CHAPTER 2

BIAS DUE TO PROBE LOCATION AND STRATIFICATION

Chapter 2 Highlights

Probe Location and Stratification Problems

Problem		Corrective Actions	Page Refs
Name	**Description**		
Stratification — All Types	Gas stratification and flow stratification produce unrepresentative sampling and bias measurements during Relative Accuracy Test Audit.	Find unstratified locations if at all possible. Use fans or gas reinjection to solve gas stratification problems. Use straightening vanes or baffles to solve flow problems.	2-9
Stable Stratification Patterns	Stratification is present but pattern does not vary over time, i.e., with load or process changes.	Sample at a point representative of the area of measurement. Monitor on a path representative of the area of measurement.	2-9, 2-10
Varying Stratification Patterns	Stratification is present and pattern varies as plant's operating conditions change.	Calibrate the monitored values to the reference values determined over the range of variation (e.g., different load/process conditions). <u>For point sampling systems</u>: Extract or monitor at multiple points. <u>For path sampling systems</u>: Monitor on paths less sensitive to variation. Monitor on multiple paths on the cross-section.	2-10, 2-11

CHAPTER 2

BIAS DUE TO PROBE LOCATION AND STRATIFICATION

2.1 INTRODUCTION

One of the principal sources of bias in CEM system certification is associated with sample probe location and gas stratification in the duct or stack. Because of the way in which a relative accuracy test is conducted, the reference method and CEM system will usually measure from two different sample points (Figure 2–1).

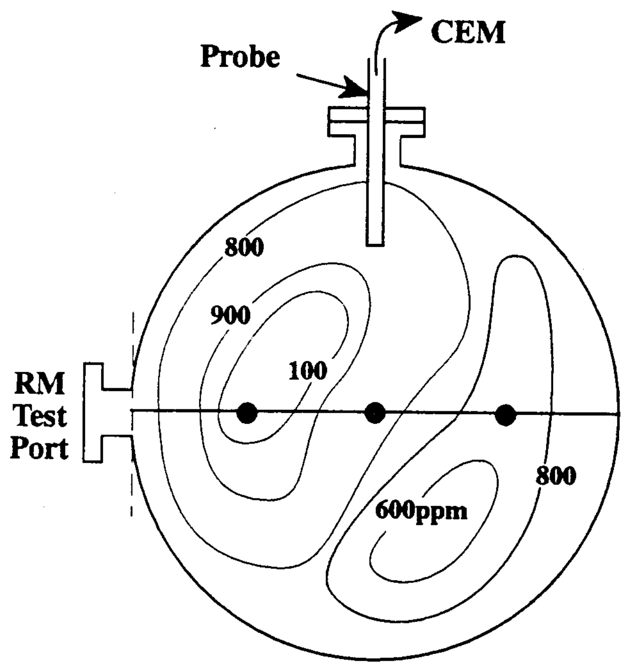

Figure 2–1. Stratification and Reference Method Testing in a Stack

The figure shows that, depending on the stratification profile, the reference method sample taken at the three required sample points shown may differ from the sample taken at the single point by the CEM system. This discrepancy may represent a constant error if the stratification profile does not change with load or plant operating conditions. However, if the profile changes with operating conditions, "blind" application of the regulatory remedy embodied in a single bias adjustment factor, or an engineering "fix" provided by a CEM correction factor, may not result in representative emissions data.

For Part 75 Acid Rain CEM systems, two types of flue gas stratification are of concern: (1) gas concentration stratification and (2) velocity stratification. Because SO_2 emission allowances are expressed in terms of mass / time (e.g., lbs / hr or tons / yr), as calculated in Eq. 2–1, both an SO_2 and a flow (velocity) monitor are necessary:

$$pmr = c_w A_s L_w \qquad \textbf{(Eq. 2–1)}$$

where:

pmr = pollutant mass rate (lbs / hr, tons / yr)

c_w = pollutant gas concentration determined on an actual, wet basis (lbs / ft^3, ppm)

A_s = stack or duct cross-sectional area

L_w = flue gas velocity

Further complexity arises when the velocity stratification and gas stratification profiles are not identical over the cross-section. In such situations, the expression of Eq. 2–1 is only an approximation to the general expression given in Eq. 2–2:

$$pmr = \int_A c_a L_a \, da \qquad \textbf{(Eq. 2–2)}$$

where:

c_a = the gas concentration in the area increment *da*

L_a = the flue gas velocity in a direction normal to the area increment *da*

da = an area increment

An example of a situation where both the gas concentration and flue gas velocity are stratified is given in Figure 2–2.

