A Comparison of Tchebycheff, Equal Area and Tracer Gas Air Flow Rate Measurements

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ABSTRACT

A series of four simultaneous tracer gas and traverse flow rate tests was performed on a specially-fabricated section of square ductwork at the Lagus Applied Technology, Inc. (LAT) facility in Escondido, California. The duct section was essentially the same as that used currently to measure makeup flow rates at ANO.

In order to provide a correlation between tracer gas-determined flow rates and those determined using a traverse technique, flow rate measurements using the tracer gas technique and two traverse methods were undertaken over a range of flow rates encompassing those utilized at ANO during operation of the CREVS in the Pressurization Mode.

Traverse flow rate measurements were performed with a calibrated hot-wire anemometer using the Equal Area method and the Log Tchebycheff (Log T) method. The particular hot wire anemometer used in the testing provides flow velocity data that are corrected to standard conditions for temperature (70 Deg F). In order to allow traverse measurements to be reduced to standard conditions (14.7 psia and 70 Deg F), a digital barometer was used to measure barometric pressure during the traverse flow measurements.

The Log T flow rate data and the Tracer Gas flow rate data are essentially identical when the Log T data are reduced to standard conditions. The flow rate determined by the Equal Area Method (at standard conditions) is approximately 6 % higher than the corresponding Log T flow rate over the approximate range of 400 SCFM to 500 SCFM.

These measurements demonstrate that the Log T method is superior to the Equal Area for determining flow rates in a square duct.

1.0 INTRODUCTION

Within the nuclear power generation industry, duct flow rates are commonly measured using point measurements of air velocity combined with a knowledge of duct area. In rectangular ducts, flow rates are usually measured using either the Equal Area Method or the Log Tchebycheff Method.

In 2001 the inleakage into the Arkansas Nuclear One (ANO) Control Room Envelope was measured using tracer gas techniques. As a part of this testing the makeup flow rates for pressurization air were also measured using a tracer gas technique. However, ANO does not possess the capability in-house to measure makeup flow rates using this technique and instead uses a point measurement traverse technique to measure these flow rates.

In order to allow ANO staff to conduct routine surveillance of makeup flow rates using traverse methods a special duct section has been fabricated. A photo of the duct section is provided in Figure 1. The ANO test duct section is approximately 12 ½ feet long and has a 12 inch by 12 inch cross section. In use, the duct section is temporarily affixed to the CREVS intake.

In order to establish a correlation between the tracer gas determined make up flow rates and those determined by a traverse technique, a series of four tests utilizing both tracer gas and traverse determinations of flow rate were undertaken over a range of flow rates encompassing those utilized at ANO during test operation of the CREVS.

2.0 MEASURING AIR FLOW RATE USING TRACER GAS DILUTION

For flow rate measurements in ducts, ASHRAE [1] recommends that measurement points be located at least 7.5 hydraulic diameters downstream and 3 hydraulic diameters upstream of a disturbance in the flow caused by, for instance an elbow or flow constriction. To encompass measurements in non-circular ducts, the hydraulic diameter is used in this criterion as opposed to duct diameter. For a circular duct the physical diameter is the hydraulic diameter. It is well known to field measurement personnel that very often this criterion cannot be met.

In addition, ASHRAE Standard 111 [2] requires that for a traverse flow rate measurement to be considered as valid more than 75% of the traverse readings must be greater than 10 % of the maximum velocity pressure. Yet sometimes a flow rate is required from a location where this criterion is not satisfied. A flow rate calculated from traverse measurements under these conditions is in error by an unknown amount. Standard 111 also requires a minimum of 25 measurement points even in relatively small ducts. For rectangular duct larger than 4.5 feet on any side the standard recommends a maximum measurement spacing of 8 inches. This requirement can necessitate a substantial investment of time in order to obtain the necessary data points.

