STACK SAMPLER CALIBRATIONS

John A. Glissmeyer
Pacific Northwest National Laboratory
Richland, Washington 99352

William E. Davis
Waste Management Federal Services of Hanford, Inc.
Richland, Washington 99352

Abstract

Tests were conducted to verify that new air monitoring systems at Hanford air exhaust stacks met the Draft HPS/ANSI N13.1 performance criteria developed for air sampling systems at nuclear facilities.[1] The standard's performance criteria address both the suitability of the air sampling probe location and the sample transport to the collection devices. The contaminants in a stack must be well mixed with the airflow at the air sampling probe location so that the extracted sample represents the whole. The sample transport criteria ensure that the contaminants are quantitatively delivered to the collection device. The specific performance criteria are described in the report.

The new systems tested provide airborne effluent measurements at the Hanford Site in Richland, Washington. The general design features a probe with a single shrouded sampling nozzle, a sample delivery line, and sample collection system. The collection system includes a filter holder to collect the sample of record and optional radionuclide continuous air monitors. The sample collectors are short-coupled to the stack, and the single sample flow is divided with a splitter.

The testing was conducted by the Pacific Northwest National Laboratory using full-size or scale-model stack mockups. Tests of candidate sampling probes were made in a wind tunnel. The results compare the performance of single and multi-nozzle isokinetic probes with single shrouded nozzle probes over a range of particle size and air velocity. The shrouded nozzle probes exhibited superior transmission of sampled particles. The velocity and tracer uniformity tests on the mockups demonstrated the detrimental effects of flow straighteners and misalignment of components. Particle penetration tests showed acceptable results for the short-coupled systems and enabled the identification of problem-causing components. The test program showed that the new monitoring systems meet all of the performance criteria for a range of exhauster configurations.

Introduction

The Department of Energy's Hanford Site contractors are actively implementing single-point sampling methodology in all new and many existing stack monitoring systems. On December 15, 1989, 40 CFR 61, Subpart H, "National Emission Standards for Emissions of Radionuclides Other than Radon from Department of Energy Facilities,"[2] came into effect. This regulation required the use of isokinetic probes, as described in ANSI N13.1-1969.[3] However, recent research indicates poor performance for isokinetic probes and shows improved performance for probes using a single shrouded nozzle.[4] These and other results were the motivation for the U.S. Environmental Protection Agency (EPA) recently to approve a DOE petition that allows an alternative method, which uses of a single shrouded probe in applications that previously required a manifold of several isokinetic probes.[5] In addition, the draft revision to ANSI N13.1 describes implementation standards for single point sampling.

Pacific Northwest National Laboratory and Waste Management Federal Services of Hanford have conducted a research and engineering program to implement the single point sampling provisions of the alternative method and the draft revision of ANSI N13.1. The program has consisted of the development of a generic stack monitoring system, testing of sampling probes, splitters and other components, and the qualification of stack configurations for the implementation of single point sampling. This paper summarizes the results of the efforts to qualify sampling probes, to determine line-loss in sample splitters and piping, and to qualify ventilation exhaust stacks for single point sampling.

Qualifying Sampling Probes

Probes

Three candidate sampling probe types (isokinetic, shrouded, and subisokinetic) were tested in the PNNL wind tunnel facility to determine their relative performance.[6] The probes tested were of the simplest possible configuration for use in small stacks with diameters less than 37 cm, with one or two nozzles and a short transport line leading to the filter holder, mounted just outside the stack. In all, six sampling probes were tested (denoted A through F), as shown in Figure 1.

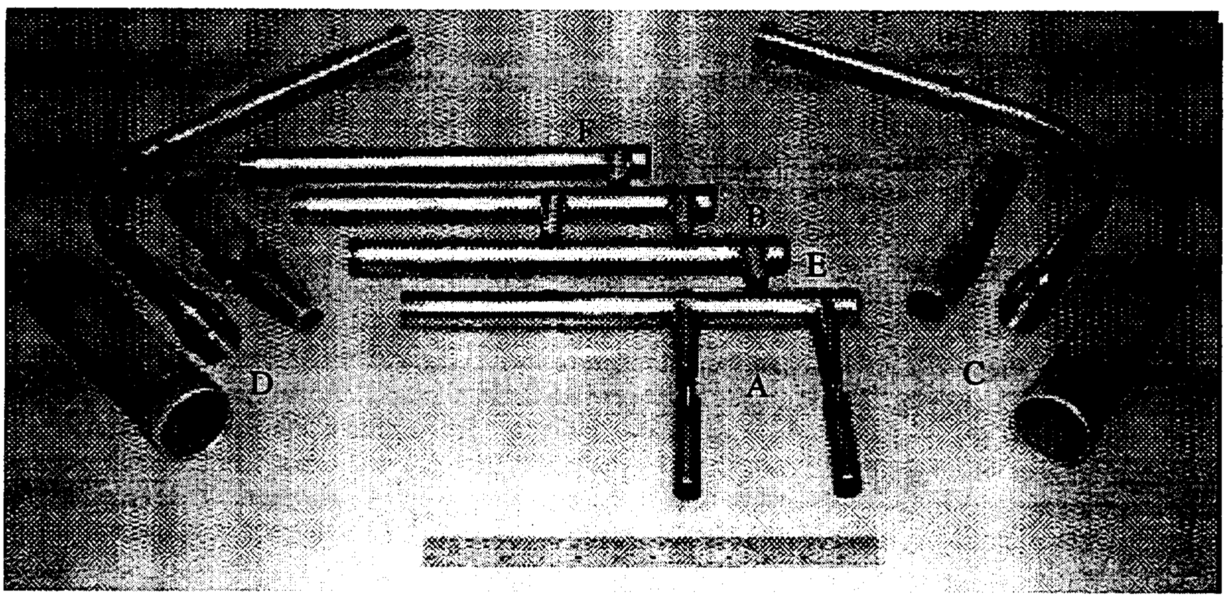


Figure 1 The six probes tested.

