# MIXING TO ACHIEVE CONDITIONS SUITABLE FOR SINGLE POINT SAMPLING IN STACKS AND DUCTS*

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## Abstract

A proposed revision to the standard for sampling stacks and ducts of the nuclear industry places limits on the coefficients of variation of velocity and contaminant profiles. At the sampling location, the coefficients of variation should not exceed 20% over an area that encompasses at least the center 2/3 of the cross sectional area. Tests were conducted to characterize the degree of mixing affected by several types of flow disturbances, including elbows and commercial static mixing elements. For elbows, the mixing seems to be significantly impacted by the upstream flow turbulence. At a distance of three duct diameters downstream of a 90°elbow, the results of this study, where a flow straightener was inserted upstream of the elbow, showed coefficient of variation for the tracer gas profile to be 77%. In contrast, when the flow straightener was removed, the tracer gas coefficient of variation was 33% at the 3 diameter location. The use of static mixing elements can greatly enhance the mixing process. A ring, which blocks the outer 56% of the cross sectional area of a 90°elbow, results in a coefficient of variation of 19% at the 3 diameter location. Pressure loss across the elbow with the ring is about eight times that of the basic elbow. One of the commercially available static mixers provides a coefficient of variation of 14% at the 3 diameter location with a pressure loss that is about 3.5 times as large as that of an elbow.


## I. Introduction

Background. Under the requirements of 40CFR61, Subparts H and I[1,2], stacks and ducts of DOE facilities and NRC licensees must be sampled if the source can potentially emit radionuclides that will cause an exposure of more than 0.1 mrem at the location of the most affected member of the off-site public. The exposure is predicted through use of meteorological dispersion models such as CAP-88PC[3], and air pollution control equipment in the effluent air flow system is not taken into account in estimating the source term of the meteorological model. Both Subparts H and I require that EPA Method 1[4] be used for selecting the sampling location in a stack or duct, and that ANSI N13.1-1969[5] be used for sampling methodology. EPA Method 1 specifies that the sampling location in a stack or duct should be at least eight duct diameters from the nearest upstream flow disturbance (e.g., a bend) and at least two diameters from the nearest downstream flow disturbance. ANSI N13.1-1969 presents designs of sharp-edged probes for extracting samples from the air flow, and recommends that the probes be operated isokinetically if the particle size is larger than approximately 2 - 5 micrometers. In addition, ANSI N13.1 recommends the use of multiple probes in circular stacks or ducts that exceed 152 mm (6 inches) diameter or in rectangular ducts with a cross sectional area greater than 0.047 $m^2$ (0.5 $ft^2$). As many as 20 probes are recommended for large rectangular stacks or ducts. Ostensibly the use of multiple probes was intended to be an attempt to obtain representative samples in situations where there may be gradients in contamination concentration across the stack cross section. EPA Method 1, which is intended for grab sampling rather than continuous emission monitoring, allows the use of shorter distances between disturbances and the sampling location provided additional traverse (sample extraction) points are used.

The key goal of ANSI N13.1-1969 was to obtain representative samples; however the application of the design recommendations produced results that were counter to that goal. Typically, the probe in a stack or duct was about 6 mm diameter (1/4 inch) and there would be high losses of supramicrometer-sized aerosol particles on the internal surfaces of the probe. Fan et al.[6] tested an ANSI-type probe in an aerosol wind tunnel and observed that about 75% of 10 μm aerodynamic diameter (AD) aerosol particles were deposited on the internal walls of the probe.

ANSI N13.1 has undergone a significant revision and that revision is currently under final review by the American National Standards Institute. The goal of obtaining a representative sample is still the foundation of the standard, but, implementation of that goal is considerably different. Instead of attempting to achieve a representative sample by specifying the design of the sampling system and using multiple sampling points, the basic tenet of the new standard is that

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a representative sample can be obtained from a single point in a stack or duct where the fluid momentum and contaminant concentration are both well mixed as manifested by the uniformity of the velocity and contaminant concentration profiles. Numerical criteria are placed on the degree of mixing and also upon the performance of the sampling system. Although the new ANSI standard has not yet been incorporated into 40CFR61 Subparts H and I, any DOE facility can use the approach because the US EPA gave a blanket approval for use of Alternate Reference Methodologies (ARM) to the DOE[7], where the ARM include essentially the same requirements for aerosol sampling as the revised ANSI N13.1.

Mixing Requirements. The mixing in a stack or duct is quantified through coefficients of variation (*COV*) of the velocity and contaminant concentration profiles, where a *COV* is defined as:

$$COV = \frac{\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}}{\bar{x}}$$

Here, $N$ is the number of points in the cross sectional area of the stack or duct at which measurements are made; $x_i$ is the value of the variable (e.g., velocity) at the i$^{th}$ grid point; and, $\bar{x}$ is the mean value of the measurements, i.e.,

$$\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$$

The protocol for characterizing the velocity and concentration profiles involves measurements of the spatial values of the parameters at pre-determined points across the cross section of the stack or duct. Those points are specified by EPA Method 1 and encompass at least the center 2/3 of the cross sectional area. The criteria for mixing in the proposed revisions to the standard include:

- The *COV* of the velocity profile at the sampling location shall be ≤ 20% over an area that includes at least the center 2/3 of the stack or duct.
- The *COV* of the concentration of tracer gas, or a contaminant that is already present in the flow stream, shall be ≤ 20% over an area that includes at least the center 2/3 of the stack or duct.
- If aerosol particles can be present in the effluent flow, the *COV* of 10 μm AD aerosol shall be ≤ 20% over an area that includes at least the center 2/3 of the stack or duct. If particles larger than 10 μm AD can be present in significant concentrations, then a particle size larger than 10 μm AD shall be used.
- Tests of the *COV*s can be conducted with either the actual stack or duct, or with a suitable model. For a model to be used, it must be geometrically similar to the prototype and the Reynolds number at which the model is tested must be within a factor of four of that of the prototype. Also, the Reynolds number of both model and prototype must be greater than $10^4$. The Reynolds number is defined as:

$$\mathrm{Re} = \frac{UD}{\nu}$$

Here: $U$ = spatial mean air velocity at the sampling location (m/s); $D$ = diameter of the stack or duct at the sampling location (m); and, $\nu$ = kinematic viscosity of the effluent air ($m^2/s$).

Objective of Present Study. Because the proposed revisions to the standard are based on the concept of obtaining a single point representative sample from a location where the velocity and contaminant profiles are relatively uniform, it is important to have knowledge of the degree of mixing that can be obtained in stacks and ducts. At the present time there is no model that can be used to predict the level of mixing in an arbitrary stack or duct on an *a priori* basis. There have been studies on mixing in straight ducts following typical flow disturbances such as an elbow[8], and in straight ducts following static mixing elements[9,10,11]. However, because the results of those studies do not deal with velocity and contaminant concentration profiles over the center 2/3 of the cross sectional area of stacks and ducts, they are of limited use. McFarland et al.[12] developed a generic mixing system that was specifically designed for achieving suitable mixing conditions in stacks and ducts of the nuclear industry. It is referred to as generic because it can be scaled in size to accommodate the effluent flow rate. The system, which is shown schematically in Figure 1, creates mixing through the generation of large scale eddies that effectively transport momentum and contaminant mass across the flow cross section. Results of tests with a generic system are given in Figure 2, where the *COV*s of velocity, tracer gas concentration, and 10 μm AD aerosol particle concentration are shown plotted as a function of the distance downstream of the mixing.