Accurate monitoring of the pollutant mass rate under such conditions can be very difficult. Either multi-point sampling systems, line averaging systems, or other methods may be necessary to obtain measurements that approximate the "true value."

Additional problems in stratification result when the flow monitoring system is not measuring in the same manner as the gas monitoring system. For example, an ultrasonic sensor may measure a line-averaged value, whereas the gas extractive system may obtain a sample from only one point.

Thus, several biases due to stratification may enter into the reported pollutant mass rate. Such biases, coupled with the biases introduced by the choice of reference method sampling points (as illustrated in Figure 2–1), may make it difficult to certify a CEM system within the relative accuracy specifications, or for it to pass the bias test without a careful diagnosis of the sources of bias and application of remedies as described below.

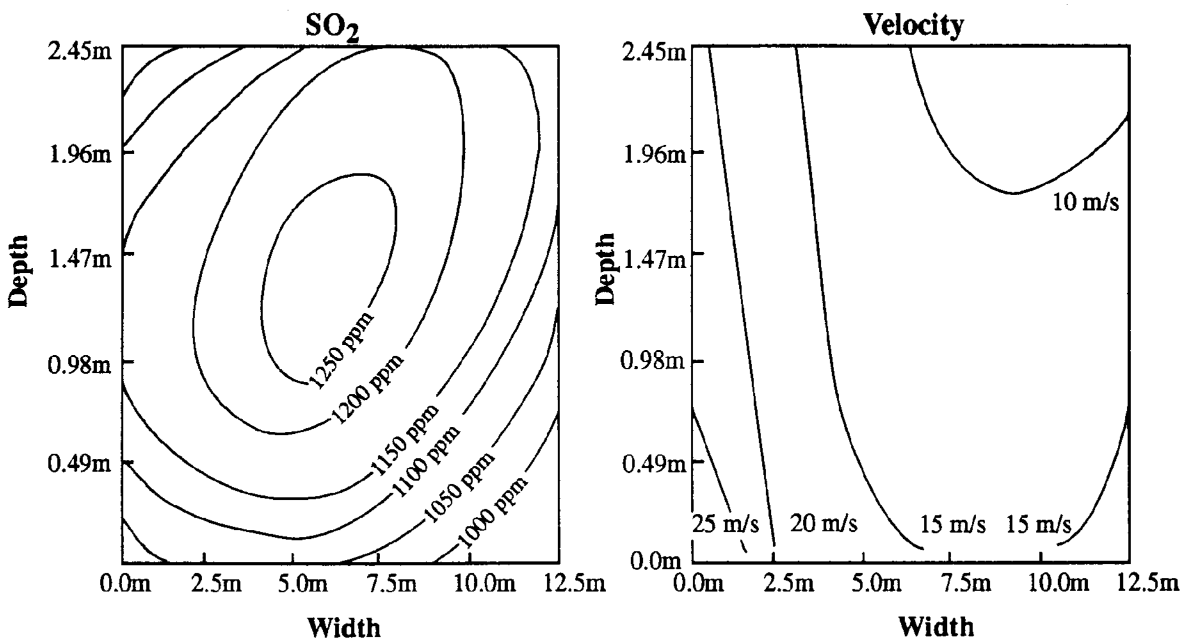

Figure 2–2. Stratification in Gas Concentration and Flue Gas Velocity (Gregory et al., 1976)

2.2 Reference Method Traverse Points and Sampling Locations

As noted above, the reference method testing for gas concentration measurements is performed on a three-point traverse rather than at a single point in the stack or duct (40 CFR 60 Appendix B PS2 §3.2). However, it should also be noted that these are "minimum" requirements and that the prevailing requirement is instead:

> "Select traverse points that assure acquisition of representative samples over the stack or duct cross section" (40 CFR 60 Appendix B PS2 §3.2), and
>
> "Select traverse points that (1) ensure acquisition of representative samples of pollutant and diluent concentration, moisture content, temperature, and flue gas flow rate over the flue cross section..." (40 CFR 75 Appendix A § 6.5.6).