Probes A and B each consisted of two isokinetic nozzles mounted perpendicular to a common transport tube. The difference between the two was that Probe A had a short open-ended tube mounted just upstream of the nozzle inlet. The purpose of the open tube was to force the turbulent airstream approaching the nozzle into alignment with the nozzle axis, and to reduce the turbulent impaction of particles at the edge of the inlet. The nozzles have an internal expansion taper to help reduce turbulence-induced impaction just inside the orifice. These two probes differ from typical ANSI N13.1-1969 design, which features a constant internal diameter and a curved connection to the common transport tube.

Probes C and D both had single shrouded nozzles as shown in Figure 2, as described by McFarland et al.[7] Both were designed for a sample flow rate of 57 L/min. (The shrouded probes are shown with the nozzle disassembled in Figure 1.) Probe C was designed for an airstream velocity of 2.5 to 8.5 m/s and Probe D for an

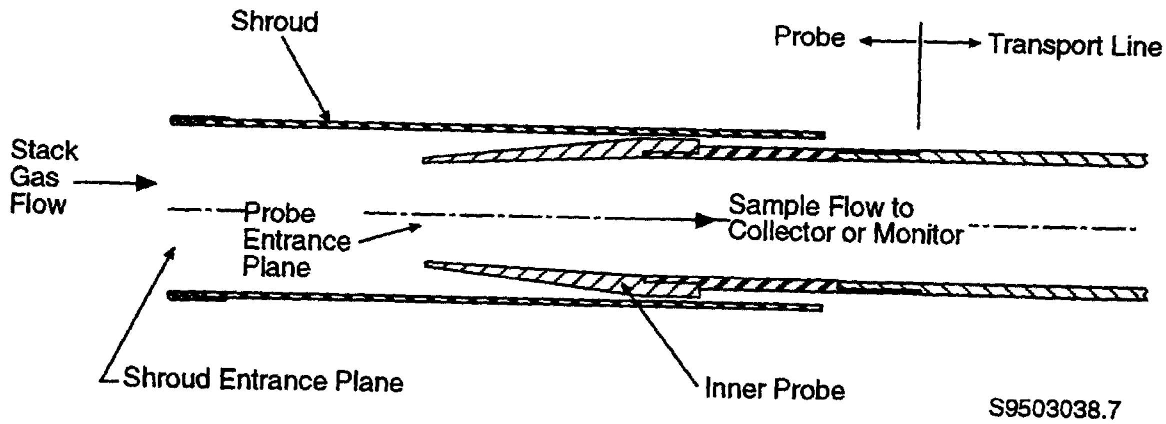


Figure 2 Features of shrouded nozzle of Probes C and D.

airstream velocity of 8 to 16 m/s. They are designed to be used at a constant sampling rate over their respective velocity ranges; therefore, the sampling flowrate would not be proportional to the air velocity. The shroud aligned the air velocity with the axis of the nozzle and decelerated the velocity of the approaching airstream. The large-diameter nozzle aspirated the sample from the central portion of the airstream, well away from the turbulence caused by the shroud's leading edge and walls. The transport line consisted of a large radius 90° bend; a short, straight section; and internally tapered adapters to accommodate the nozzle and filter holder. These probes were also tested in a mode where the flow rate was varied in proportion to the air velocity.

Probes E and F had single tapered inlet nozzles like those of Probes A and B. Probe E had a larger inlet diameter than Probe F, so that when both were operated at the same flowrate, the velocity through the inlet of Probe E was 59% of that of Probe F. Thus, while Probe F was always operated at isokinetic conditions, Probe E was operated subisokinetically. Theoretically, this would cause the sample airstream to be enriched in particles larger than approximately 2-μm aerodynamic diameter (AD), the diameter of a spherical water droplet that has the same settling velocity in quiescent air as the actual particle. To maintain a constant airstream-to-nozzle-opening velocity ratio, the flow rate through both of these probes was varied in proportion to the airstream velocity.

Probe Test Method

The testing was conducted in the PNNL recirculating wind tunnel with a test section that is 0.61-m square and 6.1-m long. The test aerosol was sodium-fluorescein-tagged oleic acid, generated with a vibrating orifice aerosol generator. Each probe was tested at air velocities from 3 to 15 m/s and particle sizes from 1 to 15-μm AD. A filter holder was attached to the end of the transport line just outside the wind tunnel wall. The particle collection on the filter was dissolved in methanol, and the fluorescence content of the solution was analyzed with a spectrofluorometer. Aerosol collected on the inside surfaces of the probes was removed with the same solution and then analyzed in the spectrofluorometer. Isokinetic reference samplers were operated concurrently in the wind tunnel to provide the basis for performance comparison.