The present study involves tests with mixing elements (elbows and static mixers) and gives results in terms of the development of the *COV*s in straight ducts downstream of the elements. The objective of this work is to provide users of

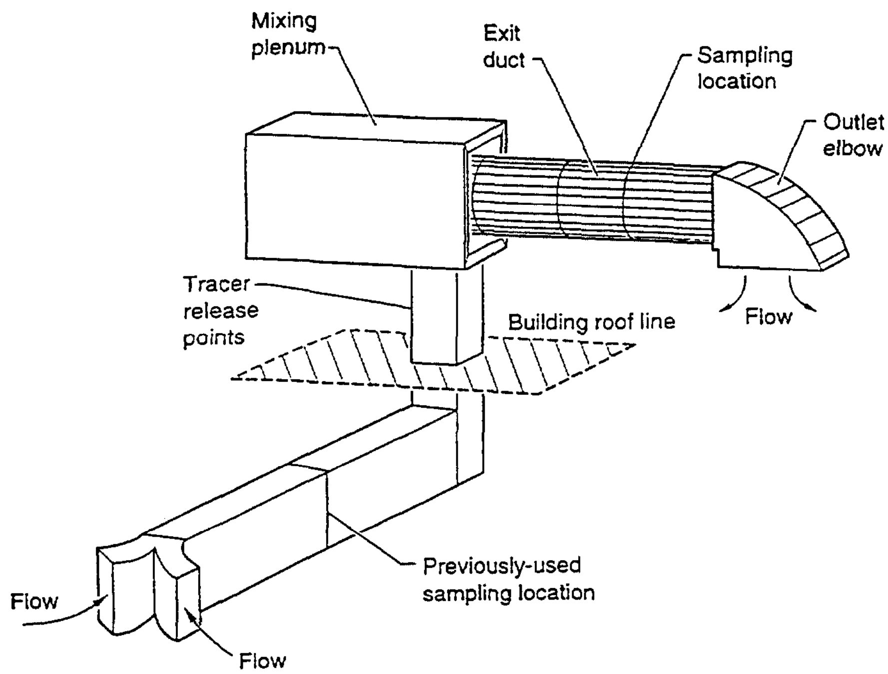


Figure 1. Generic mixer used for creating suitable conditions for single point sampling (McFarland et al., 1998).

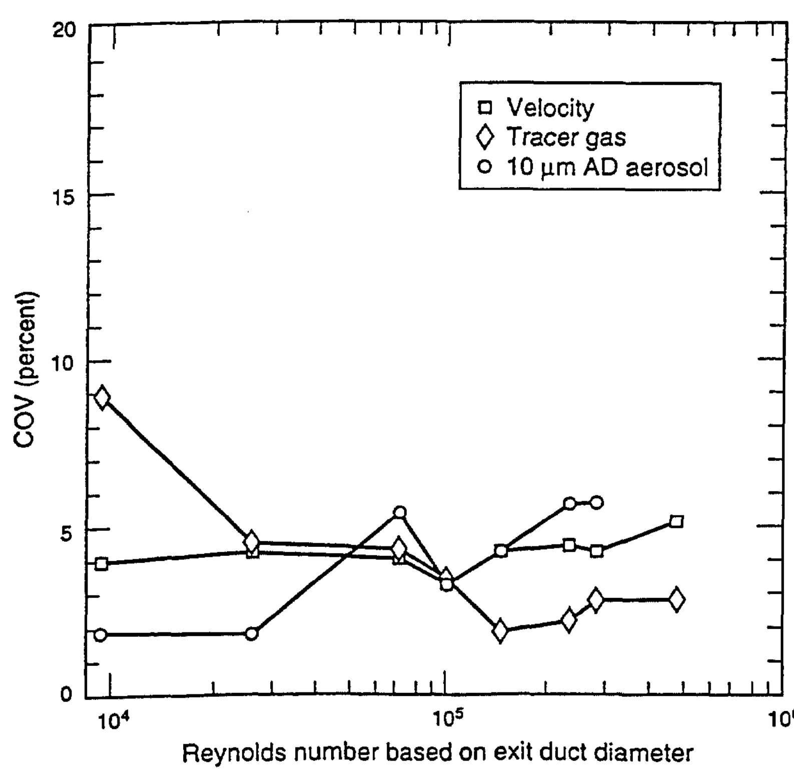


Figure 2. Coefficients of variations for the generic mixer shown in Figure 1 (McFarland et al., 1998). Reproduced from the journal *Health Physics* with permission from the Health Physics Society.

the technology with estimates on the mixing effectiveness of various flow disturbances. Also, the data should provide a basis for testing the efficacy of mixing models that may be generated in the future.

## II. Experimental Methods

Most of the tests involved use of the apparatus shown in Figure 3, which consists of a variable speed blower that discharges air into a 154 mm (6.05 inch) diameter duct. The air is forced through a flow straightener that is comprised of soda straws packed into the duct, and then into the mixing element, which is shown as a 90° elbow in Figure 1. The flow straightener eliminates any swirl in the flow, it uniformizes the velocity profile, and it reduces the size of the turbulent eddies to the size of the straws, which is about 6 mm. After passing through the mixing element, the air then flows through a straight section of 154 mm diameter ducting and is then discharged from the system. Velocity profiles in the ducting downstream of the mixing element were measured with a thermal anemometer (Model 8355, TSI Inc., Shoreview, MN) at the center 12 points of a 16 point EPA Method 1 grid. These points encompass the center ¾ of the duct cross sectional area. Profiles of tracer gas concentration were measured by injecting a continuous stream of sulfur hexafluoride, $SF_6$, into the center of the duct at a distance of 1 duct diameter upstream of the flow element. At the sampling location downstream of the mixing element, 60 mL samples of the gas were extracted with hypodermic syringes from the center 12 points of the 16 point EPA Method 1 grid. The syringes were immediately capped and the contents were subsequently analyzed with the aid of an electron capture gas chromatograph (Model 101, Lagus Applied Technology, Inc., San Diego, CA).

Two static mixers, which have body diameters of approximately 300 mm, were tested with the apparatus shown in Figure 4. The air flow was supplied by a generic mixer, which produces a uniform velocity profile (Figure 1) and has little flow swirl. A straight section of ducting, 305 mm diameter by 1.8 m long, connected the generic mixer to the mixing element being tested. Tracer gas was injected into the flow stream at a distance of 1 duct diameter upstream of the mixing element and the concentration profiles were evaluated at various downstream distances from the housing.

