W-7405-Eng-36
funding office M+A

CONF-940738--10

SINGLE POINT AEROSOL SAMPLING: EVALUATION OF MIXING AND PROBE PERFORMANCE IN A NUCLEAR STACK

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Paper Presented at:
23rd DOE/NRC Nuclear Air Cleaning and Treatment Conference
Hyatt Regency Hotel, Buffalo, NY 14202

MASTER

July 24-28, 1994

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NUCLEAR AIR CLEANING AND TREATMENT CONFERENCE

SINGLE POINT AEROSOL SAMPLING: EVALUATION OF MIXING AND PROBE PERFORMANCE IN A NUCLEAR STACK*

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Abstract

Alternative Reference Methodologies (ARMs) have been developed for sampling of radionuclides from stacks and ducts that differ from the methods required by the U.S. EPA. The EPA methods are prescriptive in selection of sampling locations and in design of sampling probes whereas the alternative methods are performance driven. Tests were conducted in a stack at Los Alamos National Laboratory to demonstrate the efficacy of the ARMs. Coefficients of variation of the velocity tracer gas, and aerosol particle profiles were determined at three sampling locations. Results showed numerical criteria placed upon the coefficients of variation by the ARMs were met at sampling stations located 9 and 14 stack diameters from flow entrance, but not at a location that is 1.5 diameters downstream from the inlet. Experiments were conducted to characterize the transmission of 10 µm aerodynamic equivalent diameter liquid aerosol particles through three types of sampling probes. The transmission ratio (ratio of aerosol concentration at the probe exit plane to the concentration in the free stream) was 107% for a 113 L/min (4-cfm) anisokinetic shrouded probe, but only 20% for an isokinetic probe that follows the EPA requirements. A specially designed isokinetic probe showed a transmission ratio of 63%. The shrouded probe performance would conform to the ARM criteria; however, the isokinetic probes would not.

I. INTRODUCTION

The U.S. Department of Energy (DOE) is required under the U.S. Environmental Protection Agency (EPA) National Emission Standards for Hazardous Pollutants (NESHAPs) to continuously monitor radionuclide emissions from stacks and ducts that could contribute more than 0.1 millirem per year to the most affected member of the public(1). The NESHAPs require use of EPA Method 1(2) for determining the location of the sampling station in the duct, and use of American National Standards Institute N13.1-1969(3) for guidance in conducting the sampling. EPA Method 1 states that the sampling should be no closer than eight duct diameters from the nearest upstream flow disturbance (elbow, fan, etc.) and no closer than two duct diameters from the nearest downstream disturbance. This so-called '8- and 2-criterion,' is intended to provide users with assurance that the sampling site is suitable for collection of representative samples with the minimum number of sampling points (probes). Closer spacing between the sampling plane and the nearest disturbances is allowed if the '8- and 2-criterion' cannot be met, provided larger numbers of sampling points are used. EPA Method 1 also requires that the average swirl angle in the flow should not

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[*] Funding was provided by the Radiological Air Emissions Management Group of Los Alamos National Laboratory and by the US NRC under Grants 04-89-353, 04-90-115 and 04-92-080.

exceed 20°, which ostensibly limits problems that might be created by off-axis sampling by probes and minimizes errors in flow measurements in stacks and ducts..

ANSI N13.1-1969 serves several roles in implementation of the requirements of the nuclear NESHAPs. First, it is intended to provide guidance on the number of sampling points that should be used at a given site, with larger ducts requiring more sampling points than smaller ducts, and rectangularly-shaped ducts requiring more sampling points than circular ducts. As many as 20 sampling points are recommended for large rectangular ducts. However, the ANSI standard recognizes that fewer points may be used if careful evaluation of the sample extraction location shows that the concentration profile is relatively flat as a result of good mixing in the stack or duct. Second, the ANSI standard provides guidance on the design of probes; it recommends sharp-edged probes followed by 90° bends, with a constant internal diameter from the inlet through the elbow. Third, when multiple probes are required under the guidance of the ANSI standard, it provides designs for rakes of such probes.

It has been known for some time(4,5,6) that the methodology prescribed in the NESHAPs needed to be improved and updated. Use of the '8- and 2-criterion' is not a reliable predictor of stack mixing conditions. In particular, it does not provide assurance that fluid momentum and contaminant concentration are both well mixed at the sampling location. Hampl et al.(7) showed that 50 duct diameters may be needed for mixing of a tracer gas in a straight pipe whereas only two duct diameters were needed for mixing downstream of two elbows in series that are placed out-of-plane. Turner et al. (5) showed that representative aerosol samples could be obtained at a distance of 1.5 diameters from a downstream disturbance (elbow).

Use of ANSI-type probes can lead to significant internal wall losses of aerosol particles. Fan et al.(8) tested such a probe and found that approximately 75% of liquid 10 µm aerodynamic equivalent diameter (AED) aerosol particles were impacted on the internals walls and only 25% transmitted through an ANSI probe to a filter collector. As a consequence of these limitations, Los Alamos National Laboratory has prepared Alternative Reference Methodologies (ARMs) for representative sampling of stacks and ducts for emissions of radionuclides(6.) These have been submitted to the EPA Administrator for approval under the provisions of 40CRF61, Subpart H.

The core concept of the performance-based ARMs is that true representative sampling of stack effluents, whether contaminated by gaseous or particulate radioactive contaminants, requires that the contaminants have become well mixed with the effluent flow across the entire cross sectional area at the sampling location. Good mixing can be the result of natural turbulence in the flow, or as a result of the use of engineered mixing devices. A most important consequence of requiring demonstration that mixing at the desired sampling location meets certain performance criteria, is that sample extraction from a single point in that profile is amply justified.