Real world practice often dictates that flow must be measured at duct locations where either the measurement point spacing or the velocity pressure criterion is not satisfied. Thus obtaining sufficient valid point measurements of flow velocity can represent a challenge to field engineering personnel tasked with obtaining this data.

For many years it has been known that a method to measure duct or stack flow rates exists that does not require Pitot tube or hot wire anemometer traverses. This method entails the use of a tracer gas dilution method. This method is a *volumetric* as opposed to a point measurement. The methodology is described in ASTM Standard E2029-99 “Standard Test Method for Volumetric and Mass Flow Rate Measurement using Tracer Gas Dilution” [3].

This technique has been used in the mine engineering, industrial hygiene and energy conservation communities, but has been largely ignored in the ventilation engineering community [4,5,6]. Several examples of the use of tracer flow rate measurements within the nuclear power industry have been described in earlier papers [7,8].

The tracer gas method relies on the dilution of a tracer gas to infer flow rate through a section of a stack or a duct. To undertake a tracer gas flow rate measurement, a gaseous tracer is continuously metered into a flowing duct at a known rate. After allowing for mixing, air samples are collected at a location downstream of the injection point and the concentration of tracer gas is measured. Assuming that the tracer gas is well mixed within the duct, the rate of flow is readily calculated from the ratio of the tracer injection flow rate to the diluted concentration as follows:

$$Q = IC \times IF / (C_{av} - C_{us}) \qquad (1)$$

where

Q = Stack (or duct) Flow Rate
IC = Tracer Injection Gas Concentration
IF = Tracer Gas Injection Flow Rate
C_{us} = Tracer gas concentration upstream of injection location
C_{av} = Mean tracer gas concentration in stack downstream of injection location

This equilibrium concentration in the stack or duct is inversely proportional to the flow rate through the duct (as given by equation (1)). Thus, the measured concentration allows calculation of the flow rate since the injection flow rate is known. The basic test setup is shown in Figure 2.

Note that equation (1) does not require knowledge of the duct area since a tracer gas flow rate measurement is intrinsically a volumetric measurement. Further, all quantities in equation (1) can be assigned an experimental uncertainty. Since the criterion for validity of equation (1) is that the tracer gas be well mixed in the flowing stream, departures from ideal mixing represent measurement uncertainties. Thus, unlike a point traverse measurement in which it is impossible to obtain a valid statistical estimate of measurement uncertainty due to the fact that the flow velocity profile is indeterminate for a given flow and duct configuration, in this technique one can calculate a statistically defensible estimate of measurement uncertainty.

The fact that the tracer concentration must be well mixed implies that the concentration values along a plane perpendicular to the axis of the duct must be constant. This provides the basis for a statistical analysis of measurement uncertainty. Departures from constant concentration along this plane represent a direct departure from the well-mixed condition and can be addressed by statistical methods.

In contrast, Figure 3 illustrates an ideal velocity profile across a plane perpendicular to the axis of a circular duct for both turbulent and laminar flows. In practice this ideal flow profile is seldom achieved. Since the flow profile is not constant across the duct and often is unknown, one cannot calculate the magnitude of departures from an ideal case. Thus from a measurement perspective it is not possible to perform a rigorous statistical analysis of the measurement uncertainty intrinsic to a point traverse flow rate measurement.

3.0 EXPERIMENTAL TECHNIQUES AND MEASURED DATA

Tracer gas and traverse flow rate tests were performed on a specially-fabricated section of ductwork during April 2006 by a team of test engineers from NCS Corporation (NCS) and Lagus Applied Technology, Inc. (LAT) at the LAT facility in Escondido, California. The duct section was essentially the same as that used currently to measure makeup flow rates at Arkansas Nuclear One (ANO) during test operations on the Control Room Emergency Ventilation System (CREVS).

Flow rate measurements using both the tracer gas technique and traverse methods were performed simultaneously over a range of flow rates to provide a correlation between tracer gas-determined flow rates and those determined using a traverse technique.