The minimum requirement for pollutant gas concentration measurements in PS2 §3.2 specifies that samples are taken on a three-point traverse on a measurement line that passes through the centroid of the stack or duct and in the direction of any expected stratification. For a measurement line less than 2.4 m, samples are taken at points that are located 16.7, 50, and 83.3% on the line (Figure 2–3a).

For larger ducts or stacks with a measuring line greater than 2.4 m and where stratification is not expected, sampling points are specified at 0.4, 1.2, and 2.0 m (Figure 2–3b). (This second option is not allowed after wet scrubbers or where two gas streams with different pollutant compositions combine.) Samples are to be taken within 3 cm of these points.

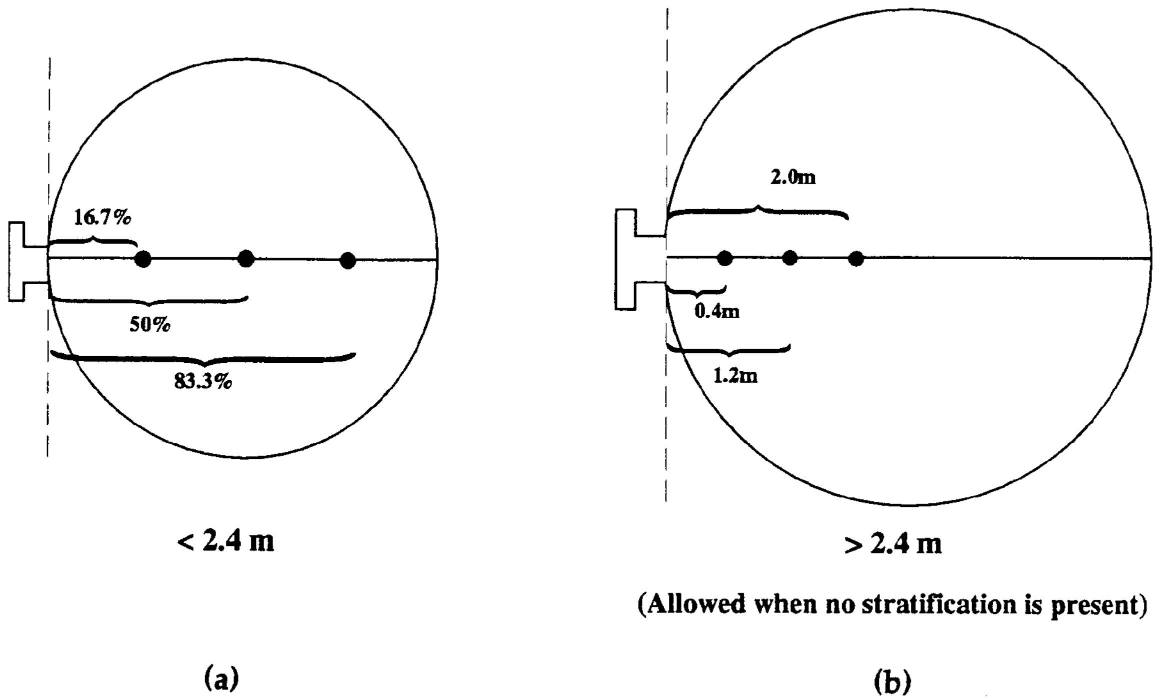

Figure 2–3. Gas Sampling Reference Method Traverse Points Specified in 40 CFR 60 Appendix B

In contrast to the gas sampling traverse points, velocity traverse points are those specified by EPA Reference Method 1. Here, a minimum of 12 or 16 points (depending on the sampling location) are to be tested.

Reference method <u>sampling locations</u> are the same as those specified for CEM systems, which are at least two equivalent diameters downstream from a disturbance, such as an elbow, a control device, or an expansion or a contraction and one-half equivalent diameter upstream from a disturbance or the effluent exhaust. Such criteria are generally not difficult to meet when the CEM system is installed in a stack; it is often difficult, however, to find two diameters of straight run in ductwork.

2.3 GAS AND FLOW STRATIFICATION

Flowing gases are generally well-mixed, but stratification can occur when there are differing temperatures or when dissimilar gas streams intersect. Figure 2–4 illustrates a number of conditions where gas concentration stratification may occur.