We show here that the most accurate and effective method of achieving continuous representative sampling of radioactive aerosol effluents is through the use of a suitably designed shrouded probe extracting samples from a single properly prepared and located point in the flow. There are two components of the ARMs proposed for achieving representative samples from a single point. The first component is the use of numerical performance criteria for determining the suitability of a sampling location in lieu of the present prescriptive method. Extractive sampling will take place at suitably qualified locations where both fluid momentum (manifested by the shape of the velocity profile) and contaminant concentration (characterized by the shape of the concentration profile) are demonstrated by measurements to be well mixed. If only gaseous radionuclides could be sampled at the site, the criteria for suitability are that the coefficients of variation in the data for the velocity profile and the concentration profile of a tracer gas will each be ≤20% over the center 2/3 of the stack or duct area. The coefficient of variation, *COV* is defined as the ratio of the standard deviation of a data set to the mean value of the data set, i.e.:

$$COV = \frac{s}{x} \tag{1}$$

where the mean and standard deviation of the data are defined as:

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{2}$$

and:

$$s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{3}$$

The parameter n is the number of data points; and, x_i is the value of the random variable (velocity or tracer concentration) at the ith location on a sampling grid.

To address the possibility of narrowly confined, high concentration flow envelopes being averaged out in the general performance criterion, an additional requirement is that over a grid set up in accordance with EPA Method 1(2), the concentration of tracer gas at any point will not be more than 30% greater than the mean concentration across the duct cross section. If aerosol radionuclide particles could be sampled at the site, the suitability criteria are the same as for gaseous radionuclides, but with the additional requirement that the *COV* of 10 μm AED aerosol particles will be ≤ 20% over the center 2/3 of the duct.

To preclude the possibility of significant emissions from a secondary flow being trapped in the boundary layer of a primary flow, no lateral flows may be introduced at a location downstream of the fan in a primary duct in a manner in which the secondary flow entrance would be flush with the wall of the primary flow duct without provision for downstream mixing elements which achieve complete mixing of the flows. This would not be a problem with junctions where the flows are of approximately the same magnitude.

The second component of the ARMs is the use of an anisokinetically operated shrouded probe for single point sampling of aerosols. This probe was developed by McFarland et al.(9). Such a probe concept is a break with the provisions of ANSI N13.-1969 methods, which emphasize isokinetic sample withdrawal from multiple points in the profile to overcome limitations in mixing. A properly designed shrouded probe, operated at a single location in a well-mixed, stable profile, will provide more representative samples than a rake of numerous small probes due to dramatically reduced wall losses of larger size particles. For a shrouded probe to be acceptable for a given application, the design must have been tested in an aerosol wind tunnel with 10 μm AED aerosol particles over the range of anticipated operational free stream velocities and sampling flow rates. The transmission ratio must be between 0.80 and 1.30 for these conditions.

At Los Alamos National Laboratory, a Waste Assay Facility (WAF) has been constructed that will serve the role of providing non-intrusive examinations of containers of radioactive waste prior to their disposal. Building ventilation air from the WAF is passed through HEPA filters before being discharged to the environment through two stacks (one that is 250 mm, or 10-inches inner diameter, and the second that is 300 mm or 12-inches inner diameter); however, because of the potential for emissions of radionuclides, the stacks will be continuously monitored. The WAF stacks are new and preceded by HEPA filters, so it is unlikely that they have been contaminated. As a consequence, we selected this facility for studies on emissions monitoring. Tests were carried out in the 300 mm diameter stack. With reference to Figure 1, effluent air from the WAF passes through the bank of HEPA filters, into an induced draft fan and then into the 300 mm diameter stack. Air, discharged from the fan, enters the stack through a rectangularly-shaped lateral element on the south side of the stack. Thus, the flow pattern in the stack initially has a

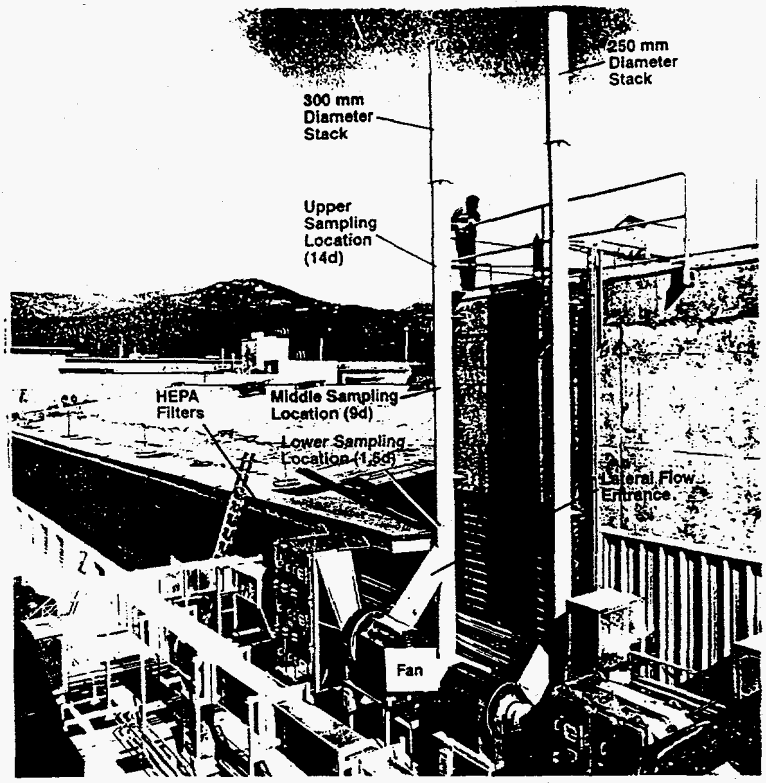


Figure 1. The air exhaust stacks of the Waste Assay Facility at Los Alamos National Laboratory.

pronounced north-south axis of disturbance. Based on pitot tube measurements that were taken by a facilities contractor before we started the study, the nominal mean velocity in the stack was assumed to be 21 m/s. Sampling stations, Figure 2, were placed in the stack at distances of 1.5 diameters, 9 diameters and 14 diameters from the flow entrance location. Totally, the height of the stack is over 20 diameters.