The electronegative gas, sulfur hexafluoride (SF6), was used as a tracer in the flow rate tests. This gas is generally recognized as non-toxic and non-reactive. Since it is easily detectable in minute quantities by means of electron capture gas chromatography, SF6 is an ideal tracer gas for ventilation system performance investigations.

In the flow rate testing, SF6 tracer gas measurements were performed by means of chromatographic instrumentation manufactured for field use by LAT. On site calibration using certified calibration standards was performed prior to initiation of the testing to ensure that instrument drift and any sensitivity variations would be minimized. Analytical sensitivity to SF6 ranged from 500 parts per trillion to approximately 35 parts per billion.

Figures 4, 5, 6 and 7 illustrate the experimental setup. A duplicate of the ANO flow rate test duct section was connected to a variable speed vane axial fan. The fan, in turn, was connected to a 20 foot section of 12 inch spiral duct. This duct was, in turn, connected to lengths of 14 inch spiral duct which ultimately exited the test area. This 14 inch duct was connected to a vertical run of 20 feet of 14 inch duct that acted as an exhaust stack.

For the tracer gas flow rate tests, a cylinder containing 103.6 ppm SF6 in nitrogen was used as the injection gas. The SF6 injection concentration was analyzed and certified to +/- 1% (traceable to NIST) of the measured concentration by an independent laboratory. Note that 28.3 standard liters per minute (SLM) is equal to 1 standard cubic foot per minute (SCFM).

A specially fabricated mass flow controller controlled tracer gas injection rates. Tracer gas injection rates were measured using a Sierra Model 821 Top Trak Thermal Mass Flowmeter. Note that since the mass flow meter is calibrated at standard conditions (14.7 psia and 70 Deg F), equation (1) implies that all tracer gas flow rate measurements will also represent duct flow rates at standard conditions.

Tracer gas was injected through three 1/4 inch OD stainless steel tubes that were plugged at one end. Each of the tubes possessed five 0.08-inch in diameter holes spaced equally along the tubing length. These tubes were emplaced into the duct at ¼, ½ and ¾ of the width of the duct through Vent Lok fittings possessing specially configured Vent Lok caps equipped with thermocouple type Swage™ fittings to ensure a leak tight insertion of the tubes into the flowing air stream within the duct.

These stainless steel injection tubes, in turn, were connected to the mass flow meter via lengths of polyethylene tubing. The tracer gas injection flow rate used for each test is provided in Table 1.

Traverse flow velocity measurements were obtained with a calibrated hot-wire anemometer using the Equal Area method and a 25 point Log Tchebycheff method [9]. These measurements were undertaken using a TSI Model 8350 Thermoanemometer. This anemometer provides flow velocity data that are corrected to standard conditions for temperature (70 Deg F).

During each set of traverse measurements the barometric pressure (denoted P_{bar} in the flow rate equations) was recorded to allow reduction of the calculated flow rate to standard conditions of 14.7 psia (denoted as P_{std} in the flow rate equations) and 70 Deg F.

The traverse locations within the square section of duct were determined by the Log T method using a 5 by 5 grid. Twenty-five traverse points (five individual five point traverses) were obtained using the Log Tchebycheff spacing for the 12 inch by 12 inch duct at a location approximately 2.5 feet from the mouth of the ANO flow test duct section. Twenty traverse points (two perpendicular 10 point traverses) were obtained using the Equal Area spacing for a 12 inch round duct at a location approximately 12 feet downstream of the vane axial fan.

Three sets of traverse flow velocity measurements were obtained during the same time period (approximately one hour) as the tracer gas sampling. Tracer gas samples were obtained on two perpendicular diameters at the Equal Area traverse location. Samples were obtained at 2”, 4”, 6”, 8” and 10” across one diameter. Samples along the perpendicular diameter were obtained at 2”, 4”, 8”, and 10”. Thus nine samples were obtained for each sample set.