Air leaking into a duct, the combining of two-process gas streams into a stack, or the reintroduction of scrubber by-pass gas into a flue can all result in such stratification. In combustion sources, air in-leakage occurs usually near the preheaters. Columns of gas with high, unmixed NO_x concentrations have even been observed after burners. The problem is further complicated because this stratification is not only spatial, but can also change temporally, as a function of time. As process-load or other conditions change, the gas or flow distributions can also vary as a function of time as well as spatially.

Numerous examples of gas stratification patterns can be found in the literature. The work of Zakak et al. (1974) gives a detailed discussion of these problems.

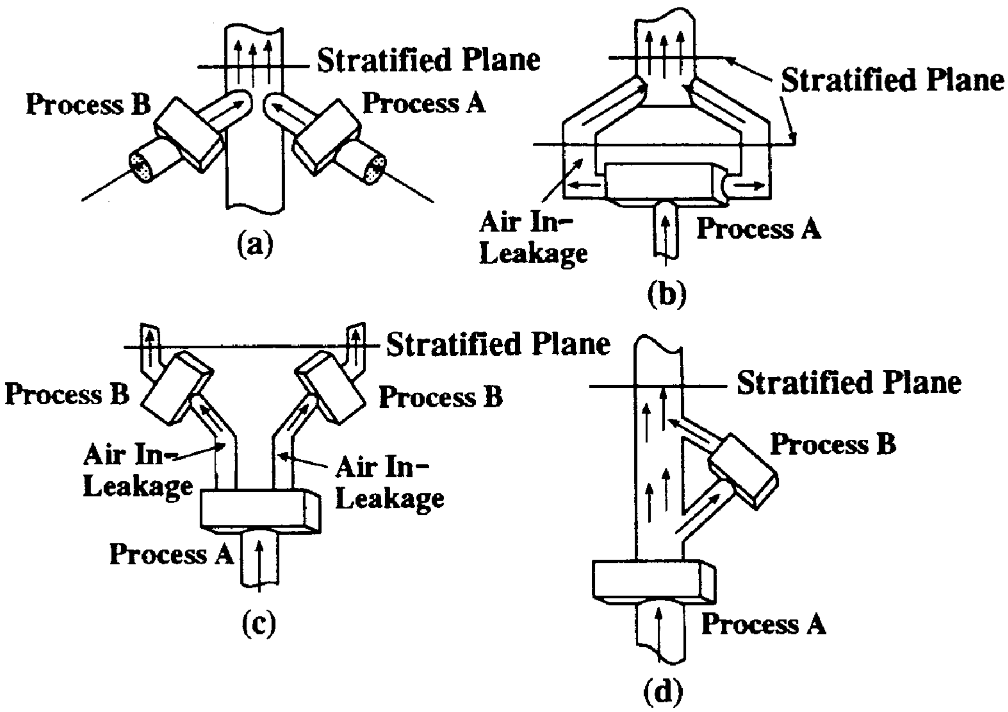

Figure 2–4. Conditions Under Which Gas Concentration Stratification May Occur (after Zakak et al., 1974)

[Combining two gas streams into a stack (a, b, d), air in-leakage (b, c), and reintroduction of scrubber by-pass gas into a flue (d).]

Velocity stratification is expected even in a fully developed flow profile, due to the effects of the stack walls on the moving flue gas. Support struts in ductwork may also cause problems in flow measurements. Eddies formed around the struts may disturb the sensing elements of a velocity monitor, or they can physically obstruct the measurement path or point.

The presence of cyclonic flow is particularly problematic, and sampling should be avoided where cyclonic flow is present. Gas streams entering tangentially to a stack can produce cyclonic, swirling flow (Figure 2–5). Velocity monitors can be particularly sensitive to flow direction.

Differential pressure sensor systems will sense different impact pressures depending on the angle of the flow relative to the impact pressure opening. Ultrasonic flow sensors can miss "pitched" gas streams or improperly weight the velocity across a line average. For this reason, it is specifically recommended in Part 75 that sampling locations be avoided where swirling flow is present.

2.4 QUANTIFYING THE DEGREE OF STRATIFICATION

It should be obvious from the above discussion that, based merely on duct diameter criteria, gas concentration or velocity stratification may or may not be present in a stack or duct. The criteria of 8- and 2-duct diameters or 2- and ½-duct diameters are regulatory constructs. In the case of gas stratification caused by temperature differentials, the gas may not become well-mixed even beyond 40-duct diameters.