Probe Test Results

Figures 3, 4 and 5 show the test results as the ratio of the aerosol collected on the sample filter to that collected on the reference samples, expressed as a percentage. This ratio can be defined as the concentration ratio. Figures 3 and 4 show concentration ratios as a function of particle size at 5 m/s and 15 m/s air velocity. Figure 5 shows concentration ratios for 10-μm diameter particles as a function of air velocity. The particle size is shown as AD. The fitted lines are shown only to clarify the trends for each probe. The ideal result in either are for Splitter 1; the upper plot is for Splitter 2. The horizontal lines in the plots represent the ideal performance for each splitter. The plots show that for particles larger than about 10 µm, the particle concentration in one leg of the splitter becomes enriched while it is depleted in the other leg. In Splitter 1, the particle mass and concentration in the larger leg, Outlet A, was enriched by 20%. In Splitter 2, Outlet A was enriched by about 25%. The internal loss for each splitter was very low and did not exceed 2%.

Sampler Line Loss Studies

The penetration of particles from the free stream to the collector should be at least 50% for 10-µm AD particles. A larger particle size should be used if larger contaminated particles are found airborne in the facility. Deposition 4.0[8] is generally used to estimate sampler line losses; however, when features not modeled are encountered, actual tests may be required. The value of measuring the sampler line loss is the identification of unexpected problems with components.

One example was the sampling system shown in Figure 9, where a splitter was used to provide samples to a record sample filter and a continuous air monitor. The system was tested using monodispersed 10-µm AD fluorescent particles. The results for the record sample are shown in Table 1. Although the acceptance criterion was met 3 of 5 times, the results exhibited poor repeatability and the mass balance of the aerosol was inconsistent. Percent line-losses in the probe, splitter, and filter holder were consistently low, so in-leakage or bypass in the filter holder were suspected. Examination of the record sample filter under a black light showed evidence of considerable particle bypass. Further testing of the filter holder showed both significant in-leakage and bypass. Based on these results, the filter holder was replaced.

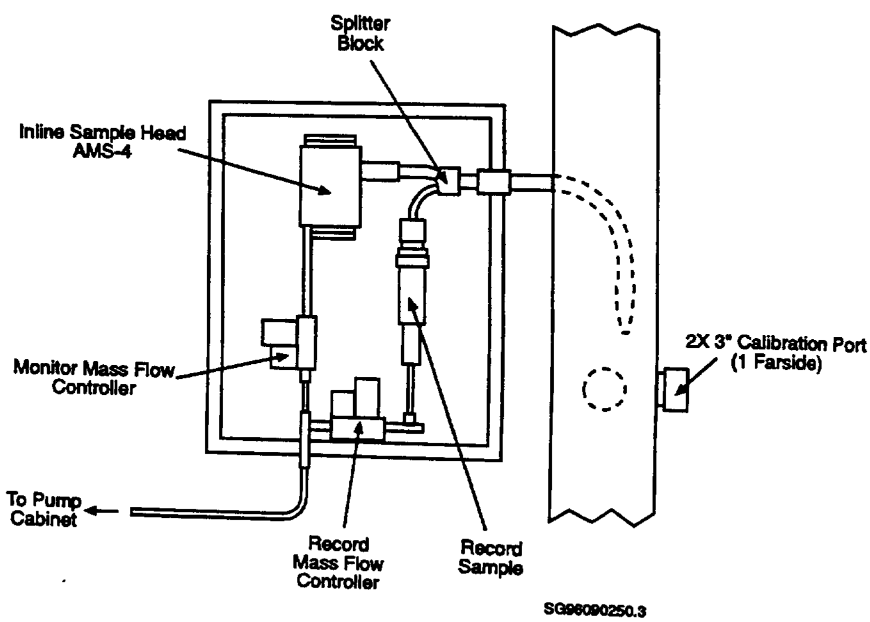


Figure 9 Sampling system tested for line-loss.

Table 1 Collection of 10-μm AD tracer particles relative to the reference sample.

Characteristic	Run PEN-1	Run PEN-2	Run PEN-3	Run PEN-4	Run PEN-6
Stack flow, cfm	491	1028	213	894	232
Mean stack air velocity, m/s	4.81	10.07	2.09	8.34	2.34
Percent of Expected Total Aerosol Deposited on Components					
Record sample filter	46.3	76.1	46.2	92.6	65.7
Probe	5.5	13.2	6.4	8.7	0.5
Splitter	0.8	2.0	2.2	2.4	0.5
Record sample filter holder	2.2	5.3	3.1	2.9	0.1
Unaccounted	45.2	3.5	42.2	-6.7	33.2

Stack Qualification Tests for Single Point Sampling

Three exhaust stacks at Hanford were qualified for single point sampling. (Another four are scheduled for testing this year.) Two were tested using full-size mock-ups and one using a scale model and follow-up field tests on the actual stack. Qualifying a stack for single point sampling requires a demonstration of uniform mixing of both gaseous and particulate contaminants within the air stream at the point where the sample is withdrawn. Four types of tests are used in the qualification. If the stack flowrate is expected to vary by >25% from the mean, the qualification tests are conducted at the flowrate extremes.

Flow Angle

Sampling nozzles are usually aligned with the axis of the stack. If the air travels up the stack in cyclonic fashion, the air velocity vector approaching the nozzle could be at an angle severe enough to impair the extraction of particles. Consequently, the flow angle is measured in the stack at the elevation of the sampling nozzle. The method was based on the EPA procedure described in 40 CFR 60, Appendix A, Method 1.[9] The flow angle should not exceed 20° relative to the long axis of the stack and the sampling nozzle.

