REDUCE FLOW BIAS THROUGH AUTOMATED TESTING

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ABSTRACT

The ability to optimize stack emissions with the new and promising continuous emissions monitors systems (CEMS) has been limited by the precision and accuracy of the EPA reference methods used to evaluate and/or calibrate these systems. Bias and inconsistency in the flow data has been of particular concern.

The EPA has completed an extensive evaluation of stack flow testing. This study showed automated testing to have reduced bias and scatter errors as compared to conventional manual testing as well as 3-D type testing. An evaluation of this study is made with a comparison against field data since the study.

The comparison shows strong support for the findings in the study. The scatter error with automated testing is demonstrated by an examination of the standard deviation over 12 run velocity traverses at several sites. The results show a typical standard deviation of 0.2% with automated testing. An evaluation of year-to-year deviation is also included. The bias error is examined based on a comparison against expected heat rate.

BACKGROUND

In the early '90s Continuous Emissions Monitoring Systems (CEMS) were installed to measure the emissions from fossil fuel fired electric utilities as required by the newly passed 40 CFR 75 rules. This new regulation imposed substantial financial burdens on the utilities. This is not just from a cost of equipment and maintenance perspective. The regulation was structured in such a way that accuracy and data availability had important financial impact as well.

The emission allowances being measured by the CEMS were made to have a market value. To use up ones allowances was now the loss of an asset. The data availability became important because the regulation required the substitution of higher values of emissions when data was lost. Accuracy became very important since any over-reporting would be an unnecessary and wasteful consumption of the asset.

The accuracy requirements in the regulation quickly became the minimum standard. The economic aspects of the regulation pressed utilities to be far more accurate than this minimum. The gas measurement accuracy has ultimately become limited by the accuracy of the protocol gas bottles used to challenge CEMS each day. The drift and accuracy of the gas monitors is for the most part assessed by observing the results of daily challenges with these protocol gases. Annual audits verified the CEMS gas measurements by having the tester use similar protocol gases to calibrate their equipment.

The measurement of flow by the CEMS has been another matter. When it came to the flow monitors, the EPA felt it necessary to relax a nearly 20-year policy that required continuous monitors to have system-wide daily calibration checks. The gas monitors, by virtue of being challenged each day with the protocol gases, continued to meet the old policy. The flow monitors had a reduced requirement with the result that different monitors performed different types of daily checks, some system wide and some not.

Flow monitors became a problem from two perspectives. First, how, without a system wide calibration check each day, could the drift and/or accuracy be assessed once calibrated? Second, how were they to be accurately calibrated in the first place? To answer the first problem, the majority of utilities went to the flow monitor with the most inclusive system wide calibration checks. This monitor also had insignificant long and short-term drift. Unfortunately, many others opted to use flow monitors with significant drift that is not fully exposed by the daily checks.

With drift not being a problem for most utilities, calibration became the only issue. The utility industry, anticipating difficulty with the flow measurement, convinced the EPA to relax the relative accuracy requirement for flow to 10% until this year when it changed to 7.5%.

FLOW ACCURACY

This relative accuracy of 7.5% by itself has little meaning except to satisfy EPA requirements. To understand why relative accuracy does not address the financial impact, one must first realize that this accuracy is merely a comparison between EPA Method 2 test results and the flow monitor. The results obtained when conducting EPA Method 2 are heavily dependent on many factors. Without discussing the implications of each of the factors, the more important ones are: the number of points sampled, construction of the pitot tube, calibration of the pitot tube, construction of the probe assembly, pressure measuring technique, sampling time, type of pressure measuring device, calibration of the pressure measuring device, zero and calibration drift of the pressure measuring device, positioned accuracy of the probe, rotational accuracy of the probe, probe bounce, integrity of the port sealed, quality of the leak checks, emission source flow characteristics, and accurate geometric data. While Method 2 does provide guidance for some of these factors, the tester is generally left to a subjective understanding of these factors. At present, there is no qualifying standard required of the tester. The utility has generally relied on its own direct oversight to determine the quality of the tester's performance. Unfortunately, utility personnel do not always fully understand the implications of the above factors on the flow results either. They are generally left to making sure that the EPA requirements for the method are met. Adding to the problem is a steady decline in the testing market. Profit margins for this work over the last several years have steadily declined forcing many testers to strictly meet the minimum EPA requirements. The result is poor repeatability, particularly year-to-year, and very significant error as compared to the actual flow volume. The EPA study indicated significant error even under the best of conditions with experienced testers and rigorous oversight.