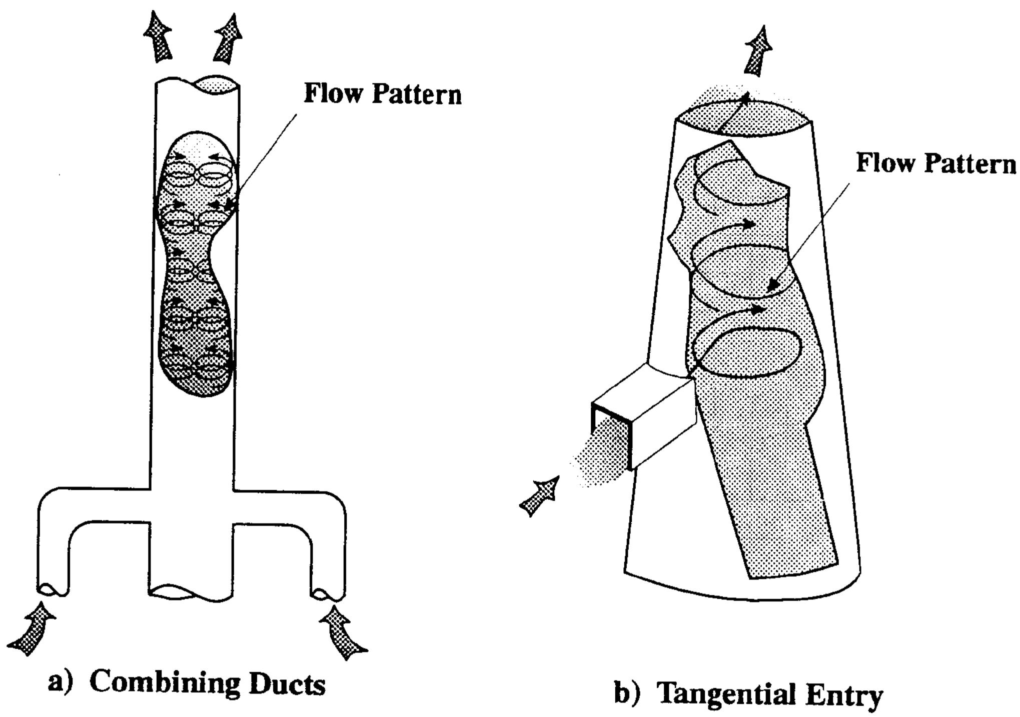

Figure 2–5. Conditions Under Which Flow Stratification or Cyclonic Flow Conditions May Occur

The degree of stratification in a duct or stack can be quantified. One method of quantification has been proposed (U.S. EPA, 1979) that involves traversing the stack or duct and obtaining gas concentration values. An example scenario for a rectangular duct would be to sample at nine sampling points of a balanced matrix. The degree of stratification at each sampling can be calculated as:

$$\begin{array}{l}\%\ Stratification \\ at\ point\ i\end{array} = \frac{\left(c_i - c_{ave}\right)}{c_{ave}} \times 100$$

where

c_i = concentration of the pollutant at point *i*

c_{ave} = average of the nine concentrations.

The sampling plane is said to be stratified if any value is greater than 10%.

When performing a stratification test, it is good practice to sample at a single point over the entire sampling period (e.g., Elam and Ferguson, 1985). This procedure is easily done using an instrumental technique. The data obtained can be used to determine if gas concentrations are changing as a function of time as well as spatially. If the concentration varies at the point over the sampling period, the traverse data will be difficult to interpret. Ideally, gas stratification studies should also be sampled isokinetically (i.e., sampling at a rate equal to the flue gas velocity) (Gregory et al., 1976), since over-isokinetic sampling of the flue gas may upset stratification patterns.

Although the quantitative determination of stratification may be useful in discussing the severity of a stratification problem, concentration or velocity isopleths (lines connecting points having the same value) are much more useful. Profiles such as those shown in Figure 2–1 and Figure 2–6 (below) can assist in siting both gas and velocity monitoring systems.

In circular stacks, stratification testing is normally conducted on the two perpendiculars of the cross-section specified by EPA Reference Method 1. Although this procedure may give reasonable values for area averages, it is often difficult to construct reasonable isopleths from the data. A modification of the EPA equal area procedure may be necessary to construct contours such as those shown in Figure 2–6. Because the object is to construct the isopleths and not to obtain an equal area average, the central point and points on diameters other than the two perpendiculars should be sampled to more completely define the stratification patterns.

