METHODOLOGY TO QUANTIFY LEAKS IN AEROSOL SAMPLING SYSTEM COMPONENTS

A Thesis

by

VISHNU KARTHIK VIJAYARAGHAVAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2003

Major Subject: Mechanical Engineering

METHODOLOGY TO QUANTIFY LEAKS IN AEROSOL SAMPLING SYSTEM COMPONENTS

A Thesis

by

VISHNU KARTHIK VIJAYARAGHAVAN

Submitted to Texas A&M University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Approved as to style and content by:

A. R. McFarland (Chair of Committee)	Dennis O'Neal (Member)
Yassin A. Hassan (Member)	Dennis O'Neal (Head of Department)

August 2003

Major Subject: Mechanical Engineering

ABSTRACT

Methodology to Quantify Leaks in Aerosol Sampling System Components. (August 2003)

Vishnu Karthik Vijayaraghavan, B. Tech., Indian Institute of Technology, Madras, India

Chair of Advisory Committee: Dr. A. R. McFarland

Filter holders and continuous air monitors (CAMs) are used extensively in the nuclear industry. It is important to minimize leakage in these devices and in recognition of this consideration, a limit on leakage for sampling systems is specified in ANSI/HPS N13.1-1999; however the protocol given in the standard is really germane to measurement of significant leakage, e.g., several percent of the sampling flow rate. In the present study, a technique for quantifying leakage was developed and that approach was used to measure the sealing integrity of a CAM and two kinds of filter holders. The methodology involves use of sulfur hexafluoride as a tracer gas with the device being tested operated under dynamic flow conditions. The leak rates in these devices were determined in the pressure range from 2.49 kPa (10 In. H_2O) vacuum to 2.49 kPa (10 In. H_2O) pressure at a typical flow rate of 56.6 L/min (2 cfm). For the two filter holders, the leak rates were less than 0.007% of the nominal flow rate. The leak rate in the CAM was less than 0.2% of the nominal flow rate. These values are well within the limit prescribed in the ANSI standard, which is 5% of the nominal flow rate. Therefore the limit listed in the ANSI standard should be reconsidered as lower values can be

achieved, and the methodology presented herein can be used to quantify lower leakage values in sample collectors and analyzers. A theoretical analysis was also done to determine the nature of flow through the leaks and the amount of flow contribution by the different possible mechanisms of flow through leaks.

DEDICATION

To my parents.

ACKNOWLEDGEMENTS

I would like to express my heartfelt gratitude to my advisor, Dr. Andrew R. McFarland, for his excellent guidance and motivation. His patience and encouragement during the study has been a source of inspiration for me. I would like to thank my committee members, Dr. Yassin A. Hassan and Dr. Dennis O'Neal, for their suggestions and review of my work.

This study was performed under funding provided by Westinghouse Savannah River Company (WSRC) with the contract (T.O. GA 0071) administered by the Education, Research & Development Association (ERDA) of Georgia Universities. Mr. Brent C. Blunt is the project officer for WSRC and Dr. Katib A. Karam is the contract administrator for ERDA. Their financial support for this work is gratefully acknowledged.

I am thankful to Carlos Ortiz for his suggestions during the experimental stage of the work. I would like to thank Hammad Irshad for his help during the initial setting up of the experiment. I thank John Haglund for his help and for the useful discussions I had with him. I would like to thank all other ATL members for their encouragement and support.

TABLE OF CONTENTS

Page

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

INTRODUCTION

Leak testing can be broadly classified into two types. The first involves finding the location of the leaks and the second involves quantifying the leak from or into a device. Methods to locate leaks include gas sniffing, ultrasonic testing (Sheen et al. 2000), chemical penetration and measurement of change in pressure (Turner and Mudford 1988). Methods that have been employed in the quantification of leaks include bubble testing (Bloomer 1973), pressure decay testing and testing using tracer gas (Reich 1987). Helium (Bley 1993; Sheen et al. 2000), hydrogen and sulfur hexafluoride (Nelson 1969; Tingey et al. 2000) are the most common tracer gases used in leak detection, but hydrogen is not as commonly used as the other two due to safety considerations. The bubble test is appropriate to quantify gross leaks; it does not detect minute leaks. The sensitivity of the pressure decay technique is affected by the size of the component for which the leak is being measured. Moreover, when the leak is very small, it may take a long time to measure the leak characteristics using a pressure decay method.