To further understand why relative accuracy alone is insufficient, the calibration and auditing of the flow monitor must be examined. Since the flow monitor is required to meet the Method 2 results, the monitor is adjusted to meet the Reference Method. This adjustment is typically done just before the "audit".

For flow monitors with little significant drift, the repeated adjustment can be attributed to the variance in the Method 2 test results. These "drift free" type flow monitors are routinely adjusted year-to-year by more than 5.0% as a result of reference method testing variance. The utility may suspect that the test results are in error, but once the monitor has been adjusted and the relative accuracy determined there is little that can be done without starting over. Putting the cost of retesting aside, what would be the sense if the tester were not capable of providing a more accurate test?

The flow monitors that can be expected to drift without detection day-to-day have a further difficulty. The relative accuracy audit only exposes the drift between the time when the monitor was adjusted last and the time when the relative accuracy test is performed. This is typically less than three days. This means that for utilities with these monitors there is not only uncertainty based on the testing results, but also the monitor's measurement over time is suspect. Recent changes to the EPA rules have mitigated this problem (flow to load quality assurance checks) to the satisfaction of the agency but the problem remains. These types of monitors can have a very significant financial impact without any indication from the relative accuracy number or the daily checks. **Better flow testing alone cannot address the long-term drift problems in these monitors.**

The problem of accuracy in the reference method becomes more important since all of manual testers in the study have been shown to generate significant high bias when using the S-type pitot. The automated approach was bias high as well but to a much lesser extent. When 48 points were used and the automated system was correcting for yaw the remaining bias could be attributed to wall effect. The EPA study of the issue culminated in modifying the reference method and adding Methods 2F, 2G and 2H to hopefully reduce error. Unfortunately, while these new methods do reduce the effects of off axis flow and wall effect, they do not address consistent high bias of the manual testers using the S-type pitot nor the degradation in precision of the 3-D probes.

The precision of the reference method testing is also of very significant importance. The EPA rules penalize the utilities for lack of precision testing by having the flow monitor adjusted upward should the RATA indicate that the monitor is reading low while requiring the monitor to be left unadjusted should the RATA indicate that the monitor is reading high. In addition, the utility may be required to adjust the monitor based upon the worst case bias at any of the loads should they fail the bias test. As a result of this bias test, some utilities have been forced to adjust their flow monitors well above the mean difference between the flow monitor and the reference method at their normal operate load. Many flow monitors are adjusted high to insure that the biased test is passed virtually guaranteeing over reporting.

AUTOMATED FLOW TESTING

The extensive EPA testing program was conducted at a number of sources with five different testers. They were asked to conduct a variety of test protocols designed to expose errors in the Method 2. Only one team used an automated system.

This automated system used four computer driven probes each capable of being accurately positioned in both a longitudinal and rotational axis. All the test points were calculated by the computer from the dimensions entered. The data collection and report generation was completely automated. The pressure measuring devices were temperature stabilized and calibrated with an NIST traceable pressure source. There was no human intervention during the actual testing. Run after run was executed until all were completed. Yaw correction was a selectable automated routine.

The study had testers use only probes calibrated by the agency. The agency and its prime contractor oversaw the testing. Each tester was selected by contract based upon known experience in conducting Method 2. Two of the sources tested were gas fired. It was felt that an accurate calculated stack flow could be determined from these sources.