Numerous problems can occur in the measurement of flow when attempting to characterize the profile, especially when the flow is nonparallel or cyclonic. Proper use of the S-type pitot tube, specified in EPA Reference Method 2, requires that the direction of gas flow be perpendicular to the plane of the impact pressure opening. EPA Reference Method 1 gives procedures that can be used to verify whether cyclonic flow is present and also provides procedures for measuring the non-axial components of flow, using a directional probe (3-dimensional pitot tube). The draft Method 2F contains additional procedures for measuring under nonparallel flow conditions. These methods should be considered before developing the stratification test plan and conducting the test.

Stratification tests are difficult to perform well and are costly if a complete characterization of pollutant flow distributions is needed. Also, many CEM systems are installed in new plants and must be on-line at the time of plant start-up. Because sampling locations are decided upon during plant design and construction, it is usually not possible to conduct stratification tests to guide CEM installation decisions in new plants. However, in such cases, computer modelling studies can be conducted from the proposed plant design. These studies have shown good agreement with testing conducted after construction (Gielow and McNamee, 1993). An alternative to computer modelling is cold-flow modelling, testing flows in Plexiglas constructions of the intended ductwork.

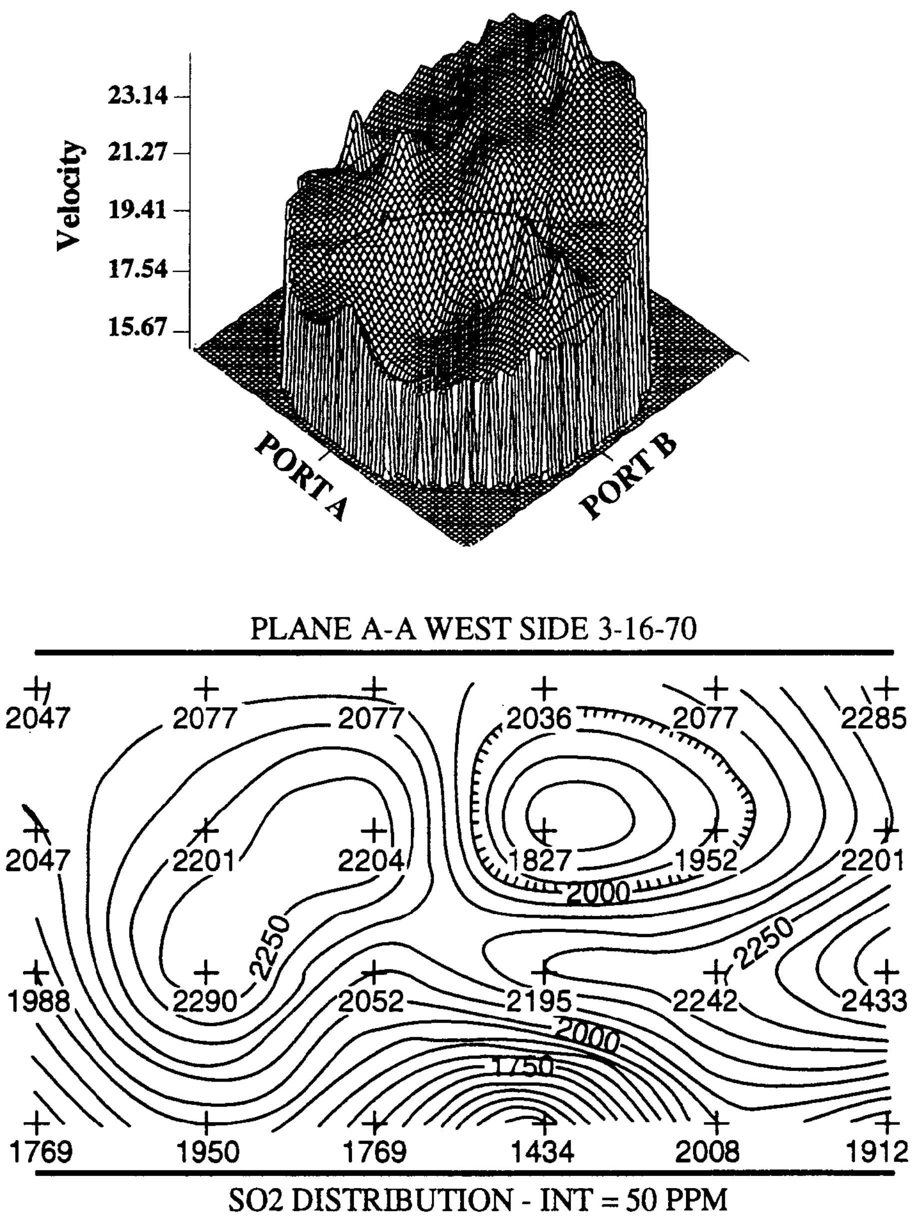

Figure 2–6. Velocity and Gas Concentration Profiles

2.5 MINIMIZING BIAS IN STRATIFIED GAS STREAMS

If at all possible, monitoring in stratified gas streams should be avoided. Other possible locations should be considered and tested to determine the presence of more uniform gas flows and concentrations. Alternatively, straightening vanes or baffles can be used to solve flow problems; fans or gas reinjection (Zakak et al., 1974) may solve gas stratification problems. Such engineering solutions may, however, require more power to move the flue gas through the ductwork and consequently add to plant operating costs. If stratification is present, either in the stack or in ductwork, a number of options are possible for minimizing bias between the monitoring method and reference method. These are listed in Table 2–1.

Table 2–1. Methods for Minimizing Bias due to Stratification

For stable stratification patterns:
C Sample at a point representative of the area measurement. C Monitor on a path representative of the area measurement. C Calibrate the monitoring system to the reference method values.
For varying stratification patterns:
C Calibrate the monitored values to reference method values determined over the range of variation (e.g., different load/process conditions). C For point monitoring systems, extract or monitor at multiple points on the cross-section. In severely stratified situations, monitor at all Reference Method 1 traverse points. C For path monitoring systems, monitor on paths less sensitive to the variation. C For path monitoring systems, monitor on multiple paths on the cross-section.

2.5.1 Stable Stratification Patterns

