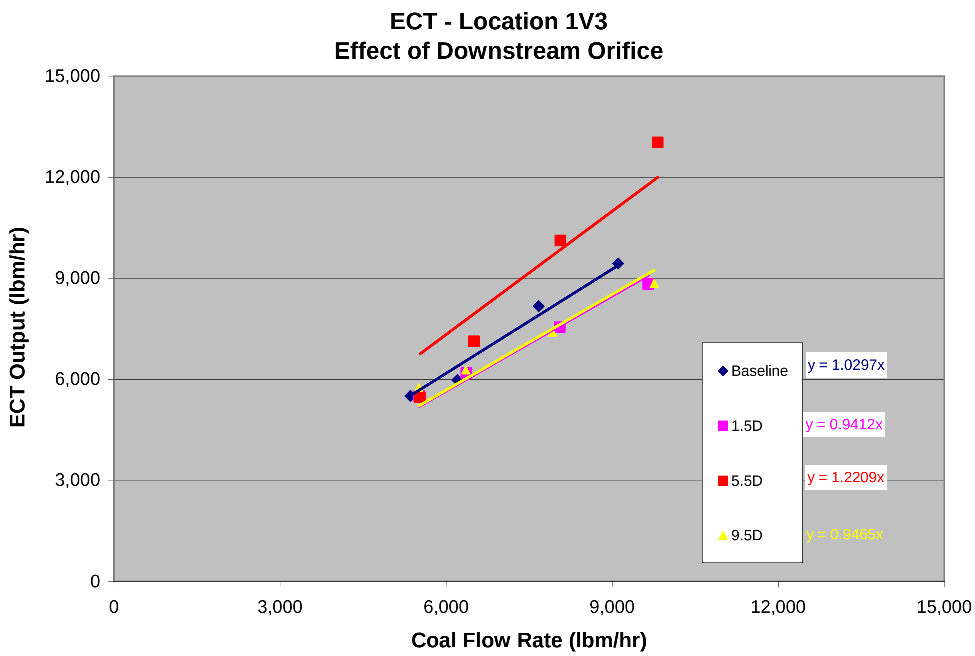


Figure 4-25
ECT Output With Downstream Orifice

4.3.2 Downstream Orifice

Three different downstream orifice distances were tested at each flow condition as depicted in Figure 4-26. The instrument was installed at Location 1V3 for these runs. The orifices were installed 1.5 diameters, 5.5 diameters, and 9.5 diameters downstream of the sensor. Again, similar to the upstream orifice tests, the baseline data were obtained following a different calibration procedure than the data taken with the orifice present. The results of these tests are summarized in Figure 4-27 where the ECT output versus coal flow rate as a function of downstream orifice distance is plotted. It can be seen that the presence of a downstream orifice has some effect on the ECT sensor output. Ignoring the baseline data, which again were obtained with a different calibration procedure, it can be seen that the data taken with the orifice at 1.5D and 9.5D are very consistent, but the data taken with the orifice at 5.5D show a considerably higher instrument output. It is difficult to say what caused the output at 5.5D to differ from the output at 1.5D and 9.5D.

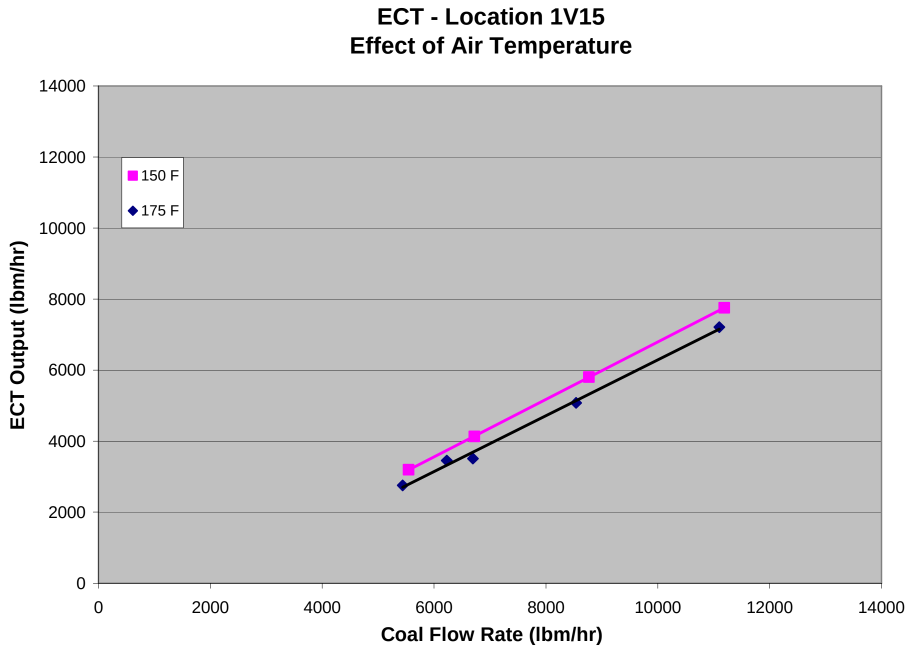


Figure 4-26
Effect of Air Temperature at Location 1V15

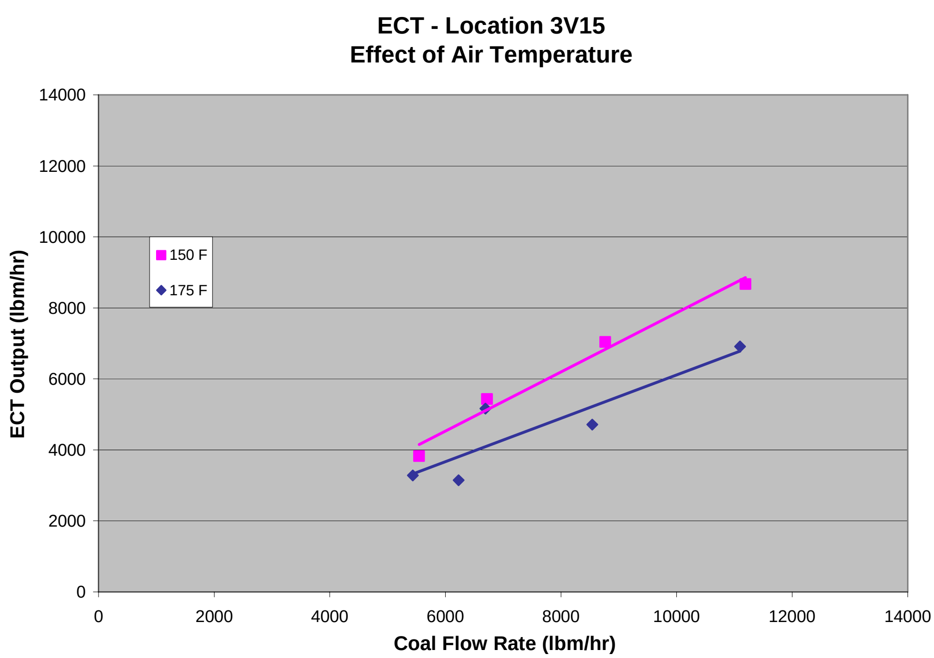


Figure 4-27
Effect of Air Temperature at 3V15

4.4 Effect of Air Temperature

The final step of the instrument assessment was to determine the effect of air temperature on signal output. With the instrument installed at locations 1V15 and 3V15, the instrument was tested with similar air and coal flow rates at both the baseline temperature of 150°F (66°C) as well as an elevated temperature of 175°F (79°C). The reduced test matrix consisted of 4 coal flow rates at an air velocity of 95 ft/s (29 m/s). The results of the elevated temperature tests can be seen below in Figures 4-28 and 4-29. It can be seen that at location 1V15, a change in temperature of 25°F (14°C) causes the instrument output to drop by 11% whereas, at location 3V15, the instrument output to drops by 27%.

4.5 Concern over Charge Build-up on Coal-Flow Loop Tests

After the evaluation was completed, concerns were raised by Foster-wheeler regarding the influence of charge build-up on the ECT sensor outputs. Since the ECT is based on an electrostatic measurement principle, a buildup of charge on the coal would cause erroneous ECT output. As a result, an investigation on the possibility of charge build-up was conducted, and ultimately dismissed. The rationale for this decision is as follows.

Two types of possible charge build-up were investigated, long term charge build-up that would occur over the course of days, and short term charge build-up that would occur over the course of a test. Because the ECT was calibrated at each location that it was tested, long-term charge build-up concerns should be minimal or non-existent. Since the sensors were moved to a new location each day, and were recalibrated at each location, there is no opportunity for any long-term charge build-up to influence the system's output. To look at the possibility of short term charge build-up, consider the approach for the test protocol. At each location, the following test matrix was run: Four tests were performed for the calibration (two air velocities, two coal flow rates). Then, at a low air velocity, four coal flows were run. At a middle velocity, five coal flows were run (one of those coal flows being zero). Finally, at a high velocity, four more coal flows were run. After this matrix was completed, the first flow test condition (low velocity, first coal flow) was repeated to check the repeatability of the instrument output. Each condition in the test matrix was run for 22 minutes, thus, without interruptions in the test sequence, there are approximately 4.5 hours between the end of the first condition (Test 5) and the beginning of the repeat test of that condition (Test 18). If Test 18 is compared with Test 5, any variables - such as charge build-up, that seem to affect the instruments' output should be noticeable. Table 4-4 shows the results of Test 5 and Test 18 at each of the locations where the ECT was tested. Also note that two instruments were tested simultaneously each on a different vertical test leg of the CFL. That is, locations 1V15 and 3V15 were tested simultaneously, as were locations 1V11 and 3V11, locations 1V7 and 3V7, and locations 1V3 and 3V3 respectively (Note that Foster Wheeler advised that the sensor at Location 3V7 was malfunctioning, and, as a result, that data set was not used in the statistical analysis of the instrument).

It can be seen from Table 4-4 that the Test 18 output of the instrument installed in the 1VX locations is generally about 80% of the output during Test 5. For the instrument installed at the 3VX locations during the same tests, the output differences between Tests 5 and 18 are closer than for the 1VX locations. Unfortunately, there was a problem with the data during Test 5 at location 3V15, so the repeatability at this location cannot be confirmed. Since the loop is completely grounded, it seems highly unlikely that there is a charge build-up impact at the 1VX locations. No similar charge build-up impact affects the 3VX locations. It is unknown why the instrument in the 3VX locations showed better repeatability than the instrument at the 1VX locations but it seems unlikely that it is the result of a charge build-up effect.

Table 4-4
Comparison between ECT Output and CFL Flow Rate for Repeat Tests at Each Location

Test Location		1V15	3V15	1V11	3V11	1V7	3V7	1V3	3V3
ECT Output	Test 5	10,681	n/a	10,309	5,500	10,775	10,330	12,341	8,177
	Test 18	8,426	6,167	8,716	5,617	8,779	10,062	10,985	8,489
Loop Coal Flow	Test 5	13,823		13,534		12,919		9,844	
	Test 18	13,867		13,570		13,676		9,230	
Elapsed Time between Tests (hr:min)		10: 4		4:31		4: 30		4:31	

4.6 Summary of the ECT System Results

The ECT system was found to have the following performance characteristics:

1. The instrument output is sensitive to installation location. This is shown in the sensitivity values of Table 4-5. In addition, since the ECT was calibrated to provide an absolute measurement indication, the sensitivity at each location should be equal to 1. Recall that an ideal sensitivity value is 1.0, which indicates a 1 to 1 relationship between instrument output and actual coal flow from the CFL. Evaluating the instrument on that basis, the instrument reads 36% low at 3V11, 33% low at 1V11, 32% low at 1V15, 29% low at 1V7 and 27% low at 3V15. At 3V3, the instrument reads 11% higher than the coal loop indication. At location 1V3, the instrument displays the ideal sensitivity of 1.00.

3. The coal mass flow output signal is slightly affected by change in air velocity. While the effect is negligible at the locations in the first vertical (1V), at the locations in the third vertical (3V) the instrument output at 75 ft/s (23 m/s) is lower than the output at the other velocities.

4. The tests to evaluate the influence of an orifice were inconclusive due to calibration inconsistencies. In hindsight, despite the reduced test matrix used for these tests, the calibration matrix should have remained unchanged.

5. An increase in air temperature results in a decrease in the instrument output as illustrated in Figures 4-26 and 4-27. The effect seems more pronounced at the double bend location than at the single bend location.

6. The uncertainty of the instrument from all tested locations ranges from +/-7.1% to +/-16.0% when all test conditions are compared.

Table 4-5
Summary of ECT Star Sensitivity (as Normalized Ratio) and Uncertainty

	All Velocities		
Location	**Sensitivity**	**Normalized Sensitivity**	**Uncertainty**
1V15	0.684	1.00	13.3
1V11	0.667	0.97	8.5
1V7	0.707	1.03	9.5
1V3	1.000	1.46	7.1
3V15	0.730	1.07	16.0
3V11	0.641	0.94	13.3
3V7	Na	Na	Na
3V3	1.112	1.62	9.2
1H50	Na	Na	Na
1H20	Na	Na	Na

5 SWR ENGINEERING SOLIDFLOW PF TESTING AND RESULTS

This section describes the results of the SWR SolidFlow instrument assessment. The SolidFlow PF is an on-line coal measuring instrument based on a microwave principle. The following passages from the SolidFlow operations manual provide a description of the instruments functionality:

> "SolidFlow is a measuring system especially developed for measuring the flow rate of conveyed solids in metallic ducts.
>
> The microwave energy is being back scattered by the solid particles and received by the sensor. These signals are evaluated in frequency and amplitude. Because of the selective frequency evaluation, only moving particles are measured.
>
> The measuring signal is independent of pressure and temperature in the duct. "

The SWR system is comprised of a number (1 to 3 depending on pipe diameter) of probes, an evaluation unit, and a communications box (c-box), if the distance between the sensors and the evaluation unit exceeds 5.9 feet (1.8 meters). In addition, software is provided so that the evaluation unit can be controlled via a desktop or laptop computer. The system uses standard 120V, 60Hz cycle electrical power and does not require any special electrical insulation, grounding or separation.

For a three-sensor system installation, mounting flanges must be welded 120 degrees apart around perimeter of the pipe. After the holes are drilled, the sensors can be installed such that the sensor probe tip is flush or slightly recessed with respect to the inside wall of the pipe, and secured to the mounting flange with a union nut. The operating manual specifies that sensors should be mounted a minimum of 5 diameters downstream and 3 diameters upstream of flow disturbances such as bends, contractions, and orifices. These minimum distances also apply to temperature or pressure sensors which may intrude into the pipe. In horizontal installations one of the sensors should be mounted on top of the pipe. A typical sensor installation arrangement is shown in Figure 5-1 for a vertical pipe test section at the Coal-Flow Loop. Figure 5-2 shows a photo of the SolidFlow PF system instrumentation used at the CFL

Figure 5-1
SolidFlow Sensors Installed in a Vertical Pipe Test Section of the Coal-Flow Loop

Figure 5-2
SolidFlow System Instrumentation Tests Conducted at the CFL

5.1 System Commissioning

The three-sensor instrument supplied by SWR was setup and configured on March 14th, 2006 at the 1V3 location. SWR personnel configured the SolidFlow system and were on site for the beginning of the evaluation period which started the same day.

5.1.1 Typical Calibration Procedure

In typical field operation, the SolidFlow system is calibrated at a minimum of two operating points: a point with zero coal or “clean air” flow and one with maximum coal flow. For a multi-pipe system, SolidFlow instruments are installed in each of the pipes. The raw sensor output values are inspected for each instrument at both the clean air calibration point and the maximum coal flow calibration point. The highest sensor value at the maximum coal flow and the lowest sensor value at the zero coal flow are then taken as the calibration values for all of the sensors in the system. Note that this procedure is constrained by the assumption that the have similar coal flows when the calibration is performed.

5.1.2 Alternative Calibration Procedure

On occasion, if SWR personnel believe that a particular installation location does not lend itself to a satisfactory calibration using the typical procedure, extractive testing, such as the ISO 9931 Swivel Sampler Method, is performed to determine coal flow rates. For the SolidFlow evaluation at the CFL, the following procedure was used for calibration: First, the zero coal flow output of the SolidFlow was determined, and this value was used to set the low point of the calibration curve. Next, the loop was set to maximum coal flow, and the SolidFlow instrument was positioned in the loop location that produced the maximum raw instrument output (Location 3V3 was determined to be the location that produced the highest instrument output through a process of experimentation). The calibration values determined at this location were used for all other locations.

5.2 Baseline Test Matrix

The evaluation proceeded by moving the instrument through the locations, flow conditions and tests described in Table 3-1. However, because of a calibration procedure inconsistency in combination with test scheduling constraints, the original test matrix was only partially completed. During the initial tests, the instrument was recalibrated after being relocated at every sampling location. It was later discovered that this procedure was not consistent with how the instrument would typically be installed in the field. The results for those initial evaluations are presented at the end of the section nonetheless. In addition, during some of the test runs, coal feed stability deviations greater than the protocol maximum of 6% occurred at five test conditions. Consequently, those tests were omitted from the analysis, two tests from Location 1V15 and one test each from Locations 1V3, 3V15 and 3V3.

5.2.1 Results for Locations 1V15 and 1V3

The first formal evaluations were performed at two locations in the first vertical up-flow pipe run after a 90 degree, horizontal to vertical elbow. The sensor was installed 15 and 3 diameters downstream of the elbow at locations 1V15 and 1V3 respectively. Figure 5-3 illustrates the various test locations in the first vertical leg.

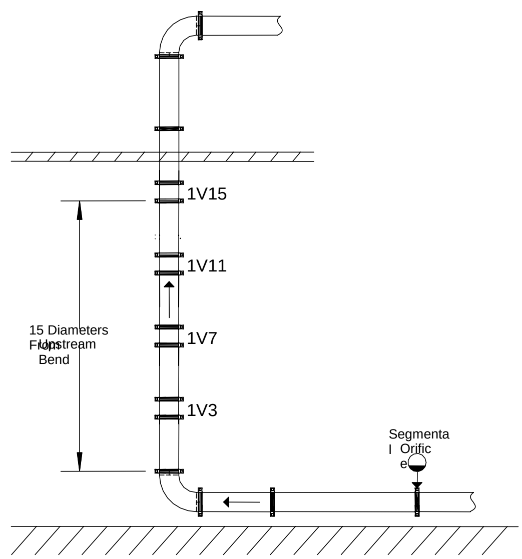


Figure 5-3
SWR Sensor Installation Test Locations at the First Vertical CFL Leg.

5.2.1.1 Effect of Air Velocity

The results for the effect of air velocity on the instrument performance for Locations 1V15 and 1V3 are presented in Figures 5-4 through 5-5 respectively. For the 1V15 results, lower air velocities tend to indicate a higher instrument output in arbitrary units (AU). The same trend is not observed in Figure 5-5 where only the 75ft/s velocity shows a higher instrument output than the higher air velocities.

5.2.1.2 Uncertainty

The calculated uncertainties for Locations 1V15 and 1V3 are +/-17.7% and +/-14.8%. Figures 5-6 through 5-7 show each line fit of the data. Note that although the line fits the points closely, the uncertainty is fairly large because the slope of the line is very shallow. This shallow slope means that large changes in coal flow rate results in only small changes in the instruments output. As a result, even small deviations from the BFSL result in large instrument uncertainty.