For single point representative sampling to be appropriate, the site must be qualified in terms of meeting numerical mixing criteria for both fluid momentum and contaminant concentration as manifested by the uniformity of the velocity and concentration profiles. In our study of the application of the proposed methodology and criteria in an unmodified operating stack, measurements were made at the three sampling locations of the velocity and concentration profiles. Two types of tests were conducted to characterize the concentration profiles; one set of tests dealt with a tracer gas and the second set dealt with aerosol particles. Sulfur hexafluoride was used as the gas tracer and oil droplets (oleic acid tagged with an analytical tracer) were used as the test aerosol.

Aerosol sampling experiments were conducted with both shrouded probes and isokinetic probes at a qualified location. We tested two different shrouded probes that had been designed to accommodate two different sampling flow rates, and made a comparison of their performances with those of corresponding isokinetic sampling probes. For these tests, 1 to 20 μm AED aerosol particles were used to challenge the probes.

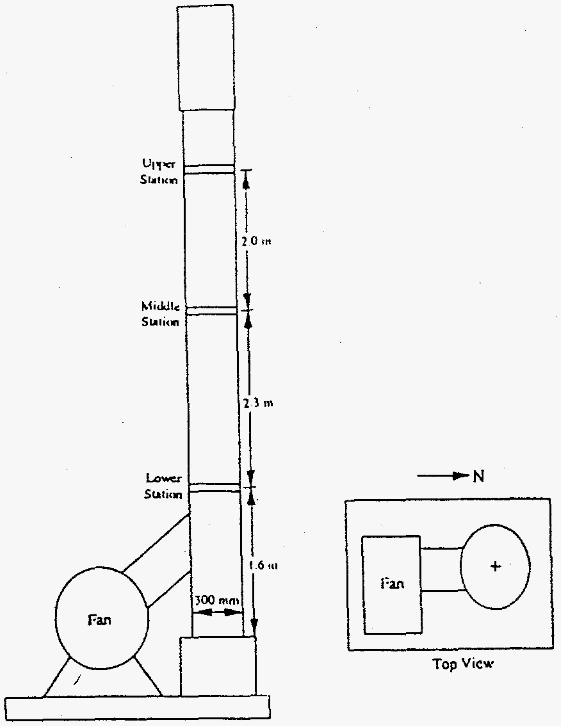


Figure 2. Location of sampling stations on the 300 mm diameter stack.

II. EXPERIMENTAL METHODS

Velocity Profiles

Velocity data were obtained at each of the three sampling locations with a two-channel hot film anemometer (TSI Model IFA 100/200, TSI, Inc., St. Paul, MN). The grid over which the velocity values were taken at each sampling location is shown in Figure 3. The hot film anemometer was initially calibrated at five different velocities in a free air jet against a pitot tube to establish the relationship between instrument output and air velocity. A daily single point calibration was used for assurance that the calibration had not shifted.

Velocity data from a hot film device are output in terms of a fixed set of reference conditions. These data were converted to actual velocity values in the stack through use of:

$$V = V_{ref}\left(\frac{P_{ref}}{P}\right)\left(\frac{T}{T_{ref}}\right) \tag{4}$$

where: V = velocity; P = pressure; T = temperature; the subscript *ref* refers to the reference conditions for the hot film output; and, the unsubscripted parameters refer to the actual stack conditions.

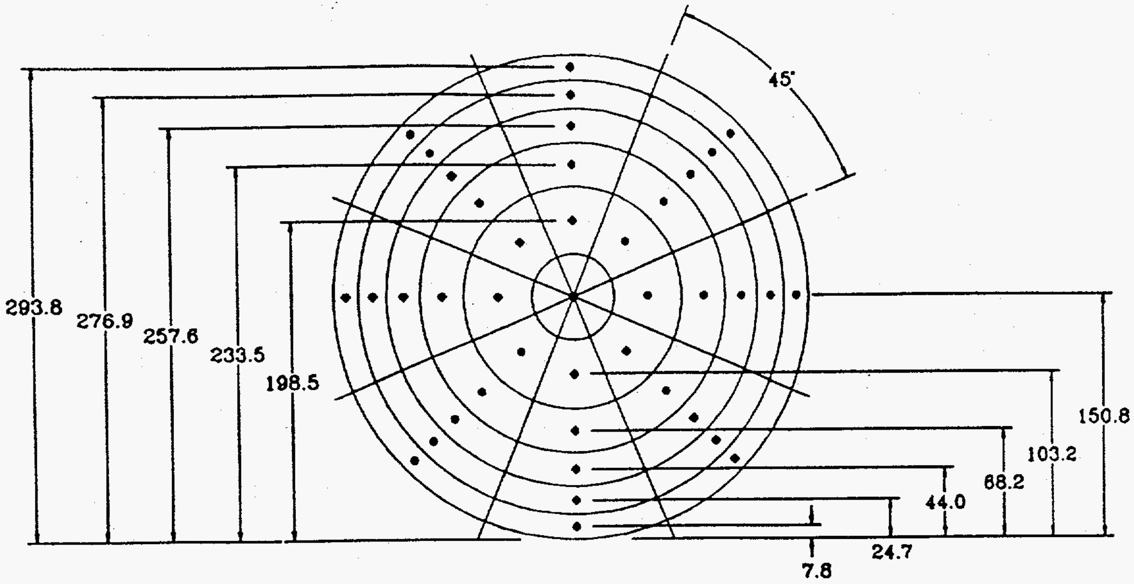


Figure 3. Grid over which velocity readings were taken. All dimensions are in mm.

Tracer Gas Profiles

Sulfur hexafluoride (SF_6) was introduced into the center of the lateral element at the stack entrance. A multipoint probe was used to sample SF_6 at various locations on two perpendicular diameters in the stack at each sampling location. The traverses were selected to be on north-south and east-west axes due to the orientation of the injected flow. Sampling positions in the stack were at distances of 13, 25, 46, 69, 104, 200, 236, and 279 mm (0.5, 1, 1.8, 2.7, 4.1, 7.9, 9.3, 10.2, 11, and 12 inches). The SF_6 concentration was determined with a photoacoustic infrared spectrometer (Multi-gas Monitor, Type 1302, Bruel & Kjaer, Naerum, Denmark).