If the stratification pattern is stable over time, as load or process conditions change, two principal options are available. The simplest option requires examining the stratification pattern to determine a point or path that is representative of the reference method emissions.

The second option is to calibrate the monitoring system to the reference method values. This practice is common with manufacturers of flow monitoring systems, who generally require a "pre-RATA" to be conducted before the actual certification. Essentially, the manufacturer determines the bias beforehand and factors it into the instrument response. Although such empirical calibrations are common in flow monitoring, they are not frequently made in gas monitoring systems.

This procedure of correcting for bias before the certification test may appear to be circumventing the performance specification criteria, particularly the bias criteria of 40 CFR 75 Appendix A §7.6.4 and 7.6.5, which do not provide a bias adjustment factor for reducing positive bias. However, it must be remembered that EPA CEM system performance specifications on the whole are performance-based, not designed-based. It does not matter if a correction factor, correction algorithm, or random number generator is used within the system itself, as long as the same internal computational routine continues to be used unmodified for certification, normal emissions measurement, and routine quality assurance / quality control (QA / QC) checks. If the resulting system can meet all of the performance specifications for calibration error, linearity, relative accuracy, etc., during a certification test and during subsequent required periodic QA / QC testing, the system will be approved.

2.5.2 Varying Stratification Patterns

The problem of obtaining representative measurements can become more complicated when the stratification pattern varies under plant operating conditions. A typical situation occurs when two ducts exhaust into a single stack, but the volumetric flow rates of the gas through each duct vary under different plant operating conditions. Flow profiles downstream of bends are also expected to vary with load. In such cases, a "representative" sampling point or monitoring path may not exist. In others, it may be possible to program a calibration curve (Stahlschmidt, 1992) into the monitor response.

If it is necessary to monitor under such conditions, a "brute force" approach can be taken to achieve system certification. Basically, if a system is designed to sample at the traverse points of the reference method, then it should be able to meet the relative accuracy criteria. For gas monitoring, a minimum of three sample probes or a tube with multiple sampling ports could be used for this purpose.

In flow monitoring, differential pressure-sensing systems using probes with sensing ports at the reference method traverse points solve this problem quite easily. Similarly, path monitors can traverse the stack or duct over multiple paths to monitor the cross-sectional area more effectively (Lynnworth et al., 1992; Kearney, 1993). However, it may be necessary to program computational routines into the instrument to correct the line averages to an area average in path monitoring systems.