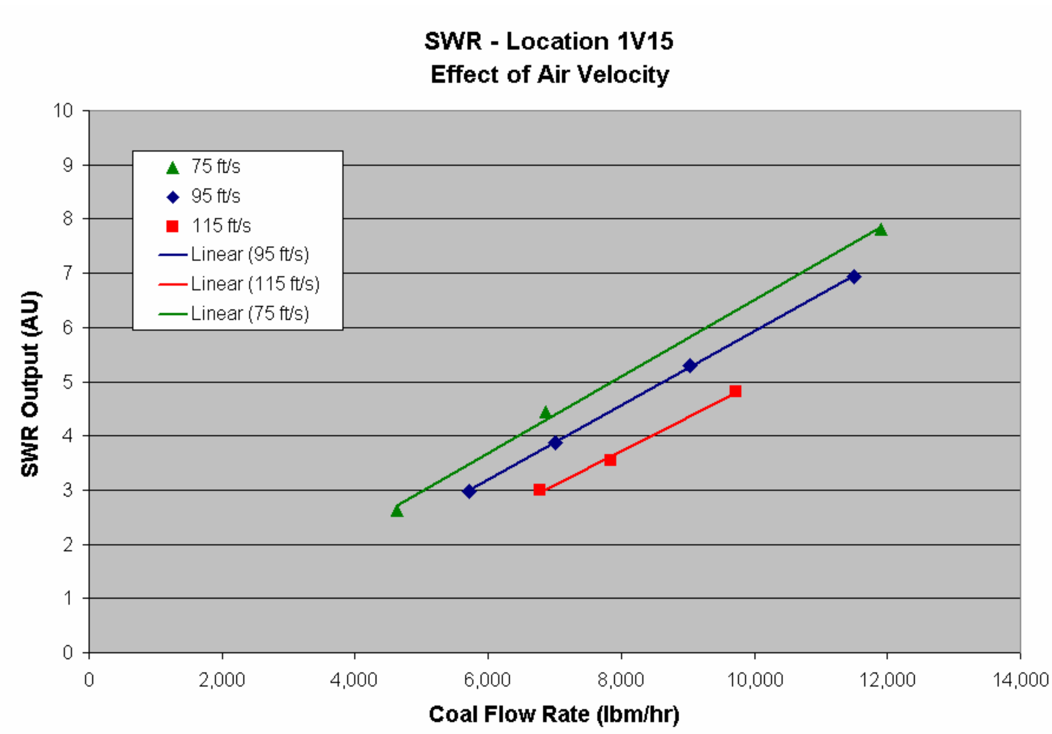


Figure 5-4
Effect of Air Velocity at 1V15

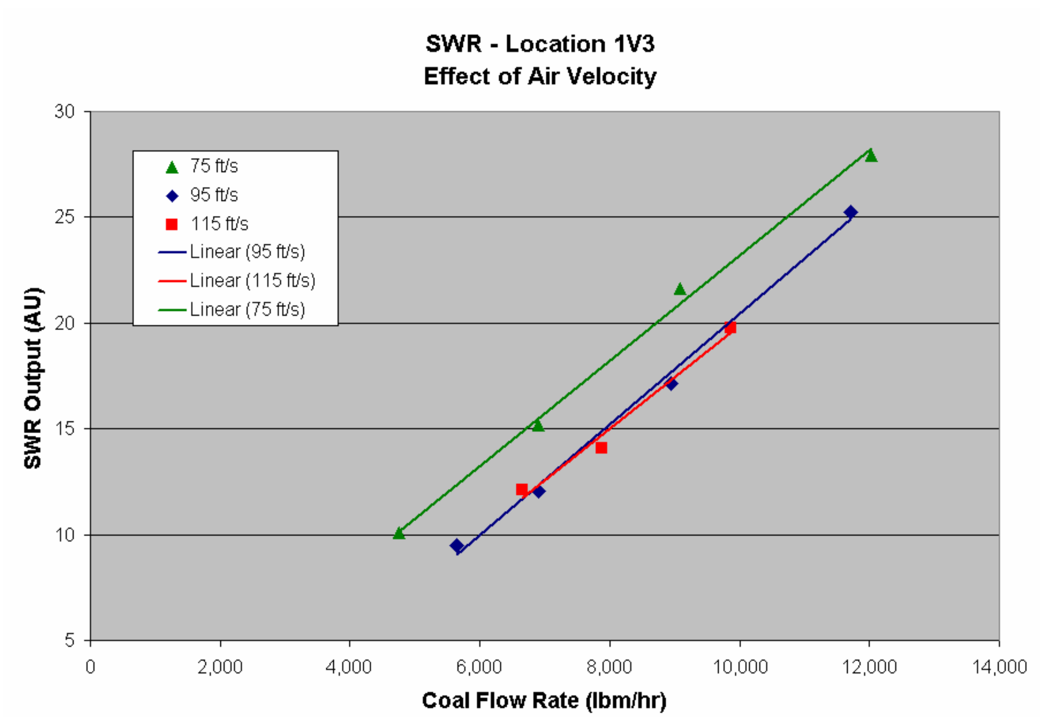


Figure 5-5
Effect of Air Velocity at 1V3

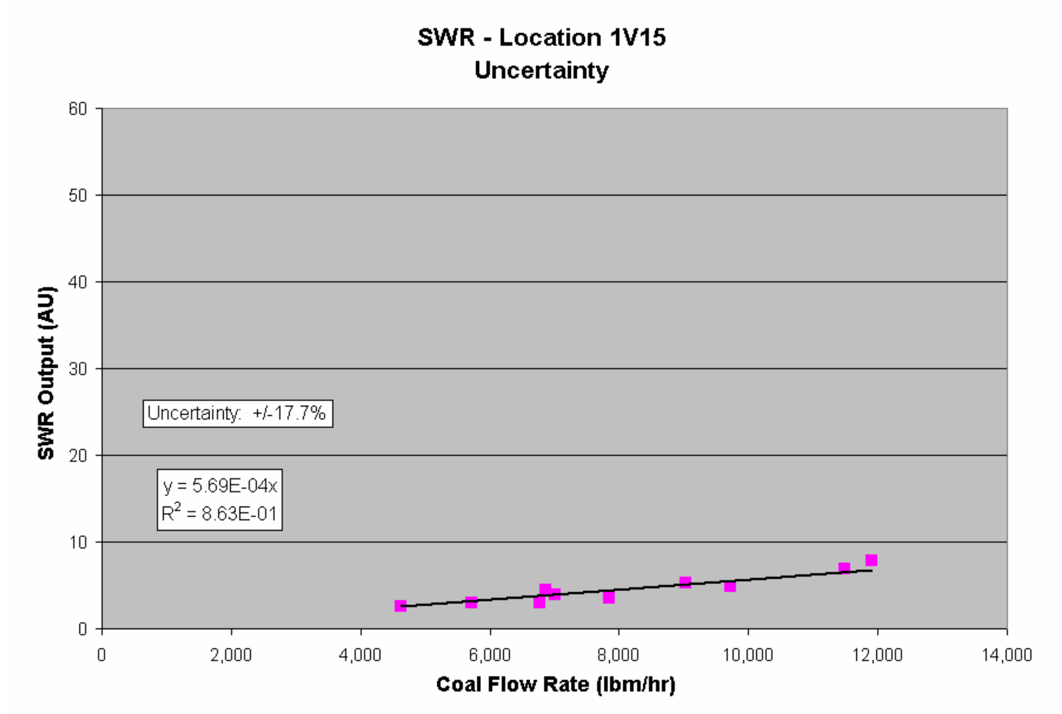


Figure 5-6
Uncertainty at Location 1V15

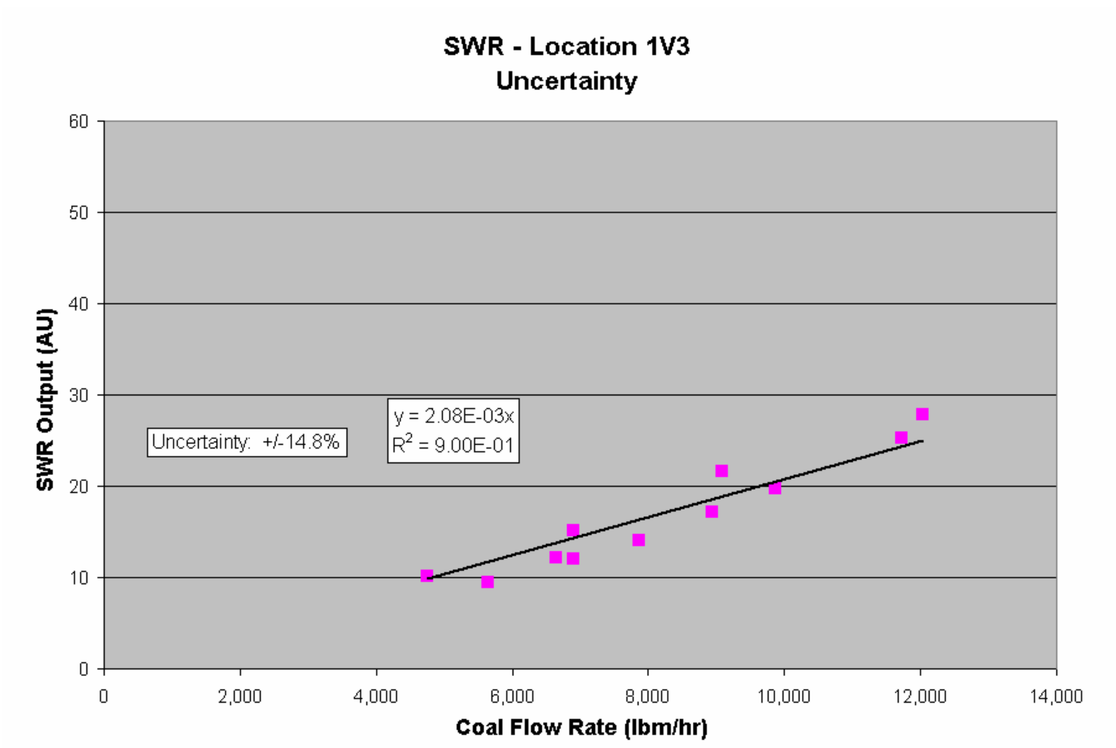


Figure 5-7
Uncertainty at Location 1V3

5.2.1.3 Effect of Location (Sensitivity)

The effect of installation location was examined for the two locations in the first vertical upflow run. Table 5-1 summarizes the sensitivity and normalized sensitivity values. Quantitative analysis using extractive testing has indicated that Location 1V15 contains the most uniform air and coal flow profiles. Therefore, 1V15 is regarded as the benchmark location used for the analysis of the instrument sensitivity. As such, the normalized sensitivity is found by dividing the sensitivity at a particular location by the sensitivity at 1V15. Normalized sensitivity provides a relative indication of the effect of location on sensor output. Thus, the normalized sensitivity is 1.00 at 1V15 and 3.65 at 1V3, meaning that the instrument output is 3.65 times higher at 1V3 than at Location 1V15 for similar test conditions.

Table 5-1
SolidFlow System Effect of Installation Location – First Vertical Leg

Location	Sensitivity	Normalized Sensitivity	Uncertainty
1V15	0.00057	1.00	17.7%
1V3	0.00208	3.65	14.8%

5.2.2 Results for Locations 3V15, 3V7, and 3V3

The effect of air velocity, uncertainty and effect of instrument location were examined at the vertical upflow run downstream of the double 90 degree out of plane double-bend, i.e., at locations 3V15, 3V7 and 3V3. Qualitative visual analysis and extractive tests conducted to date indicate that a stronger coal stratification profile is formed downstream of the double bend (3V) than after the single bend (1V). This high degree of stratification has been observed through a glass-pipe section at location 3V3 while the loop operated with ceramic particulate. At this location, a high concentration of particles followed a spiral motion along the periphery of the pipe, whereas downstream of the single bend, stratification was concentrated towards the outside wall. The instrument was calibrated at location 3V3, as this was the location where the largest raw instrument output was observed.

5.2.2.1 Effect of Air Velocity

The effect of air velocity at 3V15, 3V7 and 3V3 is illustrated below in Figures 5-8 through Figure 5-10. Based on these results, there does not appear to be any clear relationship between air velocity and instrument output as was observed at the 1V15 and 1V3 Locations. That is, the trend of lower velocity correlating with higher instrument output is not supported by this data. Changes in air velocity produced large differences in instrument output.

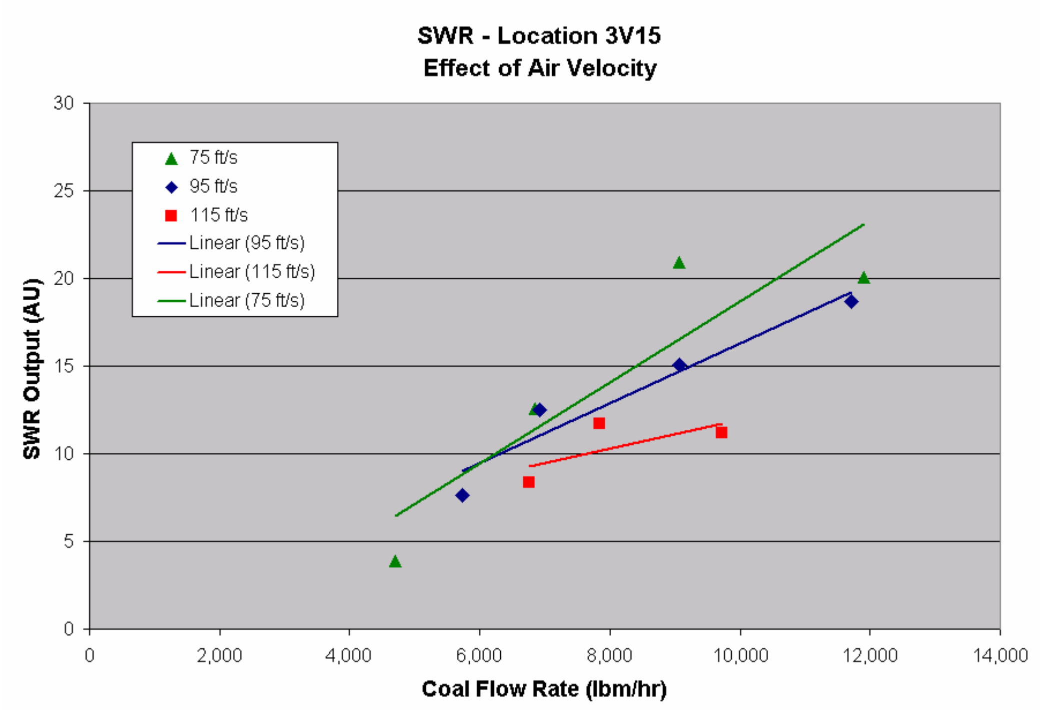


Figure 5-8
Effect of Air Velocity at Location 3V15

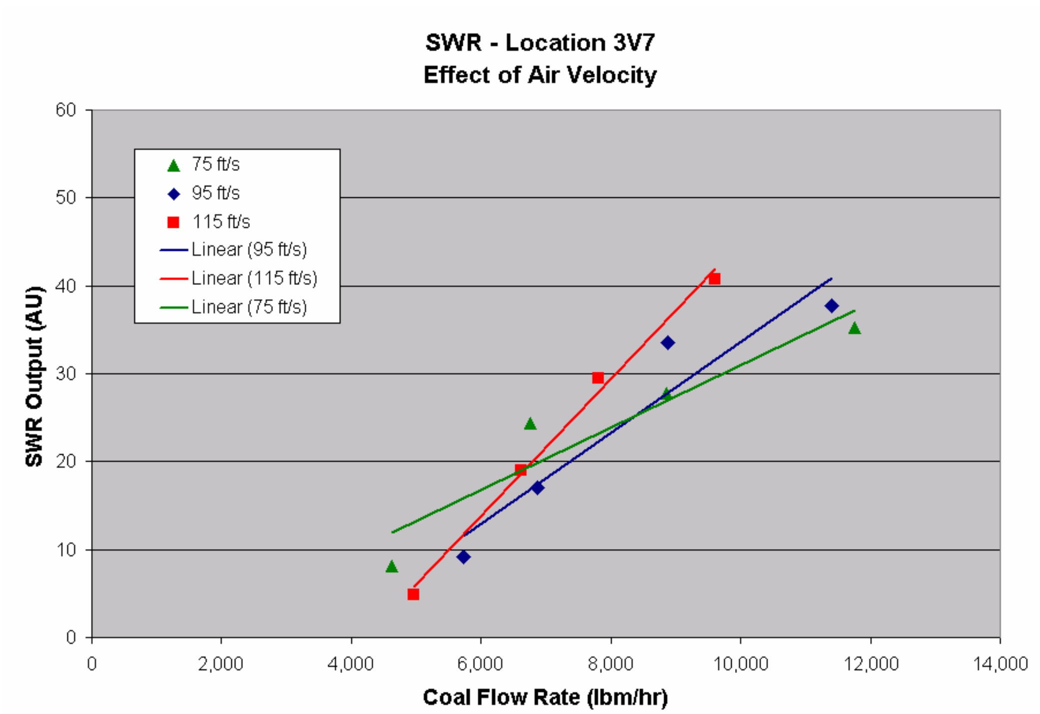


Figure 5-9
Effect of Air Velocity at 3V7

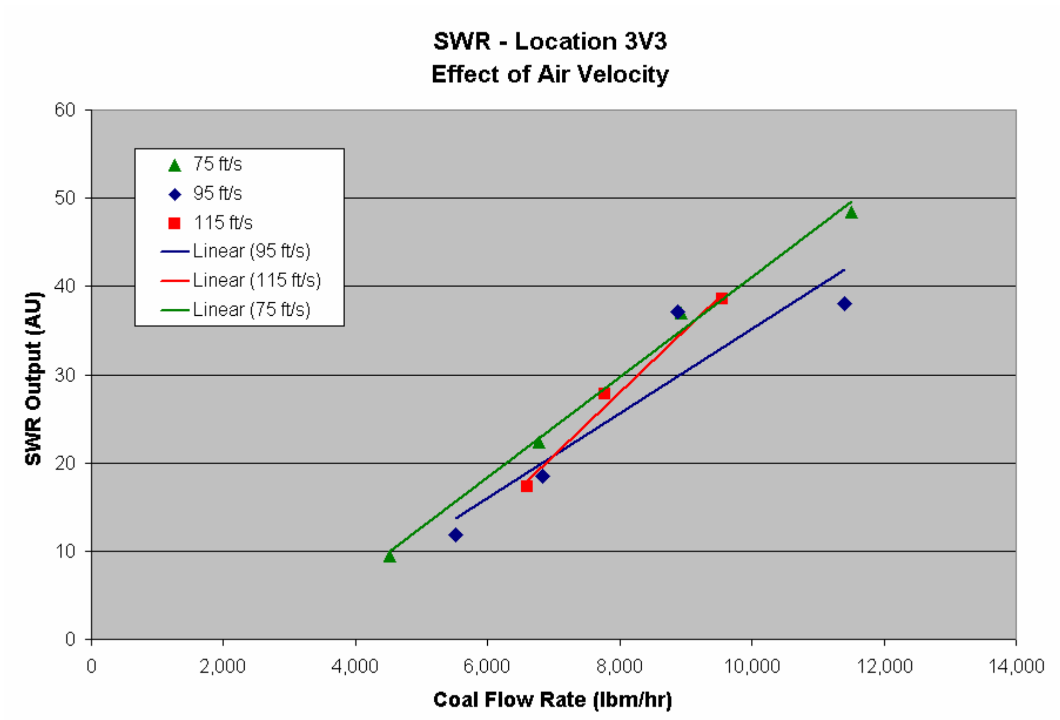


Figure 5-10
Effect of Air Velocity at 3V3

5.2.2.2 Uncertainty

The calculated uncertainties for Locations 3V15, 3V7 and 3V3 are presented in Figures 5-11 through Figure 5-13. The corresponding uncertainty values for Locations 3V15, 3V7 and 3V3 are +/- 29.4%, +/- 31.3%, and +/- 24.6%, respectively. These values are nearly double those from locations 1V3 and 1V15. The uncertainty plots also reveal that by constraining the BFSL to pass through zero contributes to the uncertainty of the instrument (i.e., if the line was not forced through zero then the line would produce a better fit to the points). Although not explored in this evaluation, the SWR instrument software is capable of accepting multiple (up to 20) calibration points. Using this option together with extractive testing may allow for the development of a calibration curve such that the uncertainty may be reduced.

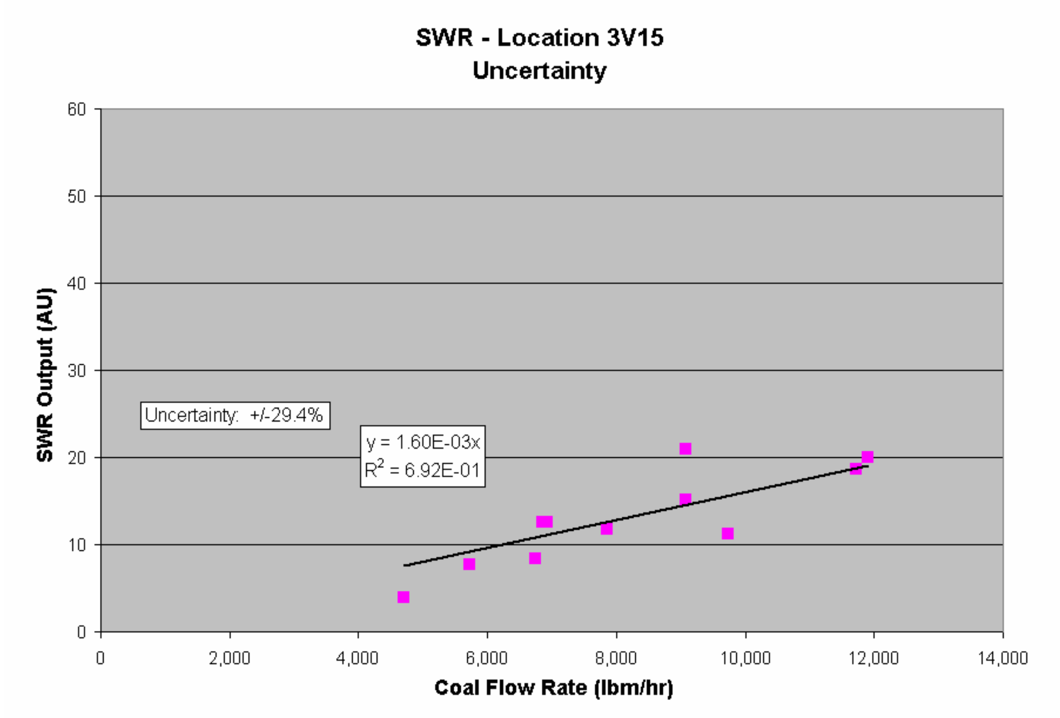


Figure 5-11
Uncertainty at Location 3V15

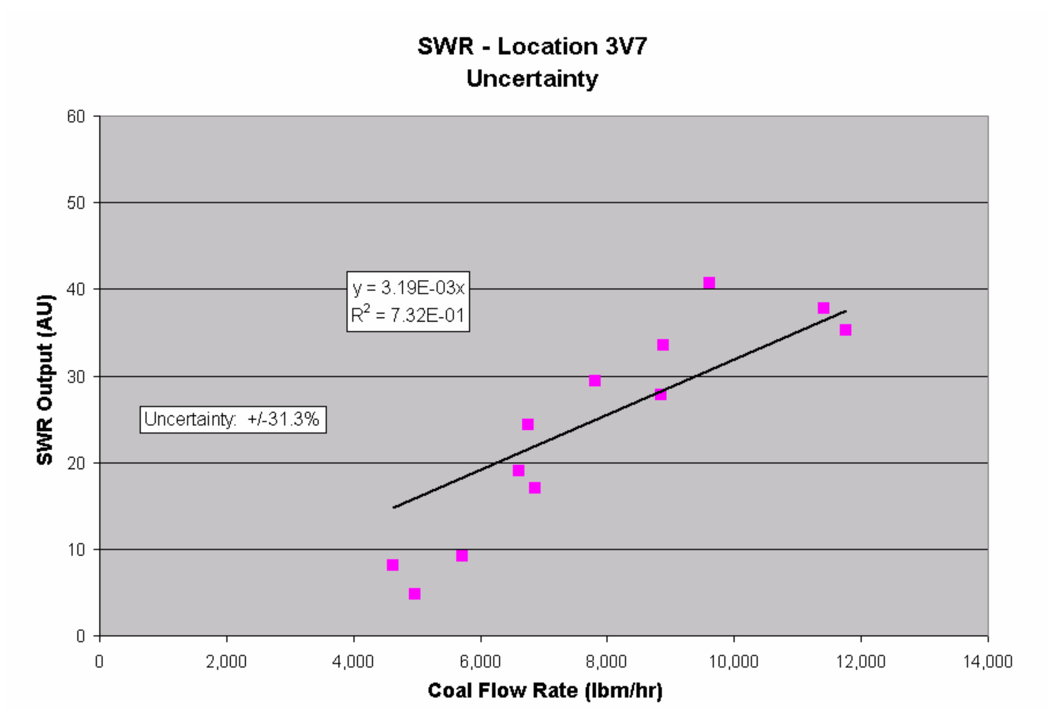


Figure 5-12
Uncertainty at Location 3V7

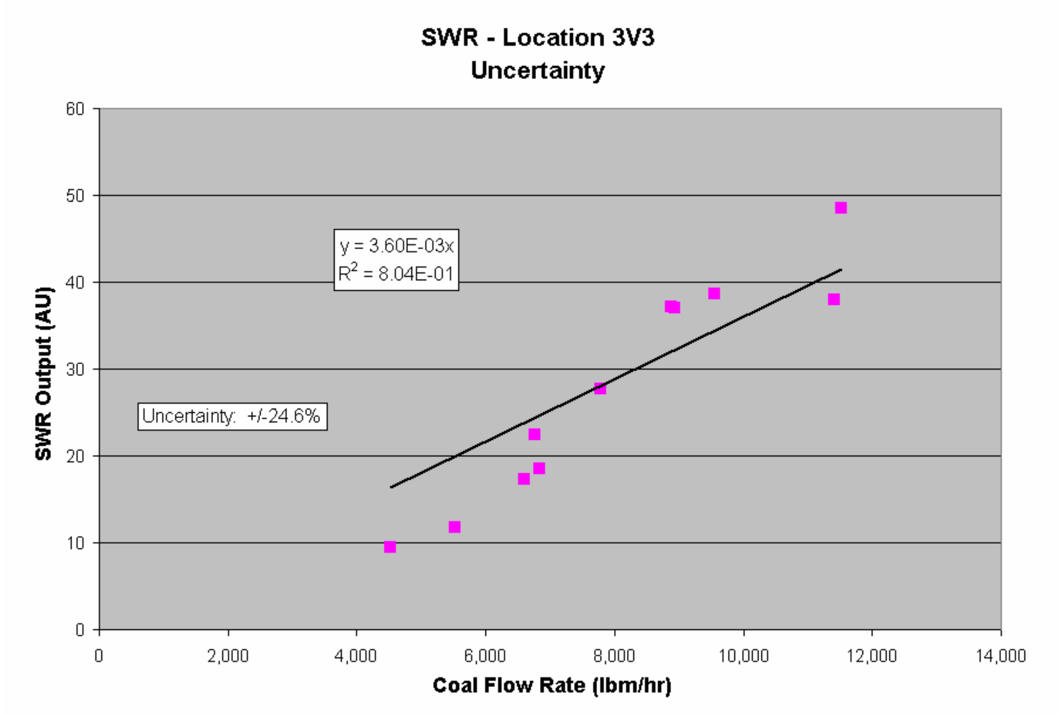


Figure 5-13
Uncertainty at Location 3V3

5.2.2.3 Effect of Location (Sensitivity)

The effect of location on the instrument sensitivity is summarized in Table 5-2 as is the normalized sensitivity value and the uncertainty. It can be seen that the instrument output was 282% high at 3V15, 561% high at 3V7, and 633% high at 3V3 as compared with Location 1V15. While these numbers are quite high in comparison to 1V15, it is important to keep the meaning of these numbers in perspective. For instance, while the instrument reads 633% high at 3V3 and 573% high at 3V7 as compared to 1V15, the instrument only reads 13% high at 3V3 as compared to 3V7 but reads 56% at low at 3V15.

Table 5-2
Effect of Installation Location – Double Bend Vertical Leg

Location	Sensitivity	Normalized Sensitivity	Uncertainty
3V15	0.00160	2.82	29.4%
3V7	0.00319	5.61	31.3%
3V3	0.00360	6.33	24.6%

5.2.3 Results for Locations 1H50

Location 1H50 is 50 diameters downstream of the coal in-feed point just upstream of the first elbow. Unlike for other tests, the segmental orifice normally placed in the horizontal run was removed for this test.