The test was conducted using a type-S pitot tube, a slant tube manometer, and a protractor level attached to the pitot tube. The measurement grid was laid out in accordance with the EPA procedure. The pitot tube was rotated until a null differential pressure reading was obtained, and the angle of rotation was then recorded. This was repeated three times at each point and averaged over the entire grid.

Velocity Uniformity

Uniform air velocity, at the elevation of the sampling nozzle in the stack, ensures that the air momentum in the stack is well mixed. To determine uniformity, air velocity was measured at the same points as those used for the angular flow test. The method was based on 40 CFR 60, Appendix A, Method 1. The equipment included a standard Prandtl-type pitot tube and an electronic manometer. The uniformity is expressed as the variability of the measurements about the mean. This is expressed using the relative standard deviation or coefficient of variance (COV, the standard deviation divided by the mean times 100). The lower the percent COV value, the more uniform the velocity. According to the Draft HPS/ANSI N13.1, the COV of the air velocity should be ≤ 20% across the center two-thirds of the area of the stack.

The velocity measurements were repeated three times at each point on the measurement grid. The three measurements were averaged and the average values were used to calculate the overall mean and standard deviation for all of the measurement points together. These statistics were also computed for only those points in the central two-thirds of the test area.

Gaseous Tracer Uniformity

A uniform contaminant concentration at the sampling elevation enables the extraction of samples of gases and small particles that represent true concentrations. This is first tested using a tracer gas. The acceptance criteria are that a) the COV of the tracer gas concentration is ≤20% across the center two-thirds of the sampling plane and b) where gaseous emissions are expected, at no point in the sampling plane does the concentration vary from the mean by >30%.

The concentration profile uniformity was first demonstrated using sulfur hexafluoride as a tracer gas. The tracer gas was injected into the air as far upstream as possible from the sampling location, but downstream of the fans, or feeder ducts. Separate tests were conducted with the tracer injected along the centerline and near the duct sides or corners. The tracer concentration was measured at points in the sampling plane using a gas analyzer. The grid of measurement points was the same as that used for the velocity characterization tests described above. The gas analyzer used was a Bruel and Kjaer (Naerum, Denmark) Model 1302 calibrated for the tracer gas.

The tracer gas concentration measurements were repeated three times at each point on the measurement grid. The overall mean, standard deviation, and COV were computed for all of the measurement points in the central two-thirds of the test area without the benefit of averaging the results for individual points.

Particle Tracer Uniformity

The uniformity in contaminant concentration at the sampling plane is further demonstrated using tracer particles of 10-µm AD. This particle size is large enough to exhibit inertial effects. Once again, a larger particle size should be used if larger contaminated particles are found airborne in the facility.

The particle tracer uniformity test is conceptually similar to the gaseous tracer uniformity test. The gaseous tracer is replaced with an aerosol containing 10-µm AD particles and the gas analyzer is replaced with optical particle counters (OPC). The tracer particles need only be injected at one location, the centerline of the stack or duct as far upstream as possible from the sampling location, but downstream of the filters, fans, or feeder ducts.

For Stacks B and C, monodisperse (single-sized) test aerosol particles of oleic acid tagged with a fluorescent dye (uranine) were created from methanol-based solutions using a vibrating orifice aerosol generator (VOAG). A greater amount of aerosol than the VOAG could produce was needed for the higher flow of the scale-model Stack C, so polydispersed vacuum pump oil droplets were produced with a spray nozzle. The particle stream was piped to the injection point at the centerline of the duct between the fan and stack.

Particle concentration was measured in the model stack using two OPCs. The probe of one OPC was set at a fixed location while the probe of the mobile OPC was moved to each measurement point in a random order.

The fixed OPC recorded the particle concentration as a function of time in case the output of the aerosol generator varied. The particle counts in the 9 to 11-µm size channel were recorded. The layout of sampling points was the same as for the other tests, except that the size of the probe did not permit sampling as close to the stack wall.

The tracer particle concentration measurements were repeated three times at each point on the measurement grid. The average concentration for each point was calculated, and the overall mean, standard deviation, and percent COV were computed for all of the measurement points in the central two-thirds of the test area.

Scale of Tests

The qualification tests can be done on full-sized or scale models. If scale models are used, additional criteria from Draft ANSI/HPS N13.1 apply:

1. The model is geometrically similar to the stack.
2. The model meets all of the qualification requirements stated above.
3. The actual sampling location is geometrically similar to the model.
4. The product of mean velocity times the hydraulic diameter for the actual stack is within a factor of 6 of that for the model.
5. The velocity profile of the actual stack meets the uniformity requirements.
6. The difference between the actual and model stack velocity COVs is not more than 5%.
7. The flow angle of the actual stack meets the requirements.