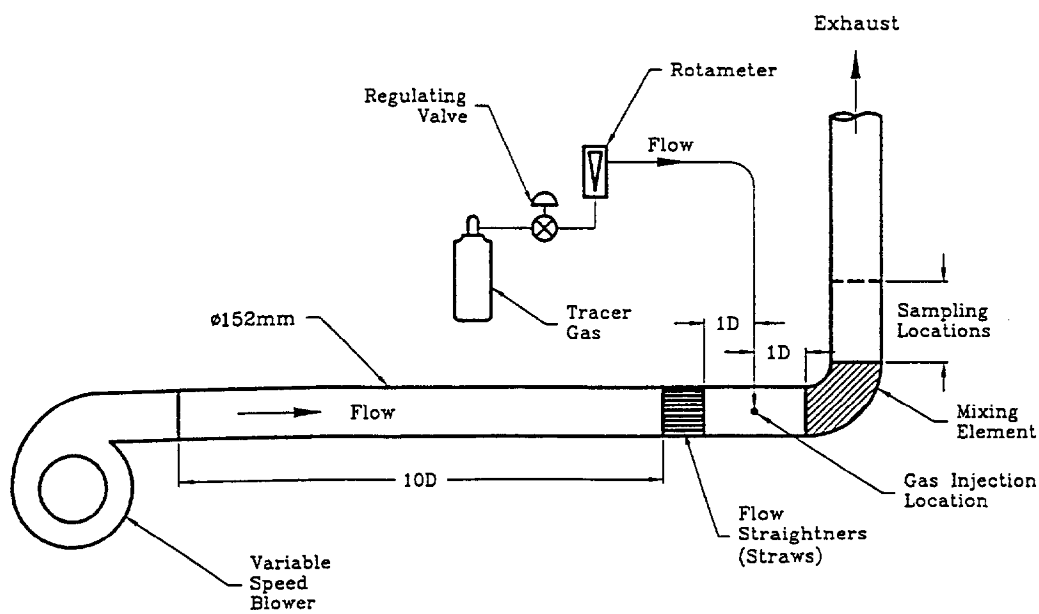


Figure 3. Apparatus used to conduct tests with mixing elements that had characteristic diameters of about 150 mm.

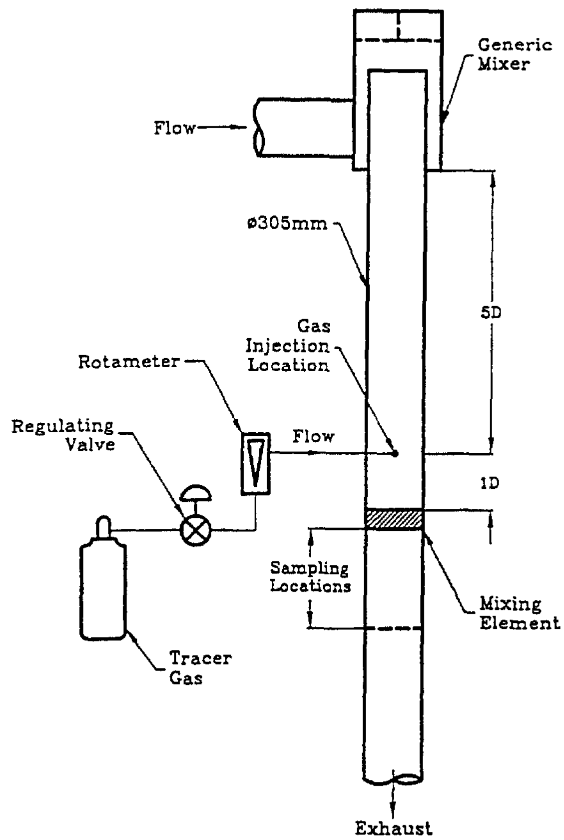


Figure 4. Apparatus used to test mixing elements with characteristic dimensions of about 300 mm.

The cost of mixing is the pressure drop across the mixing element, which can be expressed as:

$$\Delta P = C_p \frac{\rho U^2}{2}$$

Where: $\Delta P$ = pressure drop (Pa); $C_P$ = pressure coefficient; $\rho$ = air density (kg/m$^3$); and, $U$ = spatial mean air velocity at a reference location (e.g., the straight duct attached to the exit section of the mixing element). If the flow is well into the turbulent regime, the pressure coefficient $C_P$ is primarily dependent upon the geometrical configuration of the mixing element, but it may also have a slight dependency upon flow Reynolds number. Larger values of $C_P$ indicate greater costs for effecting mixing.

## III. Results

The coefficients of variation of velocity and tracer gas are shown in Figures 4 through 14 for a number of different mixing elements, and a summary of the pressure coefficients for those elements is given in Table 1. The tests with the devices covered a range of velocities from 5.6 to 15.5 m/s, which produced a range of Reynolds numbers from $6\times10^4$ to $3\times10^5$. As may be noted in Figure 1, Reynolds number has little effect on mixing provided its value exceeds about $10^4$. In general terms, when we use laboratory models to investigate the behavior of mixing in field prototypes, we limit the *COV*s to 10% to provide an allowance for additional uncertainties that may occur in field measurements. We shall use the value of 10% as an indication of acceptable mixing.

Table 1. Pressure coefficients for different mixing configurations

| Configuration | Pressure Coefficient |
|---|---|
| 90 degree elbow | 0.6 |
| 90 degree segmented elbow | 0.6 |
| Double elbow: S-arrangement | 1.7 |
| Double bend: U-arrangement | 1.0 |
| Elbow with a ring at the exit plane | 5.4 |
| Housing of a generic mixer | 1.2 |
| Mixer A | 2.1 |
| Mixer B: 2 modules in series | 5.0 |
| Mixer B: 4 modules in series | 9.1 |
| Mixer C | 0.8 |

90° Elbows. Two 90° elbows were tested; the first was a standard 6 inch Schedule 40 unit that has an inside diameter of 154 mm (6.05 inches) and a curvature ratio (radius of curvature of the bend/tube radius) of 2, and the second was a segmented sheet metal elbow with an inside diameter of 148 mm (5.8 inches) and a curvature ratio of 2. The *COV*s for the velocity and tracer gas concentration profiles of the standard elbow are shown in Figure 5, where the *COV* values are plotted as a function of the ratio of the distance downstream of the elbow to the duct diameter, *L/D*. The *COV* for velocity decays rapidly downstream of the elbow, having a value of 17% at 3 diameters, and reaching a value of less than 10% within a distance of 9 diameters from the exit plane of the elbow. On the other hand, the *COV* for tracer gas is 123% at a distance of 1 diameter from the elbow, 69% at 3 diameters, and is still at 19% at a distance of 9 diameters. The pressure coefficient for the standard elbow is 0.60.

Approximately the same results were obtained with the segmented bend, Figure 6, where *COV*s for tracer gas and velocity at the 3 diameter location were measured to be 77% and 20%, respectively. Also, the pressure coefficient for the segmented elbow was the same as that for the standard elbow, i.e., 0.6.