5.2.3.1 Effect of Air Velocity

The effect of air velocity at 1H50 is illustrated in the plots of Figures 5-14. Although the data for the two higher velocities follow a similar increasing linear trend with respect to air velocity and mass flow, the lower velocity line does not follow the same slope.

5.2.3.2 Uncertainty

The uncertainty for location 1H50 is presented below in Figure 5-15. At Location 1H50 the uncertainty is +/-29.6%.

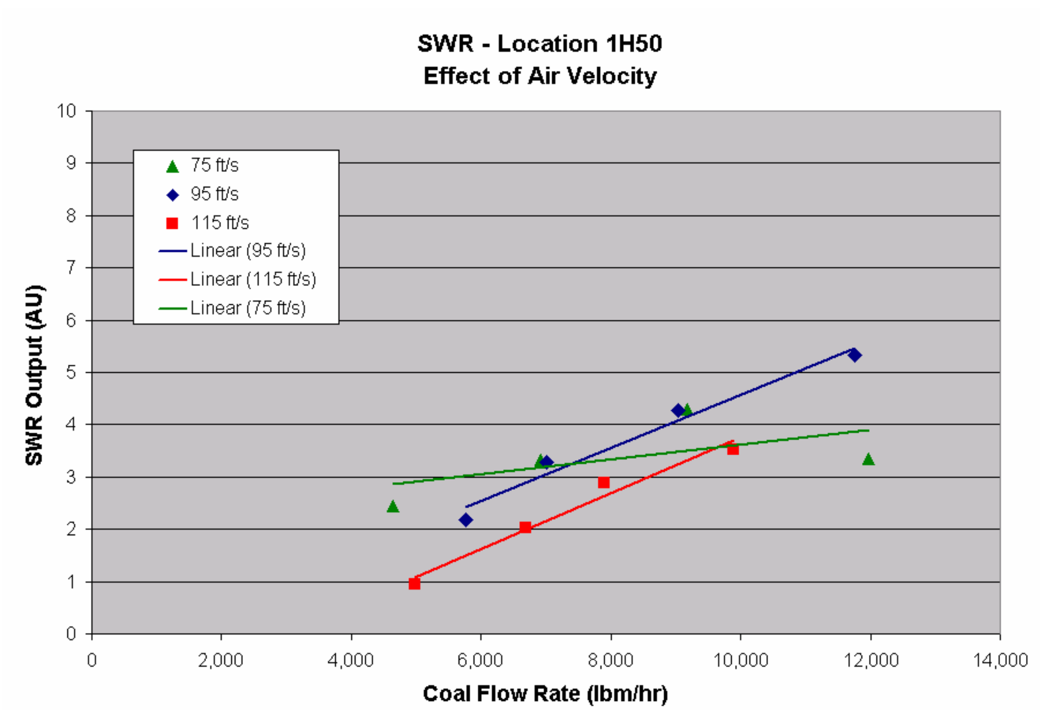


Figure 5-14
Effect of Air Velocity at Location 1H50

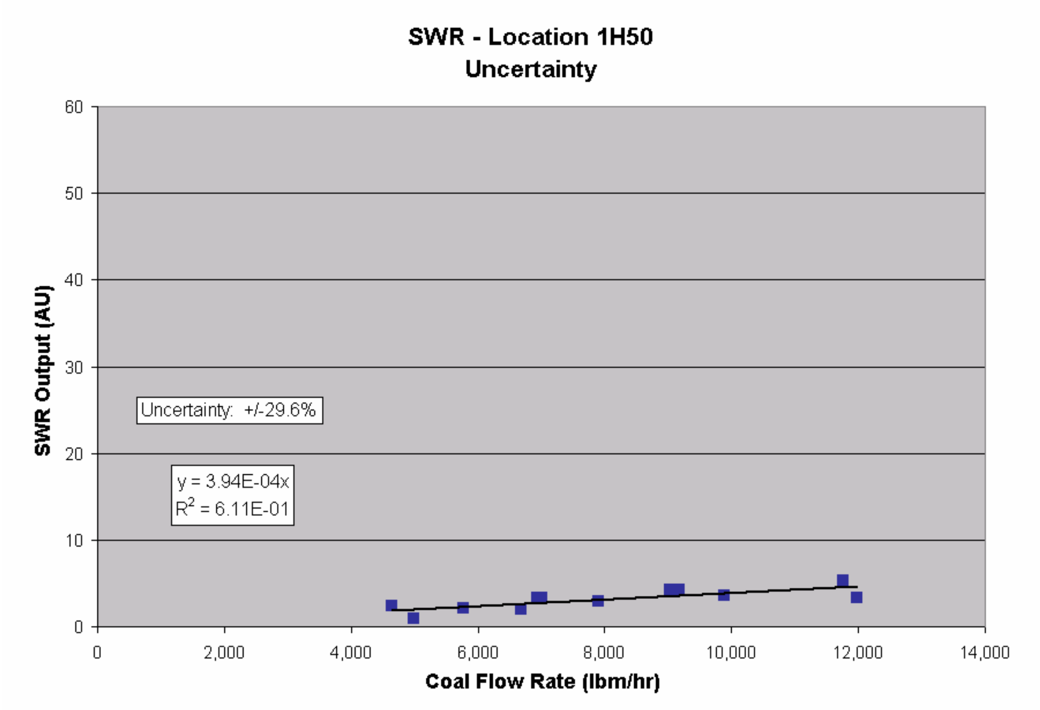


Figure 5-15
Uncertainty at Location 1H50

5.2.3.3 Effect of Location

The SolidFlow PF sensitivity at Location 1H50 is presented in Table 5-3. The normalized sensitivity at this location is 0.69 thereby indicating that the instrument reads 31% less at 1H50 than it does at 1V15.

Table 5-3
Effect of Installation Location at Location 1H50

Location	Sensitivity	Normalized Sensitivity	Uncertainty
1H50	0.00039	0.69	29.6%

5.3 Effect of Orifices

A series of tests was performed to determine the effect of upstream and downstream orifices at varying distances from the instrument. For this investigation, a 56% open concentric circular orifice, fabricated from 0.090” aluminum, was used. Also, a reduced test matrix was completed at each location that consisted of 4 coal flows and a nominal air velocity of 95 ft/s (29 m/s).

5.3.1 Upstream Orifice

Due to time constraints, the investigation of the effect of an upstream orifice was not completed with this instrument for this calibration procedure.

5.3.2 Downstream Orifice

Although data for this test was collected, the results do not lead to highly conclusive trends. Three different downstream orifice distances were tested at each flow condition as indicated in the sketch of Figure 5-16. The instrument was installed at Location 1V3 for these runs and the orifices were located at one, five, and nine diameters downstream of the sensor. The data collected from these tests are summarized in Figure 5-17 where the SolidFlow output versus coal flow rate, as a function of downstream orifice distance, are plotted. Note that the data for the test with the orifice placed nine diameters downstream of the sensor was deemed invalid because of coal feeder malfunction had occurred. From the limited data set, it appears that while the presence of a downstream orifice does have an effect on the SolidFlow output, the proximity of that orifice to the SolidFlow sensors, at least as far as 5 diameters downstream, does not have a significant effect on output. It cannot be determined from this set of tests, how far downstream an orifice needs to be placed to minimize the effect on instrument output.

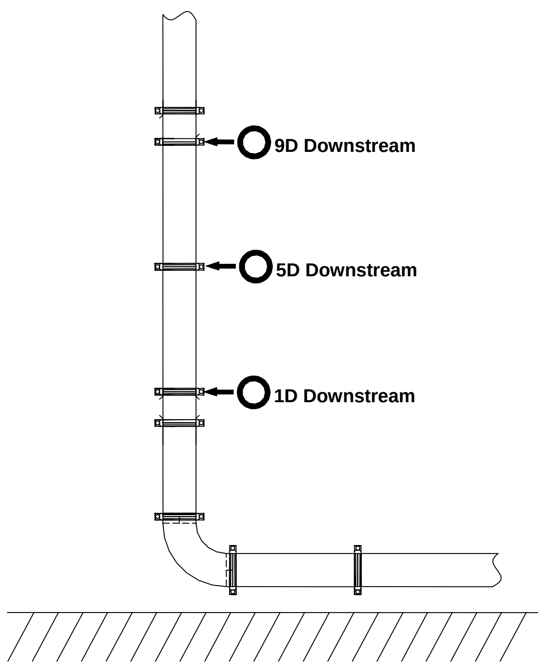


Figure 5-16
Placement of Annular Orifices in 1st Vertical Leg Downstream of 90° Bend

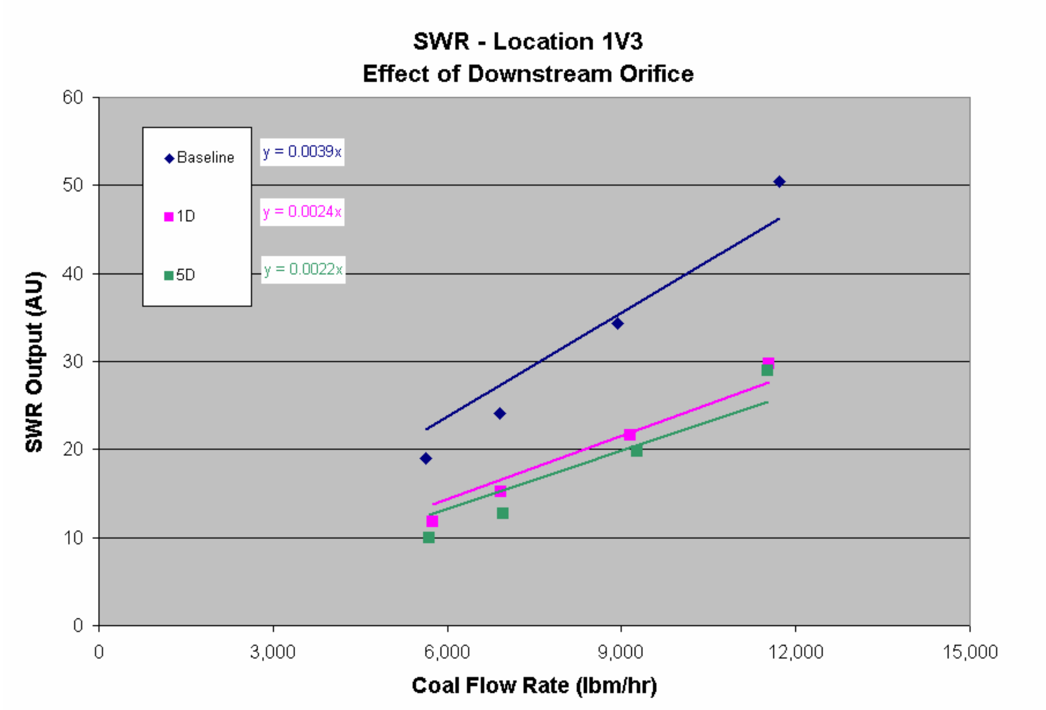


Figure 5-17
SolidFlow PF Output for Downstream Orifice Tests

5.4 Effect of Air Temperature

The final instrument assessment test was to determine the effect of a change in air temperature on signal output. With the instrument installed at location 3V15, the instrument was tested with similar air and coal flow rates at both the baseline temperature of 150°F (66°F) as well as an elevated temperature of 175°F (79°C). The reduced test matrix consisted of 4 coal flow rates at an air velocity of 95 ft/s (29 m/s). The results of the elevated temperature tests are plotted in Figure 5-18. From the results, changing the temperature by 25°F (14°C) had a negligible effect on the SolidFlow output.

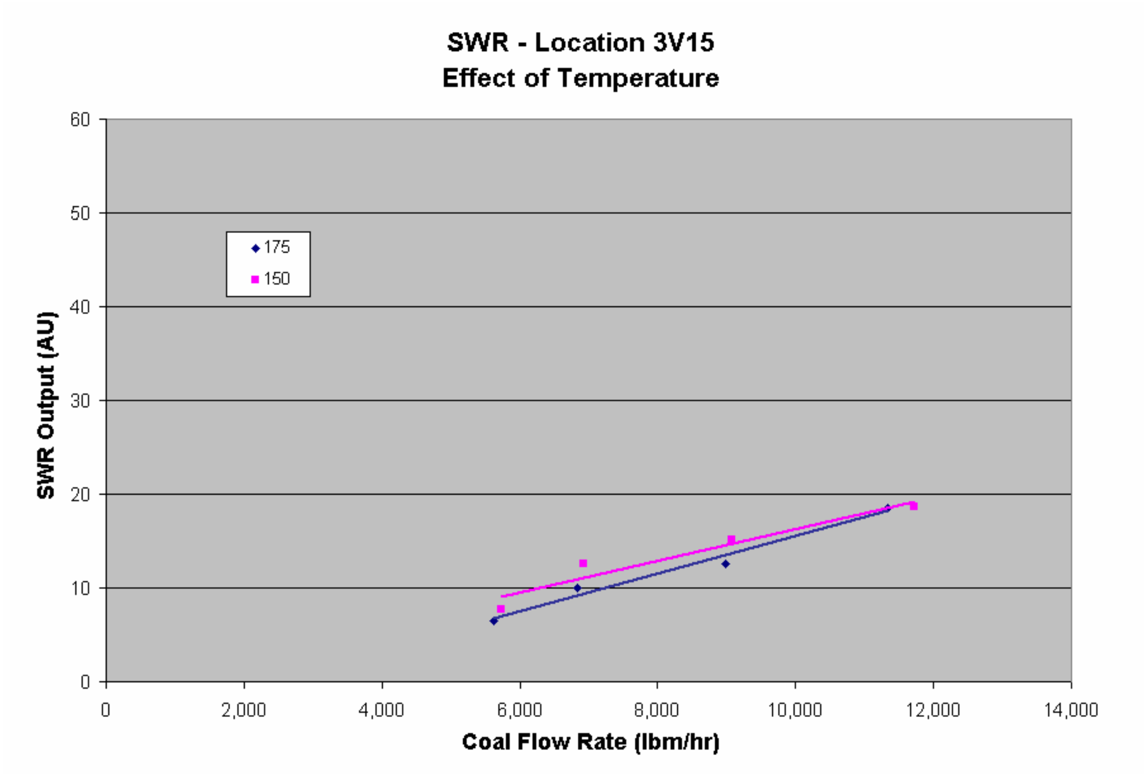


Figure 5-18
Effect of 25°F (14°C) Air Temperature Change on SolidFlow PF Output

5.5 Assessment of Alternate Calibration Method

While SWR does not typically use extractive testing to calibrate the SolidFlow system, it is used occasionally in multi-pipe systems (such as coal mills) or when the instruments are installed in locations where extreme stratifications are thought to exist. Recalling from Section 5.1.1, the SolidFlow system is typically calibrated at a minimum of two points, zero coal flow and max coal flow. For this alternative calibration method, a SolidFlow instrument is installed in each of the pipes from one mill. Then, the coal mill is set to maximum load, and an extractive test is performed in each of the pipes while raw sensor values are recorded from the SolidFlow instruments. These sensor values are then used as weighted factors based on the results of the extractive test for that pipe (The details of properly inputting these calibration points into the SolidFlow system can be found in the SWR operations manual). Finally, the coal mill is operated in clean air mode, and the raw sensor values are recorded from each instrument to be used as the zero coal flow calibration point (additional points, other than full-loading, may be taken to further develop the calibration curve). Testing was performed at the CFL in order to evaluate the SolidFlow instrument as if it were being calibrated based on extractive testing. Recall that different locations along the CFL exhibit different coal flow profiles as a function of flow conditions. Therefore, testing instruments at different CFL locations is equivalent to testing a true coal mill system in multiple pipes. Bearing that in mind, at each location, the CFL was set to ~12,000 lb/hr of coal (Air flow was set at 95 ft/s), and the raw instrument output was recorded to be used as the max load calibration point. Similarly, at each location, the CFL was run in clean air mode (Again, 95 ft/s), and the raw instrument output was recorded to be used as the "zero" calibration point. Coal flow information was taken directly from the CFL instrumentation as opposed to an actual extractive test.

5.5.1 Effect of Air Velocity

The effect of air velocity at 1V15, 1V7, 1V3 and 3V3 is illustrated in Figures 5-19 through Figure 5-22. From these plots, air velocity appears to have an effect on the SolidFlow output. For locations 1V15, 1V7, and 1V3, the instrument output increased as line velocity decreased. For instance, at a given coal flow rate at Location 1V15, decreasing the velocity by 40 ft/s from 115 ft/s to 75 ft/s (23 m/s) causes an increase in the instrument output of approximately 50%. At location 3V3, a similar trend is followed with the data from 95 ft/s (29 m/s) showing a lower output than the data from 75 ft/s (23 m/s). The data from 115 ft/s does not follow the trend, however, as its output is lower than the other velocities at low coal flows and higher than the other velocities at high coal flows.

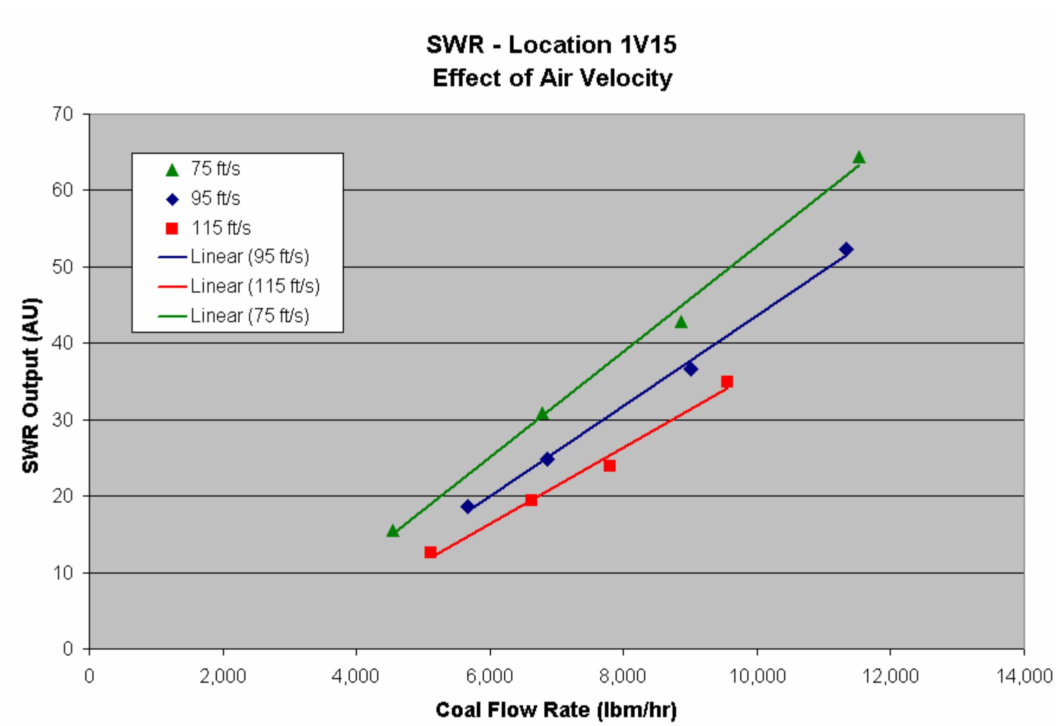


Figure 5-19
Effect of Air Velocity at Location 1V15 Using Alternative Calibration Method

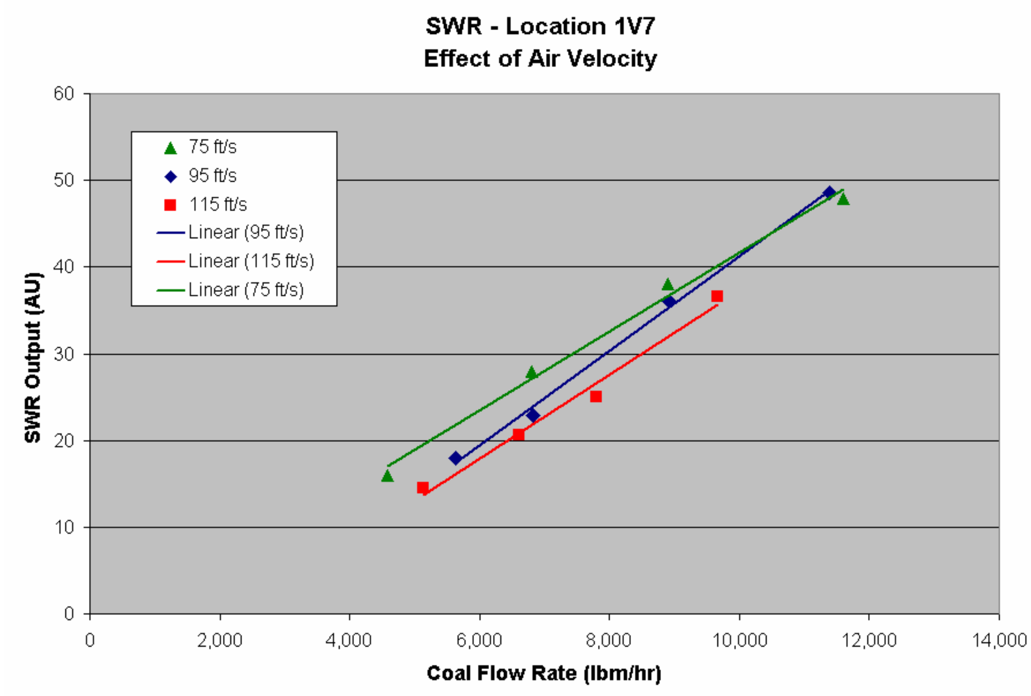


Figure 5-20
Effect of Air Velocity at Location 1V7 Using Alternative Calibration Method

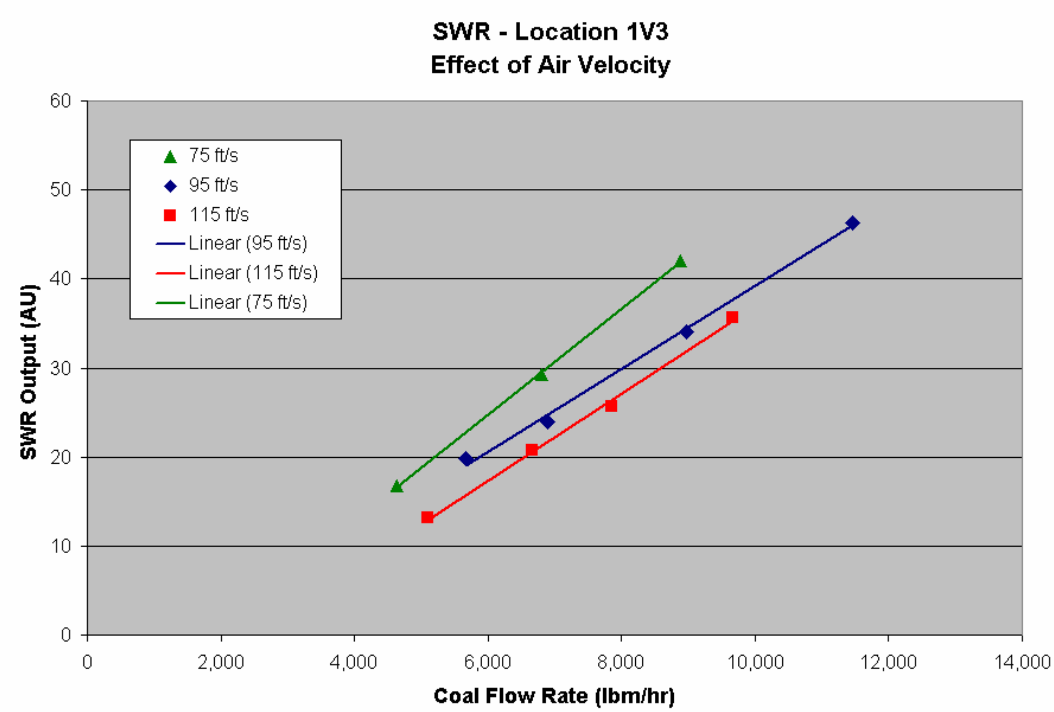


Figure 5-21
Effect of Air Velocity at Location 1V3 Using Alternative Calibration Method

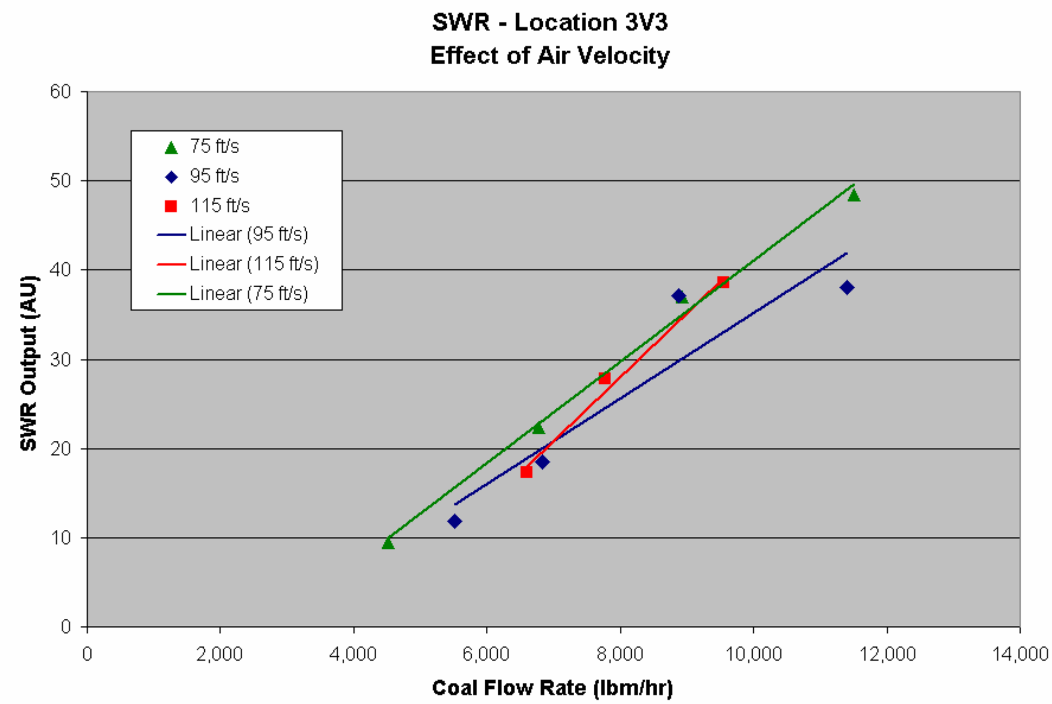


Figure 5-22
Effect of Air Velocity at Location 3V3 Using Alternative Calibration Method

5.5.2 Uncertainty

The calculated uncertainties for Locations 1V15, 1V7, 1V3 and 3V3 are +/-28.2%, +/-15.4%, +/-17.5%, and +/-24.6%, respectively. Graphical representation of the date for these locations is presented Figures 5-23 through Figure 5-26. For most locations, the effect of air velocity is a large contributor to the uncertainty.