Aerosol Concentration Profiles

Monodisperse particles were generated with a Berglund-Liu vibrating jet atomizer (TSI, Inc., St. Paul, MN) from the mixture of oleic acid and the analytical tracer, sodium fluorescein, dissolved in isopropyl alcohol. This aerosol was introduced into the center of the rectangular lateral flow element, which is located just upstream of the stack. Light scattering particle counters (MET-1, Grants Pass, OR) were used to measure the particle concentrations in the stack. Average particle size generated by the vibrating jet atomizer was 10.5 μm, which allowed a channel in an optical particle counter with a lower limit of 10 μm to provide size discrimination. The actual particle size was determined microscopically using the technique of Olan-Figureroa et al.(10). Two particle counters were operated simultaneously at a given sampling location during a stack testing. One particle counter sampled through a probe from a position near the center of the stack profile. Data from this device was used as a reference for the experiments. The second particle counter sampled through a probe that was sequentially placed at each position on a traverse across the stack profile. The initial point was 25 mm (1 inch) from the stack wall and subsequent points were spaced 50 mm (2 inches) apart. Two traverses, at 90° to each other, were made at each of the sampling locations. The traverses were oriented so that one was along a north-south axis and the other along an east-west axis. Triplicate measurements were conducted at each location.

Tests of Sampling Probes

The Berglund-Liu vibrating jet atomizer was used to generate monodisperse aerosol, which was introduced into the lateral entrance section of the stack. Testing of the probes was performed only at the upper (14 diameter) location. The test protocol consisted of operating each probe alternately at the center of the stack for a period of 5 minutes and then replacing that probe with the next to be tested.

A set of tests was conducted to determine the effect of particle size on aerosol transmission through the probes. These tests were conducted with particle sizes from 1 to 20 µm AED at a velocity of 25 m/s. A second set of tests explored the effect of velocity upon the transmission of 10 µm AED aerosol particles. Here, the probes were tested at free stream velocities of 13 and 25 m/s. At least four replicate tests were conducted with each probe at each set of experimental conditions.

One of the isokinetic probes was constructed similar to the recommendations given in the ANSI standard -- it consists of a sharp edged inlet that is 6.5 mm (0.255 inch) in diameter followed by an expansion to 8.7 mm rather than having a constant internal diameter. Because the straight section of the probe and the subsequent elbow have a larger internal diameter than the inlet, it is to be expected the wall losses in this ANSI probe would be less than those in a probe that perfectly matches the ANSI recommendation. For the experiments reported herein, a filter was placed at the exit of the elbow. In the discussion that follows, this probe shall be referred to as the 'ANSI' probe.

A second isokinetic probe was fabricated following the design of Chandra(11). It has a sharp-edged inlet that is 7.54 mm (0.297 inches) in diameter and it is followed by a gradual expansion of the flow stream to a diameter of 32 mm (1.25 inches). A filter sampler was placed at the exit of the expansion. In the discussion that follows, this probe shall be referred to as the 'isokinetic' probe.

Two shrouded probes were tested to determine aerosol transmission; one of the shrouded probes was designed to be operated at a nominal flow rate of 57 L/min (2 cfm) and the second was designed to be operated at 113 L/min (4 cfm). The shroud diameter of the 57 L/min unit was 50 mm (2-inches) and the diameter of the inner probe inlet was 15.5 mm (0.610-inches). The corresponding dimensions of the 113 L/min unit were a shroud diameter of 75 mm (3-inches) and an inlet diameter of the internal probe of 20.8 mm (0.818 mm).

Typically in the nuclear industry, the nominal flow rate for a stack sampling device is 57 L/min (2 cfm); however, it is commonplace to have two sampling systems operated at the same location with one used for alarming purposes and the second for collection of archival samples. In some applications a 113 L/min (4 cfm) probe is used to collect samples for both purposes. A flow splitter, placed outside of the duct, divides the flow stream so that a representative sample will be provided to each sampling device.

The parameter of principal interest in characterizing the probes is the transmission ratio, T, which is defined as the ratio of aerosol concentration at the exit plane of the sampling system to the aerosol concentration in the free stream. The parameter is determined for liquid aerosol particles and takes into account losses on the internal walls of a probe. Symbolically, it is expressed as:

$$T = \frac{C_e}{C_\infty} \tag{5}$$

where C_e = aerosol concentration in at the exit plane of the probe; and, C_∞ = aerosol concentration in the free stream. The parameter C_e is established from measurements of the aerosol mass that is transmitted through the probe and that which is collected on the filter, together with data on the volume of air sampled by the probe. Aerosol concentration in the free stream was determined from use of the Chandra-type probe. That probe was operated isokinetically, so the aerosol concentration at the 'isokinetic' probe inlet, $C_{i,iso}$ was the same as the free stream concentration, i.e.:

$$C_{i,iso} = C_{\infty} \tag{6}$$

A sample collected by a filter at the exit of this probe is deficient because of losses of aerosol particles to the internal walls of the probe, i.e.:

$$C_{e,iso} = C_{i,iso} - C_{wl,iso} \tag{7}$$

where: $C_{e,iso}$= aerosol concentration at the exit plane of the 'isokinetic' probe; and, $C_{wl,iso}$= aerosol concentration that is lost to the walls. In these experiments, the wall losses from the 'isokinetic' (Chandra-type) probe were recovered by washing the internal walls of the probe with isopropyl alcohol. Combining the concentration determined from the wall losses together with the concentration determined from aerosol transmitted through the probe allowed calculation of concentration at the probe inlet, which, from Equation 6, provided the value of the free stream aerosol concentration.

III. RESULTS

Velocity Profiles

With reference to Figures 4, plots are shown of the velocity profiles at the three sampling locations. Average velocity in the stack at operational conditions was about 25 m/s; however, data were also taken with the stack operated at about 1/2 that velocity to determine if the stack flow Reynolds number would significantly affect the mixing.