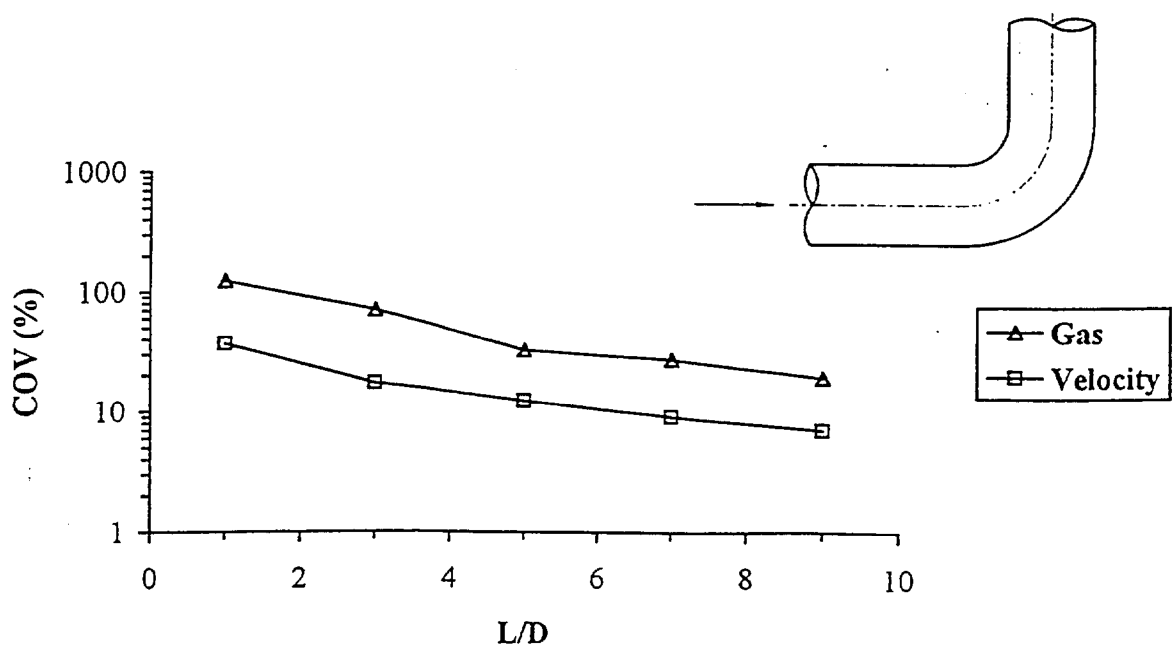


Figure 5. Coefficients of variation for velocity and tracer gas profiles in a straight tube downstream from a standard 90° elbow.

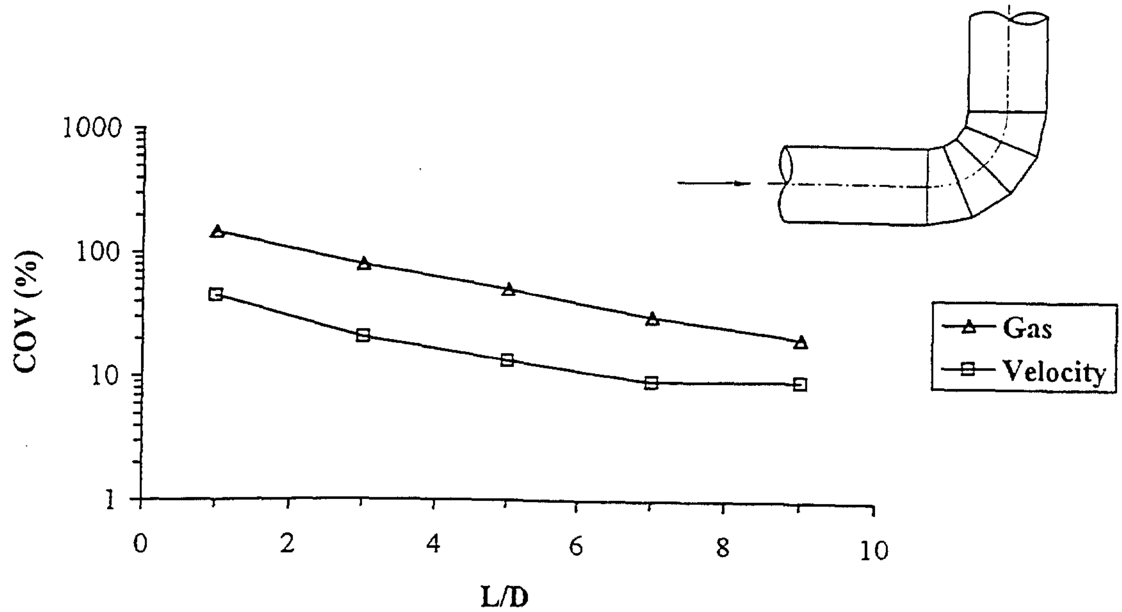


Figure 6. Coefficients of variation for velocity and tracer gas profiles downstream from a segmented 90° elbow.

A ring was placed at the exit plane of the standard elbow. It had an inside diameter of 102 mm and an outer diameter of 154 mm, i.e., the ring blocked 56% of the cross sectional area, Figure 7. At the 3 diameter location, the *COV*s of tracer gas and velocity were 19% and 21%, respectively. At a distance of approximately 5 diameters, the *COV*s of tracer gas and velocity were both less than 10%. The pressure coefficient for this configuration was 5.4, which is about the same as that anticipated for 9 standard elbows in series.

Twelve consecutive gas concentration measurements were taken at the center of the duct at the 9 diameter location for both the standard and the segmented elbows. The ratio of the standard deviation of the gas concentration measurements to the mean of the concentration measurements for the standard elbow was 2.7% and that for the segmented elbow was 1.0%. These values represent the inherent reproducibility of the gas concentration measurement methodology.

Hampl et al.[8] tested the mixing downstream of a 90° elbow and observed the *COV* was about 2.5% at a distance of 9 diameters; however, they introduced tracer gas at four points across the duct in the upstream region of the bend. Also, it appears that the air flow was introduced either directly into the entrance of the elbow or into a straight duct just upstream of the elbow. Without using either flow staighteners in the duct or a bell mouth at the entrance of the duct or elbow, there would be flow separation in the entrance region, which would cause an artificial enhancement of mixing. We tested the 90° standard elbow with the upstream flow straighteners removed from the test fixture and observed tracer gas *COV*s of 33% at 3 diameters and 6% at 9 diameters. In contrast, when the flow straighteners were used, the corresponding *COV*s were 69% and 19%, respectively. This effect of upstream flow conditions suggests the work of Hampl et al. should not be used for characterizing mixing for compliance with the requirements of the revised ANSI N13.1.