In this study, sulfur hexafluoride (SF_6) was chosen to be used as tracer gas to detect leaks because its concentration can be measured by gas chromatography whereas the concentration of helium or hydrogen is usually measured using mass spectrometry. It is easily detected at low concentrations, and it can be easily separated from other gases using a gas chromatograph column. The background concentration of sulfur hexafluoride in the ambient atmosphere is also very low, i.e., approximately 4.2 ppt (IPCC 2001) and also it is inert to chemical reactions, non-toxic and non-flammable.

This thesis follows the style and format of Health Physics Journal.

Most previous attempts at leak detection were static in nature (Nelson 1969; Bley 1993; Tingey et al. 2000; Sheen et al. 2000), where the component was either filled with tracer gas or kept in a gas charged chamber. The rate at which the tracer gas accumulated either in the device or the chamber was used to quantify the leak. In this paper we attempt to quantify the leak under actual working condition of the components. Therefore we allow the flow of air through the components while measuring the leak rate. This dynamic testing is particularly germane to air sampling components that must meet numerical leakage criteria, because static testing may influence the integrity of some seals.

In previous studies (Baron et al. 2002 a, 2002 b) the leakage around filters in filter holders was investigated. In those studies the primary concern was particle leakage around filters and not the leakage occurring between the environment and the filter holder. In contrast to that, in our present study we focused on external leakage between the filter holder and environment.

It is required by ANSI (ANSI/HPS N13.1-1999) that a sampling system be inspected for leaks at the time of installation, when any significant maintenance is performed or during a routine planned inspection (e.g., annual). Methodology is suggested for measuring leaks which involves plugging the inlet of the nozzle and attaching a mass flow meter to the exit port of the collector or analyzer. A vacuum source would be attached to the flow meter and the absolute pressure in the flow tube between collector or analyzer and vacuum source would be maintained at about the same level as that experienced during actual sampling. In nuclear applications, use of this

approach could be undesirable because the nozzles may be relatively inaccessible or because of safety concerns related to breaching the integrity of seals in a contaminated stack or duct.

The leakage limit set in the ANSI standard, 5% of the sample flow rate, is quite high in comparison with actually achievable levels. While the flow meter technique may be compatible with leakage rates that are in the percentage range, it is not particularly useful if the leakage is on the order of 0.01%, where flow rates on the order of 1 mL/min would need to be measured.

In addition to quantifying leakage of the overall sampling system, there is a need for nuclear facilities to have a reference method to specify the leakage of collectors and analyzers. Facilities may wish to know the leakage rates when they procure collectors and analyzers, and vendors may wish to show the effectiveness of their systems in either minimizing errors caused by leakage or in precluding personnel exposures that could be caused by out-leakage of contaminated samples from collectors and analyzers.

Herein, a simple and effective means to quantify either in-leakage or out-leakage of a collector or analyzer is provided, and the results from testing three devices is compared with the ANSI criterion. The leak testing was performed on two filter holders and a prototype CAM. An exploded view of the CAM is shown in Fig. 1 and the flow path through the CAM is depicted in Fig. 2. The exploded views of the two filter holders, which are identified as FH_1 and FH_2, are shown in Figs. 3 and 4.