An examination of the data shows significant differences between the results from testers using manual methods and this automated approach.

The tables below are an extraction from studies done by the EPA in 1997 and 1998. The flow percentage data for the runs is as it appeared in that report. The averages and data analysis is by the author.

The data represents the percentage difference between the various testers' results compared to the calculated value (BTCE -Boiler Turbine Cycle Efficiency Method) generated from plant operating parameters. These two plants were selected to be gas fired so that the calculated value for flow would be reasonably accurate and that no one tester's results would be considered to be a reference.

Table A (Lake Hubbard S- Straight) gives an analysis that clearly shows a consistent and considerable high bias in the manual results. The automated test results were also biased high but to a much lesser extent. The manual testers average approximately 6.0% high. The automated results measuring the same points (1) averaged 2.3% high. This indicates that all four manual testers measuring the same points were higher than the automated results by 3.5% to 4.0%.
The variance in the manual data is seen to be approximately five times greater than the variance in the automated data. This is demonstrated by the standard deviation and the min-max.

The "nulled" (yaw corrected) data for 16 points (2) reduces the high bias by an additional approximately 0.6%. This measurement accounts for the yaw in the flow and has become part of the new Method 2G.

The automated measurements went on to do 48 points both corrected and uncorrected for yaw. The automated yaw corrected 48 point results show an agreement with the calculated value of better than 1% on all runs. The standard deviation was approximately 10 times better than the manual test results.

The comparison table at the bottom shows how the data from each of the manual testers compared against the automated system. The results were obtained by taking the difference between the errors obtained by the two methods. The numbers (1), (2), (3), (4), represent the automated tests against which the manual results are compared.

Table B (Lake Hubbard S- Nulled) --This yaw corrected type of test also shows a consistent high bias. The manual testers average over 4.0% high. The automated results measuring the same points (2) averaged 1.78% high. This indicates that all four manual testers were higher than the automated results by 1.5% to 2.5% when measuring the same points.

The variance in the manual data is seen to be approximately five times greater than the variance in the automated data.

The automated measurements went on to do 48 points both corrected and uncorrected for yaw. The automated yaw corrected 48 point results again show an agreement with the calculated value of better than 1% on all runs. The standard deviation was approximately 10 times better than the manual test results. The 16 point manual test results were more than 3.0% higher than the automated 48 point results when both were yaw corrected.

Table C (Decordova S-Nulled) -- The analysis of this source again shows a consistent high bias even when correcting for yaw ("nulled"). The manual testers averaged high by over 5.0%. The automated results measuring the same points (2) averaged 1.39% high. The manual testers were higher than the automated results by 3.5% to 4.5% when measuring the same points.

The variance in the manual data is again approximately five times greater than the variance in the automated data.

The automated yaw corrected 48 point results show an agreement with the calculated value of better than 1% on average. The standard deviation was approximately 10 times better than the manual test results. The 16 point manual test results were better than 4.0% higher than the automated 48 point results when both were yaw corrected.
Table D (Decordova 3-D) Unlike tables A through C this data compares the automated S-type pitot measurement results against the most commonly used 3D probe. The data generated by the manual testers using these 3-D type probes differs considerably from the data they generated using the S-type pitot.

The most significant difference was the variance between each manual tester's results. Unlike the S-type data, no two manual test teams got the same results. Even the standard deviation was not as consistent as it was with the S-type.

The average results of one manual tester (K-DAT) were more than 4.0% higher than another tester (M-DAT). This was surprising since all manual testers were using the same type of probe testing the same points. Some testers' results were bias below the calculated value while others were bias high. If one accepts the calculated value to be within 1.0% accuracy, it is hard to reconcile the negative bias results. The 16 point traverses results are expected to have a high bias of approximately 1.5% to 3.0% as a result of the lack of sufficiently accounting for the wall flow effect. Even 48 point traverses are expected to result in high bias from wall effect be it only 0.5% to 1.0%.