Double Elbows. Two elbows were placed in series in two different configurations; namely, one that formed an "S," Figure 8, and the second that formed a "U," Figure 9. The S-configuration gives considerably better mixing than a single bend, with the *COV*s at the 3 diameter location being 45% and 16% for tracer gas and velocity, respectively. The pressure coefficient for this configuration was 1.7. At a distance of approximately 6 diameters, both the tracer gas and velocity *COV*s are less than 10%. The two elbows formed into a "U" configuration were only tested for tracer gas uniformity at the 5 and 9 diameter locations and gave results that were approximately the same as those obtained from tests with a standard elbow. The pressure coefficient is 1.0 for the "U" configuration.

The data from tests with the double elbows suggest that the mixing in a bend is driven by twin vortices of the secondary flow. In the "U" configuration, the twin vortices are setup in the first elbow and continue with the same patterns in the second elbow[13]. However, for the "S" configuration, the twin vortices setup in the first elbow are reversed in direction in passing through the second bend, which causes additional mixing and additional loss of pressure.

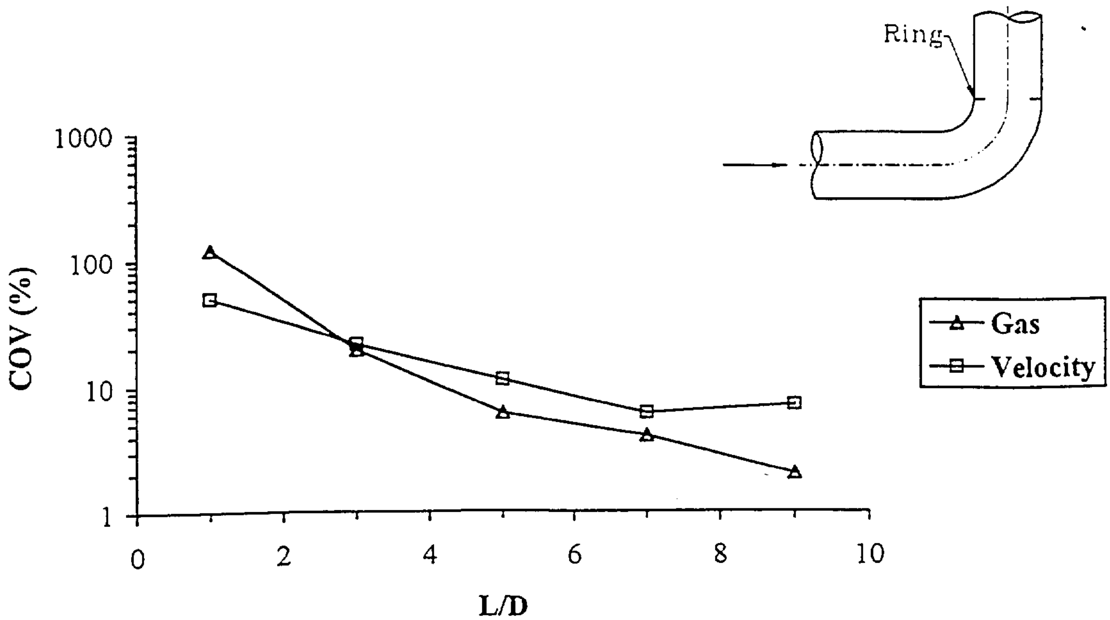


Figure 7. Coefficients of variation for velocity and tracer gas profiles in a standard 90° elbow fitted with a ring at the exit plane. The ring blocked 56% of the flow area.

Housing of Generic Mixer. The generic mixer shown in Figure 1 has internal elements that promote mixing. Tests were conducted in the present study with a housing of generic mixer that had no internal elements. The housing was scaled to provide an exit duct diameter of 152 mm (6 inches), and the apparatus shown in Figure 2 was used for the tests. With reference to Figure 10, the *COV*s for tracer gas and velocity at the 3 diameter location were 17% and 3%, respectively. Within a distance of 4 diameters, both of the *COV*s were less than 10%. Pressure coefficient for the generic mixer housing is 1.2. By comparison, a generic mixer with its internals in place generates *COV*s of less than 7% at the 2.5 diameter location at an energy expenditure represented by a pressure coefficient of 4.5 (McFarland et al., 1998).

Commercial Static Mixers. Three types of commercial static mixers were tested, which are designated herein as Mixers A, B and C. Mixer A, Figure 11, has two sets of concentric vanes that produce rotations in opposite directions. Th outside diameter of Mixer A is approximately 304 mm, and the unit was tested using the apparatus shown in Figure 3. Mixer B (Figures 12 and 13), has two flow deflectors and a tab that cause the flow to be forced to the center of the duct. This mixer is designed to be used with modular units in series, and the tests were conducted with a system comprised of two modules and a system comprised with four modules. This mixer was tested with the apparatus shown in Figure 2. Mixer C, (Figure 14) resembles egg crating with alternate layers of passages misaligned relative to one another. The mixer has a diameter of about 300 mm and tested using the apparatus shown in Figure 3.

Mixer A produced *COV*s of 14% and 3% for the tracer gas and velocity profiles at a distance of 3 diameters downstream from the element, Figure 11. *COV*s for both tracer gas and velocity were less than 10% at a downstream distance of 4 diameters. Tests were conducted at two flow rates through the system, which provided linear velocities of 5.6 m/s and 12.2 m/s. There is little difference in the *COV*s at the two flow rates, which indicates the mixing is controlled by the geometry of the system rather than flow properties such those included in a Reynolds number. The pressure coefficient for Mixer A is 2.1.

Tests with two Mixer B modules in series were conducted at velocites of 7.4 and 15.5 m/s, Figure 12. The mixer produced *COV*s of 3% for tracer gas and 7% for velocity at the 3 diameter location. Both the tracer gas and velocity *COV*s were less than 10% at the 2.5 diameter location. Velocity did not significantly affect the mixing, again indicating that turbulent mixing is controlled by geometry rather than flow properties. The pressure coefficient for two Mixer B modules in series is 5.0.

When tests were conducted with four Mixer B modules in series, the *COV*s for tracer gas and velocity were approximately 2.5% and 5.5% at the 3 diameter location, Figure 13. At a distance of approximately 1.5 diameters, the *COV*s for tracer gas and velocity were both less than 10%. The tests were conducted at two velocities, 6.4 m/s and 12.7 m/s, with similar results obtained at both flow rates. The pressure coefficient for the system with four units in series was 9.1.