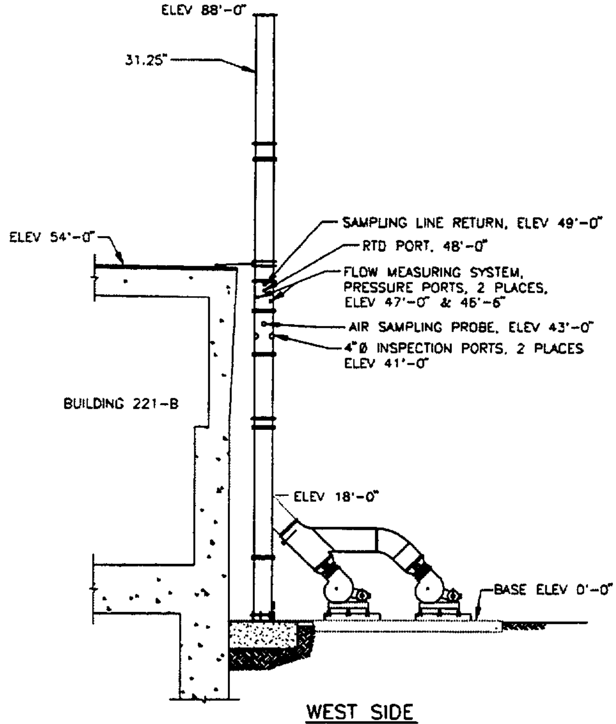
For the scale model, modeling the geometry is the key if the Reynolds number is maintained greater than 20,000. Field measurements of the flow angle and velocity uniformity are used to validate the applicability of the model. The air velocity in the model should be about the same as in the actual stack.

There are several advantages to using a scale model. Access to test ports on a stack can involve work in a contaminated area, construction of a work platform, or use of a manlift. A scale model can be assembled in the horizontal position, practically eliminating the need for work platforms. The model can often be constructed before the stack and modifications identified can then be incorporated into the stack design. The testing work can also proceed quicker and with fewer staff in a laboratory environment. Further, if difficulties are found in the sampling site, a new one can be readily tested. In this study, two small exhausters were qualified with full-scale testing and a larger stack was qualified using a scale model.

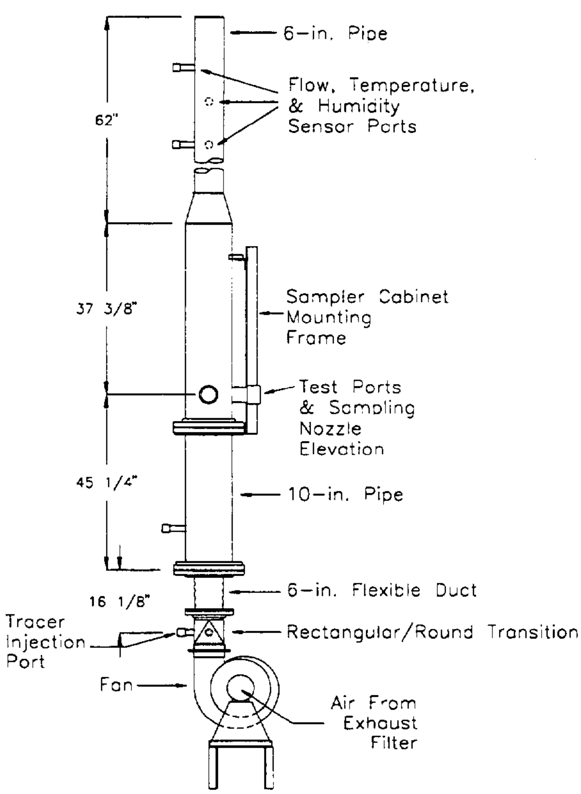
Stack A - Results of Scale Model Testing and Field Verification

The three stacks tested are shown in Figure 10. The largest of the three, Stack A, is 90 feet high and the sampling nozzle elevation is 9.4 stack diameters from the inlet duct. It is fed by one of two fans located on the common feeder duct. The flow range is 7,500 to 18,000 cfm. A scale-model approach was used for the qualification tests because of the size of the stack, safety considerations, cost, and time savings. The scale model tests were validated by measuring the flow angle and velocity uniformity on the actual stack. The scale model was a factor of 2.6 smaller in all dimensions and the flow range covered was 1,000 to 2,750 cfm.

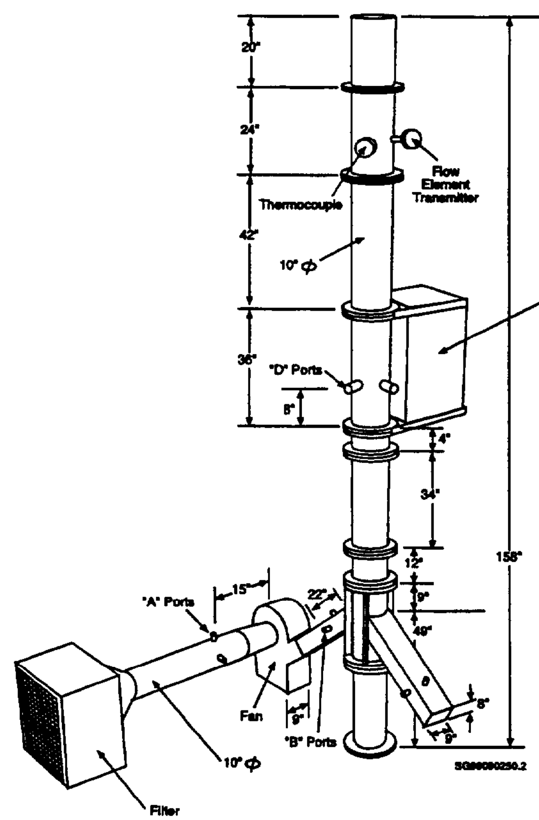
The flow angle measurements were made on the scale model parallel to, perpendicular to, and at 45° angles to the sampling probe insertion direction. The validation measurements were made along the intermediate 45° directions on the actual stack. The mean flow angle ranged from 2°- 5° on the scale model and 1°- 2° on the actual stack.