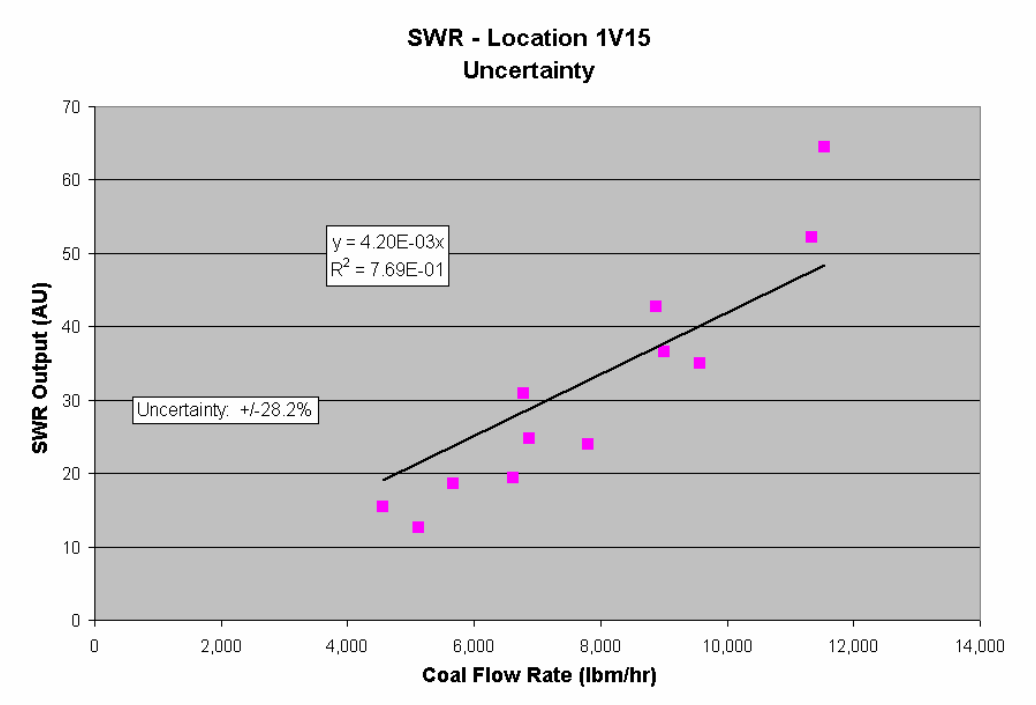


Figure 5-23
Uncertainty at Location 1V15 – Alternate Calibration

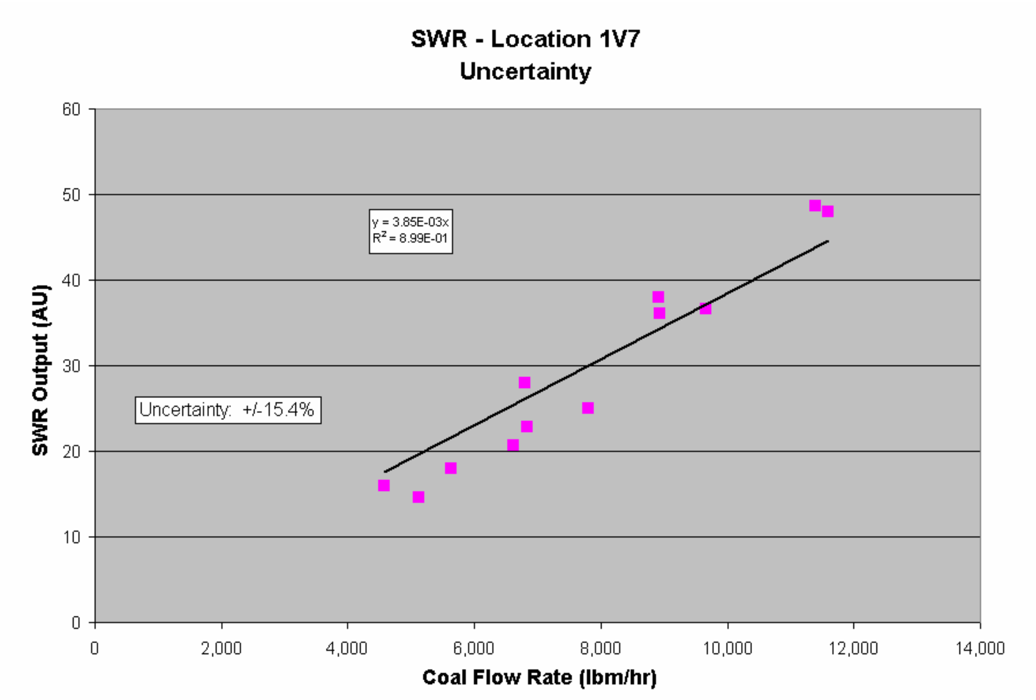


Figure 5-24
Uncertainty at Location 1V7 – Alternate Calibration

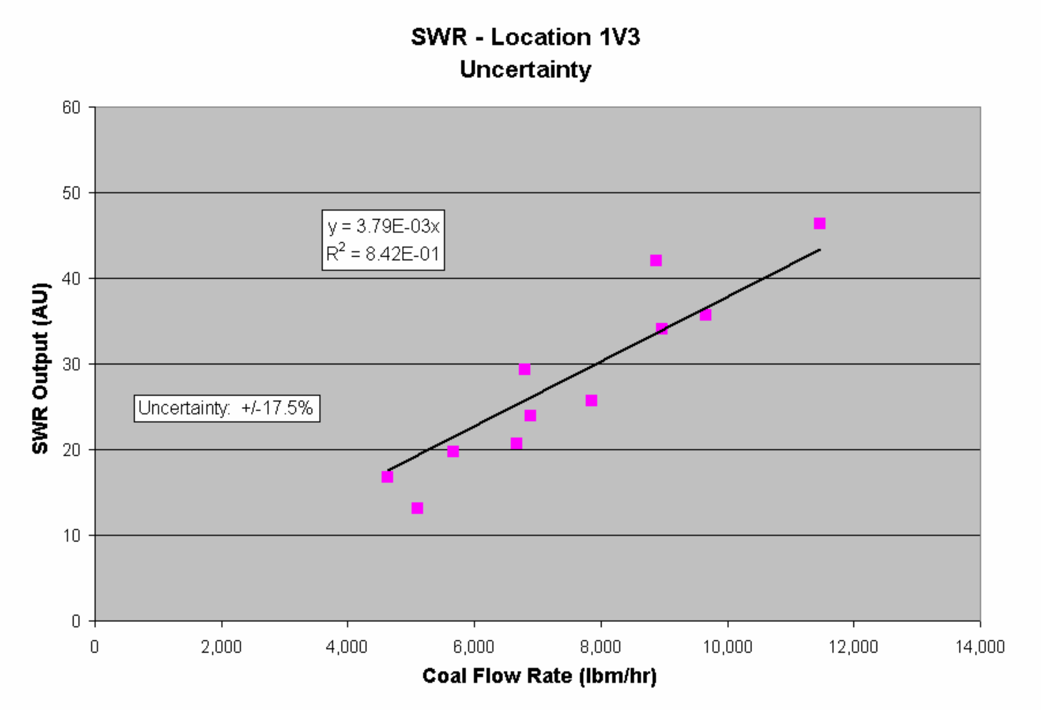


Figure 5-25
Uncertainty at Location 1V3 – Alternate Calibration

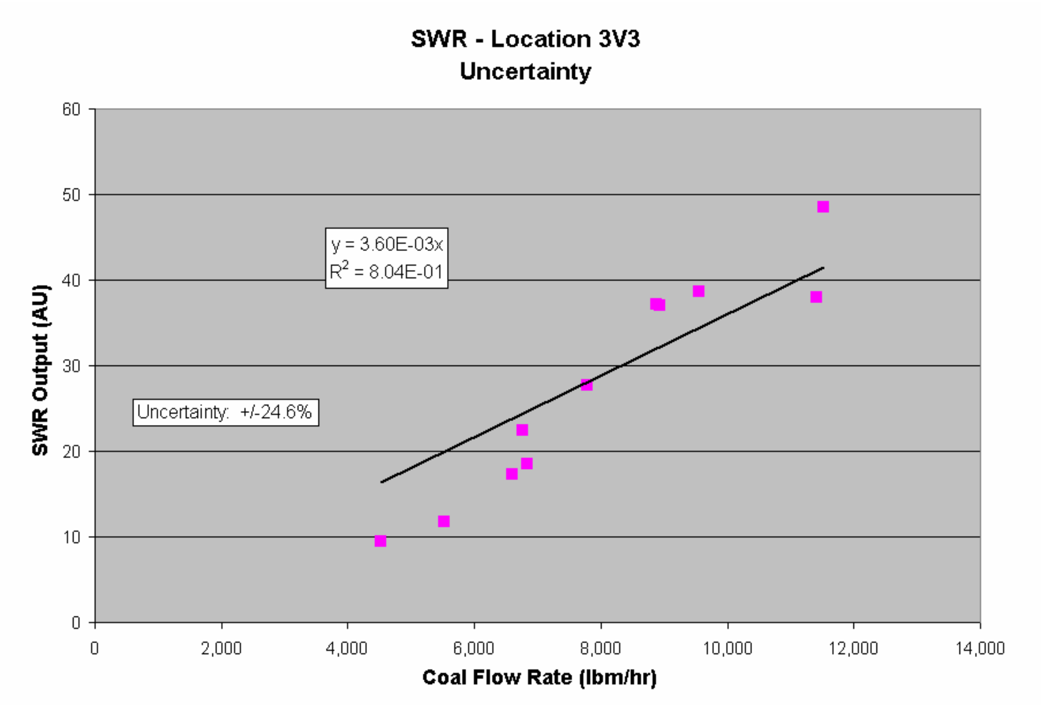


Figure 5-26
Uncertainty at Location 3V3 – Alternate Calibration

5.5.3 Effect of Location (Sensitivity)

The effect of instrument installation (location) was examined for the locations in the first vertical upflow run, and is detailed below in Table 5-4. Recall that 1V15 is the reference location used for the analysis of the instrument sensitivity. Therefore, the normalized sensitivity is 1.00 at 1V15, 0.92 at 1V7, 0.90 at 1V3, and 0.86 at 3V3. With the exception of location 1V15, which reads slightly high to the others, the SolidFlow instrument output is relatively insensitive to instrument location using this calibration method. Theoretically, this calibration method should remove the effect of location such that the normalized sensitivity should be one at each location.

Table 5-4
Summary of Sensitivity and Uncertainty Using Alternate Calibration Method

Location	Sensitivity	Normalized Sensitivity	Uncertainty
1V15	0.00420	1.00	28.2%
1V7	0.00385	0.92	15.4%
1V3	0.00379	0.90	17.5%
3V3	0.00360	0.86	24.6%

5.5.4 Upstream Orifice

For the upstream orifice evaluation the instrument was located at Location 1V15. Four different upstream orifice distances were tested at each flow condition. As shown in Figure 5-27, the orifices were installed at one, three, and seven diameters in the upstream direction and a case was also run where the orifice was installed in the horizontal pipe four diameters upstream of the horizontal-to-vertical bend. As in the previous test, the instrument was recalibrated for each orifice location.

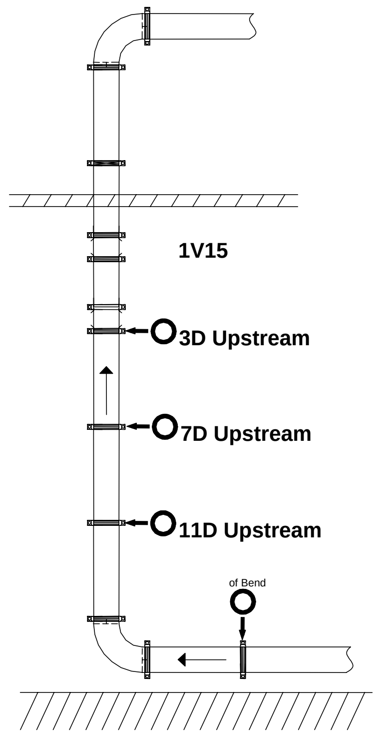


Figure 5-27
Locations for Upstream Orifice Tests – Distance from 1V15 Location

The results of the upstream orifice tests are summarized in Figure 5-28 where the SolidFlow output versus actual coal flow rate, at the various upstream orifice distances, are plotted. It is difficult to draw any conclusions from the data, as the data from the baseline test and the data from the repeat of the baseline test bracket all of the data from the tests at the various orifice locations. One possible explanation is that the SolidFlow is insensitive to the presence of an upstream orifice when calibrated in this manner, but it is highly sensitive to the actual calibration conditions (i.e., a small change in the raw instrument output during calibration results in a large change in instrument output given at certain flow conditions). Notice also the peculiar trend for all the data points at the high coal flow rates. These points do not fall in-line with their respective lower coal flow data points but do seem to experience an equivalent upward shift. The cause for this behavior is not known but it is inferred that may be derived from the proximity of the data to the upper bound calibration threshold of the SolidFlow. As can be seen in Figure 5-29, the line between the SolidFlow maximum calibration point and the “zero” calibration point falls well above the line through the three intermediate coal loads in all tests.

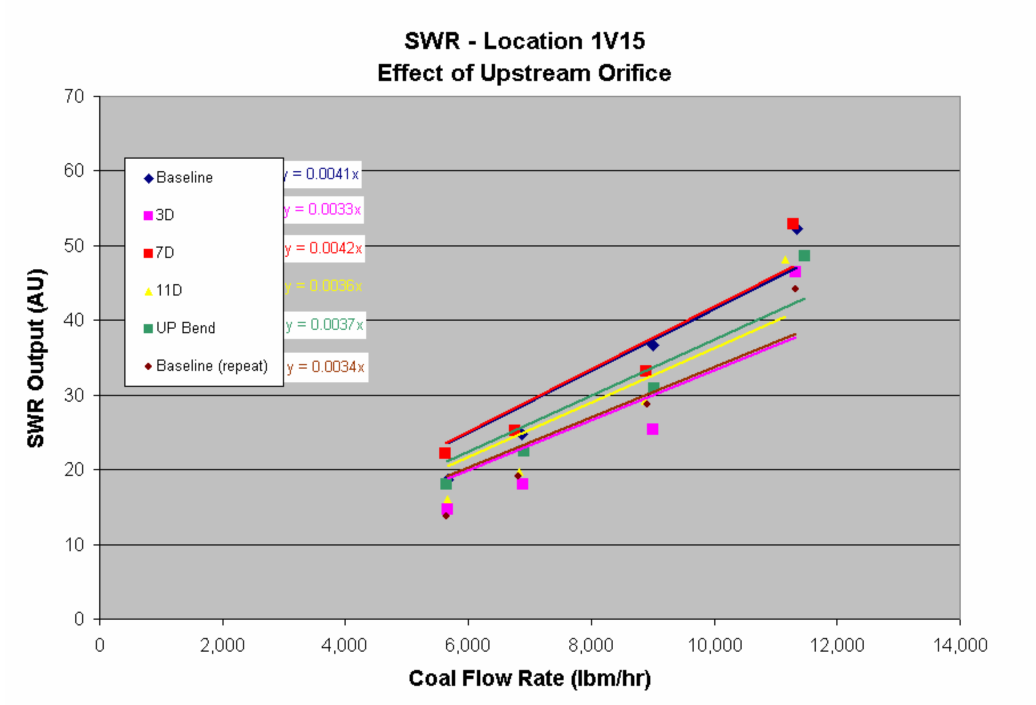


Figure 5-28
Effect of Upstream Orifice at Location 1V15 – Alternate Calibration

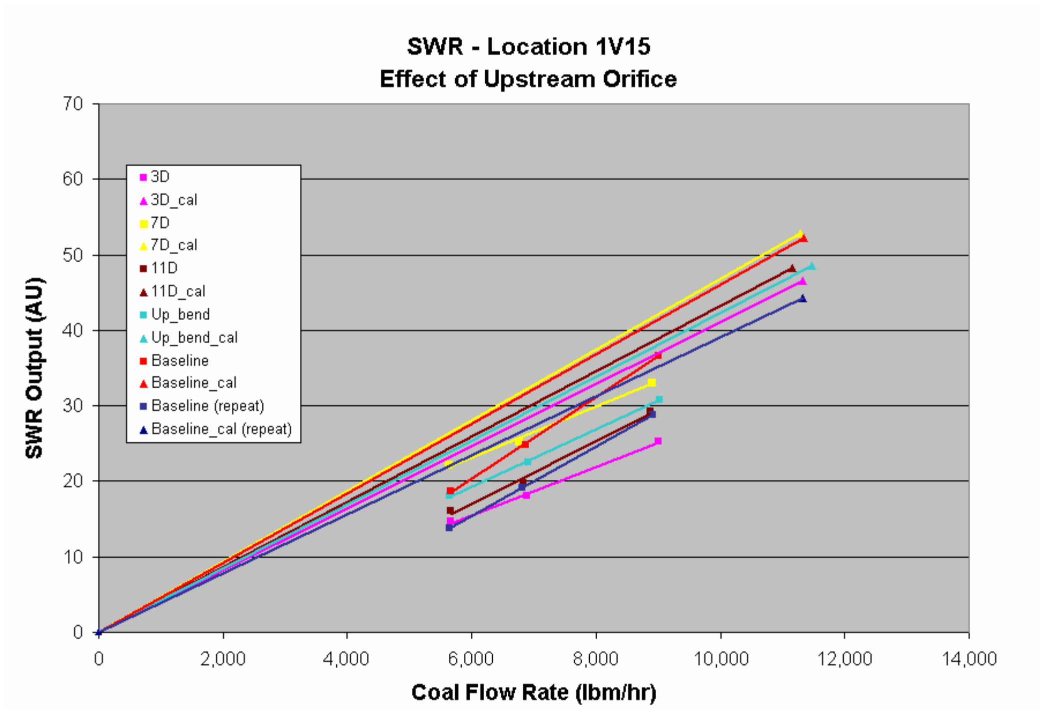


Figure 5-29
Zero and Maximum Coal Flow Calibration Lines and Intermediate Test Data For Orifice Tests

5.6 Summary of the SolidFlow System Results

Two sets of data pertaining to the SWR instrument are presented in this effort, the first set was collected using the typical calibration method and the second set was collected using an alternative calibration method.

5.6.1 Typical Calibration Method Conclusions

Based on the results from the data reduction for tests conducted using the standard or most typically used calibration procedure, according to SWR, the following observations of the performance characteristics can be made:

1. The coal mass flow output signal is affected by changes in air velocity. While the general trend seems to indicate higher velocities result in lower instrument output, there are some instances where this trend does not hold up.

2. The tests to evaluate the influence of a downstream orifice were inconclusive. It appears that the presence of an orifice does affect the instrument output, but there is no data to give insight as to how far away the orifice must be placed such that it does not affect the instrument signal.

3. The change in air temperature test indicated little change in the SolidFlow output, thus no significant effect of air temperature can be expected.

4. The instrument uncertainties, for all tested locations, range from +/-14.8% to +/-31.3% and are summarized in Table 5-5. For the interest of the reader, statistical analysis of the data without the 75 ft/s (23 m/s) is also presented in the Table. Although some improvement to the uncertainty and sensitivity numbers is observed under those circumstances, the results still range from +/-11.8% to +/-31.3%.

5. Sensitivity and Normalized Sensitivity are also summarized in Table 5-5. Normalized sensitivity ranges from 0.69 to 6.33 for all tested locations. The data suggests that the instrument is highly sensitive to installation location. For example, the instrument indicated readings 6.33 times higher at Location 3V3 than for the same test conditions at Location 1V15. Excluding the 75ft/s data, sensitivity values improve at some locations while becoming worse at others. Thus no clear improvement trend is observed from omitting the 75ft/s data.

Table 5-5
Summary of Uncertainty and Sensitivity Values for All Tested Locations Using Standard Calibration Method

	All Velocities			75 ft/s Omitted		
	Sensitivity	Normalized Sensitivity	Uncertainty	Sensitivity	Normalized Sensitivity	Uncertainty
1V15	0.00057	1.00	17.7%	0.00054	1.00	15.8%
1V3	0.00208	3.65	14.8%	0.00194	3.62	11.2%
3V15	0.00160	2.82	29.4%	0.00148	2.76	20.6%
3V7	0.00319	5.60	31.3%	0.00327	6.09	31.3%
3V3	0.00360	6.33	24.6%	0.00343	6.40	24.7%
1H50	0.00039	0.69	29.6%	0.00040	0.75	24.4%

5.6.2 Alternate Calibration Method (Extractive Approach) Conclusions

In lieu of conducting extractive testing to determine actual coal flow rate, the CFL instrumentation coal flow rate was used to set-up the lower and upper calibration points for the SWR instrument. The following observations can be made from these results:

1. The coal mass flow output signal is, in many cases, significantly affected by changes in air velocity. In general higher velocities result in lower instrument output.

2. The tests to evaluate the influence of an upstream orifice were inconclusive. Since the baseline test and the repeat of that baseline test bracket all of the other tests, it is difficult to draw a conclusion on how an upstream orifice affects the SolidFlow's output.

3. The SolidFlow output is less sensitive to installation location when using this calibration approach. This is shown in the normalized sensitivity values of summary Table 5-6. In particular, Location 1V15 demonstrates a slightly higher input (~0.1%) than Locations 1V7, 1V3, and 3V3. The latter sensitivities are very close to one another (within +/ 0.05%).