Air samples were obtained using disposable polypropylene syringes in conjunction with a pump/manifold sampling system. The pump/manifold sampling system consists of a pump connected to a multi-position sampling valve. A Swagelok™ tee and septum fitting was affixed to the sample pump exhaust. This allowed duct air samples to be obtained using polypropylene syringes. A length of polyethylene tubing was connected to a stainless steel tube that was moved along a diameter within the duct to sequentially obtain tracer gas-air samples.

During each test, a background air sample was taken at the intake of the test duct section. No detectable tracer gas concentration was measured at this location. Thus any concentration values at the intake are below the detection limit of the analyzers (approximately 0.05 ppb). This low value demonstrated that no re-entrainment from the exhaust stack occurred during the testing and implies that the value of C_{us} in equation (1) could be safely ignored.

Mean tracer concentration data are provided in Table 2 and are denoted as Test #F1 through #F5 where the # sign is replaced by the numbers 1, 2, 3, and 4 respectively corresponding to the four tests. From these data it is clear that the tracer concentration within the duct was adequately mixed. The standard deviation of tracer measurements expressed as a percentage of the mean is also shown for each sample suite.

Parenthetically it should be noted that these tests were undertaken during an unusually windy period in southern California. The variability of these winds resulted in greater than normal variability in the duct flow rate (due to wind effect on the exhaust stack) and hence a greater than normal variability in the duct tracer concentrations. The resulting standard deviations are at least a factor of two larger than those that are usually encountered using this technique.

The standard deviation is a statistical measure of how much a collection of measurements differs from the mean of the collection. The smaller the standard deviation, the closer individual values in the collection are to the mean. Inspection of the concentration data in Table 2 discloses that the standard deviation of the mean concentration (relative standard deviation) for the four sample suites ranged from approximately 2.3 % to approximately 3.8 % thereby confirming that tracer concentration was adequately mixed within the duct.

Measured results are provided in Table 3 showing Log T flow rate, Tracer Gas Flow rate, and Equal Area flow rate in the approximate range of 400 SCFM to 500 SCFM.

4.0 DISCUSSION

Regression analysis of the tracer gas flow rate in SCFM as a function of the measured Log T flow rate in SCFM yields the following equation that is valid over the approximate range of 400 SCFM to 500 SCFM:

$$\textbf{Flow Rate (by Tracer Gas Method)} = 0.986 \times \textbf{Flow Rate (by Log T Method)} \times (P_{bar}/P_{std}) + 10.4$$

Regression analysis of the flow rate in SCFM determined using the Equal Area method as a function of the flow rate in SCFM determined by the Log T method yields the following equation that is valid over the approximate range of 400 SCFM to 500 SCFM:

$$\textbf{Flow Rate (by Equal Area Method)} = 1.101 \times \textbf{Flow Rate (by Log T Method)} \times (P_{bar}/P_{std}) + 20.4$$

Note that these equations assume that duct flow velocities are measured by a temperature compensated anemometer such as the TSI Model 8350.

The 25 point traverse Log T flow rate data and the Tracer Gas flow rate data are statistically indistinguishable when the Log T data are reduced to standard conditions. The flow rate determined by the Equal Area Method (at standard conditions) is approximately 6 % higher than the corresponding Log T flow rate over the approximate range of 400 SCFM to 500 SCFM. A plot of these two equations is provided in Figure 7.

Since, as discussed above, it is not possible to perform a rigorous uncertainty analysis of the traverse data, no uncertainty analyses are reported for the tracer gas flow rate data. However the regression line for the tracer gas-determined and the Log T-determined flow rates exhibits a slope of essentially unity.