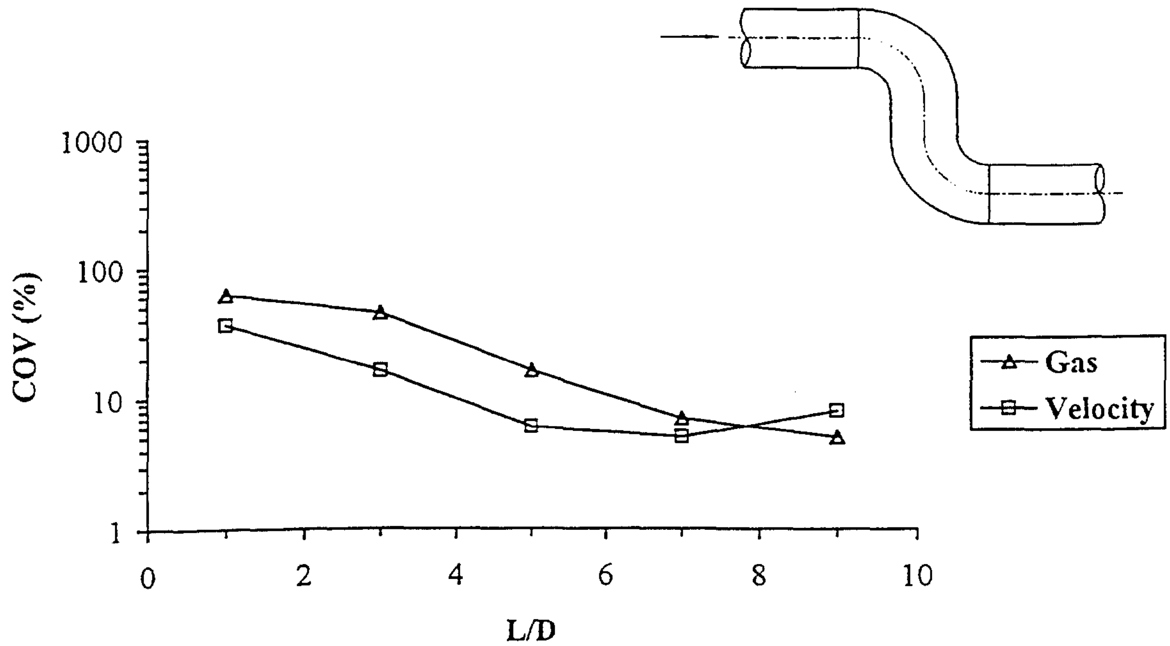


Figure 8. Coefficients of variation for velocity and tracer gas profiles in a mixer comprised of two 90° configured into an "S" shape.

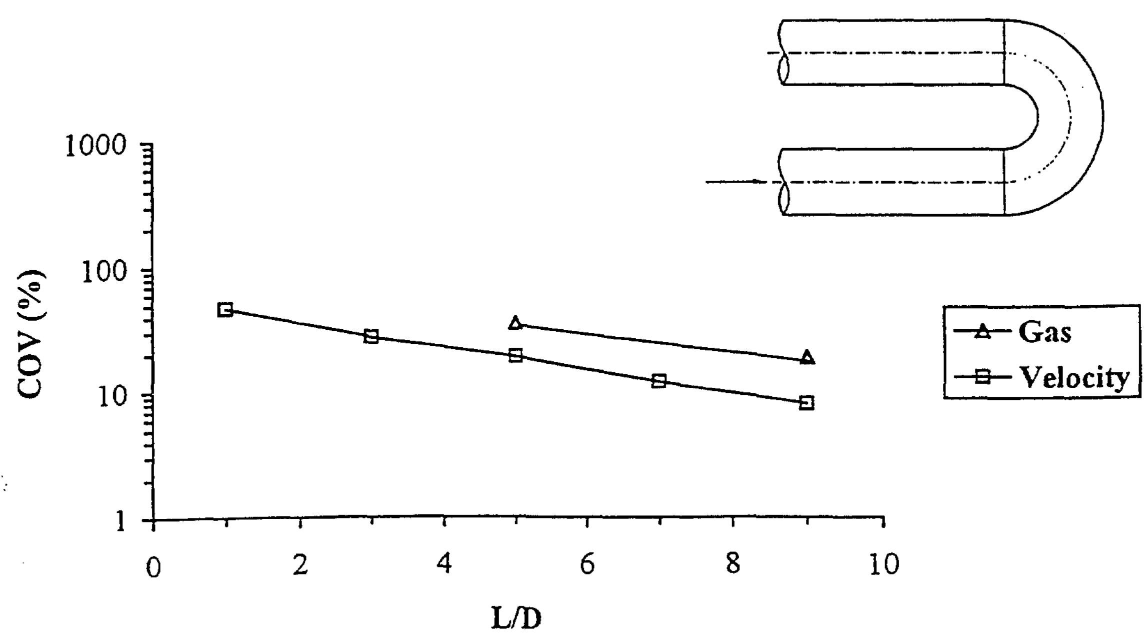


Figure 9. Coefficients of variation for velocity and tracer gas profiles in a mixer comprised of two 90° configured into an "U" shape.

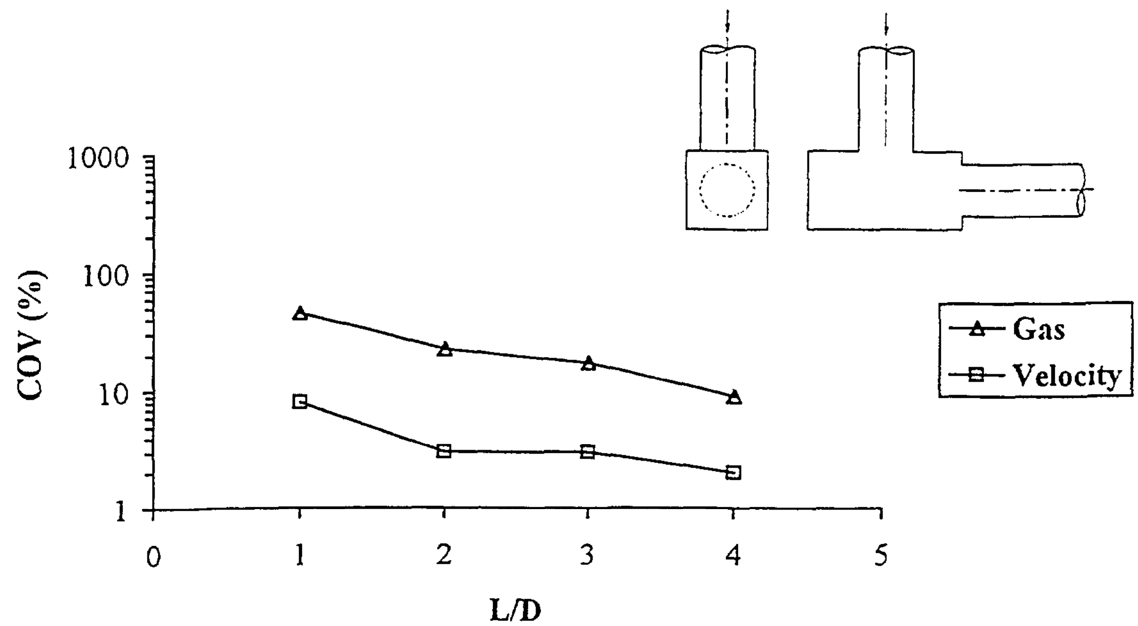


Figure 10. Coefficients of variation for velocity and tracer gas profiles generated by the housing of a generic mixer.