Two of the testers read higher than the automated S-type results even when the automated tester used 16 point and no correction for yaw and two read lower.

If one took all the 3-D data on average the high bias might be said to be removed. Unfortunately, the inconsistency between testers exposes a potential problem. The year-to-year test results may vary considerably as compared to what can be expected from the automated equipment or even manual S-type.

Other 3-D type probes were tested. However, when used in a coal-fired stack they were found to be unacceptable. In addition, it should be mentioned that the 3-D type probe required significantly more apparatus and were far more difficult to leak check.

Figure 1 is an extraction from a paper by Dave Naegele from American Electric Power. The data were taken from 22 sites showing the average improvement based on heat rate of the automated system compared to manual testing. The automated system was the same as that used for the EPA study. Only 16 point traverses were used. No yaw correction or wall effect adjustments were done. The data agrees well with what one would predict from study.

Dave's paper also showed the substantial reduction in the year-to-year variance.

Table E was generated from data taken at a site with three sources. The site had been calibrated, certified and audited using manual methods. These tests were done last year therefore no yaw correction or wall effect adjustments were done. The table shows the substantial financial impact of the automated approach.

At another site the study showed the automated equipment's ability to consistently find yaw angles. A series of runs were made in a large coal-fired stack that was known to have a significant yaw flow component. The automated system consistently measured the yaw angle near the wall. All four probes found the same yaw angle repeatedly over a series runs within 1.0 degree.

RECENT IMPROVEMENTS

The EPA study resulted in the adoption of three alternate reference methods for flow. Method 2F gave the procedures for conducting 3-D pitot tube tests. This method allows the tester to compensate for off axis flow in both pitch and yaw. Based on the above variance using the 3-D this author believes it should not be considered unless high pitch angles are expected. Yaw angles, it is felt, would be better handle using an S-type probe to conduct Method 2G. Yaw angles are far more prevalent in large diameter round stacks particularly at typical CEMS and testing port locations.

Method 2H gives the procedure for conducting a series measurements near the wall of the stack. It has been long known that the fewer test points used for flow the greater the high bias. This occurs because the velocity measured at the points nearest the wall is used as an estimate for the velocity for the area all the way to wall. This over estimates the velocity for this area since the velocity goes to zero at the wall. The fewer points used in the traverse the further from the wall the last point. This makes the "wall effect" more pronounced. It has been estimated, however, that even a 48 point traverse will over report by approximately 0.5% as a result of this wall effect.

To reduce the bias from off axis flow and wall effect these new methods should be considered. Method 2H most always reduced high bias. Methods 2F and 2G may not. These two methods only produce the benefit if significant off axis flow is present. Utilities would do well to evaluate which stacks have significant off axis flow before added the significant expense of running either of these two methods. Generally test teams are being asked to do a run by Method 2 and 2G each load to determine the potential benefit of yaw compensation. The precision of the automated method exposes differences and allows benefits of less than 1% to be realized.

CONCLUSION

- S-type pitot tubes produce little bias when operated in a precise and automated manner.
- Methods 2G and 2H alone do not address the systemic high bias found using the manual approach.
- 3-D data shows a significant variance between testers.
- Better agreement with plant parameters is achieved through precise automated testing.
- Significant financial benefit is generally being realized with automated testing.