Stack A



Stack B



Stack C

Figure 10 Stacks A, B, and C.

On the scale model, the velocity uniformity COVs ranged from 2.1 - 4.9 %. The results for the actual stack varied from 1.7 - 4.2%. There were no particular trends observed as the operating conditions varied. The velocity uniformity was found to be insensitive to the scale of the stack and to the operating flowrate and Reynold's number.

The gaseous uniformity measurements were made only on the scale model, parallel to and perpendicular to the sampling probe insertion direction. With the fan nearest the stack operating and the tracer injected in the 45° duct feeding the stack, the COV results ranged from 2.1 - 7.3%, with the highest result when the gas was injected on the centerline of the duct. When the fan farthest from the stack was operating and with the tracer injection points in the 45° duct feeding the common duct, the results ranged from 0.9 - 1.3 %. It appears that the common duct and additional two 45° turns in direction promote better mixing.

The particle tracer uniformity measurements were done only on the scale model at the sampling probe elevation and along its insertion direction and perpendicular to it. When operating the fan nearest the stack, the COV results ranged from 9 - 15 % with the highest result at the highest flowrate. When the fan farthest from the stack was operating, the results ranged from 4.8 - 5.2 %. It appears that the common duct and additional two 45° turns in direction promote better mixing for the particles as well as for the gaseous tracer.

Stack B Results

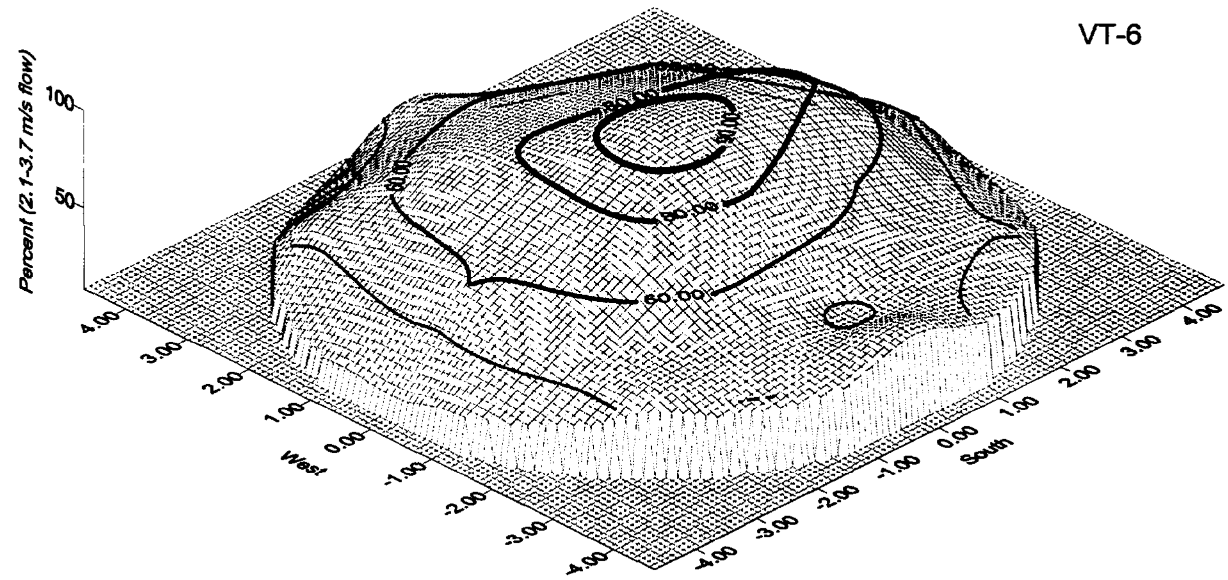
Stack B, the smallest of the three, was originally designed as a 6-in. diameter stack. The design was enlarged to accommodate the shrouded nozzle and fitted with reducer at the top for the flow instrumentation and to increase the discharge velocity. The stack is mounted atop a sudden expansion on top of an upward-discharging fan. The sampling nozzle elevation is only five stack diameters above the sudden expansion. The flow range is 200 - 1,200 cfm.

All of the qualification tests were made on a full-scale model.[10] The flow angle measurements were made along the sampling probe insertion direction and perpendicular to it. Over the entire flow range, the flow angle only ranged from 4.4° - 5.4°.

After the first velocity uniformity test, it was observed that the system would fail this test with COVs ranging from 29 - 33%. It was discovered that the fan was misaligned with the stack by about 1 in. After this was corrected, the COV results ranged from 7 - 11%. The estimated surface plots in Figure 11 illustrate the change in the velocity profile at about 300 cfm before and after correcting the fan alignment. Before alignment, the peak velocity was at one side of the stack. After alignment, the peak moved to the center.

The gas tracer tests were only conducted on Stack B after the fan alignment was corrected. For two flowrates, measurements were made with the tracer gas injected at five different locations in the same plane between the fan and the flexible duct. The tracer was injected at points 1 in. from the wall on the north, south, east, and west sides of the rectangle/round transition. In these cases, the results ranged over 7 - 11% COV. When the tracer was injected at the center of the same transition, the results were lower, ranging from 2.1 - 3.8%. Additional tests were done at the extremes of the stack flowrate (a 4:1 range), using the worst-case (west) injection location. These COV results ranged from 10.8% at 306 cfm to 9.9% at 1210 cfm, showing that the result was not dependent on the flowrate or Reynold's number over this range.