The profile at the 1.5 diameter station (Figure 4a) shows a reverse flow on the south side of the stack where the flow enters laterally, and a high speed region on the opposite side of the stack (north) where the velocity reaches a value of approximately 32 m/s. The *COV* of velocity at this station, calculated for the entire flow, is 28% while that over the region that includes 2/3 of the stack cross sectional area is 22%. These values, together with other *COV*s are shown in Table 1.

Data obtained at the second (9 diameters) level are shown in Figure 4b, where it may be noted the back flow has disappeared and the profile is much more uniform than at the lower level. However, there is still an excess velocity on the south side as compared with the north side. The coefficient of variation for the entire profile is 13% while that for the center 2/3 of the stack cross sectional area is 6%.

The velocity profile at the upper sampling station, which is 14 diameters downstream from the lateral entry, is shown in Figure 4c. Here, the profile is well developed, with a *COV* across the entire cross section of 12% and a *COV* of 4% for the center 2/3 of the stack. To determine if there was a flow Reynolds number influence on mixing, we measured the velocity profile at a flow rate of approximately 1/2 that of the normal operational value for the system. With reference to Figure 4d, the velocity profile for the middle (9 diameter) station at the reduced flow rate is still well developed and has a *COV* of 16% for the entire cross section.

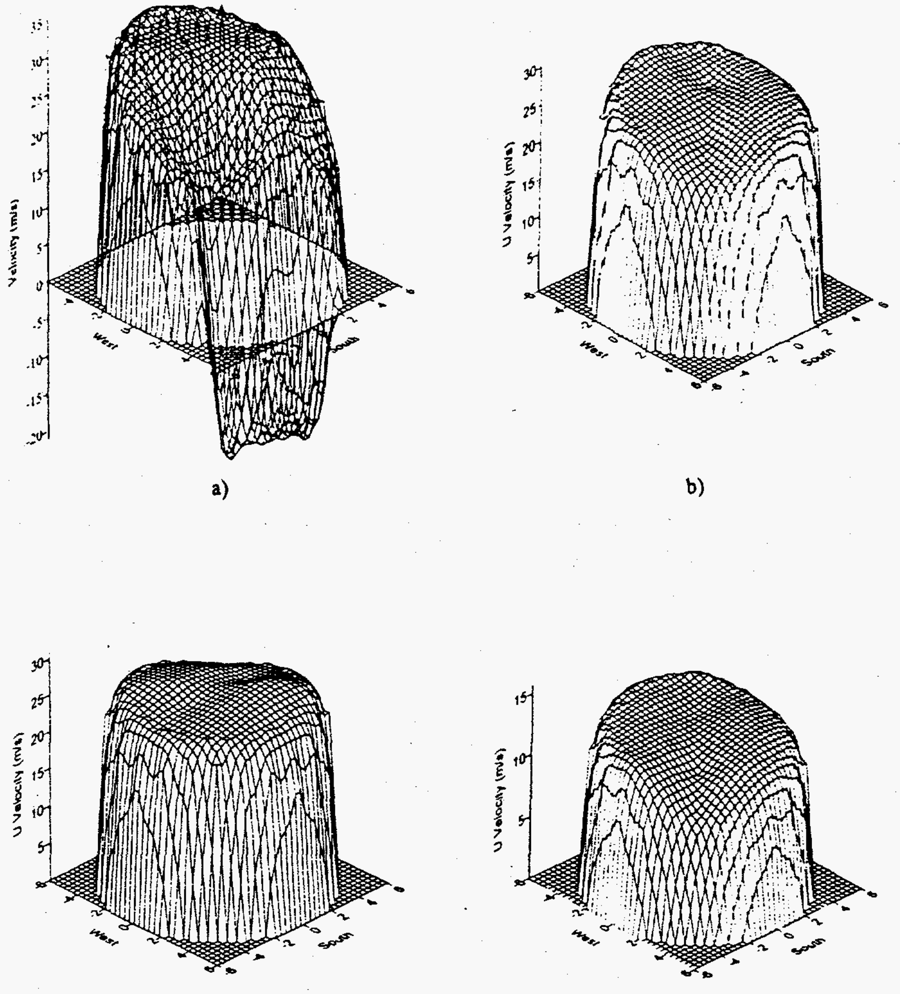
Tracer Gas Profiles

Average velocity in the stack was 23 m/s when the SF_6 measurements were made. The SF_6 concentration profile at the lower level is shown in Figure 5a. The units of concentration are relative, with the measured concentration at each point normalized to the mean concentration. The range of relative concentration values shown in Figure 5a is 0.59 to 1.39. The *COV* is 26% for both the entire data set and for the center 2/3 of the duct area.

Mixing of tracer gas is much improved at the 9 diameter station as compared with that at the 1.5 diameter location. A plot of the concentration profile at the former location is shown in Figure 5b. The *COV* is 5.9% full data set, and 4.2% for the center 2/3 of the stack. At no location on the entire grid is the

Table 1. A comparison of the uniformity of velocity and concentration profiles recommended in the Alternative Reference Methodologies with the values experimentally observed in the WAF stack. All data are for the high velocity condition.

Criterion	ARM acceptability criteria	1.5 diameter location	9 diameter location	14 diameter location
Velocity *COV* over the center 2/3 of stack area	≤20%	27%	6%	4%
Velocity *COV* over the entire grid	No criterion	28%	13%	12%
Tracer gas *COV* over the center 2/3 of the stack area	≤20%	26%	4.2%	2.1%
Maximum of tracer gas relative to the mean	≤30%	39%	12%	5%
10 μm AED aerosol particle *COV*. Center 2/3 of stack area	≤20%	74%	5%	5%
Average swirl angle	≤20°	9°	6°	9°



a) b)

c) d)

Figure 4. Velocity profiles at the three sampling locations: a) the 1.5 diameter location when the mean velocity was 26 m/s; b) the 9 diameter location when the mean velocity was 26 m/s; c) the 14 diameter location when the mean velocity was 26 m/s; and, d) the 14 diameter location at when the mean velocity was 11 m/s.

concentration more than 12% greater than the mean concentration (the range of measured concentration values was 0.92 - 1.12).