The Log T method has been demonstrated to provide a more realistic measurement of the flow rate in a duct by means of a series of very closely spaced Pitot tube traverse measurements (140 points on a 14 x 10 grid in a 28 inch x 20 inch duct) [10]. The reason that the Log T method is more precise is that the method obtains data points closer to duct walls thereby accounting for increased friction loss (and hence lower air velocities) close to the walls. However, obtaining such a large number of points is not a viable option for everyday flow rate measurements. For the 28 x 20 duct the Log T Method calls for a 5 x 5 measurement grid of 25 points.

The fact that the tracer gas method is based on the conservation of mass and is flow rate and duct size independent (subject to the criterion of good mixing of the tracer gas) suggests that the tracer gas method can be used as a primary calibration technique for point velocity traverse measurements at any given duct location.

Calibration of a traverse location by this method would be especially useful at those locations where measurements must be obtained even though there is doubt about the veracity, the validity, or the actual utility of point traverse measurement data. Once a point traverse location is validated or calibrated by the tracer gas technique, plant personnel can have added confidence that traverse data obtained at this location accurately represent flow rate data.

5.0 CONCLUSIONS

Simultaneous traverse and tracer gas flow rate tests were performed on a specially-fabricated section of ductwork to investigate the relationship between the flow rate determined by the tracer gas method, the Log Tchebycheff method and the Equal Area method.

The Log T flow rate data and the Tracer Gas flow rate data are statistically indistinguishable when the Log T data are reduced to standard conditions (14.7 psia and 70 Deg F). The flow rate determined by the Equal Area method (at standard conditions) is approximately 6 % higher than the corresponding Log T flow rate over the range of approximately 400 SCFM to 500 SCFM.

More generally, since the tracer gas method is based on conservation of mass principles and is flow rate ass well as duct size (and shape!) independent-subject to good mixing-this method can be used to provide in-situ calibration of flow measurement devices such as air flow stations, annubar dP sensors, rotating vane anemometers, and other flow measurement devices

6.0 REFERENCES

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TABLE 1

Tracer Gas Injection Flow Rates
(103.6 ppm SF6 in N2)

Test #	Injection Flow Rate (SLM)
1	2.51
2	2.53
3	3.02
4	3.03

TABLE 2

Concentration Means for Flow Rate Tests
(Concentration in ppb)

TEST	Cav	TEST	Cav	TEST	Cav	TEST	Cav
1F1	23.56	2F1	20.98	3F1	23.13	4F1	22.33
1F2	22.97	2F2	19.58	3F2	22.71	4F2	22.82
1F3	22.82	2F3	20.83	3F3	23.70	4F3	21.49
1F4	22.24	2F4	20.10	3F4	24.06	4F4	21.60
1F5	21.30	2F5	19.80	3F5	23.06	4F5	21.96
MEAN	22.58	MEAN	20.26	MEAN	23.33	MEAN	22.04
RSD	3.8%	RSD	3.1%	RSD	2.3%	RSD	2.5%

TABLE 3

Tracer Gas Flow Rate Test Results (SCFM*)