The particle tracer uniformity tests were conducted after the fan alignment was corrected and at three different flowrates. The results are summarized in Table 2. The results were acceptable in all cases. The third test (PT-3) had the highest COV, which may be due in part to counting errors associated with the lower particle concentration at the highest stack flowrate.



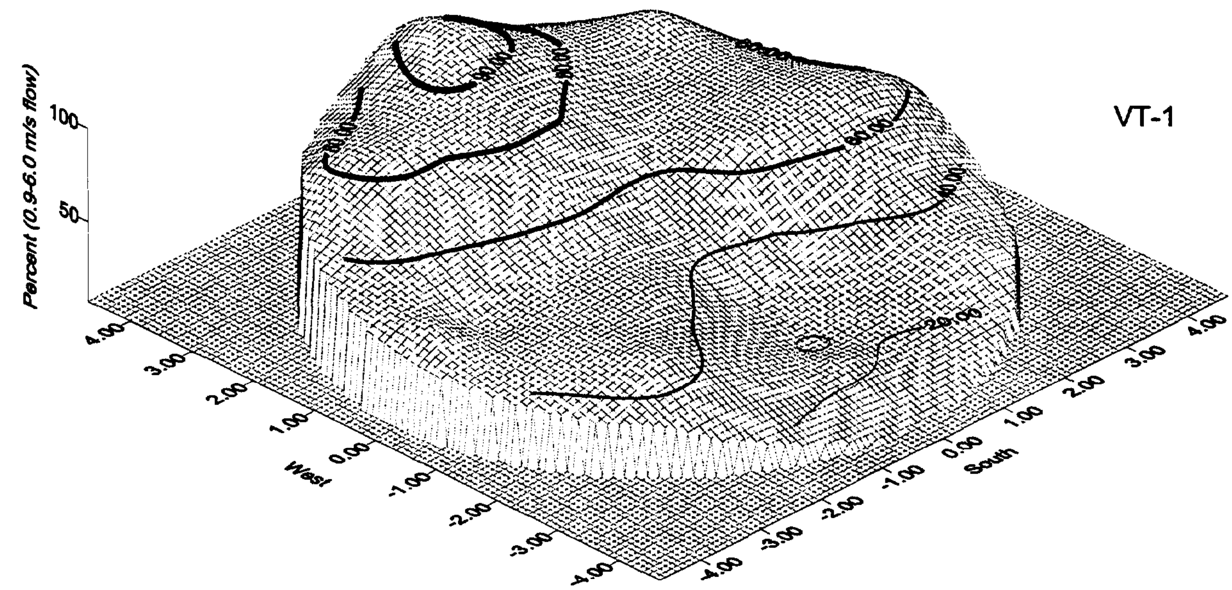


Figure 11 Before and after fan alignment,VT-1 at 340 cfm yields a COV of 32.8, VT6 at 306 cfm yields a COV of 10.4.

Table 2 Tracer particle mixing results over the center two-thirds of the stack.

	Test PT-1	Test PT-2	Test PT-3
Stack flowrate, cfm	491	213	1028
Overall mobile OPC percent COV	13.7	15.7	19.9

Stack C Results

Stack C is 10 in. in diameter and has two supply fans, each discharging at a 45° angle upward on either side of the stack. Only one fan is used at a time. The sampling nozzle is located only seven diameters above the inlet ducts. The qualification tests covered a flow range of roughly 700 - 1,200 cfm and were done on a full-scale model.(11) The stack was originally designed with a flow straightener just above the inlets. An empty spool piece was installed instead of the straightener for some of the tests.

The flow angle measurements were made both parallel to the sampling probe insertion direction and perpendicular to it. With the flow straightener installed, the flow angle ranged from 0.7° - 3.5° and 0° - 3.3° without the flow straightener.

The velocity uniformity test was conducted with and without a flow straightener installed above the inlets to the stack. The COVs ranged from 20.4 - 21% with the straightener, and 5.1 - 6.3% without. The effect is illustrated on the estimated surface plots in Figure 12. The elevation of the sample nozzle was only five diameters above the straightener, and the presence of the straightener served to preserve the expected asymmetrical flow up one side of the stack. Without the straightener, the velocity was more uniform, and the test was passed.