Figure 1

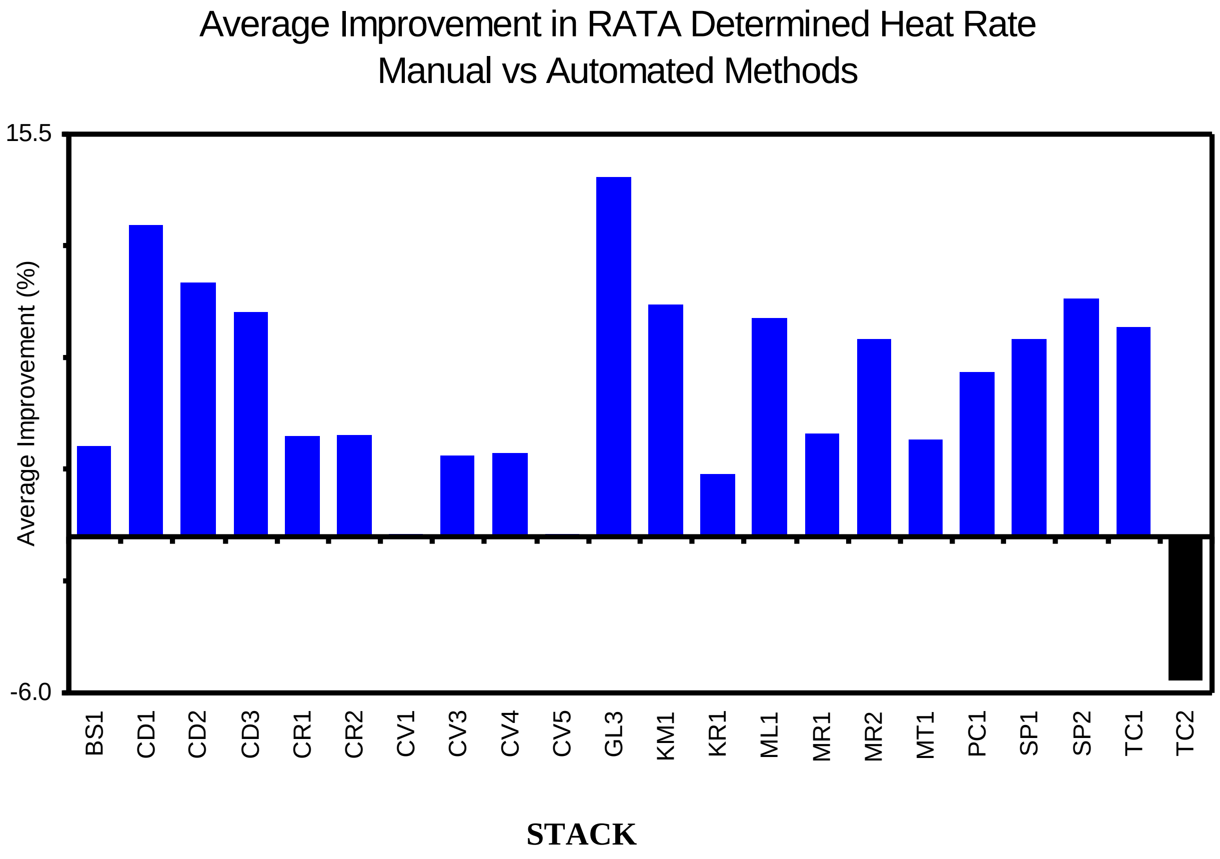

TABLE A

FIELD TEST SUMMARY									
LAKE HUBBARD STATION									
TABLE A - VOLUMETRIC FLOW PERCENT DIFFERENCE FROM BTCE									
MATRIX B RUNS 9-12 TYPE S PROBES STRAIGHT									
			Percent Difference from BTCE				AVG.%	STDEV	MIN
			Run 9	Run 10	Run 11	Run 12	ERROR	%	MAX
S-10 Straight		16Pt.	7.83%	6.32%	5.53%	4.30%	6.00%	1.28%	3.53%
S-11 Straight		16Pt.	4.57%	9.63%	5.25%	5.42%	6.22%	2.00%	5.06%
S-12 Straight		16Pt.	4.78%	4.94%	8.36%	6.91%	6.25%	1.48%	3.58%
S-13 Straight		16Pt.	7.09%	4.89%	4.24%	8.07%	6.07%	1.56%	3.83%
Autoprobes 16 Pt. Straight (1)			2.87%	2.23%	2.37%	1.79%	2.32%	0.39%	1.08%
Autoprobes 16 Pt. Nulled (2)			1.62%	1.81%	1.47%	2.21%	1.78%	0.28%	0.74%
Autoprobes 48 Pt. Straight (3)			1.41%	1.27%	1.29%	1.42%	1.35%	0.07%	0.15%
Autoprobes 48 Pt. Nulled (4)			0.52%	0.49%	0.45%	0.90%	0.59%	0.18%	0.45%
BTCE			0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
			Comparisons Against AUTOPROBE Avg.						
	Manual Teams		HIGH BIAS						
			(1)	(2)	(3)	(4)			
	S-10 Straight Avg.		3.68%	4.22%	4.65%	5.41%			
	S-11 Straight Avg.		3.90%	4.44%	4.87%	5.63%			
	S-12 Straight Avg.		3.93%	4.47%	4.90%	5.66%			