TEST	LOG T FLOW RATE	TRACER FLOW RATE	EQ AREA FLOW RATE
1	402	406	430
2	449	456	462
3	473	474	495
4	499	503	539

* Referenced to 70 Deg F and 14.7 psia

Figure 1. Photo of ANO duct flow rate section

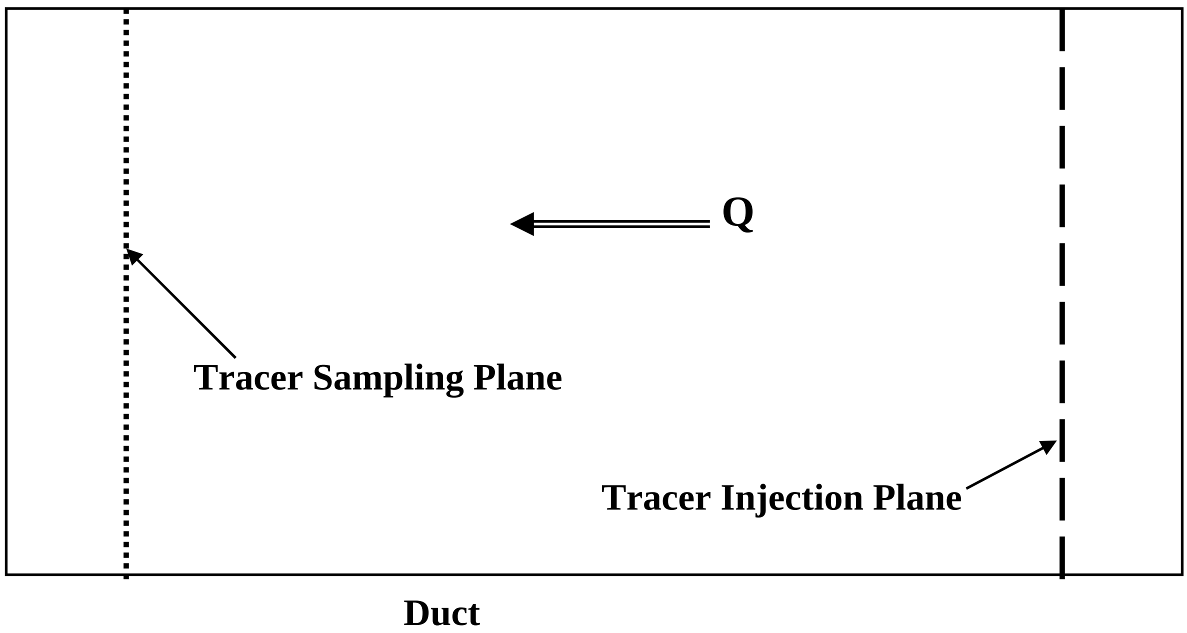

Figure 2. Schematic representation of tracer gas flow rate test.