4. The uncertainty of the instrument from all tested locations ranges from +/-15.4% to +/-28.2%. Also presenting an instance where some improvement is observed compared to the other calibration approach. Improvement is also observed when the 75 ft/s (23 m/s) data is omitted from the analysis.

Table 5-6
Summary of Uncertainty and Sensitivity Values for All Tested Locations Using the Extractive Calibration Method

	All Velocities			75 ft/s Omitted		
	Sensitivity	Normalized Sensitivity	Uncertainty	Sensitivity	Normalized Sensitivity	Uncertainty
1V15	0.00420	1.00	28.2%	0.00374	1.00	22.5%
1V7	0.00385	0.92	15.4%	0.00370	0.99	16.7%
1V3	0.00379	0.90	17.5%	0.00361	0.96	13.9%
3V3	0.00360	0.86	24.6%	0.00343	0.92	24.7%

6
SUMMARY AND RECOMMENDATIONS

6.1 Foster Wheeler / TR-Tech ECT Star Results

Table 6-1 summarizes the calculated performance values for this system. The following observations are offered:

- The instrument output is sensitive to installation location. This is shown in the sensitivity values of Table 6-1. In addition, since the ECT was calibrated to provide an absolute measurement indication a unity value is expected for optimum sensitivity. Evaluating the instrument on that basis, the instrument reads 36% lower and 11% higher than the coal loop indication depending on location.
- The coal mass flow output signal is slightly affected by a change in air velocity. While the effect is negligible at the locations in the first vertical (1V), at the locations in the third vertical (3V) the instrument output at 75 ft/s (23 m/s) is lower than the output at the other velocities. The uncertainty of the instrument from all tested locations ranges from +/-7.1% to +/-16.0%. Note that omitting the lower velocity is not possible in this instance because this velocity was one of the two instrument calibration points.
- The tests to evaluate the influence of an orifice were inconclusive due to calibration and procedural inconsistencies.
- A 25°F (14°C) increase in air temperature yielded an 11% decrease in output at Location 1V15 and 27% drop in output at the more stratified double bend location.

Table 6-1
Summary of ECT Star System Results

	All Velocities		
Location	**Sensitivity**	**Normalized Sensitivity**	**Uncertainty**
1V15	0.684	1.00	13.3
1V11	0.667	0.97	8.5
1V7	0.707	1.03	9.5
1V3	1.000	1.46	7.1
3V15	0.730	1.07	16.0
3V11	0.641	0.94	13.3
3V7	na	na	na
3V3	1.112	1.62	9.2
1H50	na	na	na
1H20	na	na	na

na = data not available

6.2 SWR Engineering SolidFlow Results

Two sets of data pertaining to the SWR instrument are presented in this report. The first set was collected using the typical calibration method, as advised by SWR, and the second set was collected using an alternative calibration method.

6.2.1 Typical Calibration Method Conclusions

Based on the data reduction for tests conducted using the standard or most typically used calibration procedure, the following observations of the performance characteristics can be made:

- Sensitivity and Normalized Sensitivity are also summarized in Table 6-2. Normalized sensitivity ranges from 0.69 to 6.33 for all tested locations. The data suggests that the instrument is highly sensitive to installation location. For example, the instrument indicated readings 6.33 times higher at Location 3V3 than for the same test conditions at Location 1V15. Excluding the 75ft/s (23m/s) data, sensitivity values improve at some locations while becoming worse at others.
- The coal mass flow output signal is affected by changes in air velocity. While the general trend seems to indicate higher velocities result in lower instrument output, there are some instances where this trend does not hold up. Uncertainties, for all tested locations, range from ±14.8% to ±31.3%. Little improvement was observed by omitting low velocity data.

- The tests to evaluate the influence of a downstream orifice were inconclusive. It appears that the presence of an orifice does affect the instrument output, but there is no data to give insight as to how far away the orifice must be placed such that it does not affect the instrument signal.
- The change in air temperature test indicated little influence in the SolidFlow output, thus no significant effect of air temperature can be expected.

Table 6-2
Summary of Uncertainty and Sensitivity Values for All Tested Locations Using Standard Calibration Method

	All Velocities			75 ft/s Omitted		
	Sensitivity	Normalized Sensitivity	Uncertainty	Sensitivity	Normalized Sensitivity	Uncertainty
1V15	0.00057	1.00	17.7%	0.00054	1.00	15.8%
1V3	0.00208	3.65	14.8%	0.00194	3.62	11.2%
3V15	0.00160	2.82	29.4%	0.00148	2.76	20.6%
3V7	0.00319	5.60	31.3%	0.00327	6.09	31.3%
3V3	0.00360	6.33	24.6%	0.00343	6.40	24.7%
1H50	0.00039	0.69	29.6%	0.00040	0.75	24.4%

6.2.2 Alternate Calibration Method (Extractive Approach) Conclusions

In lieu of conducting extractive testing to determine actual coal flow rate, the CFL instrumentation coal flow rate was used to set-up the lower and upper calibration points for the SWR instrument. The following observations are summarized from these results:

- The SolidFlow output is less sensitive to installation location when using this calibration approach. This is shown in the normalized sensitivity values of summary Table 6-3. In particular, Location 1V15 demonstrates a slightly higher input (~0.1%) than Locations 1V7, 1V3, and 3V3. The latter sensitivities are very close to one another (within ±0.05%).
- The coal mass flow output signal is, in many cases, significantly affected by changes in air velocity. In general higher velocities result in lower instrument output. The uncertainty of the instrument from all tested locations range from ±15.4% to ±28.2%. Also presenting an instance where some improvement is observed compared to the other calibration approach. Improvement is also observed when the 75 ft/s (23 m/s) data is omitted from the analysis.
- No temperature tests were conducted for this method based on the first test results.
- The tests to evaluate the influence of an upstream orifice were inconclusive. Since the baseline test and the repeat of that baseline test bracket all of the other tests, it is difficult to draw a conclusion on how an upstream orifice affects the SolidFlow's output.

Table 6-3
Summary of Uncertainty and Sensitivity Values for All Tested Locations Using the Extractive Calibration Method

	All Velocities			75 ft/s Omitted		
	Sensitivity	Normalized Sensitivity	Uncertainty	Sensitivity	Normalized Sensitivity	Uncertainty
1V15	0.00420	1.00	28.2%	0.00374	1.00	22.5%
1V7	0.00385	0.92	15.4%	0.00370	0.99	16.7%
1V3	0.00379	0.90	17.5%	0.00361	0.96	13.9%
3V3	0.00360	0.86	24.6%	0.00343	0.92	24.7%

6.3 Recommendations

Based on the findings from this study, operators considering the use of these technologies at their plants are encouraged to follow up these guidelines:

1.0 Although many of these technologies respond linearly to increases in coal flow, the output signal is affected by operating parameters that may vary over time during normal plant operation. Coal moisture, particle fineness, air to coal ratio, air velocity and air temperature fall within this classification. Therefore, the operator should establish the range of operating conditions experienced by the plant fuel delivery lines before installing any on-line system.

2.0 Install sensor probes or antennae at coal pipe locations that can be readily accessible such that verification of probe conditions can be efficiently monitored.

3.0 Considering items 1 and 2, the instruments should be installed at locations where the coal flow profiles will be the most uniform, i.e., avoid long horizontal runs, or locations in close proximity to flow obstructions such as elbows. Results from this study suggest a minimum of seven diameters away from obstructions in order to reduce those effects.

4.0 Consider establishing a verification test plan. Traditional methods to measure coal flow could be used to both calibrate and assess the output of these instruments. Guidelines for improved extractive techniques are discussed in EPRI report 1010319 (October 2006).

Although advancements in technology will foster more opportunities to improve the current state-of-the art for coal measurement, the ultimate objective is to use a reliable measurement indication such that active control scheme can be adopted and real-time boiler fine tuning can be achieved.

A
EPRI COAL-FLOW MEASUREMENT AND CONTROL LABORATORY ECT STAR PRE-EVALUATION REPORT (EXCERPTS)

EPRI Coal-Flow Measurement and Control Laboratory

Instrument Pre-Evaluation Report

TRTech: ECT

ASC Document R-05-CL4-04

December 22, 2005

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Instrument Information

Model/Name: Electric Charge Transfer System (ECT)

Manufacturer: TR-Tech OY

Distributor or Representative: Foster Wheeler North America, Clinton, NJ

Instrument Procurement Arrangement: The ECT system tested was on loan to TVA/EPRI and is property of Foster Wheeler / TRTech.

Principle of Operation:

The ECT is a real-time system that measures the electric field created by electrostatic charges present in any two-phase flow application. The measured charge is not dependent on the dispersion of particles and accounts for random coal roping. The ECT system works in accordance with Coulomb's law in which a point charge creates an electric field around itself. Electrostatic charging occurs when two materials come in contact with each other and then separate. In this case, when coal particles impact the conduit wall in transportation, electrons will be transferred from one material to the other. Both materials end up with a net charge, one positive and one negative. The ECT system measures the voltage produced by changes in this generated electric field. The system does not need a contact between the probe and coal particles.

Quantities Measured:

The ECT system is capable of measuring coal particle velocity, relative coal mass flow, absolute coal mass flow, coal particle fineness and economizer flyash for sootblower effectiveness monitoring.

Serial Number/Software Version: ECT Data Server, version 4.51, Supervisor controller version 1.0

Description of System Components:

ECT STAR System: The ECT STAR System has individual ECT node computers that are connected to a central ECT SERVER computer. Figure A-1 shows a basic schematic hardware arrangement for the ECT STAR system.

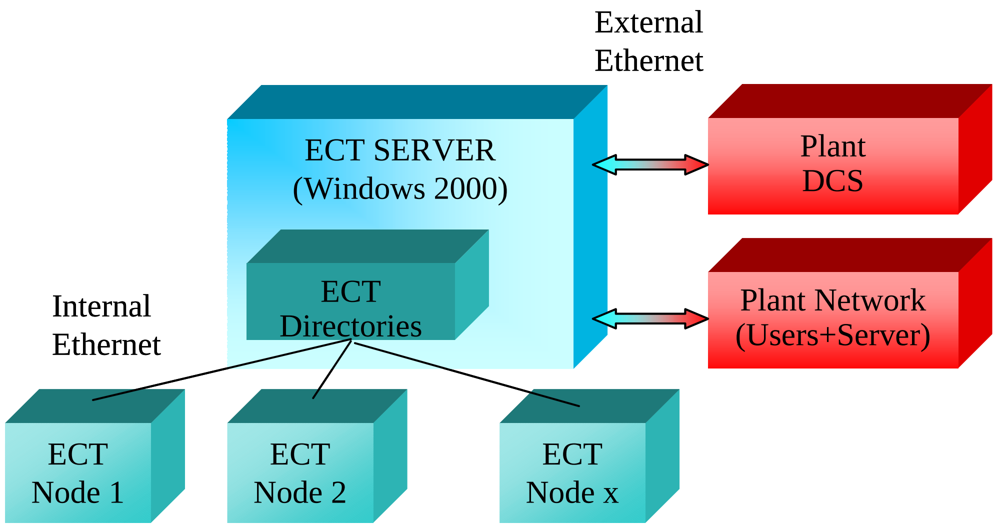


Figure A-1
ECT STAR System Description

The ECT server connects via Ethernet to all ECT node processors. It collects the data, manages the internal ECT network and forwards the information to the plant's network, a DCS or a combustion optimization computer. The isolation of measurement tasks (node computers) from the data management and external communication (server computers) allows for unlimited scale-up of the ECT system. This architecture allows a single ECT server computer to accommodate a single boiler with a large number of coal pipes. Coal pipes of several boilers can be served by a single ECT server/cabinet and later upgrade of an existing system is easily possible.

Typically, plant users access the ECT information via Ethernet connection or dial-in. Foster Wheeler and TR-Tech have also realized solutions that allow connection to a NetDDE server and an OsiSoft PI System. Other communication solutions are possible. The Server can also be configured to output 4 to 20 mA signals, if required. The ECT SERVER can be placed in the control room and acts as the file server for all ECT node processors, or it can be integrated into the central electronic cabinet and accessed via the external Ethernet connection.

A typical ECT system consists of the following hardware:

- • ECT probes with local junction boxes
- • ECT node computers
- • ECT Signal Conditioning Units (SCU)
- • ECT STAR server – industrial grade computer (on Windows 2000 platform)
- • 15" flat panel monitor, PS-2 keyboard and mouse
- • Ethernet hub for ECT node-to-server computer communication
- • ECT Cabinet with the above equipment mounted in 19" racks

<u>Sensor Installation In Pipe:</u>

3 probes mounted 120 degrees apart, 3 additional probes mounted 50 mm downstream of the first set in the same plane The ECT probes are installed through threaded holes in the coal pipes.

<u>Preferred/Minimum Installation Location:</u>

A suitable probe location should chosen that approximately six (6) pipe diameters downstream and one (1) diameter upstream from any bend, valve, or other internal obstruction. Either horizontal or vertical runs are adequate. Placement should also take account future accessibility.

<u>Typical Field Setup & Calibration:</u>

FW engineers connect all wiring to the sensors and connect coaxial cables to the computer at the ECT workstation. No calibration required for velocity measurement. For mass flow measurement, extractive sampling is performed at a minimum of 2 mill loads and ramp tests of each mill are performed. ECT is then calibrated remotely using a communications interface. Sampling is also required to calibrate for optional on-line, real time coal particle fineness measurement.

<u>Supplied Documentation:</u>

No documentation was supplied for this testing.

Evaluation Procedure

<u>Facility Description</u>

One of the primary purposes of the Coal-Flow Measurement and Control Laboratory (CFMCL) is the evaluation of various techniques and instrumentation for measuring the mass flow rate of pneumatically transported pulverized coal. The CFMCL, or coal loop, closely replicates the scale, piping, and flow conditions found in a typical coal fired power plant. The coal loop is able to provide precisely known and controlled air and coal flow rates and temperature to serve as a reference for evaluating Coal-Flow Measurement instruments. The coal loop operates in a continuous, closed loop mode. Both air and coal are continuously recycled through the loop.

The air flow rate through the loop is measured with a Hershel type low loss venturi. The venturi was calibrated over the Reynolds number operating range of the coal loop. The calibration was performed at Alden Research Laboratory of Holden Massachusetts. The calibration is NIST traceable with an uncertainty of 0.25%. A calibration report can be supplied upon request. The venturi flow calculation takes into account the effects of Reynolds number, compressibility, air density, and thermal expansion. Air properties are calculated using real air correlations supplied by Techware Engineering. Air properties are calculated as a function of pressure, temperature, oxygen concentration, and relative humidity. Calculated air properties include density, molecular weight, specific heat, viscosity, and dew point. Air flow control is maintained through feedback control between the venturi DP and the variable frequency drive controlling the fan.

The loop can operate at line velocities up to 135 ft/sec. In order to control the explosion potential of pulverized coal, the coal loop operates with a reduced oxygen atmosphere. Oxygen levels in the loop are maintained below 8% by purging the loop with nitrogen.

The coal flow rate through the loop is measured using a loss in weight gravimetric feeding system. An isolated weigh hopper with a capacity of 800 pounds is suspended from load cells and the coal flow rate is calculated from the drop in weight of the hopper over time. The weighing system has a static accuracy of +/-0.25 pounds. Calibration data can be provided upon request. The hopper is refilled as needed from the coal stored above in the filter/receiver. During the refill process, the feeder operates in volumetric feeding mode. The coal flow rate is controlled by a variable speed rotary feeder at the bottom of the weigh hopper. Coal flow rates up to 20,000 lbm/hr can be achieved. The rotary feeder is connected to a vibratory feeder which functions to smooth out the dumping action of the rotary feeder. The vibratory feeder then feeds the material into the pipe. A dedicated computer continuously monitors and logs the coal feeding process. A steady, known feed of coal can be maintained within +/- 2%.

The coal loop has a tube and shell type heat exchanger for heating the transport air. The service media is water and propylene glycol heated with a 50kW electric heater. The air temperature is maintained through feedback control between the test section RTD temperature probe and a proportioning water flow control valve. Temperature can be maintained within +/- 2 F and the loop can operate at temperatures up to 180 F.

The first coal to be used in the loop is a Pittsburgh seam coal, pulverized to ~75% less than 200 mesh. The coal was provided by Consol Energy and pulverized at their facility in South Park, Pennsylvania. Ultimate and sieve analyses are available upon request. Because the coal is continuously recycled through the loop, the coal particle size has a tendency to decrease over time. As part of the test procedure, coal samples will be taken immediately before, during, and immediately after the instrument is evaluated. A portion of these samples will be sent to a laboratory for size analysis. The remainder of the sample will be held in case it is needed for future reference.

The test section piping of the loop is composed of 12" schedule 40S steel pipe connected with Victaulic type grooved pipe fittings. The pipe is cut grooved. The test section contains the piping configurations most commonly found in a power plant. The test section consists of a long horizontal run, a vertical upflow run, a vertical down flow run, a short horizontal run, and a vertical upflow run with a double bend (out of plane) inlet. The double bend inlet results in a substantially higher degree of roping than the single bend inlet.

The coal loop is controlled with a Siemens PLC and a PC based HMI interface. The control system manages flow set points, alarms, and data logging. Typically, data is logged every 15 seconds.

<u>Instrument Installation Locations</u>

In general, there is a preferred installation location for a particular instrument. However, it is quite common that in a power plant the preferred location either does not exist or is too inaccessible to be used. For this reason, each instrument will be tested at a range of locations.

Figure 3 illustrates the layout of the coal loop and the test section piping. The coal in-feed location is shown in the Figure along with all the locations at which the instrument will be tested.

Location 1 is 33 pipe diameters downstream of the coal in-feed location in the first horizontal run. This location is designated 1H33 (first horizontal run, 33 diameters from in-feed). Location 2 is 57 pipe diameters downstream of the coal in-feed location in the first horizontal run. This location is designated 1H57.

Location 3 is 3 pipe diameters downstream of the bend in the first vertical run. This location is designated 1V3. Location 4 is 7 pipe diameters downstream of the bend in the first vertical run. This location is designated 1V7. Location 5 is 15 pipe diameters downstream of the bend in the first vertical run. This location is designated 1V15. When the instrument is installed in the first vertical run, a "segmental orifice" will be installed in the upstream horizontal run 12 diameters upstream of the bend. The segmental orifice is a straight flat plate blocking the bottom third of the horizontal pipe (leaving a "D" shaped open area in the top two thirds of the pipe). A picture of the segmental orifice is shown in Figure 4. The purpose of the orifice is to "kick" the coal flow off of the bottom of the pipe and provide a more uniform coal flow profile at the inlet to the bend. Extractive testing has shown that the orifice reduces the degree of coal stratification (roping) in the vertical pipe. The orifice was added to address the concern that the long horizontal run of pipe (and resulting stratification of coal towards the bottom of the pipe) is causing an unrealistic degree of stratification in the vertical pipe. Because the third vertical pipe run (locations 3V3, 3V7, 3V15, described below) has a very high degree of stratification, it is desired to have a vertical pipe run with relatively low stratification.

Location 6 is 3 pipe diameters downstream of the double bend in the third vertical run. This location is designated 3V3. Location 7 is 7 pipe diameters downstream of the double bend in the third vertical run. This location is designated 3V7. Location 8 is 15 pipe diameters downstream of the double bend in the third vertical run. This location is designated 3V15.

<u>Baseline Test Matrix</u>

At each location, a series of air velocities and air/coal ratios will be run and the response of the instrument to various flow rates will be examined. Three air velocities, 75, 95, and 115 ft/sec, will be run. At 75 ft/s (23 m/s)ec air/coal ratios of 1.0, 1.5, 2.0, and 3.0 will be run. At 95 ft/s (29 m/s) air/coal ratios of 1.5, 2.0, 2.5, and 3.5 will be run. At 115 ft/sec air/coal ratios of 2.0, 2.5, 3.0, and 4.0 will be run. The baseline test matrix also includes a zero coal flow point at 95 ft/s. This has been included to see how the instrument output at zero flow may be influenced by location. At the end of the test matrix the first flow condition of the matrix will be repeated in order to look at repeatability of the instrument output. A matrix of these conditions and the associated air and coal flow rates is shown in Figure 5. The loop will be operated at a air temperature of 150 F for the baseline test matrix.

It should be noted that while some of the instruments to be evaluated include coal velocity as one of their outputs, the coal-flow loop does not have the ability to evaluate the accuracy of this measurement. While the air velocity within the loop is accurately known, the coal velocity may be either higher or lower than the air velocity depending on location.

Each flow condition will be run for 22 minutes; 5 minutes to allow the coal loop and instrument reading to stabilize, 15 minutes during which the instrument reading and coal loop flows will be logged for comparison, and an additional 2 minutes at the end to allow for any data logging timing differences between the coal loop and the system being evaluated. The baseline test matrix will be run at all 8 test locations.

Elevated Temperature Tests

In order to evaluate how the instrument responds to changes in air temperature, the 95 ft/s (29 m/s) portion of the test matrix will be re-run at an elevated temperature of 175 F. The elevated temperature tests will be performed at locations 1V3, 1V15, and 3V3.

Influence of Orifice Tests

A series of tests will be performed to evaluate how the instrument responds to the presence of an orifice in the pipe. The effects of an upstream orifice and a downstream orifice will both be evaluated. An orifice upstream of the sensor can potentially influence the sensor output by changing the air and coal flow profile through the sensor and also by directly interacting with the sensor signal. A downstream sensor will influence the instrument only by interacting with the sensor signal. All of the orifice tests will be run at a air velocity of 95 ft/sec and air/coal ratios of 1.5, 2.0, 2.5, and 3.5.

A simple square edged concentric orifice will be used for the test. It will be fabricated from 0.090" aluminum plate with an open area of 56%.

The upstream orifice tests will be performed with the instrument installed at the 1V15 location. The orifice will be installed at distances of 2.5D, 6.5D, and 10.5D upstream of the instrument. The orifice will also be installed four diameters upstream of the bend going into the vertical run.

The downstream orifice tests will be performed with the instrument installed at the 1V3 location. The orifice will be installed at locations 0.5D, 4.5D, and 8.5D downstream of the instrument.

Sensor Installation

Sensors and reflector rods are installed by means of Factory provided threaded inserts that are seal welded into holes drilled or cut into the pipe. Accurate location of the threaded inserts is assisted through the use of a Factory supplies drilling layout template and a centering jig to position the threaded inserts while they are being tack welded. The temperature sensor is attached to the outside of the pipe using thermally conductive epoxy. Factory provided cables connect the pipe-mounted sensors to the transmitter enclosure.

Instrument Setup

Due to such factors as pipe inner diameter, concentricity, accuracy of sensor installation, etc, each pipe constitutes a unique waveguide, and therefore must undergo a parameterization process using a software utility program called Pf-PRO. The semi automated process, which takes less than five minutes per pipe, establishes the measurement parameters for each pipe. Note that parameterization can be performed on either a operating or empty pipe.

The second step in the commissioning process is to zero the system's density measurement. This entails taking the corresponding mill out of service and purging the pipes for 10-15 minutes to make sure all coal is cleared. Density measurements taken while the pipes are clean are used to determine the density zero offset factor for each pipe, which is then installed using the Pf-PRO utility.

Test Procedure

Once the instrument setup has been completed, the instrument evaluation will proceed. The instrument will first be installed in a test location that is considered most ideal for that particular instrument. The baseline test matrix will be run and the instrument output compared to the actual conditions. This comparison will be made to verify that the instrument is functioning in a reasonable manner before proceeding with the complete test plan. There is no point in proceeding with the evaluation if the instrument is not functioning properly. Of course, defining "functioning properly" is very difficult. The comparison will be performed by ASC and EPRI personnel and the coal loop flow data will be kept confidential. However, graphical comparisons will be shared with the instrument manufacturer/representative and their comments invited. If it is decided that the instrument is not functioning properly, the evaluation will be stopped and a plan for proceeding will be worked out.