At the upper (14 diameter) location, Figure 5c, the mixing is slightly improved over that at the 9 diameter location. The coefficient of variation for the full set of data points at the upper level is calculated to be 2.8% and the *COV* for the center 2/3 of the stack area is 2.1%. The range of concentration values was 0.97 to 1.05.

Aerosol Concentration Profiles

The aerosol concentration profiles for the 1.5, 9 and 14 diameter locations are shown in Figure 6. The particle size for these data is 10.5 μm and the average velocity in the stack was 24 m/s. The concentration profile at the 1.5 diameter location, Figure 6a shows considerable skewness. Aerosol was introduced into the lateral on the south side of the stack and the data for a north-south traverse show the

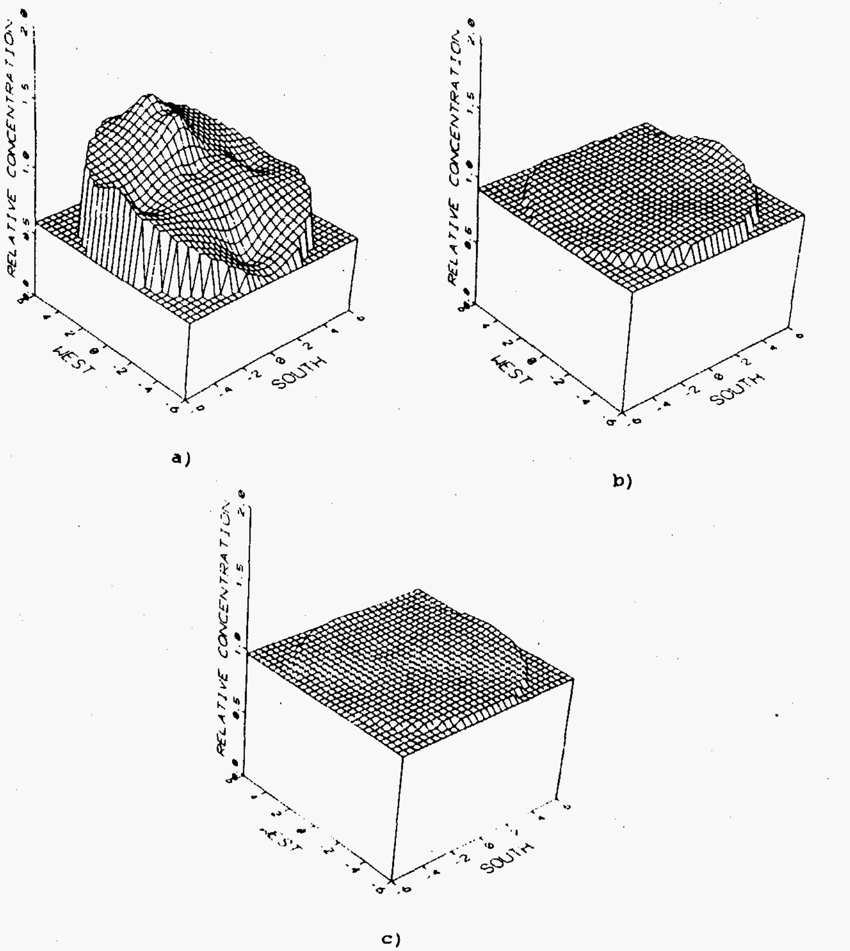


Figure 5. Tracer gas concentration profiles. Mean stack velocity was 23 m/s during these tests. a) The 1.5 diameter location. b) The 9 diameter location. c). The 14 diameter location.