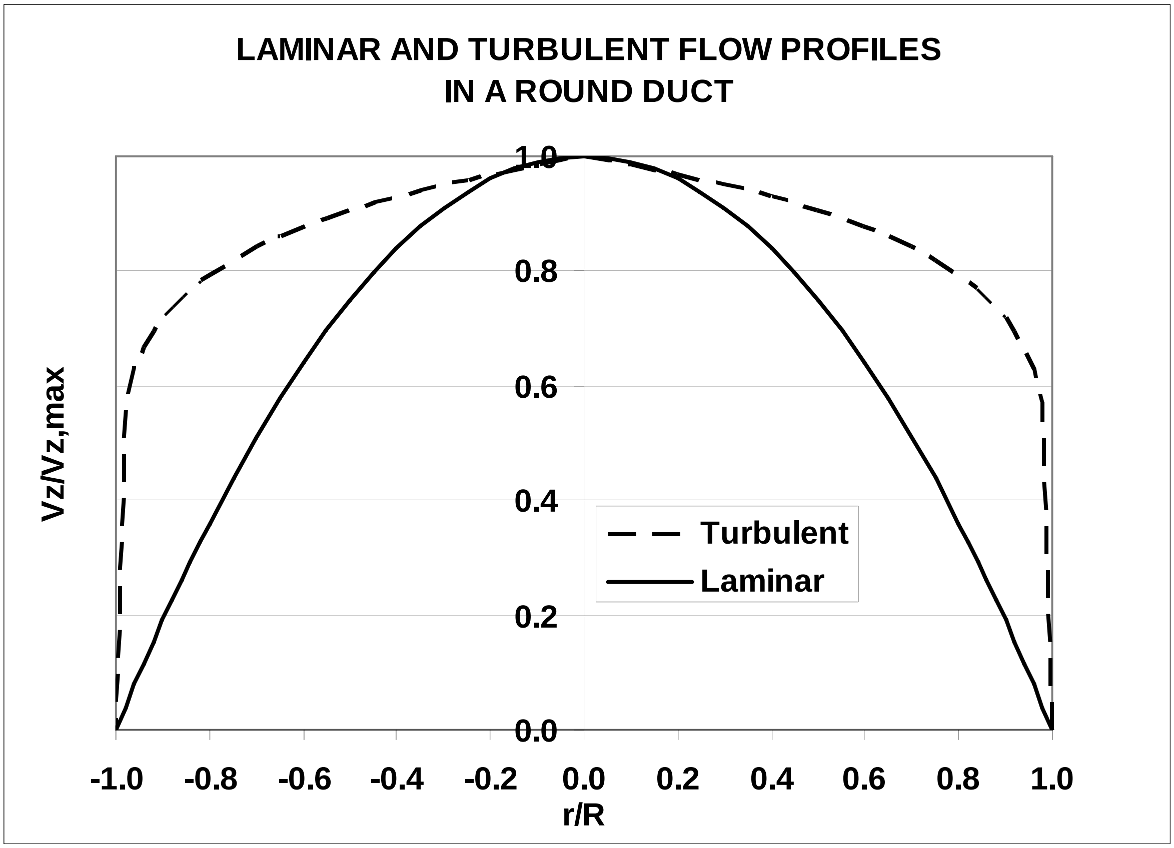

Figure 3. Laminar and Turbulent Flow Velocity in a Circular Duct

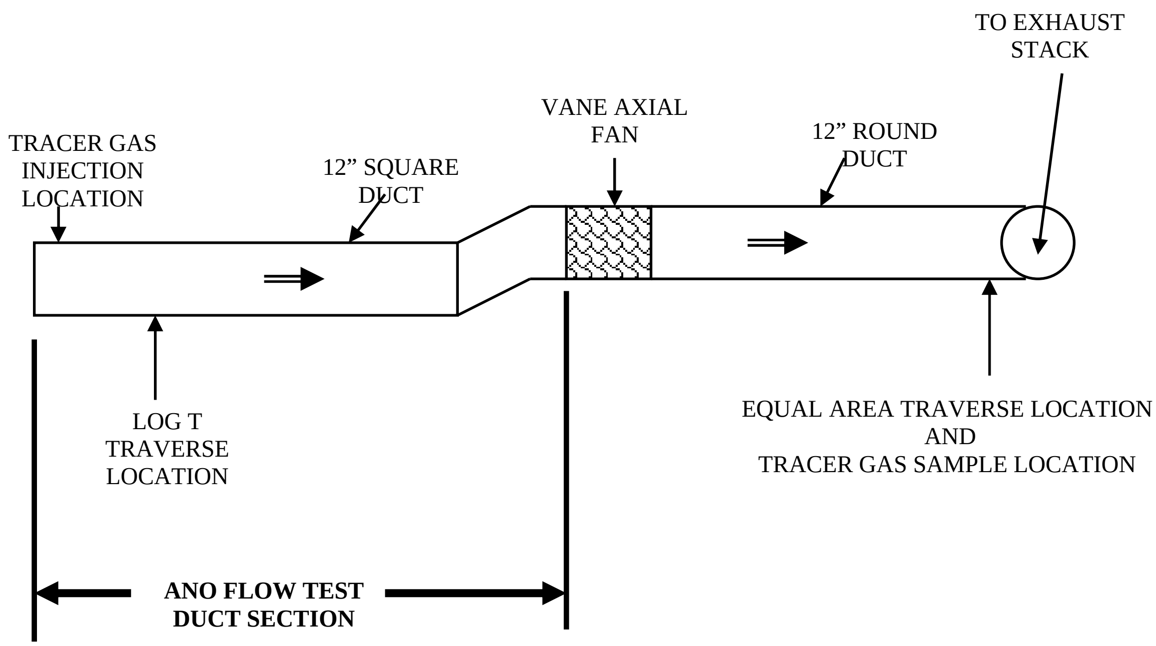

Figure 4. Schematic representation of ANO duct flow rate test.