If the instrument is functioning properly, the evaluation will then proceed by moving the instrument through the locations, flow conditions, and tests described above. The evaluation will follow these guidelines:

- •The instrument representative may be present during the evaluation.
- •At each test location, the baseline test matrix will be performed in random order (both air and coal flows). Elevated temperature tests, when performed, will be run after the baseline test matrix. The test matrix flows, temperatures, and run times will be pre-programmed in the coal loop computer. The computer will automatically advance through the matrix once the test is started.
- The test matrix will be performed blind. The order of the test matrix at each location will not be disclosed.
- Data from the instrument will be provided to ASC at the completion of each test location.
- The preferred data logging interval for the instrument is 15 seconds.
- After each flow rate change, a 5 minute period will be given for the coal loop and instrument readings to stabilize. The coal loop flows and instrument readings will then be compared over the following 15 minute period.
- No adjustments will be made to the instrument during a test run at a particular location.

- No adjustments will be made to the instrument when moving the instrument to a new location unless these adjustments have been discussed and agreed upon prior to the evaluation. "Zeroing" the instrument at each location (zero coal flow) will be permitted as this process can also be easily performed in the field.
- Coal samples will be obtained from the loop coal feeder at the start of the evaluation and after completion of each test location. The first and last coal samples will be sieved to determine any change in fineness during the evaluation. Intermediate samples may also be analyzed.
- Coal loop flow data will be provided to the instrument manufacturer/representative within 30 days of the completion of the evaluation testing.

A complete test matrix is presented in Appendix D.

<u>Manufacturer/Representative Comments</u>

This pre-evaluation report was provided to the manufacturer/representative for comment and questions prior to the instrument evaluation. Whenever possible, points of disagreement were discussed and resolved and the content of the report modified accordingly. In cases where agreement was not reached on some point, the manufacturer/representative is invited to provide their own comments below.

The manufacturer/representative is also invited to note and discuss any differences between the coal loop and an actual power plant which may impair or improve the instrument's performance.

MANUFACTURER COMMENTS FOLLOW:

April 6, 2006

General Report comments: (see attached EPRI Response for items not directly addressed in this text)

- Overall this DRAFT report, as written, would seem difficult for the typical plant engineer to fully discern without spending considerable amount of time analyzing each and every section of information. Could the results be summarized in simpler ways for the layman? The sensitivity values, the normalizing results to a "tester selected" optimal location (1V15) and the uncertainty values summarized across all the tests, sometimes seem to contradict each other the way its presented.
- When coal is circulated in a flow loop such as at the CFL, static electric charges will build up and at a certain state, when the voltage gets high enough, a discharge will take place. This will cause coal to actually stick and build up on metallic components inside the pipe. The static charges in the loop are inherently unstable. This is not the case in a power plant. FW and TR TECH presented this concern to EPRI early in the program. No comments regarding this effect and how they were addressed is presented in the report.

- All ECT systems currently in operation provide coal particle velocity measurement. This is a key capability used by ECT owners to monitor and control primary airflow as well as coal layout in conduits. We therefore believe the ECT and other systems' velocity capability should be presented and compared with the CFL's conduit air velocities, even if there is a difference.
- Of the 30 plus ECT-equipped coal fired units, all use it to provided relative coal flow distribution information. The CFL single pipe arrangement did not evaluate this primary application. Absolute coal flow is requested in less than 10% of the applications. Generally for absolute coal flow, more calibration may be required. Reviewing many of these results, better calibration would have resulted in improved accuracy for all tests. The benefit of calibration can be seen by the high degree of accuracy obtained immediately downstream of the elbows and orifices. For future work multiple outlets should be studied. See EPRI TVA Coal Flow technology Assessment Report relative to this subject.
- Has anyone looked at how this data for all the tested technologies compares with the earlier EPRI /TVA Coal Measurement Assessment Report?

EPRI Response: No this effort is concentrating only on the CFL test results.

Specific Report Comments:

Pg x : ECT Star System Results

Items 1 & 2:

- Recommend comments on the "sensitivity" values and suggest the results be presented similar to the normalized results and discussions.

  EPRI response: addressed in report

- Why would you normalize the data to some other selected data when you have actual measured CFL coal flow as a comparison to the instrument? Presenting sensitivity and normalized sensitivity comparisons confuses the results. If the chosen location for normalization was not optimal, then this data would translate to a large portion of the conclusions making them all in error. It's possible that 1V15 may not be the ideal location in the CFL. Some of the coal could very well be is dropping /slipping back down the pipe. This happens especially at marginal transport conditions or transients coal flow conditions.

  EPRI Response:

  As indicated, most installations of the ECT system are used to provide relative coal flow indication between multiple pipes as opposed to absolute coal flow on each pipe. Bearing that in mind, a reasonable way to investigate the accuracy of the device, when used in this capacity, is to compare (and hence normalize) the sensitivities at different locations. For instance, a comparison of two different locations in the coal loop is equivalent to comparing a two-pipe system that has identical pipe design, with the sensor installed at a different location on each pipe. Using this method, it can be demonstrated how sensitive the instrument is to installation location. For example, assume that at a given coal flow (say 200 lbs/hr) the ECT reads 100 lbs/hr at location 1V11 and only 50 lbs/hr at location 1V3. If this two- pipe mill system contained an actual coal flow rate of 200 lbs/hr, and the ECT was installed at a location 1V11 in Pipe 1 and 1V3 in Pipe 2, then the instrument would indicate that there is twice as much coal in pipe 1 than in pipe 2, even though both pipes have equal coal flow.

Based on the above example, the negligible impact of choosing a basis location for sensitivity normalization can also be illustrated. For instance, if in the above example the normalization location was 1V11, the normalized sensitivities would be 1.000 in Pipe 1 and 0.500 in Pipe 2. Conversely, if we chose to normalize by 1V3, then the normalized sensitivities would be 2.000 in Pipe 1 and 1.000 in Pipe 2. Either way, it is evident that Pipe 1 will read twice as much as Pipe 2 at a given coal flow. .

- Where in the report does it mention that following the installation of the ECT system, the system discovered that the CFL coal flow was not always steady and that it exceeded the assumed fluctuation of 2 to 3%? That in fact, CFL coal flow swings ranging over +/- 15% from set point did occur. These swings would significantly affect the presented results. How were they considered in the results?

  EPRI response: report has been edited and tests for which data was questionable due to coal flow instability have been omitted from analysis.

- For significance, suggest adding at the end of sentence "*across 12 test conditions and 143 tests*".

  EPRI response: Uncertainties only estimated for baseline test matrix (84 test conditions) not including air temperature and orifice tests.

Section 2, pg 2.1:

- In this section, paragraph one states that the closed loop laboratory "closely replicates the scale, piping and flow conditions found in a typical coal fired power plant". The facility tries to do so with the arrangement and all the flow rates, but that is where the similarity ends. No power plant recirculates the same coal over several weeks. Recirculation and the associated static charge buildup was an initial concern that Foster Wheeler and TR TECH noted to EPRI during the invitation process. Our concern was that recirculating the coal particles would change the static charges and even the particle size. Since the ECT measures static charges, we believe there are changes in charges that could be affecting the ECT results and the results of other systems. We mention this because the differences we are seeing in some of the CFL cases are significantly different that what we have seen at actual plants and in the EPRI TVA report.

  EPRI response: See the attached document

Pg 2-2 Air Measurement and Coal Measurement

- Suggest presenting a graph that confirms the ability of the CFL to maintain the stated clean airflow accuracy of 0.25%, by plotting clean air flow versus time for all 3 velocities. From our ECT data the velocities can cycle more than 0.25%

  EPRI response: See response for air measurement in attached document.

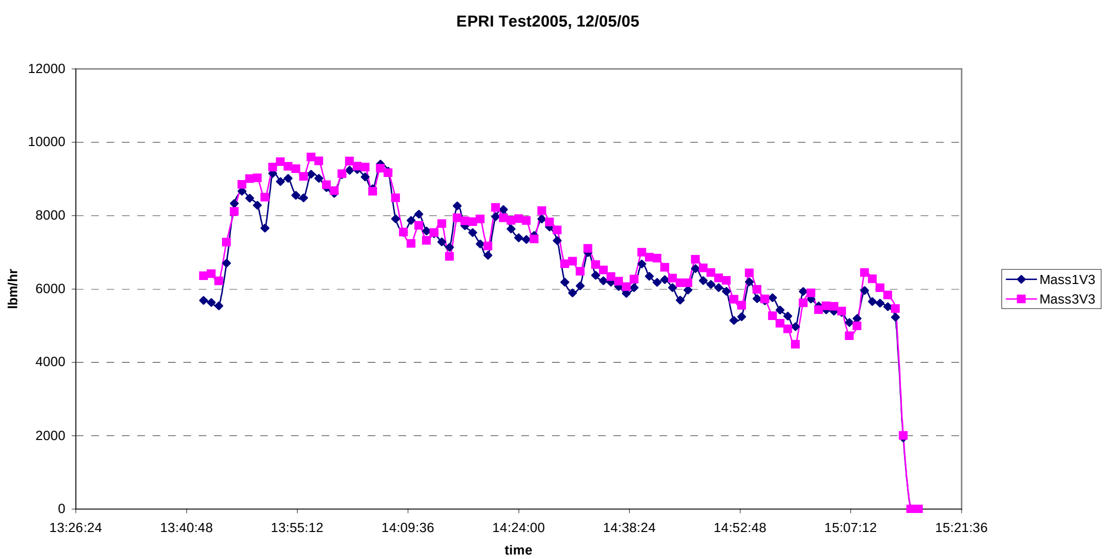
- Recommend a similar graph of CFL measured coal flow versus time that confirms the ability of the CFL to maintain a steady coal flow within 2 to 3 percent from set point.

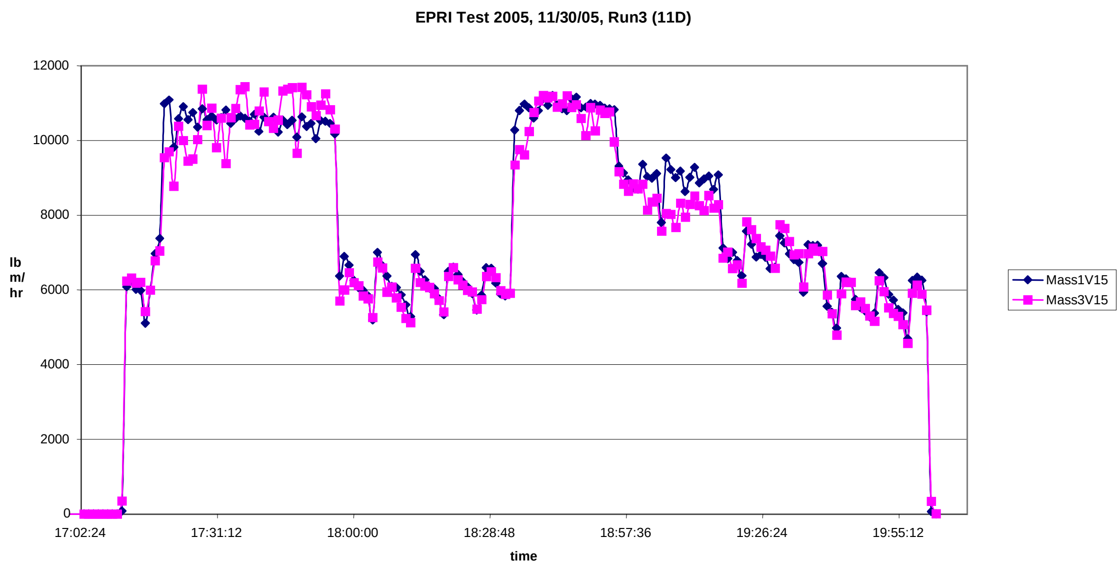
  EPRI response: See attached response on Coal flow stability

- The 2 to 3% accuracy effect is never mentioned with respect to the ECT instruments measured results. Is this accounted for in the results? How does the CFL Coal-Flow Measurement compare to industry extractive methods that are familiar to most plant engineers?

  EPRI response: Same as above

- There is no mention in the entire report of a very important CFL problem the ECT uncovered. The CFL coal flow fluctuated significantly through numerous tests. The two graphs below show as much as +/-16% fluctuation. One of the values shown is 1H15, which was used as the normalization value. This would significantly affect the summary results.





- In addition to the coal flow cycling concerns, there is no mention what effect the feeder operating in a volumetric feeding mode has on measurement accuracy and the validity of the results?

  EPRI response: The feeder operation in volumetric mode should have no effect on the accuracy or stability of the feed. When the feeder is in volumetric mode, the rotary feeder velocity (rpm) remains constant, even during the refill cycle. However, during the refill cycle, the coal feed data is not logged and hence it is not incorporated into the data analysis. Unfortunately, there is no way to verify that the feed is not affected because it is impossible to take a meaningful load cell reading during the refill process.

PG 2-3:

Temperature Control

- Show graph of typical CFL temperature control over time to confirm temperatures were maintained within stated +/-2 °F.

  EPRI response: See response in attached document

Particle Size

- State particle fineness before and after ECT test program.

EPRI response: Actual reports will be included in the appendices. Here is a summary table:

	BEFORE TEST	AFTER TEST
Mesh	% Passing	% Passing
48	100.00%	100.00%
100	100.00%	100.00%
200	99.10%	99.43%
325	89.22%	89.49%
Pan	65.81%	71.33%

Pg 2-4: Instrument Installation Locations

- Suggest including locations 1H50 and 1H20 somewhere in the layout. 1H57 and 1H33 are shown but not used in the ECT tests.

  EPRI response: This is a generic pictorial of where the general test locations are, for your instrument the 1H20 and 1H50 are near the other 1H locations indicated in the plot..

- Suggest Figure 2-3 should be made larger and the orifice locations identified.

  EPRI response: Orifice locations shown in figures-4-24 and- 4-26

Section 3-1: Baseline Test matrix

- Where is the data / information substantiating the "zero coal flow". Did the ECT zero out?

  EPRI response: Data is not presented or used in the data analysis.

- Suggest at the end of the lower paragraph, the point be made about data collection every 15 seconds, instead of having to find this much later on.

  EPRI response: These sections are generic to all tested instruments, thus details such as these are reserved for each specific instrument section.

- Suggest inserting ECT information comparing the CFL clean PA velocity at the 3 tested velocities versus some ECT velocity data.

  EPRI response: See attached response.

Section 3.2.1:

Effect of Air velocity

- Based on Table D-1 there are more than four coal flow rates. Perhaps clarification is required to show that are differing coal flow rates for each air velocity test.

4.2.1.3: Effect of Location (Sensitivity)

- Provide the qualitative and extractive protocol that supports the fact that 1V15 is the best location. How did the extractive method then match the CFL? Why can't each point stand on its own against the CFL data? The ECT, because of the circumferential probe layout can do pretty well even close to elbows and/or orifices with good calibration.

  EPRI response: Same point as before, see attached response.

Figures 4-4 to 4-11:

- Why do locations 1V15, 1V11 have ECT output in lbm/hr while, locations 1V7 and 1V11 use "Arbitrary Units" or AU's? Similar on other figures? Where is the definition of these "Arbitrary Units" and the explanation of why both approaches?

  EPRI response: Plot axis will be corrected to read the correct units – not AUs

4.2.2.1: Effect of air Velocity

- During these tests the mass flow was cycling. We should also consider that the calibration wasn't perhaps perfect for the lower velocities. At a plant we analyze the measurement signals for a period of approximately one week and use that data for improving the absolute mass flow calibration. This was not possible for these tests.

  EPRI response: Because the calibration details are unknown to us, we are not in a position to comment on the improvement of the measurement if more calibration time were used. Calibration time was discussed before the test was conducted at the CFL and agreed upon before the test start..

4.2.2.2 Uncertainty

- With the ECT circumferential coverage, installation of probes close to elbows can yield good measurements with calibration.
- Again what are the Arbitrary Units?

  EPRI response: We will correct the mislabeled axes on these plots.

4.2.2.3: Effect of Location (Sensitivity)

- On location 3V7 the signal was malfunctioning occasionally, which was also mentioned in the data sent to EPRI (See attachment Amf ModOutput 12-02-05T11, run2.xls). Was this used in the data analysis?

  EPRI response: It was included in the data presented, we will omit the questionable stability runs and recalculate uncertainties and sensitivities. See revised summary table in the attached response.

4.3.1: UPSTREAM ORIFICE

- Why aren't there uncertainty values for this case?

  EPRI response: It would be misleading to compare the uncertainties for this case with the full tests as there are much fewer data points and only 1 velocity represented. Also, a different calibration procedure was used than for other baseline matrix tests

- In a real plant we would generally try not to install antennas very close to an orifice, especially down stream. If that were the only possible location, we would consider that in the calibration procedure. However, we think that the explanation in this report that tries to explain why there is a difference between some tests and baseline should not be attempted. We have never bumped into a situation like this in any power plant, even though there are orifices used on some of them. The calibration process provides increased accuracy even in such location.

4.3.2: DOWNSTREAM ORIFICE

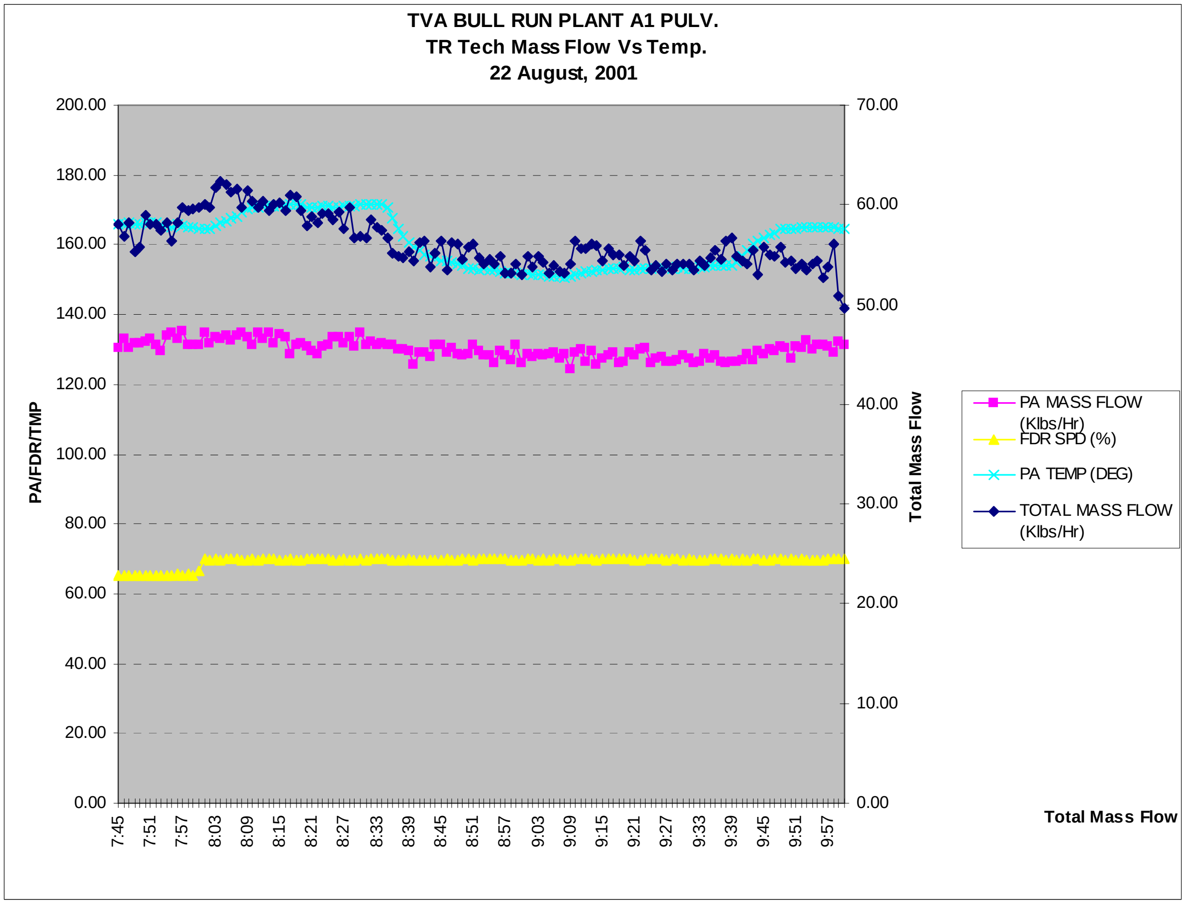
- Where are the uncertainty values for this case too???

  EPRI response: Same as above, not enough data collected to run uncertainty analysis.

4.4: EFFECT OF TEMPERATURE

- Based on the EPRI test conducted at Bull Run and other installations, we have not seen such significant affects due to PA air temperatures. The slight changes we have seen are also opposite to what is presented in this report in Figures 4-28 and 4-29. At Bull Run, as temperatures decreased from approximately 170 to 150 °F, the ECT showed an approximate 7% decrease in absolute coal flow as opposed to the increase shown in the CFL results.

  EPRI response: Data is plotted correctly as was measured at the CFL. Do not know the reason for the observed difference from the TVA Bull Run data.



Appendix 13

The chart data shows that pulverizer coal and air outlet temperature changes have almost no lasting affect on the indicated total mass coal flow measured by the FWC TR-Tech system. This test is considered a success.

Expanded EPRI Response to Comments from Foster Wheeler

Charge Build-up

The impact of charge build-up on the ECT system tests at the CFL can be evaluated as follows: because the ECT was calibrated at each location that it was tested, long term charge build-up concerns should be minimal or non-existent. Consider the approach for the test protocol and focus on the charge build-up that might have occurred during a test at a single location. At each location, the following test matrix was run: Four tests were performed for the calibration (2 air velocities, 2 coal flow rates). Then, at a low air velocity, four coal flows were run. At a middle velocity, 5 coal flows were run (one of those coal flows being zero). Finally, at a high velocity, 4 more coal flows were run. After this matrix was completed, the first flow test condition (low velocity, 1st coal flow) was repeated to check the repeatability of the instrument output. Each condition in the test matrix was run for 22 minutes, thus, without interruptions in the test sequence, there are approximately 4.5 hours between the end of the first condition (Test 5) and the beginning of the repeat test of that condition (Test 18). If Test 18 is compared with Test 5, we should be able to tell if there are any variables, such as charge build-up, that are affecting the instruments' output.

Table 1 below shows the results of Test 5 and Test 18 at each of the locations where the ECT was tested. Also note that two instruments were tested simultaneously each on a different vertical test leg of the CFL. That is, locations 1V15 and 3V15 were tested simultaneously, as were locations 1V11 and 3V11, locations 1V7 and 3V7, and locations 1V3 and 3V3 respectively.

Table 1
Results of Repeat Tests taken at Each Location

		1V15	3V15	1V11	3V11	1V7	3V7	1V3	3V3
Coal Flow [lbm/hr]	Test 5	13,823	13,823	13,534	13,534	12,919	12,919	9,844	9,844
	Test 18	13,867	13,867	13,570	13,570	13,676	13,676	9,230	9,230
ECT Output [lbm/hr]	Test 5	10,681	N/A	10,309	5,500	10,775	10,330	12,341	8,177
	Test 18	8,426	6,167	8,716	5,617	8,779	10,062	10,985	8,489
	Elapsed time between Test 5 and Test 18	10:04:00	10:04:00	4:31:15	4:31:15	4:31:00	4:31:00	4:31:15	4:31:15

It can be seen from Table 1 that the Test 18 output of the instrument installed in the 1VX locations is generally about 80% of the output at Test 5. For the instrument installed at the 3VX locations during the same tests, the output differences between Tests 5 and 18 are closer than for the 1VX locations. (Unfortunately, there was a problem with the data during Test 5 at location 3V15, so the repeatability at this location can not be evaluated). Since the loop is completely grounded, it seems highly unlikely that there is a charge build-up impact at the 1VX locations, but no similar charge build-up impact affects the 3VX locations. It is unknown why the instrument in the 3VX locations showed better repeatability than the instrument at the 1VX locations .