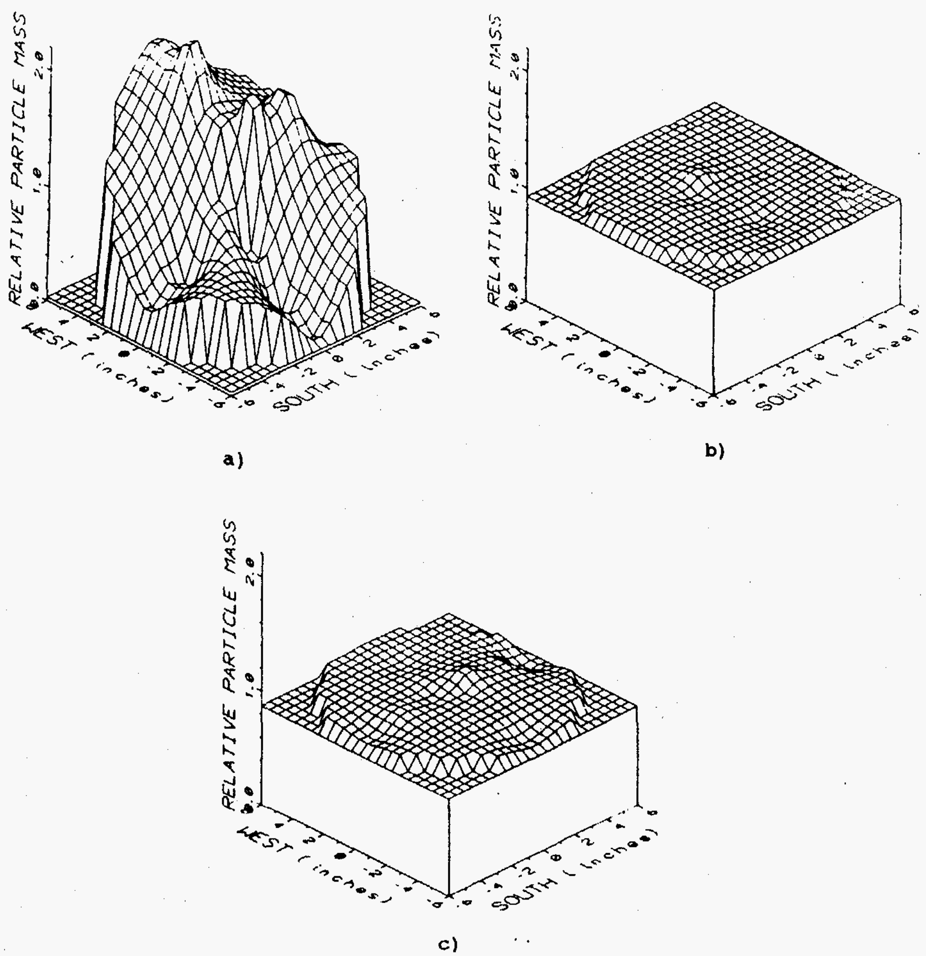


Figure 6. Aerosol concentration profiles for 10.5 μm diameter particles. The average stack velocity during these tests was 24 m/s. a) The 1.5 diameter location. b) The 9 diameter location. c) The 14 diameter location.

south side has a concentration defect and the north side has considerable concentration enrichment. The peak concentration on the north side of the stack is about 200 relative mass units while a near-zero concentration was measured at a distance of 25 mm (1 inch) from the wall on the south side. The *COV* for the full data set at this location is approximately 80% while that for the center 2/3 of the stack is 74%. Also, the maximum concentration across the entire grid is 212% of the mean concentration.

The large-scale mixing produced by the lateral entrance has a significant effect on the particle concentration profile as may be observed from the data taken at the middle station (9 diameters), Figure 6b. Both of the traverses show relatively uniform concentration values. The *COV* of the entire data set is 4% and that for the center 2/3 of the duct area is 5%, where the latter value is an acceptable level under the ARMs (which stipulates the maximum *COV* should not exceed 20% over the center 2/3 of the stack). The ratio of the maximum concentration to the mean concentration across the entire sampling grid is 8%.

The traverses for aerosol concentration at the upper level produced the data shown in Figure 6c. A *COV* of 8% is associated with the full data set, while the *COV* for the data points that correspond to the center 2/3 of the stack area is 5%. The maximum concentration is 14% greater than the mean value over the entire sampling grid.

Probe Performance

The transmission ratios as functions of particle sizes for the four tested probes are shown in Figure 7. At a particle size of 1.0 µm AED, the transmission ratio of all probes is approximately unity. Larger particle sizes had an adverse effect upon the ANSI probe transmission performance. At 10 µm AED, the transmission ratio was 20% and at 20 µm AED, the transmission was only 4%. In contrast, both shrouded

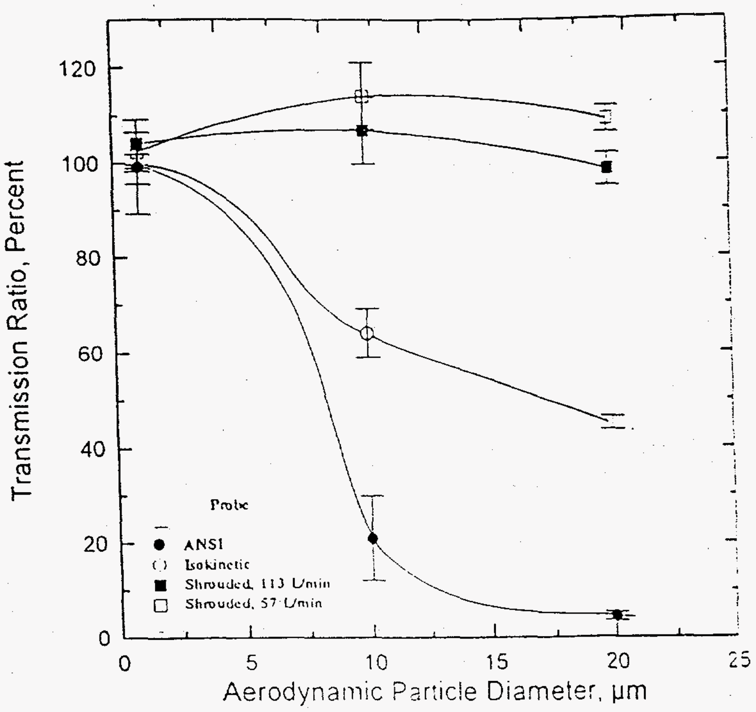


Figure 7. Effect of particle size on the transmission ratios of four different aerosol sampling probes. Mean velocity in the stack during these tests was 24 m/s.

probes showed relatively constant performance, with the 113 L/min (4 cfm) shrouded probe having transmission ratio values from 98% to 107% over the range of particle sizes of 1 to 20 µm AED. The 57 L/min (2 cfm) shrouded probe showed transmission values from 102 to 115% over the same range of particles sizes. Data for the 'isokinetic' probe showed transmission values intermediate to those of the ANSI and shrouded probes, with observed transmission ratio being 63% for a particle size of 10 µm AED.

The effect of stack velocity upon the transmission ratio of 10 µm AED aerosol particles through the various probes are shown in Figure 8. The transmission ratio of the 113 L/min shrouded probe changes from 107% to 92% (a relative change of 14%) as the velocity is decreased from 25 m/s to 13 m/s. In contrast, for the same change in velocity, the transmission ratio of the ANSI probe increases from 20% to 33% (a relative change of 65%). The transmission ratio of the 'isokinetic' was constant at about 63% as the velocity was changed.

Under the Alternate Reference Methodologies, a qualified probe will need to have a transmission ratio within the range of 80% to 130% for 10 µm AED aerosol particles and for the anticipated range of operational conditions. The data from stack tests show both of the shrouded probes (57 L/min and 113 L/min flow rate units) meet these criteria; however, neither the ANSI probe nor the Chandra-type 'isokinetic' probe would be suitable.

Estimate of Experimental Errors.