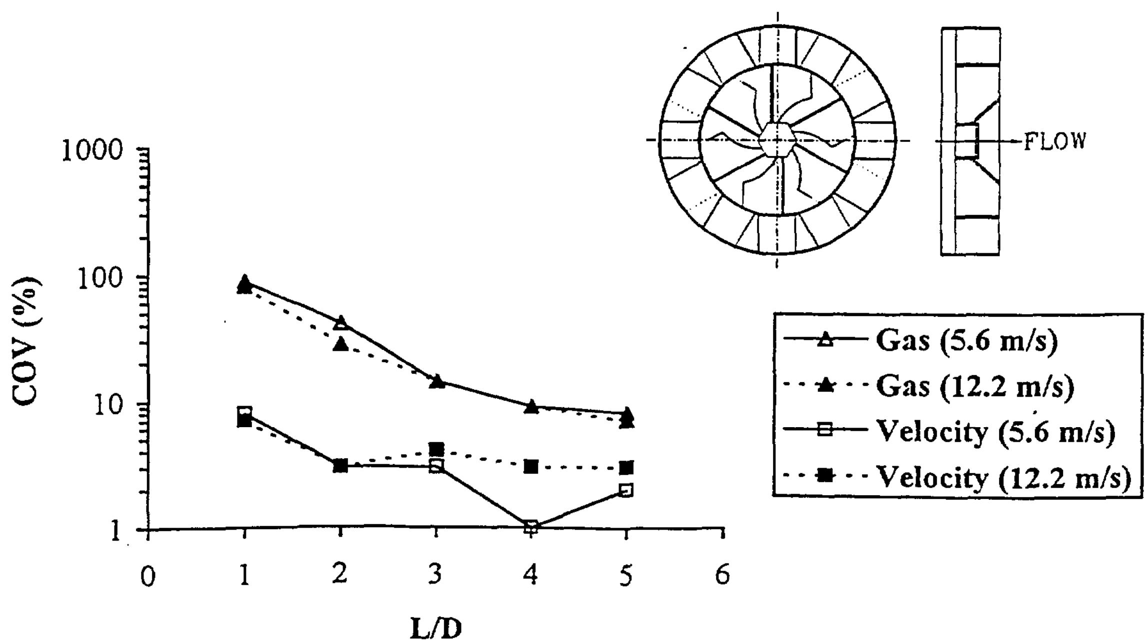


Figure 11. Coefficients of variation for velocity and tracer gas profiles measured downstream of Mixer A.

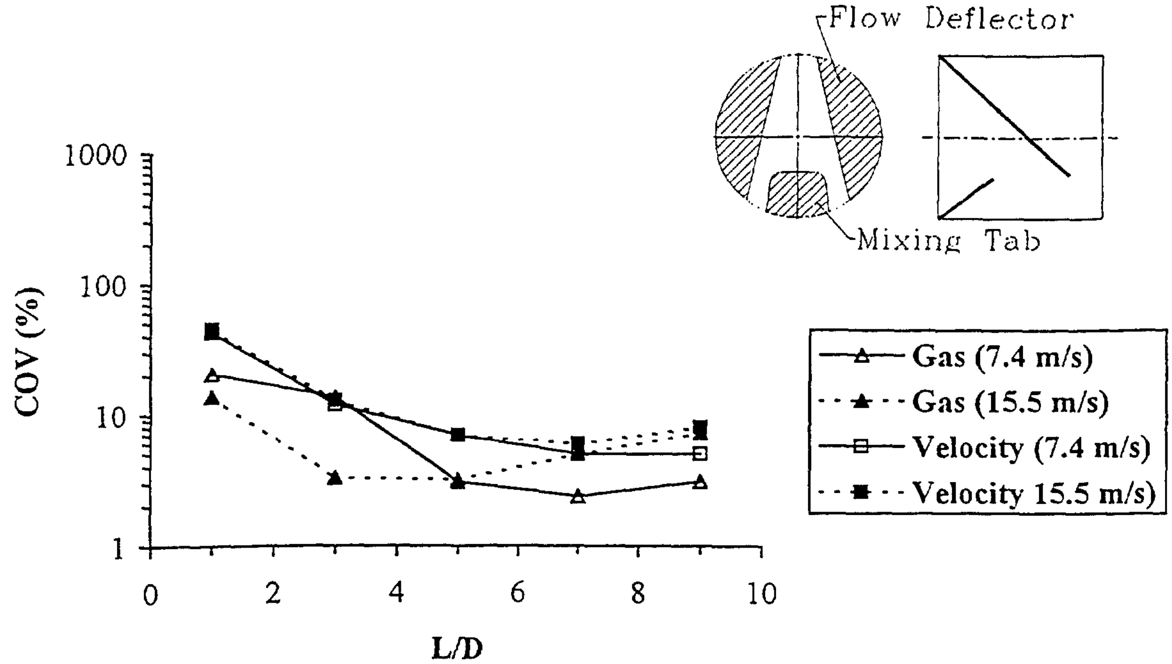


Figure 12. Coefficients of variation for velocity and tracer gas profiles measured downstream of a system comprised of two Mixer B modules in series.

Tests with Mixer C, Figure 14, showed *COV*s of 23% and 9% at a distance of 3 diameters downstream from the exit plane of the mixer. The *COV* for tracer gas did not reach a level of 10% within the maximum *L/D* of 5 diameters that was tested; however, the velocity *COV* was less than 10% even at 1 diameter. Pressure drop across this unit is low as reflected by the pressure coefficient of 0.8. The physical layout of this unit is not conducive to good cross stream mixing – the twisted egg crating arrangement should produce good mixing within each egg crate cell; but, there is no mechanism to affect mixing from one side of a duct to the other.

In several types of tests, twelve replicate tracer gas samples were collected from the center point of a sampling location to check the reproducibility of the methodology. For tests with Mixer A, the reproducibility at the 5diameter location was 3% for the flow velocity of 5.6 m/s and 2% for the flow velocity of 12.2 m/s. For static Mixer B with two modules in series, the reproducibility at the 5diameter location was 1.4% for the velocity condition of 7.4 m/s and 2.1% for the velocity condition of 15.5 m/s. When the four Mixer B modules were used in series, the reproducibility of the tracer gas measurements was 2.3% for the velocity condition of 6.4 m/s and 1.4% for the velocity condition of 12.7 m/s.