Coal Feed Stability

It is important first, to make a clear distinction between the terms accuracy and stability with respect to the coal flow rate determination . The mass flow rate of the coal through the loop is measured by a system of load cells that measure the loss in weight of the coal in the weigh hopper. The accuracy of this measurement is simply the accuracy of the load cells, which is better than 3%. The stability of the feed, on the other hand, relates to how closely a particular coal flow rate can be maintained throughout the period of the test. In order to evaluate the stability of the feed, we analyze the standard deviation of the coal flow rate numbers (as measured by the load cells, roughly 1 measurement every 15 seconds) normalized by the average coal flow rate over the time period for a given test. The coal feed stability is shown in Tables 2 through 6 for the entire test matrix. The coal standard deviation presented in these tables is found by using Equation 1 below over the time frame of each test, where n is the total number of data points for the test, x is the value of each of the discreet data points, and mdot_avg is the average coal flow rate for the test.

$$\frac{\sqrt{\frac{n\sum x^2-\left(\sum x\right)^2}{n(n-1)}}}{mdot\_avg}$$

Table 2
Coal Feed Stability for Locations 1V15 and 3V15.

1V15/3V15				
Test Number	**Average Coal**	**Coal St Dev**	**Average Air**	**Air Vel SD**
5	13,823	2.0%	12,842	1.0%
6	9,050	6.9%	12,969	1.1%
7	6,623	2.8%	13,042	1.0%
8	4,456	3.2%	13,087	0.9%
9	11,190	2.1%	16,217	0.9%
10	8,766	2.2%	16,232	0.9%
11	6,721	2.2%	16,263	0.9%
12	5,545	3.5%	16,323	0.9%
14	4,785	6.6%	19,471	0.5%
15	6,351	3.8%	19,263	1.0%
16	7,640	1.5%	18,675	0.7%
17	9,378	2.3%	18,231	0.7%
18	13,867	1.5%	12,799	0.9%
1	12,256	5.2%	12,933	0.9%
2	5,483	5.0%	13,089	1.1%
3	8,492	1.5%	18,972	0.7%
4	5,287	5.1%	19,106	0.6%

Table 3
Coal Feed Stability for Locations 1V11 and 3V11

1V11/3V11				
Test Number	Average Coal	Coal St Dev	Average Air	Air Vel SD
5	13,534	6.1%	12,778	1.0%
6	9,417	2.9%	12,909	1.0%
7	6,748	2.8%	12,999	1.3%
8	4,551	3.5%	13,044	0.9%
9	11,254	2.1%	16,070	0.9%
10	8,886	1.9%	16,143	0.8%
11	6,812	1.5%	16,224	0.7%
12	5,583	2.6%	16,274	0.7%
14	5,001	3.7%	19,398	0.5%
15	6,519	3.0%	18,960	0.8%
16	7,759	2.3%	18,607	0.7%
17	9,650	1.8%	18,189	0.8%
18	13,570	4.5%	12,805	1.4%
1	12,202	5.8%	13,028	1.5%
2	5,533	3.6%	13,080	0.9%
3	8,498	1.7%	19,176	0.7%
4	5,280	4.4%	19,405	0.7%

Table 4
Coal Feed Stability for Locations 1V7 and 3V7.

1V7/3V7				
Test Number	Average Coal	Coal St Dev	Average Air	Air Vel SD
5	12,919	9.8%	12,866	1.0%
6	9,154	5.9%	12,930	0.9%
7	6,594	4.4%	13,056	1.1%
8	4,438	3.3%	13,099	0.8%
9	11,278	2.3%	16,150	0.8%
10	8,780	2.0%	16,286	0.8%
11	6,804	1.7%	16,303	0.9%
12	5,565	2.7%	16,351	0.7%
14	4,985	3.5%	19,541	0.5%
15	6,543	3.0%	19,080	0.7%
16	7,730	2.3%	18,720	0.7%
17	9,538	2.0%	18,318	0.7%
18	13,676	3.5%	12,850	1.0%
1	12,271	4.9%	12,884	1.1%
2	5,459	3.6%	13,086	1.0%
3	8,490	2.0%	19,254	0.8%
4	5,327	4.1%	19,454	0.6%

Table 5
Coal Feed Stability for Locations 1V3 and 3V3.

1V3/3V3				
Test Number	Average Coal	Coal St Dev	Average Air	Air Vel SD
5	9,844	8.7%	12,937	1.9%
6	7,933	11.3%	13,008	1.3%
7	6,169	4.9%	13,077	1.2%
8	4,667	4.4%	13,136	1.1%
9	9,108	7.1%	16,249	1.0%
10	7,671	5.5%	16,309	1.0%
11	6,202	3.4%	16,374	1.0%
12	5,357	4.9%	16,442	0.7%
14	4,606	10.1%	19,609	0.9%
15	6,024	3.5%	19,177	0.7%
16	6,947	2.3%	18,780	0.8%
17	8,308	3.0%	18,388	0.9%
18	9,230	11.2%	12,942	1.6%
1	9,538	10.0%	13,039	1.5%
2	5,418	4.8%	13,113	0.9%
3	7,622	2.9%	19,357	0.8%
4	5,233	5.3%	19,495	0.6%

Table 6
Coal Feed Stability for Locations 1H50 and 1H20.

1H50/1H20				
Test Number	Average Coal	Coal St Dev	Average Air	Air Vel SD
5	10,526	12.7%	13,030	1.2%
6	7,740	18.3%	13,136	1.1%
7	6,545	3.1%	13,210	1.0%
8	4,804	5.1%	13,263	0.9%
9	8,710	12.6%	16,400	0.8%
10	7,977	12.0%	16,474	0.8%
11	6,562	2.6%	16,526	0.7%
12	5,569	3.6%	16,563	0.7%
14	5,086	6.7%	19,804	0.7%
15	6,239	5.7%	19,377	0.7%
16	6,877	10.9%	18,994	0.5%
17	7,420	12.3%	18,623	0.8%
1	10,341	9.8%	13,130	1.2%
2	5,492	3.5%	13,247	1.1%
3	7,438	8.7%	19,627	0.7%
4	5,396	4.2%	19,720	0.6%

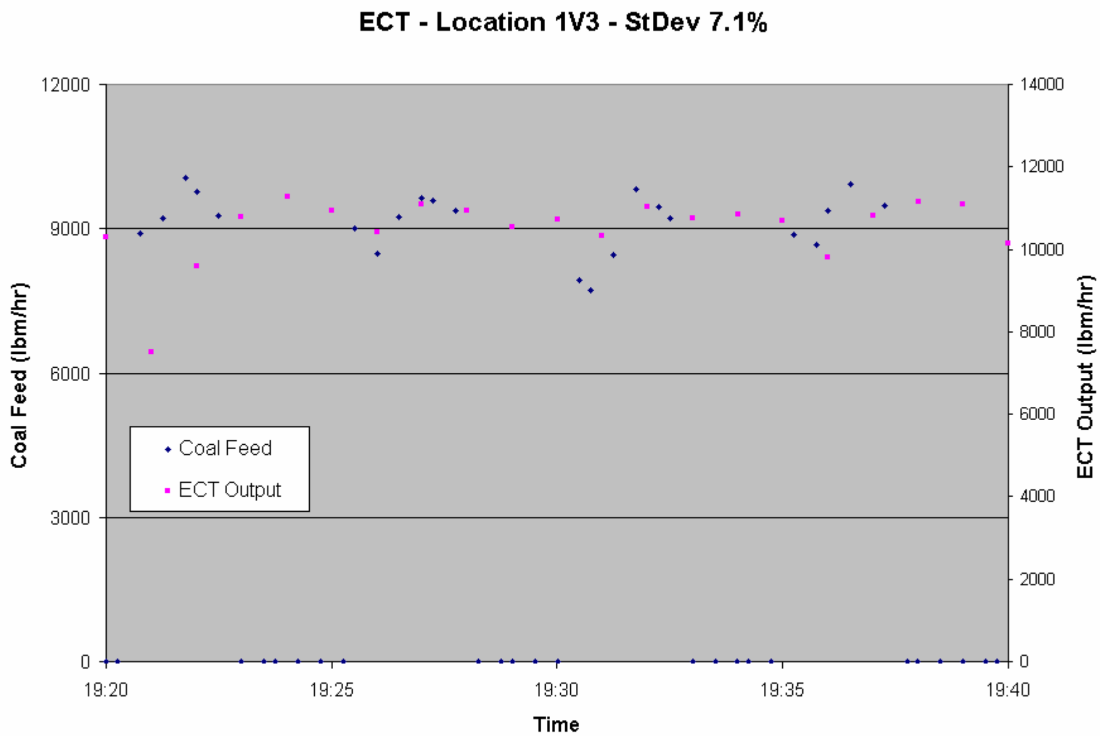
As can be noted from the Tables, in some instances the coal flow rate standard deviation was higher than the typical value of 3%. It was later confirmed that the cause of the observed flow behavior was related to mechanical wear of some seal components in the coal feed mechanism.. This condition caused occasional instability of the coal flow, especially for the last two tests (1H20, 1H50).

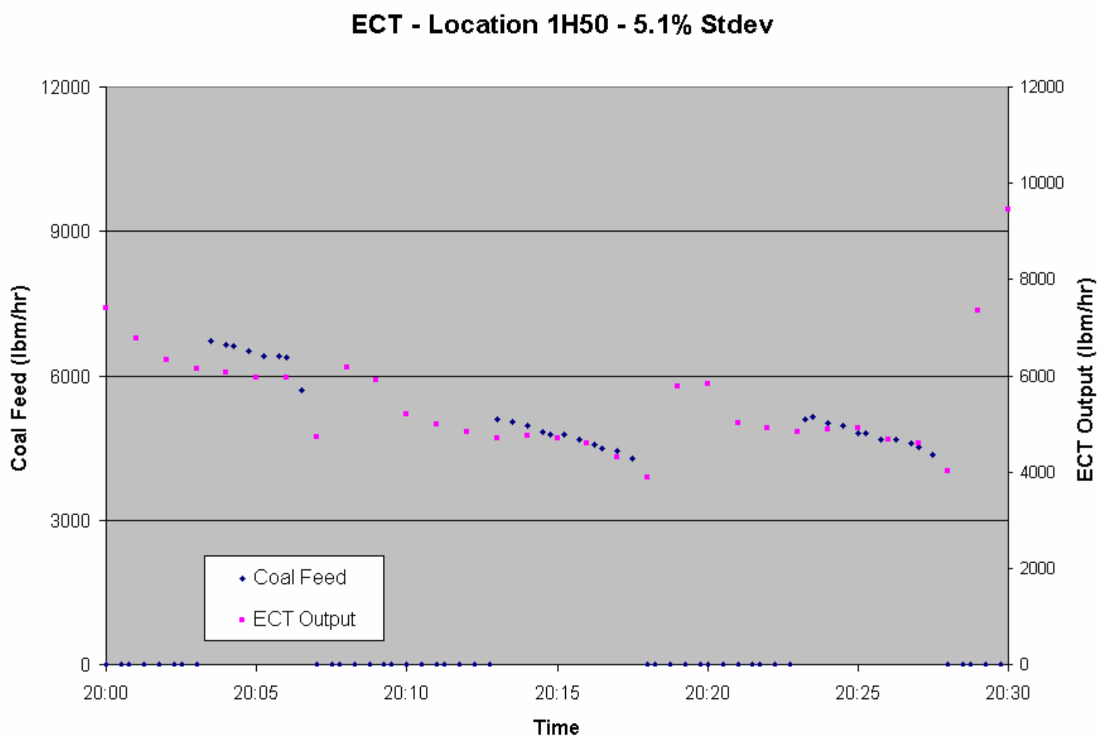
In order to present examine the impact of the high coal flow instability on the ECT's test results, tests with a coal flow rate standard deviation greater than 6% were omitted from the data analysis. The 6% criterion was chosen based on the following:

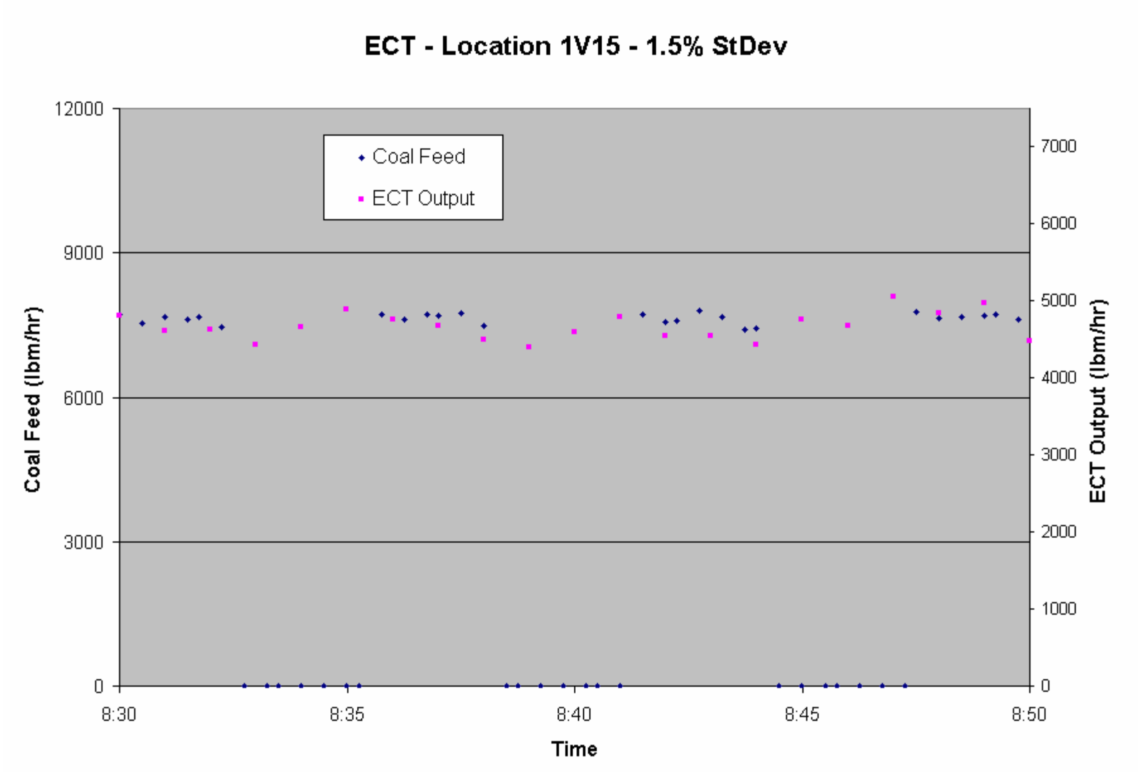
- the typical stability of the coal feed at the coal-flow loop is generally 3% but could spike up to 6% on some instances.
- The ECT is generally calibrated in the field using the ISO 9931 methodology (i.e., "Rotorprobe™"). Based on CFL and other industry testing of the Rotorprobe™, the error that can be expected is on the order of +/-8%. This error can be dependent on the location of the test ports with respect to an upstream elbow. Using a value of 6% standard deviation thus ensures that the CFL is providing an accurate and stable flow within the attainable range from field collected data during ECT commissioning.[1]

Coal Feed Stability Over Time

Another method to observe the impact of the higher standard deviation in coal flow rate from the CFL is to observe the instrument response to the coal flow over time. The following three plots, Figures 1through 3, demonstrate how the ECT instruments track the actual coal feed over 3 different test conditions. The first plot shows a test with a coal feed standard deviation of 7.1%, the second plot shows a test with a coal feed standard deviation of 5.1%, and the third plot shows a test with a coal feed standard deviation of 1.5%. It can be seen in all three plots that the ECT tracked the coal feed trends closely (note that the data label on the right side of the plots is incorrect. It should read "ECT Output (lbm/hr)" as opposed to "Feeder Speed (RPM)").


ECT - Location 1V3 - StDev 7.1%
Coal Feed (lbm/hr)
ECT Output (lbm/hr)
Time
Coal Feed
ECT Output
12000
9000
6000
3000
0
14000
12000
10000
8000
6000
4000
2000
0
19:20
19:25
19:30
19:35
19:40


ECT - Location 1H50 - 5.1% Stdev
Coal Feed (lbm/hr)
ECT Output (lbm/hr)
Time
Coal Feed
ECT Output
12000
9000
6000
3000
0
12000
10000
8000
6000
4000
2000
0
20:00
20:05
20:10
20:15
20:20
20:25
20:30



Revised Data Reduction

The uncertainty and sensitivity of the ECT at the tested locations, for both original calculations and with revised criteria for coal stability are in Table 7. Similarly, due to sensor malfunction, the data for location 3V7 will not be presented in the report).

Table 7
Uncertainty and sensitivity at each location for original data reduction and for data reduction omitting data with greater than 6% coal flow rate SD.

	Sensitivity		Normalized Sensitivity		Uncertainty	
Test Location	All data	(<6% SD)	All data	(<6% SD)	All data	(<6% SD)
1V15	0.687	0.684	1.00	1.00	13.9	13.3
1V11	0.688	0.667	1.00	0.97	10.9	8.5
1V7	0.751	0.707	1.09	1.03	12.2	9.5
1V3	1.099	1.000	1.6	1.46	14.0	7.1
3V15	0.722	0.730	1.05	1.07	16.3*	16.0
3V11	0.590	0.641	0.86	0.94	26.9	13.3
3V7	1.001	0.997	1.46	1.46	31.8	24.5
3V3	1.072	1.112	1.56	1.62	15.8	9.2
1H50	1.002		1.46		6.1	
1H20	1.136		1.65		8.8	

ECT Particle Velocity and CFL Air Velocity

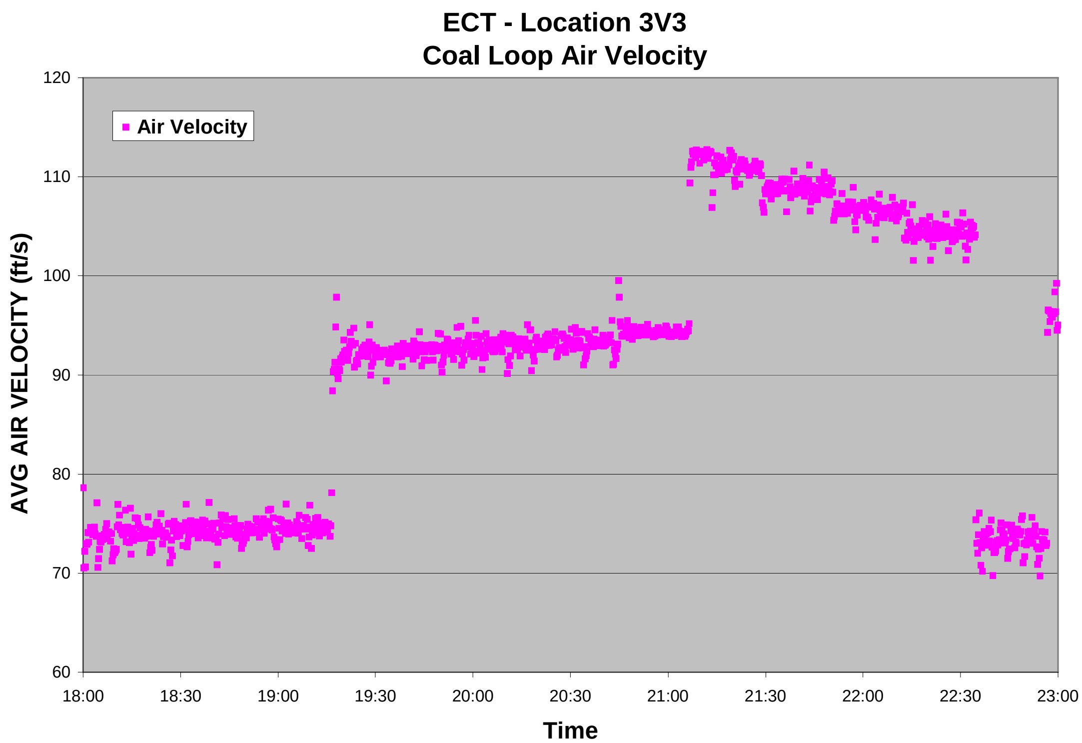
We will present the ECT coal particle velocities along with the loop's air velocity in the report. At each location, the velocities from the 4 tests at each velocity (actually 5 tests for the ~95 ft/s velocity due to the zero coal flow condition) were averaged and are presented below in Table 8.

Table 8

	Loop Air Velocity	ECT Coal Velocity	Percent Difference
1V15	74.4	78.9	6.05%
	93.2	98.7	5.89%
	108.4	113.9	5.01%
3V15	na	na	na
	93.2	82.9	-11.10%
	108.4	105.1	-3.06%
1V11	74.7	77.4	3.57%
	93.5	96.3	3.08%
	108.6	111.9	3.05%
3V11	74.7	68.4	-8.46%
	93.5	86.5	-7.47%
	108.6	107.5	-1.03%
1V7	74.6	74.9	0.48%
	93.2	94.5	1.31%
	108.2	110.0	1.72%
3V7	74.6	70.3	-5.75%
	93.2	90.7	-2.76%
	108.2	108.1	-0.10%
1V3	74.1	70.9	-4.36%
	92.8	90.6	-2.33%
	107.7	103.3	-4.08%
3V3	74.1	73.5	-0.75%
	92.8	89.8	-3.24%
	107.7	102.2	-5.15%

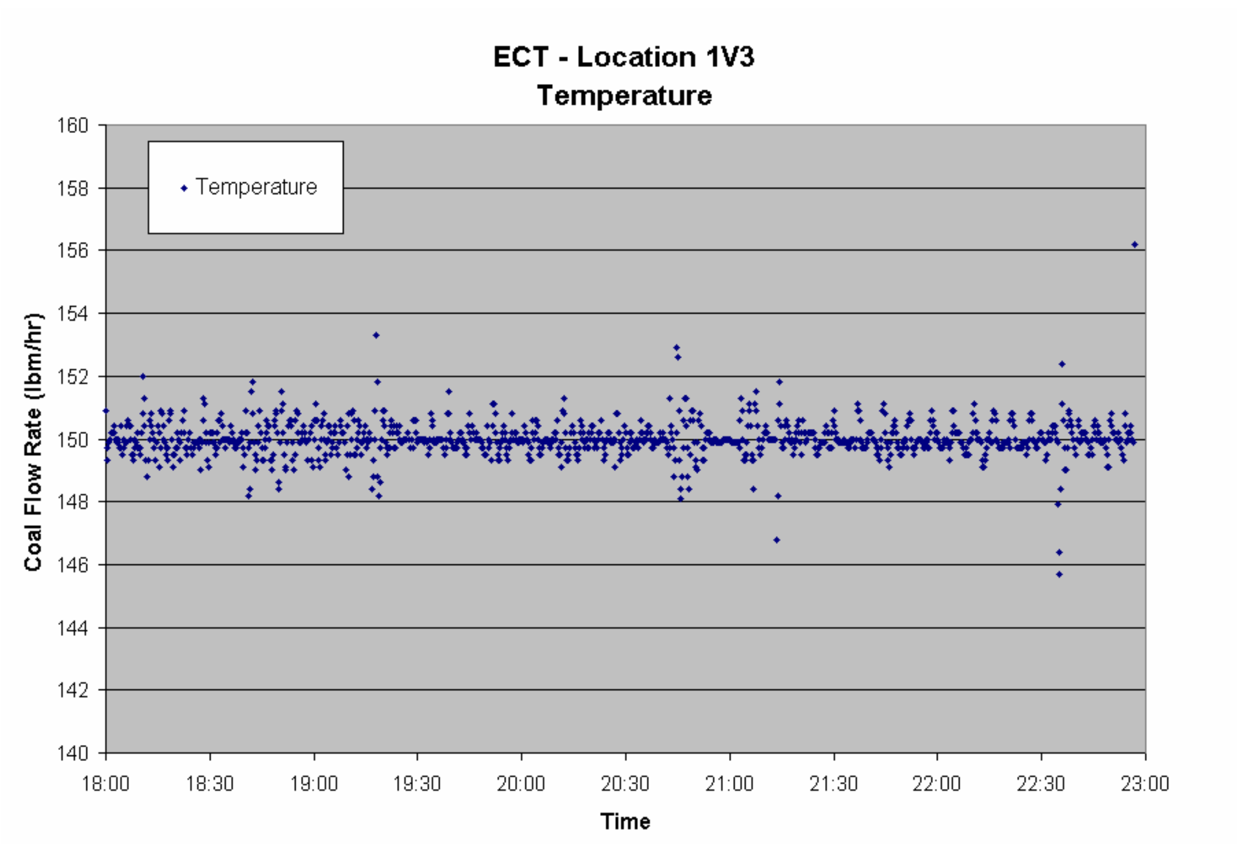
Air Velocity Over Time

The accuracy of the venturi (air flow measurement) is 0.25%. The stability of the airflow is maintained at a standard deviation of less than 1.5% during each test.