Replicate tests were conducted with each type of experiment. The normalized average standard deviation (standard deviation of the velocity measurements at each point divided by the mean at that point) of the velocity profile tests was 7% for the upper station, 9% for the mid station, and 16% for the lower station. For tests with tracer gas, the normalized average standard deviation averaged for all sampling

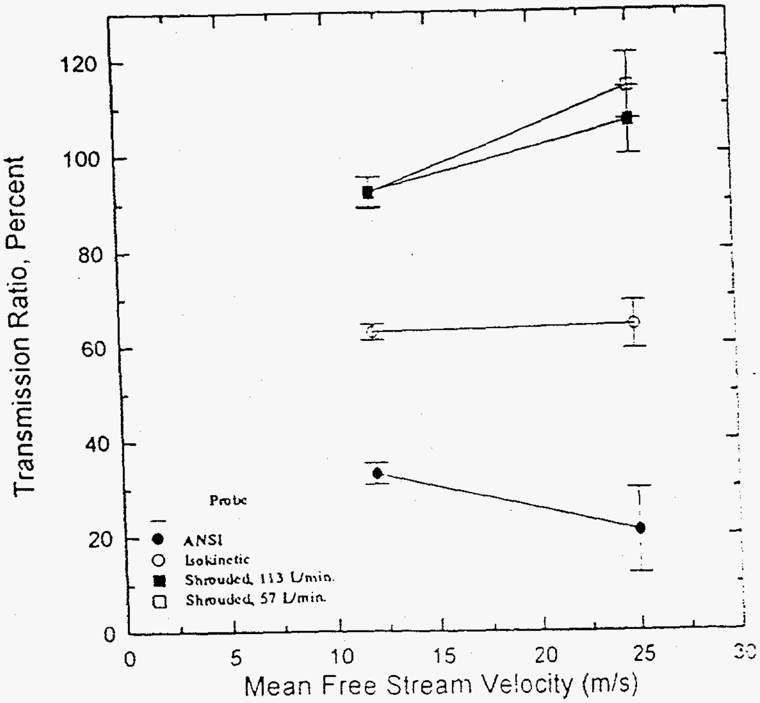


Figure 8. Effect of stack velocity on the transmission ratios of sampling probes. Particle size for these tests was 10 µm AED.

stations was 2%. Data for tests with aerosol particles showed the normalized average standard deviation was 18% at the lower lever and 10% at both the intermediate and upper levels. With respect to reproducibility of tests with probes, error bars that represent ± one standard deviation on the transmission ratio are shown in Figure 7.

IV. DISCUSSION

A comparison of the experimental results with the criteria presented as Alternative Reference Methodologies (ARMs) is given in Table 1. At the lower sampling station (1.5 diameters), the velocity profile over the center 2/3 of the stack area is 27% in contrast with the maximum value of 20% under the ARM . Also, the *COV*s of tracer gas and particle concentration are in excess of the proposed maximum values. Over the entire stack area, the maximum value of tracer gas was 39% more than the average value, which exceeds the proposed range of ≤30%. Average swirl angle was 9° at the lower location. Clearly, as indicated by the *COV*s of the velocity profile, tracer gas, and 10.5 µm diameter particle data, mixing at the lower sampling station is inadequate. However, the swirl data suggest that sampling stations located further downstream would not be rejected by the swirl angle criterion because it is anticipated that in a straight stack, the swirl angle would only decrease with downstream distance.

The 9 diameter location meets all of the numerical mixing criteria of the ARMs. The *COV*s over the center 2/3 of the stack area for velocity, tracer gas, and 10 µm aerosol particles are 6%, 4.2% and 5% respectively, which all compare favorably with maximum *COV*s of 20% stipulated in the ARMs. The maximum concentration of tracer gas was 12% greater than the mean value, as compared with the maximum of 30% allowed under the ARMs. Average swirl angle was 6°.

It should be anticipated that if mixing is suitable at a given location in a straight stack, then the mixing should also be suitable at any subsequent location, provided that indeed there are no obstructions or changes in the internal geometry. Data for velocity, tracer gas concentration and aerosol particle concentration demonstrate the nine diameter location is suitable for single point sampling and the data summarized in Table 1 show that the mixing is even better at the 14 diameter location. Although the nine diameter location would be suitable, the 14 diameter location is to be used for sampling the WAF stack because it can be serviced from the roof of the building.

The EPA '8- and 2-criterion'(2) may have provided acceptable guidance for selection of a sampling site in this stack. A sampling station placed at the 8-diameter location would probably have tested satisfactorily because the 9-diameter location is suitable. However, as demonstrated by the work of Hampl et al.(7), the guidance of the '8-and 2-criterion' would not be satisfactory as judged by the ARMs criteria for many configurations of stack flow. In the case of the WAF stacks, where there is a lateral entry followed by a straight section, the large scale eddy mixing transfers both sufficient fluid momentum and contaminant mass across the stack to render the profiles acceptable within a 9-diameter (and probably an 8-diameter) distance.

A test was conducted to determine if flow Reynolds number would produce a significant change in the mixing. The velocity profile at the 14 diameter location was characterized for a mean velocity of 11 m/s as well as for the velocity condition of 24 m/s. The results for the entire flow cross sectional grid showed a *COV* of 16% for the low flow condition as compared with a *COV* of 12% for the high flow rate. We do not consider this to be a major effect (see the section on experimental errors), and conclude that the Reynolds number, as impacted by mean velocity, does not appear to have a substantial effect on the mixing.

Tests of sampling probes showed the 113 L/min (4 cfm) shrouded probe to have the best performance. At the high velocity condition, the transmission ratio for this probe was between 98% and 107% for particles sizes in the range of 1 to 20 µm AED. In contrast, the ANSI probe and the 'isokinetic' probes only showed only 20% and 63% transmission of 10 µm AED aerosol particles at the high velocity condition. The Alternate Reference Methodologies includes a performance criterion for probes; namely, that the transmission ratio of a acceptable probe should within the range of 80% to 130% over the range of anticipated operating conditions. Based on the results of the stack tests, both of the shrouded probes would satisfy this criterion; but, neither the ANSI probe nor the 'isokinetic' probe would be acceptable.

V. REFERENCES

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