2.6 References

Elam, D., and Ferguson, B. 1985. Quality Assurance Aspects of Total Reduced Sulfur Continuous Emission Monitoring Systems. In Transactions—Continuous Emission Monitoring: Advances and Issues (J.A. Jahnke, Ed.). Air Pollution Control Association, Pittsburgh. pp. 82-102.

Gielow, R.L., and McNamee, M.R. 1993. Numerical Flue Gas Flow Modeling for Continuous Emissions Monitoring Applications. EPRI CEM Users Group Meeting. Baltimore. RP1961-13.

Gregory, M.W., Crawford, A.R., Manny, E.H., and Bartok, W. 1976. Determination of the Magnitude of SO_2, NO, CO_2, and O_2 Stratification in the Ducting of Fossil Fuel Fired Power Plants. Air Poll. Control Assoc. Meeting Paper. Portland: 76-35.6.

Kearney, B.J. 1993. Successful Siting of an Ultrasonic Flow Monitor in a Rectangular Duct with Stratified Flow. Continuous Emission Monitoring - A Technology for the 90s. Air & Waste Mgmt. Assoc., Pittsburgh, pp. 44-52.

Lynnworth, L.C., Matson, J.E., Bradshaw, J.E., Hall, K.A., Jacobson, S., Kucmas, P.G., Murphy, R.J., Nguyen, T.H., and Talcherkar, N.S. 1992. Point, Line and Area-Averaging Ultrasonic Flow Measurements in Ducts and Stacks. EPRI / ASME Heat Rate Improvement Conference. Birminghar

Stahlschmidt, D. 1992. Ultrasonic Flow Measurement of Gases for EPA Monitoring. Air & Waste Mgmt. Assoc. Meeting Paper. Kansas City: 92-121.07.

U.S. Environmental Protection Agency. 1979. Standards of Performance for New Stationary Sources. Continuous Monitoring Performance Specifications. 44 FR 58602. October 10, 1979.

Zakak, A. Siegel, R., McCoy, J., Arab-Ismali, S., Porter, J., Harris, L., Forney, L., and Lisk, R. 1974. Procedures for Measurement in Stratified Gases. EPA 650 / 2-74-086a,b.

2.7 Additional Reading

Brooks, E.F., and Williams, R.L. 1976. Flow and Gas Sampling Manual. EPA-600 / 2-76-203.

Brooks, E.F., Beder, E.C., Flegal, C.A., Luciani, D.J., and Williams, R. 1975. Continuous Measurement of Total Gas Flowrate from Stationary Sources. EPA-650 / 2-75-020.

Brooks, E.F., Flegal, C.A., Harnett, L.N., Kolpin, M.A., Luciani, D.J., and Williams, R.L. 1975. Continuous Measurement of Gas Composition from Stationary Sources. EPA-600 / 2-75-012.

Jackson, J.A., and Sommerfeld, J.T. 1986. Oxygen Stratification in Industrial Boiler Stacks. J. Air Poll. Control Assoc. 36:1238-1243.

Olin, J.G. 1993. The Effect of Non-Uniform Flows on CEMS Flow Monitors. Air & Waste Mgmt. Assoc. Meeting Paper. Denver: 93-TA-32.01.

Traina, J.E. 1992. Feasibility of Installing Volumetric Ultrasonic Flow Monitors on Non-Optimal Ductwork. Air & Waste Mgmt. Assoc. Meeting Paper. Kansas City: 92-66.14.

U.S. Environmental Protection Agency. 1978. Manual 1 - Source Selection and Location of Continuous Emission Monitoring Systems - Resource Manual for Implementing the NSPS Continuous Monitoring Regulations. EPA 340 / 1-78-005A. PB-283433.

U.S. Environmental Protection Agency. 1993. Standards of Performance for New Stationary Sources - Appendix A - Reference Methods. U.S. Code of Federal Regulations. U.S. Government Printing Office, Washington, D.C.

U.S. Environmental Protection Agency. 1993. Standards of Performance for New Stationary Sources - Appendix B - Performance Specifications. U.S. Code of Federal Regulations. U.S. Government Printing Office, Washington, D.C.

U.S. Environmental Protection Agency. 1993. Standards of Performance for New Stationary Sources - Appendix B - Performance Specification 1 -- Specifications and Test Procedures for Opacity Continuous Emission Monitoring Systems in Stationary Sources. U.S. Code of Federal Regulations. U.S. Government Printing Office, Washington, D.C.