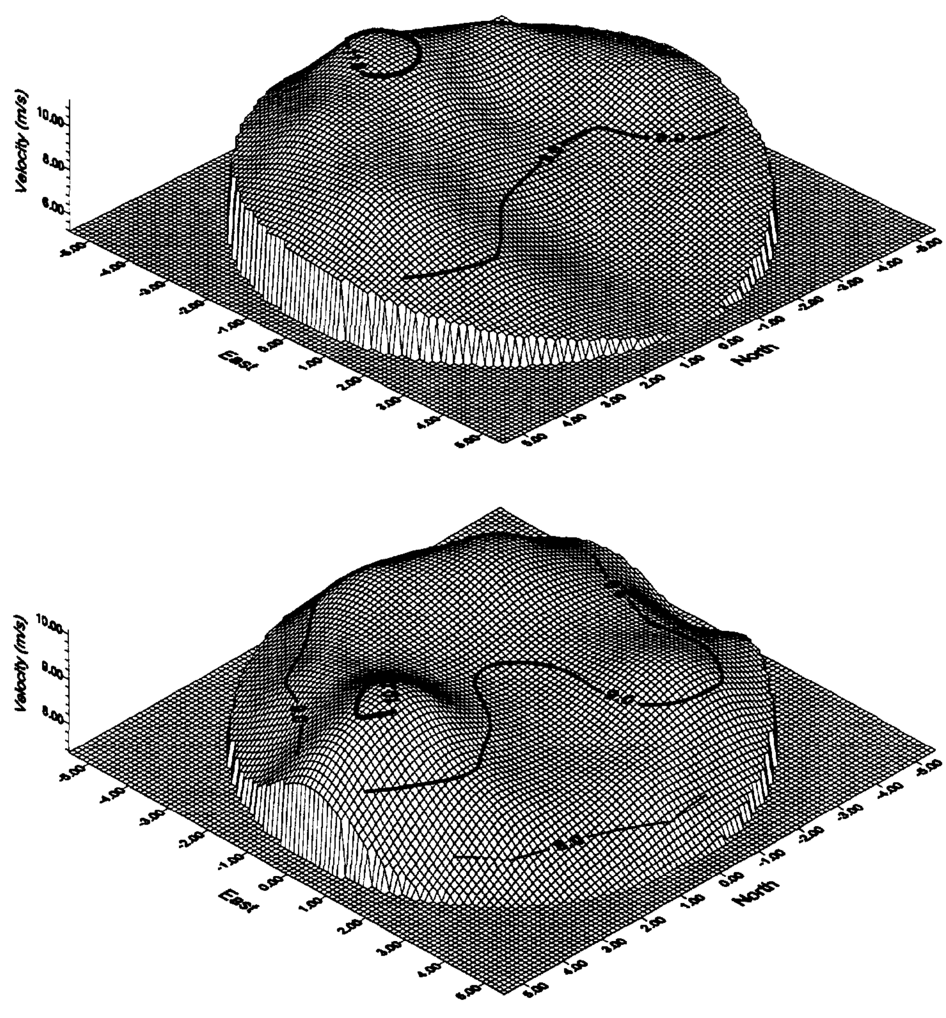


Figure 12 Velocity profile with (top) and without (bottom) the flow straightener (flow is about 950 cfm).

The gas tracer uniformity test was also conducted with and without the flow straightener above the inlet to the stack. The COV values ranged from 2.4 - 10.6 % without the straightener. (To give a feel of how large a concentration range is represented by a 10.6% COV, the range was 40 - 58 ppm.) With the tracer injected at the worst-case side position and with the straightener installed, the COV result was 42% (the concentration range was 14 - 67 ppm). Again, the presence of the straightener served to preserve the expected bias of the concentration toward the side of the stack opposite the air inlet. Without the straightener, the concentration was still highest on the same side, but with lower variation.

Three particle tracer uniformity tests were conducted to investigate the repeatability of the results. They were conducted outdoors in early winter and late in the afternoon when the temperature was falling. A decline in the particle concentration measured by the OPCs correlated with the falling temperature. Insulating and heating the OPCs, probes, and aerosol delivery piping were ineffective.

Table 3 summarizes the results from the particle uniformity tests. The upper half of Table 3 shows the temperature range, mean particle concentration, and the percent COV result for each test. The mean particle concentrations were noticeably lower and the COVs higher during the coldest test, PT-5, relative to the other two tests.

Table 3 Tracer particle mixing results over the center two-thirds of Stack C.

	Test PT-1	**Test PT-4**	**Test PT-5**
Each measurement is the mean of:	two 1-min. counts	five 1-min. counts	five 1-min. counts
Ambient temperature during test, °F	50 - 46	56 - 47	48 - 45
Mean mobile OPC particles/ft^3	110	88	49
Mobile OPC % COV	28	19	28

Conclusions

Based on the testing components, measuring line loss, and qualifying stacks for single point sampling, using models and full scale stacks, several conclusions and recommendations can be made:

- Sampling probes with single shrouded nozzles can deliver samples with much less particle-size bias (over the range tested, up to 15-µm AD) than the isokinetic probes tested. The shrouded nozzle probe operated in proportional flow mode shows less sensitivity to particle size and velocity than in the fixed-flow mode.

- Flow splitters exhibited very small (≤2%) internal losses as a function of particle size. For particles smaller than about 10-µm AD, the devices split the sampled particles according to the flow rate ratios so that the concentrations in the streams exiting the splitter are equal. As particle size increased, however, the concentrations in the exit streams did become unequal. This effect is likely caused by aerodynamic focusing of those particles possessing relatively large inertia. This effect may be remedied by altering the angles of the outlets relative to the inlet.

- One of the benefits of testing the sampler piping rather than modeling is the opportunity to discover problems with the sampling system.

- Comparisons of velocity profiles in the field with model testing in the laboratory clearly show that the scale models represented the flow patterns within the specifications of the draft ANSI standard. The use of scale models can be less costly and safer than field testing. Models can enable all-weather testing and safer working conditions without elevated work platforms and work in contaminated areas.

- Many common stack designs generally do not promote mixing. It is recommended that a design be selected that promotes good mixing in the stack. Flow straighteners should be avoided upstream of the sampling probe.

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