	S-13 Straight Avg.		3.76%	4.30%	4.73%	5.48%			

TABLE B

FIELD TEST SUMMARY									
LAKE HUBBARD STATION									
TABLE B - VOLUMETRIC FLOW PERCENT DIFFERENCE FROM BTCE									
MATRIX B RUNS 9-12 TYPE S PROBES NULLED									
			Percent Difference from BTCE				AVG.%	STDEV	MIN
			Run 9	Run 10	Run 11	Run 12	ERROR	%	MAX
S-10 Nulled		16Pt.	6.29%	5.37%	2.50%	3.22%	4.35%	1.54%	3.79%
S-11 Nulled		16Pt.	2.85%	6.36%	4.59%	3.99%	4.45%	1.27%	3.51%
S-12 Nulled		16Pt.	2.83%	4.12%	7.41%	6.13%	5.12%	1.77%	4.58%
S-13 Nulled		16Pt.	4.58%	0.05%	2.32%	6.52%	3.37%	2.42%	6.47%
Autoprobes 16 Pt. Straight (1)			2.87%	2.23%	2.37%	1.79%	2.32%	0.39%	1.08%
Autoprobes 16 Pt. Nulled (2)			1.62%	1.81%	1.47%	2.21%	1.78%	0.28%	0.74%
Autoprobes 48 Pt. Straight (3)			1.41%	1.27%	1.29%	1.42%	1.35%	0.07%	0.15%
Autoprobes 48 Pt. Nulled (4)			0.52%	0.49%	0.45%	0.90%	0.59%	0.18%	0.45%
BTCE			0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
			Comparisons Against AUTOPROBE Avg.						
	Manual Teams		HIGH BIAS						
			(1)	(2)	(3)	(4)			
	S-10 Nulled Avg.		2.03%	2.57%	3.00%	3.76%			
	S-11 Nulled Avg.		2.13%	2.67%	3.10%	3.86%			
	S-12 Nulled Avg.		2.81%	3.35%	3.78%	4.53%			
	S-13 Nulled Avg.		1.05%	1.59%	2.02%	2.78%			