Loop Air Temperature Control

- The plot below shows the temperature control over the course of an entire test matrix. The temperature stays within 2 degrees of the set point for greater than 99% of the time.



B
EPRI COAL-FLOW MEASUREMENT AND CONTROL LABORATORY SWR SOLIDFLOW PRE-EVALUATION REPORT (EXCERPTS)

EPRI Coal-Flow Measurement and Control Laboratory Instrument Pre-Evaluation Report

<u>SWR: SolidFlow PF</u>

ASC Document R-04-CL3-02

Prepared By:

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Livonia, MI 48150
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Instrument Information

Model/Name

SolidFlow PF

Manufacturer

SWR engineering Messtechnik GmbH
Mr. Ralf Schmedt
Mittlerer Weg 22
79424 Auggen

GERMANY

Distributor or Representative

None at this time.

Instrument Procurement Arrangement

Three sensor installation sockets and sensors were purchased by EPRI directly from SWR. The signal processing box was rented to EPRI for the evaluation.

Principle of Operation

Reflective microwave.

Quantities Measured

When the microwave sensors are installed, and all electrical wiring is done correctly the system outputs a value proportional to coal mass flow for every pipe.

The signal output is linear. All sensors have the same sensitivity, thus the values output for the pipes of a given pulverizer show the relative flow distribution between the burners. Uniform sensitivity of all sensors is guaranteed by special production procedures; proven and certified according the DIN EN ISO 9001:2000 Quality system.

To achieve an absolute massflow measurement for all conduits the easiest way is to use the SWR Calibration Software. This software enables the user to set calibration factors for every pipe in the calibration mode. To define calibration factors, the sum of all measurements from a given pulverizer should be compared to the amount of coal fed into pulverizer by the feeder in a given period of time.

To simplify this procedure the SWR program offers a resetable totalizer function.

Software versions are available in the three languages English, French and German. The engineering units of the output can be easily configured for a wide range of metric and imperial units.

The system does not provide data logging capability. A PC, data acquisition card, and data logging software was provided by Airflow Sciences to record the unit's output.

Serial Number/Software Version

The signal processor is serial number 345318. Sensor 1 is serial number 345319, sensor 2 is 345320, and sensor 3 is 345321. The software version is 1.07.

Description of System Components

The system consists of sensors mounted to the coal pipe, a sensor junction box, and a digital transmitter unit. The number of sensors installed on a pipe will vary with the application. Three sensors were used for the coal-flow loop evaluation. A photo of the sensor installation is shown in Figure 1.

The digital transmitter unit uses a small PLC controller and text-based LCD touch screen. Using the touch screen the user can scroll through and modify all the various system parameters. The system software allows for configuration of the system, calibration, setting damping times, configuring analog and digital outputs, and setting engineering units. When in run mode the screen displays the current flow rate. More sophisticated data display and data logging may be provided through an industrial PC (not supplied with system). The digital transmitter unit and data logging computer is shown in Figures 2.

Because of the digital bus-connection the distance between sensors and transmitter units can be easily 1000 meters. Sensors are available for hazardous environments, certified according ATEX Norm. The transmitter units KME 300 are designed as 19" electronic cards and can be supplied already mounted in 19" –rack system, which makes it easy to mount all units in a cabin. Each KME 300 delivers a 4-20 mA signal for the coal flow.

Sensor Installation In Pipe

The number of sensors used for measuring the flow in one pipe is dependant on the pipe diameter:

	pipe diameter (mm)	pipe diameter (inches)
1 sensor	up to 200	up to 8
2 sensors	200…400	8…16
3 sensors	400… 600	16…24

If 2 sensors are used they will be mounted in a 90° angle. If 3 sensors are used they will be mounted 120° apart each other around the pipe. In both cases the sensors will be installed in the same axial plane. This means there is no axial distance required between the sensors. In horizontal pipe runs one of the installed sensors must be on top of the pipe. In vertical pipe runs the sensor positions around the pipe are free.

The sensor socket will be welded at the chosen sensor position and subsequently a 20 mm hole is drilled into the pipe wall. Then the sensor spacers will be adjusted for the wall thickness such that the tip of the sensor is flush or slightly recessed with the inside wall of the pipe. The sensor is retained in the mount with a union nut. The sensor and mount extend approximately 12” out from the pipe.

Each of the three sensors has a 3/8” diameter 6’ long cable running to the junction box. The cable between the junction box and the transmitter box is user supplied. It carries power (24VDC) and a digital signal (2 conductor) between the junction box and transmitter box.

Preferred/Minimum Installation Location

The operating manual specifies that the sensors should be mounted a minimum of 5 diameters downstream and 3 diameters upstream of flow disturbances such as bend, contractions, and orifices. These minimum distance also apply to temperature or pressure sensors which may intrude into the pipe. In horizontal installations one of the sensors should be mounted on top of the pipe.

No other information was provided.

Typical Field Setup & Calibration

No information specific to pulverized Coal-Flow Measurement applications was provided. For absolute flow measurement, the system is designed around being able to perform a field calibration using an external reference measurement. In addition to adjusting a single calibration factor, the system has the capability of using a calibration table (of up to 20 points) to deal with any non-linearity which may be present. As stated above in “Quantities Measured”, the sum of the output from all pipes can be scaled using the total coal flow from the mill feeder.

However, the manufacturer states that extractive measurements are done as part of the field calibration in some installations. Additional information is provided in the system Operating Instructions, attached.

Supplied Documentation

The following documents were supplied by the manufacturer

SolidFlow PF Operating Instructions.

Sensor Installation

Airflow Sciences was responsible for installing the SolidFlow PF sensors and configuring the system.

The three sensors were mounted to a 2' long section of 12" schedule 40S steel pipe with cut Victaulic grooves on both ends. The sensors were mounted at 120 degree spacing with all sensors in the same plane. The sensor installation is shown in Figure 1.

The sensor installation consisted of welding the sensor mounts to the pipe section, drilling through the pipe wall with a 20 mm drill (down the center of the sensor mount, using it as a drill guide), de-burring the hole on the inside of the pipe, and installing the sensor in the mount. The sensors were installed such that the end of the sensor is flush with or recessed no more than 1 mm below the pipe inner wall.

The sensors were installed with the polarization mark in the flow-wise direction (e.g. the mark is on top of the sensor for vertical upward flow).

Instrument Setup

The SolidFlow PF software was configured with following settings:

1.0 Measurement Range

1.1	Tag	FME300
1.2	Unit	%
1.3	Dec. Pt.	000.0
1.4	Begin	0.0
1.5	End	100.0
1.6	Filter	15.0 s

2.0 Alarms
No configuration made

3.0 Analog Output

3.1	Begin	4.0 mA
3.2	End	20.0 mA
3.3	Min	0.0 mA
3.4	Max	22.0 mA
3.5	Alarm	3.0 mA
3.6	Filter	15.0 s
3.7	Calibr.	4.0 mA
3.8	Calibr.	20.0 mA

4.0 Calibration

4.1	Cal Faktor	1.0
4.2	Filter	60.0 s
4.3	Seg. Points	2

4.4 Calib. Sensor 1
- 4.4.1 Sensor ON
- 4.4.2 Faktor 1.0
- 4.4.3 Val P1 0.0
- 4.4.4 Calib P1
- 4.4.5 Val P2 100.0
- 4.4.6 Calib. P2

4.5 Calib. Sensor 2
- 4.5.1 Sensor ON
- 4.5.2 Faktor 1.0
- 4.5.3 Val P1 0.0
- 4.5.4 Calib P1
- 4.5.5 Val P2 100.0
- 4.5.6 Calib. P2

4.6 Calib. Sensor 2
- 4.6.1 Sensor ON
- 4.6.2 Faktor 1.0
- 4.6.3 Val P1 0.0
- 4.6.4 Calib P1
- 4.6.5 Val P2 100.0
- 4.6.6 Calib. P2

5.0 Pulse Out
No configuration made

6.0 Digital In
No configuration made

7.0 System
- 7.1 Baud Rate 9600
- 7.2 Address 1
- 7.3 Contrast
- 7.4 Language ENG

The instrument was setup and configured by Airflow Sciences and SWR personnel.

As part of the setup of the SolidFlow PF, the instrument output must be zeroed and spanned. The zeroing procedure is done with air flowing in the pipe at 85 ft/s and no coal flow present. With air flowing and no coal flow, menu options 4.4.4, 4.5.4, and 4.6.4 are selected and the instrument is “told” that the zero flow condition is present. The instrument was run in the zeroing mode until stable readings were obtained.

The spanning procedure is performed similarly at an air velocity of 85 ft/s, but with a high coal flow present in the pipe. A coal flow at the high end of the baseline test matrix was selected. Menu options 4.4.6, 4.5.6, and 4.6.6 are selected and the instrument is told that the high flow condition is present. The instrument was run in the span mode until stable readings were obtained.

The zero and span was configured with the instrument installed at Location 5. This location is considered most favorable by the manufacturer. Once the instrument span reading had been set, it was not changed for subsequent locations. The instrument zero reading was however taken at each new Location.

This setup procedure is considered representative of what can be performed in a typical power plant without requiring extractive testing. A mill can be run at high load to provide a relatively high flow through a pipe and a mill can be run air only to provide zero coal flow through the pipe. At high mill load the flow through the individual pipes is not uniform and is not know, thus it would not representative to span the instrument at each location within the coal loop with the same, known, coal flow. However, zero coal flow can be accurately known through all pipes of mill, thus re-zeroing the instrument at each location is valid.

The instrument analog output was connected to a data acquisition card and Windows PC supplied by Airflow Sciences. The instrument output and time stamp will be logged every 15 seconds to a text CSV file.

Manufacturer/Representative Comments

This pre-evaluation report was provided to the manufacturer/representative for comment and questions prior to the instrument evaluation. Whenever possible, points of disagreement were discussed and resolved and the content of the report modified accordingly. In cases where agreement was not reached on some point, the manufacturer/representative is invited to provide their own comments below.

The manufacturer/representative is also invited to note and discuss any differences between the coal loop and an actual power plant which may impair or improve the instrument's performance.

No comments were provided by the manufacturer.

C
COMPLETE TEST MATRIX

Table C-1 summarizes the baseline test matrix. Table C-2 on the following pages provides the complete test program.

Table C-1
Summary of Baseline Test Matrix

Air Velocity (ft/sec)	Air/Coal Ratio (-)	Air Flow (lbm/hr)	Coal Flow (lbm/hr)
75	1.00	13,370	13,370
75	1.50	13,370	8,913
75	2.00	13,370	6,685
75	3.00	13,370	4,457
95	NA	16,940	NA
95	1.50	16,940	11,293
95	2.00	16,940	8,470
95	2.50	16,940	6,776
95	3.00	16,940	5,647
115	2.00	20,500	10,250
115	2.50	20,500	8,200
115	3.00	20,500	6,833
115	4.00	20,500	5,125

Table C-2
Complete Test Program

Test #	Location	Air Velocity (ft/sec)	Air/Coal Ratio (-)	Temp (F)	Orifice	Run Time (min)	Notes
VERTICAL 1 TESTS (Single Bend)							
1	1V15	75	3.0	150	None	22	Baseline Test Matrix
2	1V15	75	2.0	150	None	22	Baseline Test Matrix
3	1V15	75	1.5	150	None	22	Baseline Test Matrix
4	1V15	75	1.0	150	None	22	Baseline Test Matrix
5	1V15	95	Clean	150	None	22	Baseline Test Matrix
6	1V15	95	3.5	150	None	22	Baseline Test Matrix
7	1V15	95	2.5	150	None	22	Baseline Test Matrix
8	1V15	95	2.0	150	None	22	Baseline Test Matrix
9	1V15	95	1.5	150	None	22	Baseline Test Matrix
10	1V15	115	4.0	150	None	22	Baseline Test Matrix
11	1V15	115	3.0	150	None	22	Baseline Test Matrix
12	1V15	115	2.5	150	None	22	Baseline Test Matrix
13	1V15	115	2.0	150	None	22	Baseline Test Matrix
14	1V15	95	3.5	175	None	22	Elevated Temperature Test
15	1V15	95	2.5	175	None	22	Elevated Temperature Test
16	1V15	95	2.0	175	None	22	Elevated Temperature Test
17	1V15	95	1.5	175	None	22	Elevated Temperature Test
ORIFICE INSTALL						40	
18	1V15	95	3.5	150	3DU	22	Effect of orifice 3D upstream of inst.
19	1V15	95	2.5	150	3DU	22	Effect of orifice 3D upstream of inst.
20	1V15	95	2.0	150	3DU	22	Effect of orifice 3D upstream of inst.
21	1V15	95	1.5	150	3DU	22	Effect of orifice 3D upstream of inst.
ORIFICE MOVE						40	
22	1V15	95	3.5	150	7DU	22	Effect of orifice 7D upstream of inst.
23	1V15	95	2.5	150	7DU	22	Effect of orifice 7D upstream of inst.
24	1V15	95	2.0	150	7DU	22	Effect of orifice 7D upstream of inst.
25	1V15	95	1.5	150	7DU	22	Effect of orifice 7D upstream of inst.
ORIFICE MOVE						40	
26	1V15	95	3.5	150	11DU	22	Effect of orifice 11D upstream of inst.
27	1V15	95	2.5	150	11DU	22	Effect of orifice 11D upstream of inst.
28	1V15	95	2.0	150	11DU	22	Effect of orifice 11D upstream of inst.
29	1V15	95	1.5	150	11DU	22	Effect of orifice 11D upstream of inst.
ORIFICE MOVE						40	
30	1V15	95	3.5	150	4DU BEND	22	Effect of orifice around upstream bend of inst.
31	1V15	95	2.5	150	4DU BEND	22	Effect of orifice around upstream bend of inst.
32	1V15	95	2.0	150	4DU BEND	22	Effect of orifice around upstream bend of inst.
33	1V15	95	1.5	150	4DU BEND	22	Effect of orifice around upstream bend of inst.
INSTRUMENT MOVE & REMOVE ORIFICE						120	
34	1V7	75	3.0	150	None	22	Baseline Test Matrix
35	1V7	75	2.0	150	None	22	Baseline Test Matrix
36	1V7	75	1.5	150	None	22	Baseline Test Matrix
37	1V7	75	1.0	150	None	22	Baseline Test Matrix
38	1V7	95	Clean	150	None	22	Baseline Test Matrix
39	1V7	95	3.5	150	None	22	Baseline Test Matrix
40	1V7	95	2.5	150	None	22	Baseline Test Matrix
41	1V7	95	2.0	150	None	22	Baseline Test Matrix
42	1V7	95	1.5	150	None	22	Baseline Test Matrix
43	1V7	115	4.0	150	None	22	Baseline Test Matrix
44	1V7	115	3.0	150	None	22	Baseline Test Matrix
45	1V7	115	2.5	150	None	22	Baseline Test Matrix
46	1V7	115	2.0	150	None	22	Baseline Test Matrix

Table C-2 (continued)
Complete Test Program

INSTRUMENT MOVE						90	
47	1V3	75	3.0	150	None	22	Baseline Test Matrix
48	1V3	75	2.0	150	None	22	Baseline Test Matrix
49	1V3	75	1.5	150	None	22	Baseline Test Matrix
50	1V3	75	1.0	150	None	22	Baseline Test Matrix
51	1V3	95	Clean	150	None	22	Baseline Test Matrix
52	1V3	95	3.5	150	None	22	Baseline Test Matrix
53	1V3	95	2.5	150	None	22	Baseline Test Matrix
54	1V3	95	2.0	150	None	22	Baseline Test Matrix
55	1V3	95	1.5	150	None	22	Baseline Test Matrix
56	1V3	115	4.0	150	None	22	Baseline Test Matrix
57	1V3	115	3.0	150	None	22	Baseline Test Matrix
58	1V3	115	2.5	150	None	22	Baseline Test Matrix
59	1V3	115	2.0	150	None	22	Baseline Test Matrix
60	1V3	95	3.5	175	None	22	Elevated Temperature Test
61	1V3	95	2.5	175	None	22	Elevated Temperature Test
62	1V3	95	2.0	175	None	22	Elevated Temperature Test
63	1V3	95	1.5	175	None	22	Elevated Temperature Test
ORIFICE INSTALL						40	
64	1V3	95	3.5	150	1DD	22	Effect of orifice 1D downstream of inst.
65	1V3	95	2.5	150	1DD	22	Effect of orifice 1D downstream of inst.
66	1V3	95	2.0	150	1DD	22	Effect of orifice 1D downstream of inst.
67	1V3	95	1.5	150	1DD	22	Effect of orifice 1D downstream of inst.
ORIFICE MOVE						40	
68	1V3	95	3.5	150	5DD	22	Effect of orifice 7D downstream of inst.
69	1V3	95	2.5	150	5DD	22	Effect of orifice 7D downstream of inst.
70	1V3	95	2.0	150	5DD	22	Effect of orifice 7D downstream of inst.
71	1V3	95	1.5	150	5DD	22	Effect of orifice 7D downstream of inst.
ORIFICE MOVE						40	
72	1V3	95	3.5	150	9DD	22	Effect of orifice 9D downstream of inst.
73	1V3	95	2.5	150	9DD	22	Effect of orifice 9D downstream of inst.
74	1V3	95	2.0	150	9DD	22	Effect of orifice 9D downstream of inst.
75	1V3	95	1.5	150	9DD	22	Effect of orifice 9D downstream of inst.
VERTICAL 3 TESTS (Double Bend)							
INSTRUMENT MOVE						90	
76	3V15	75	3.0	150	None	22	Baseline Test Matrix
77	3V15	75	2.0	150	None	22	Baseline Test Matrix
78	3V15	75	1.5	150	None	22	Baseline Test Matrix
79	3V15	75	1.0	150	None	22	Baseline Test Matrix
80	3C15	95	Clean	150	None	22	Baseline Test Matrix
81	3V15	95	3.5	150	None	22	Baseline Test Matrix
82	3V15	95	2.5	150	None	22	Baseline Test Matrix
83	3V15	95	2.0	150	None	22	Baseline Test Matrix
84	3V15	95	1.5	150	None	22	Baseline Test Matrix
85	3V15	115	4.0	150	None	22	Baseline Test Matrix
86	3V15	115	3.0	150	None	22	Baseline Test Matrix
87	3V15	115	2.5	150	None	22	Baseline Test Matrix
88	3V15	115	2.0	150	None	22	Baseline Test Matrix

Table C-2 (continued)
Complete Test Program

INSTRUMENT MOVE						90	
89	3V7	75	3.0	150	None	22	Baseline Test Matrix
90	3V7	75	2.0	150	None	22	Baseline Test Matrix
91	3V7	75	1.5	150	None	22	Baseline Test Matrix
92	3V7	75	1.0	150	None	22	Baseline Test Matrix
93	3V7	95	Clean	150	None	22	Baseline Test Matrix
94	3V7	95	3.5	150	None	22	Baseline Test Matrix
95	3V7	95	2.5	150	None	22	Baseline Test Matrix
96	3V7	95	2.0	150	None	22	Baseline Test Matrix
97	3V7	95	1.5	150	None	22	Baseline Test Matrix
98	3V7	115	4.0	150	None	22	Baseline Test Matrix
99	3V7	115	3.0	150	None	22	Baseline Test Matrix
100	3V7	115	2.5	150	None	22	Baseline Test Matrix
101	3V7	115	2.0	150	None	22	Baseline Test Matrix
INSTRUMENT MOVE						90	
101	3V3	75	3.0	150	None	22	Baseline Test Matrix
102	3V3	75	2.0	150	None	22	Baseline Test Matrix
103	3V3	75	1.5	150	None	22	Baseline Test Matrix
104	3V3	75	1.0	150	None	22	Baseline Test Matrix
105	3V3	95	Clean	150	None	22	Baseline Test Matrix
106	3V3	95	3.5	150	None	22	Baseline Test Matrix
107	3V3	95	2.5	150	None	22	Baseline Test Matrix
108	3V3	95	2.0	150	None	22	Baseline Test Matrix
109	3V3	95	1.5	150	None	22	Baseline Test Matrix
110	3V3	115	4.0	150	None	22	Baseline Test Matrix
111	3V3	115	3.0	150	None	22	Baseline Test Matrix
112	3V3	115	2.5	150	None	22	Baseline Test Matrix
113	3V3	115	2.0	150	None	22	Baseline Test Matrix
114	3V3	95	3.5	175	None	22	Elevated Temperature Test
115	3V3	95	2.5	175	None	22	Elevated Temperature Test
116	3V3	95	2.0	175	None	22	Elevated Temperature Test
117	3V3	95	1.5	175	None	22	Elevated Temperature Test
HORIZONTAL 1 TESTS							
INSTRUMENT MOVE						90	
118	1H33	75	3.0	150	None	22	Baseline Test Matrix
119	1H33	75	2.0	150	None	22	Baseline Test Matrix
120	1H33	75	1.5	150	None	22	Baseline Test Matrix
121	1H33	75	1.0	150	None	22	Baseline Test Matrix
122	1H33	95	Clean	150	None	22	Baseline Test Matrix
123	1H33	95	3.5	150	None	22	Baseline Test Matrix
124	1H33	95	2.5	150	None	22	Baseline Test Matrix
125	1H33	95	2.0	150	None	22	Baseline Test Matrix
126	1H33	95	1.5	150	None	22	Baseline Test Matrix
127	1H33	115	4.0	150	None	22	Baseline Test Matrix
128	1H33	115	3.0	150	None	22	Baseline Test Matrix
129	1H33	115	2.5	150	None	22	Baseline Test Matrix
130	1H33	115	2.0	150	None	22	Baseline Test Matrix
INSTRUMENT MOVE						90	
131	1H57	75	3.0	150	None	22	Baseline Test Matrix
132	1H57	75	2.0	150	None	22	Baseline Test Matrix
133	1H57	75	1.5	150	None	22	Baseline Test Matrix
134	1H57	75	1.0	150	None	22	Baseline Test Matrix
135	1H57	95	Clean	150	None	22	Baseline Test Matrix
136	1H57	95	3.5	150	None	22	Baseline Test Matrix
137	1H57	95	2.5	150	None	22	Baseline Test Matrix
138	1H57	95	2.0	150	None	22	Baseline Test Matrix
139	1H57	95	1.5	150	None	22	Baseline Test Matrix
140	1H57	115	4.0	150	None	22	Baseline Test Matrix
141	1H57	115	3.0	150	None	22	Baseline Test Matrix
142	1H57	115	2.5	150	None	22	Baseline Test Matrix
143	1H57	115	2.0	150	None	22	Baseline Test Matrix

D
LABORATORY COAL INFORMATION

STANDARD LABORATORIES INC.
NORTHERN DIVISION
P.O. BOX 214
CRESSON, PA 16630
(814) 886-7400

STANDARD LABORATORIES, INC.

DATE: 3-14-2006
SAMPLE NO. 888107

AIR FLOW SCIENCES CORP.
37501 SCHOOLCRAFT ROAD
LIVONIA, MI 48150-1009

SAMPLE ID: PULVERIZED COAL

OPERATING CO.:
SAMPLED BY: CUSTOMER PROVIDED
MINE:
LOCATION:

DATE SAMPLED: 3/6/06
DATE RECEIVED: 3/6/06
WEATHER:
GROSS WEIGHT:

OTHER ID: REW: CRAIG ROOD

CERTIFICATE OF ANALYSIS

SCREEN TEST		CUMULATIVE DOWN	CUMULATIVE UP
+8M	0.00%	0.00%	100.00%
8M X 14M	0.00%	0.00%	100.00%
14M X 28M	0.00%	0.00%	100.00%
28M X 48M	0.00%	0.00%	100.00%
48M X 100M	0.57%	0.57%	100.00%
100M X 200M	9.94%	10.51%	99.43%
200M X 325M	18.16%	28.67%	89.49%
325M X 0	71.33%	100.00%	71.33%
	100.00%		

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Page 1 of 2
111

BLACK SEAL ANALYSIS

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