Figure 4. Tracer injection location showing injection stingers mounted in Vent Lok fittings.

Figure 5. ANO duct section, van axial fan, and transition to 12 inch spiral duct.

Figure 6. Transition to 14 inch duct and connection to exhaust stack

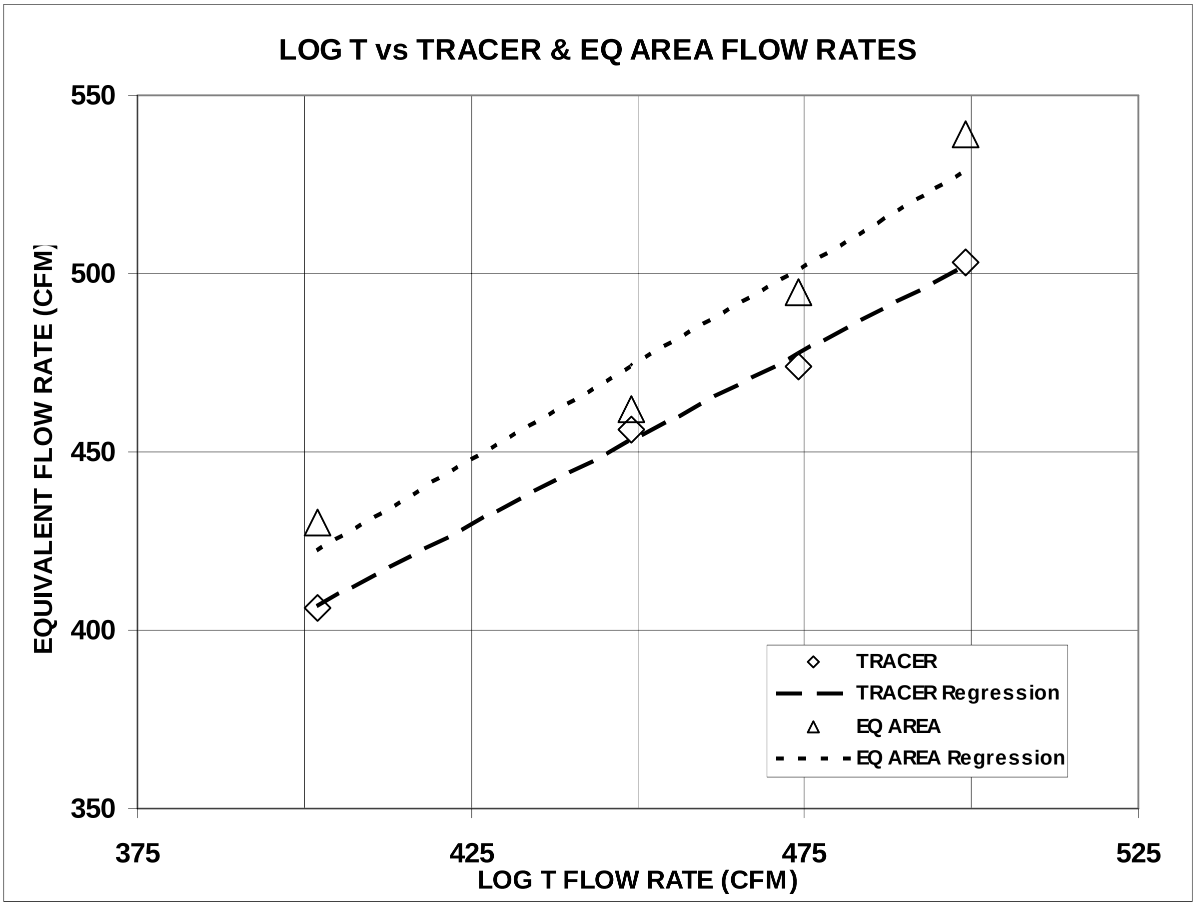

Figure 7. Log T flow rate versus Tracer Gas flow rates and Equal Area flow rates.