TABLE C

FIELD TEST SUMMARY									
DECORDOVA STEAM ELECTRIC STATION									
TABLE C - VOLUMETRIC FLOW PERCENT DIFFERENCE FROM BTCE									
MATRIX B RUNS 9-12 TYPE S PROBES NULLED									
			Percent Difference from BTCE				AVG.%	STDEV	MIN
			Run 9	Run 10	Run 11	Run 12	ERROR	%	MAX
S-10 Nulled		16Pt.	6.95%	6.90%	4.98%	4.86%	5.92%	1.00%	2.09%
S-11 Nulled		16Pt.	5.03%	6.33%	7.70%	4.83%	5.97%	1.15%	2.87%
S-12 Nulled		16Pt.	3.38%	4.34%	6.50%	5.88%	5.03%	1.23%	3.12%
S-13 Nulled		16Pt.	4.68%	4.77%	6.12%	4.49%	5.02%	0.65%	1.63%
Autoprobes 16 Pt. Straight (1)			1.39%	1.46%	1.51%	1.74%	1.53%	0.13%	0.35%
Autoprobes 16 Pt. Nulled (2)			1.19%	1.25%	1.35%	1.77%	1.39%	0.23%	0.58%
Autoprobes 48 Pt. Straight (3)			0.66%	0.56%	0.79%	1.24%	0.81%	0.26%	0.68%
Autoprobes 48 Pt. Nulled (4)			0.74%	0.47%	0.67%	1.09%	0.74%	0.22%	0.62%
BTCE			0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
			Comparisons Against AUTOPROBE Avg.						
	Manual Teams		HIGH BIAS						
			(1)	(2)	(3)	(4)			
	S-10 Nulled Avg.		4.40%	4.53%	5.11%	5.18%			
	S-11 Nulled Avg.		4.45%	4.58%	5.16%	5.23%			
	S-12 Nulled Avg.		3.50%	3.64%	4.21%	4.28%			
	S-13 Nulled Avg.		3.49%	3.63%	4.20%	4.27%			

TABLE D

FIELD TEST SUMMARY										
DECORDOVA STEAM ELECTRIC STATION										
TABLE D - VOLUMETRIC FLOW PERCENT DIFFERENCE FROM BTCE										
	MATRIX B RUNS 14 - 17 DAT PROBES									
			Percent Difference from BTCE				AVG.%	STDEV	MIN	MIN
			Run 14	Run 15	Run 16	Run 17	ERROR	%	MAX	MAX
E-DAT		16Pt.	2.66%	0.81%	3.54%	2.76%	2.44%	1.00%	2.73%	
K-DAT		16Pt.	3.38%	3.27%	3.58%	4.10%	3.58%	0.32%	0.83%	4.10%
M-DAT		16Pt.	-0.34%	-1.42%	0.44%	-0.90%	-0.56%	0.69%	1.86%	
T-DAT		16Pt.	-1.08%	-0.78%	2.41%	1.96%	0.63%	1.57%	3.49%	-1.08%
										5.18%
Autoprobes 16 Pt. Straight (1)			1.85%	1.68%	1.91%	1.74%	1.80%	0.09%	0.23%	
Autoprobes 16 Pt. Nulled (2)			2.01%	1.39%	1.51%	1.28%	1.55%	0.28%	0.73%	
Autoprobes 48 Pt. Straight (3)			1.29%	1.06%	1.10%	0.96%	1.10%	0.12%	0.33%	
Autoprobes 48 Pt. Nulled (4)			1.28%	0.87%	0.91%	0.84%	0.98%	0.18%	0.44%	
BTCE			0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
			Comparisons Against AUTOPROBE Avg.							
	Manual Teams		HIGH BIAS							
			(1)	(2)	(3)	(4)				
	E-DAT		0.65%	0.90%	1.34%	1.47%				
	K-DAT		1.79%	2.04%	2.48%	2.61%				
	M-DAT		-2.35%	-2.10%	-1.66%	-1.53%				
	T-DAT		-1.17%	-0.92%	-0.48%	-0.35%				

TABLE E

	Flow (MSCFH)				SO2	
	Before	After	% Change		(ppm)	
Unit #1	74.03	67.39	-8.97		2150	
Unit #2	75.59	72.39	-4.23		2010	
Unit #3	90.61	82.85	-8.56		2035	
			Diff.	Price	Savings	Savings *
	Mass SO2 Emission Rate (Tons/HR)		(Tons/HR)	($/Ton)	($/Hr)	($/Yr)
Unit #1	13.2	12.0				
Unit #2	12.6	12.1				
Unit #3	15.3	14.0				
	41.1	38.1	3.03	$150.00	$454.42	$3,402,697.11
lbs.(SO2)/scf	0.166		* Six days per week			