## VI. Summary and Conclusions

The proposed revision to the standard method for sampling stacks and ducts in the nuclear industry, ANSI N13.1, is based on the concept of single point sampling at a location where the velocity and contaminant concentration profiles are relatively uniform (*COV*s ≤ 20% over an area that includes at least the center 2/3 of the flow cross section). It would be helpful to those involved in achieving compliance with the requirements of ANSI N13.1 if there were an *a priori* method for determining the degree of mixing in a stack or duct; however, at the present time there are no suitable predictive models. This study has focused on generation of an experimental data base for estimating the mixing downstream of various types of flow disturbances and should provide some designers with insight into the mixing in their proposed ducting systems, and it should provide a basis for some users to achieve acceptable mixing in existing stacks and ducts through use of static

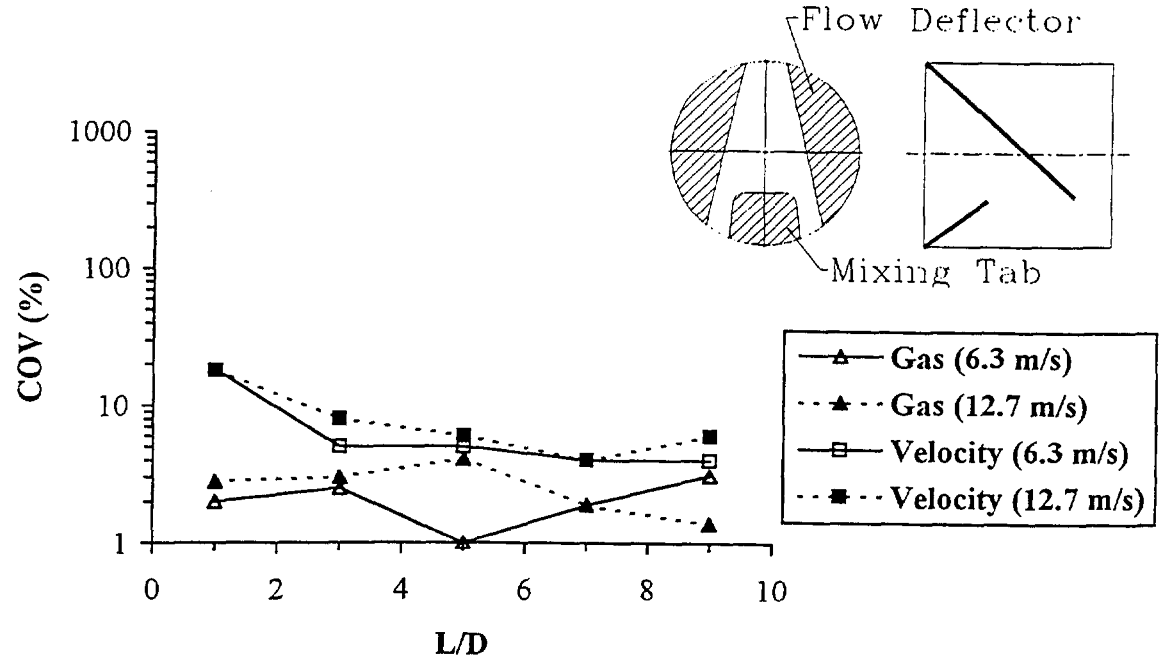


Figure 13. Coefficients of variation for velocity and tracer gas profiles measured downstream of a system comprised of four Mixer B modules in series.

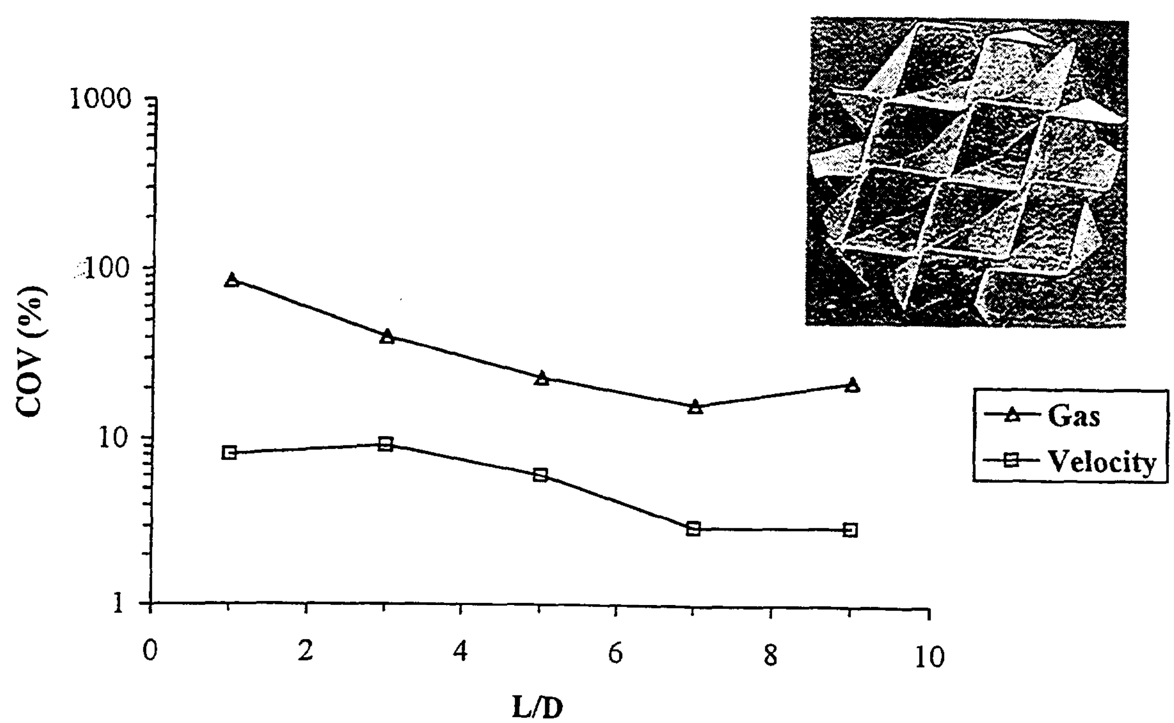


Figure 14. Coefficients of variation for velocity and tracer gas profiles measured downstream of a Mixer C.

mixing elements. Because in some the nuclear applications, there are HEPA filters upstream of possible sampling locations, and those HEPA filters would damp out flow turbulence upstream of the mixing element, most of the testing was done with flow straighteners placed at a distance of 1 diameter upstream of the mixing element.

Tests with 90° elbows showed that considerable distances are needed to achieve suitable mixing. In our studies that use data from laboratory models to predict the performance of field prototypes, we typically set the *COV* criteria at 10%, rather than the 20% used in the proposed revisions to ANSI N13.1. For a 90° elbow preceded by a flow straightener that reduces the scale of turbulence to approximately 6 mm, the *COV* for tracer gas is about 20% even at a distance of 9 diameters. The level of turbulence upstream of the mixing element can significantly affect the mixing downstream of an elbow. If the flow straighteners are removed from the test setup, the tracer gas *COV* is 6% at the 9 diameter location.

Three commercially-available static mixers were tested. Mixer B has flow vanes that promote cross stream mixing whereas Mixer C has twisted egg-crate flow passages that retard cross stream mixing. When two Mixer B modules are used in series, the *COV* of tracer gas is about 3% at a distance of 3 diameters downstream of the mixer. The pressure coefficient is 5.0 for two Mixer B modules in series. In contrast, the gas *COV* for Mixer B at the same location is 23%. Mixer A has vanes that produce concentric counter rotating vortices. This unit produces *COV*s of velocity and tracer gas that are both less than 10% within a distance of 4 diameters downstream of the unit. The pressure coefficient for this unit is 2.1.

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**List of Figures**