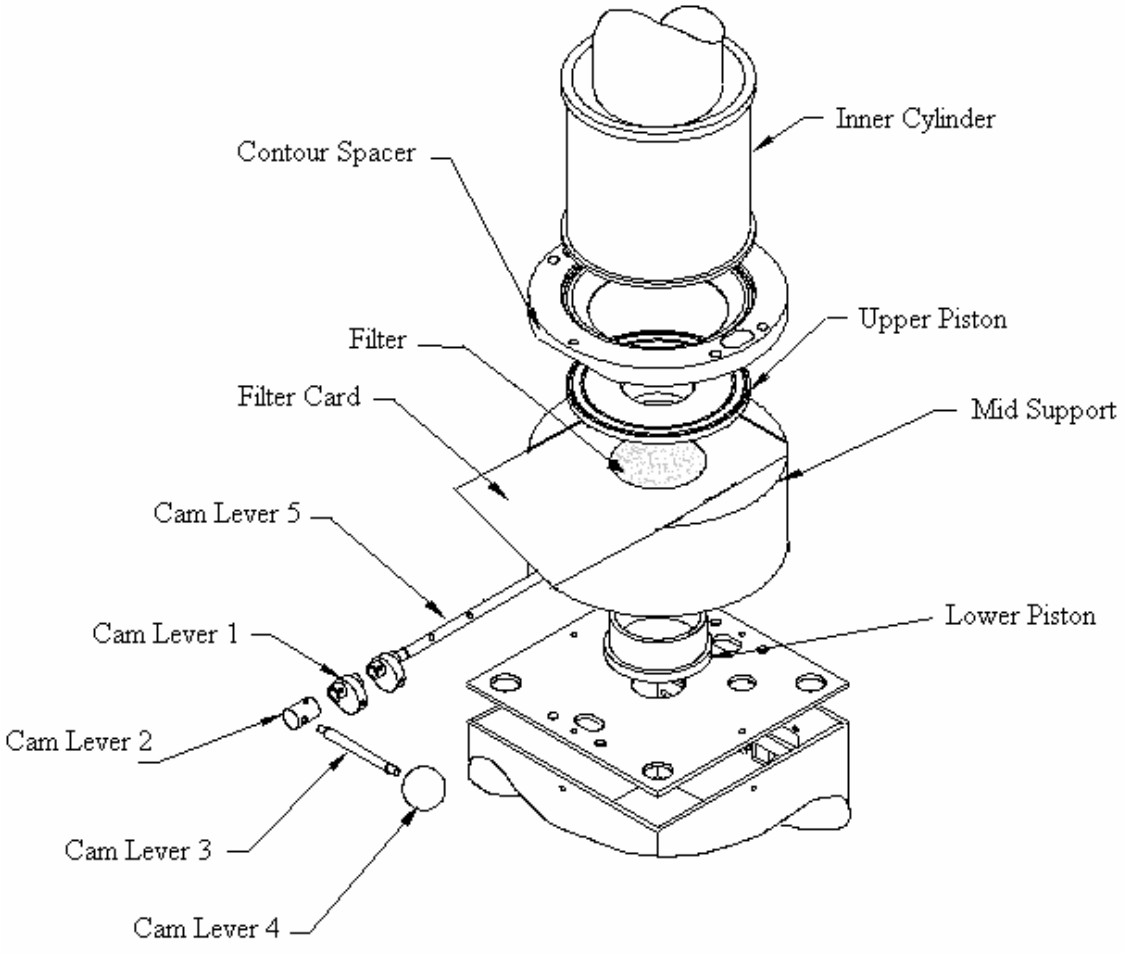

Figure 1. Exploded view of CAM

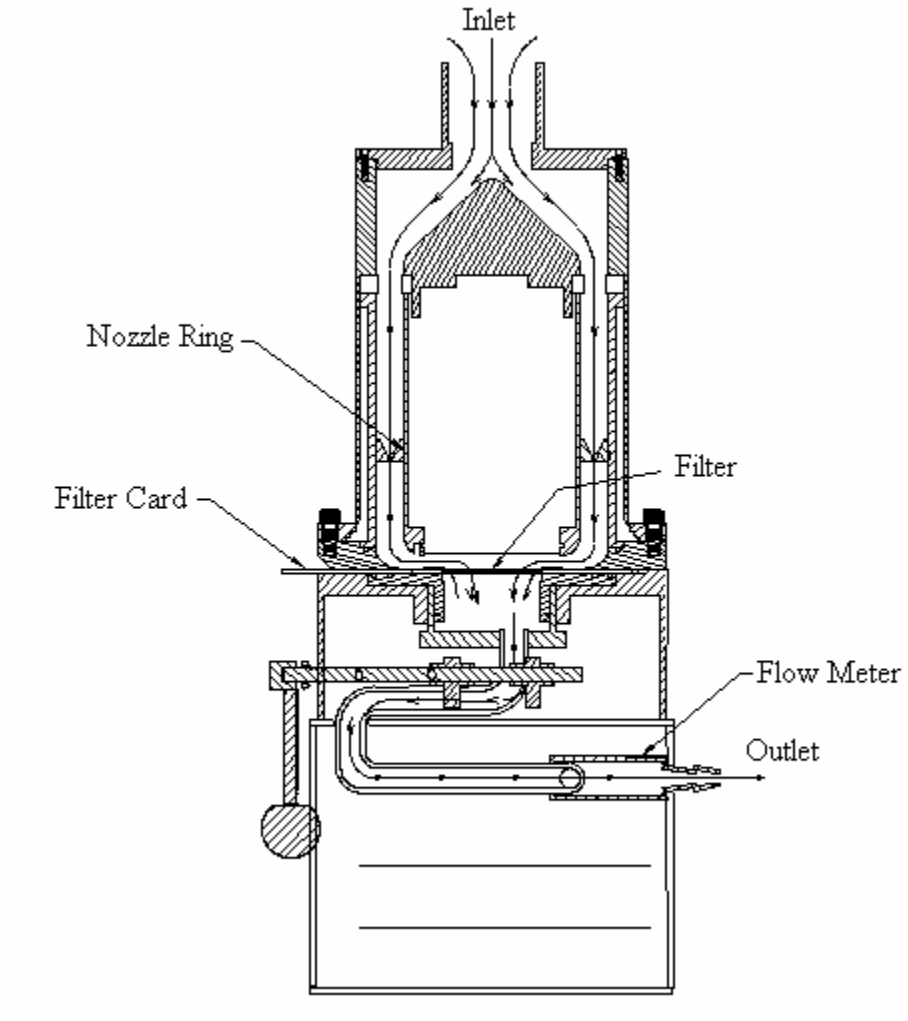

Figure 2. Flow schematic of CAM

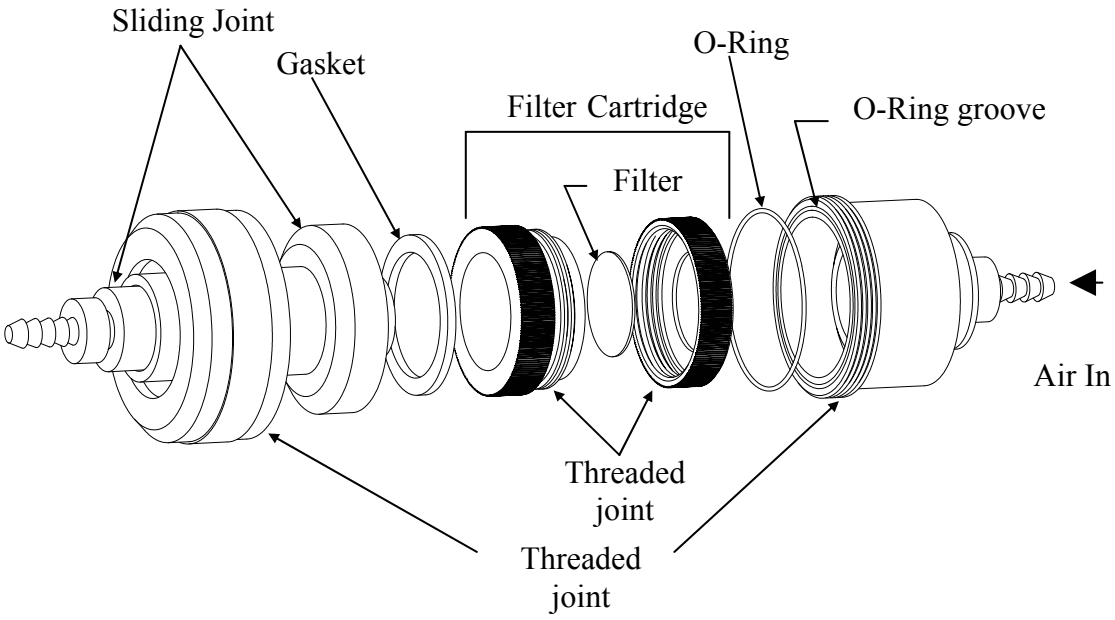

Figure 3. Exploded view of Filter Holder FH_1

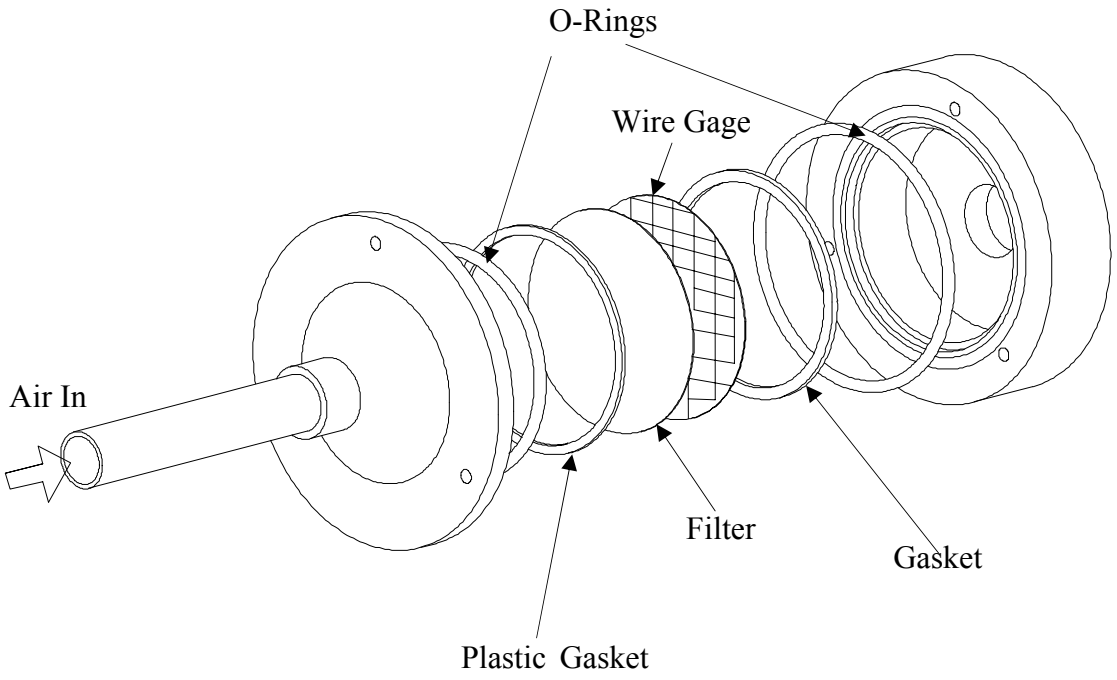

Figure 4. Exploded view of Filter Holder FH_2

THEORY

Definitions and units

Leak is defined to be the physical opening that unintentionally allows the passage of a fluid into or out of a fluid container or transport system. Leakage is the measurable quantity of fluid escaping from a leak. Volume flow rate is measured in $m^3\ s^{-1}$ in SI units. The leakage rate is defined as the quantity (mass) of gas leaking in one second. The SI unit for leakage is Pa $m^3\ s^{-1}$. Leakage is measured in terms of the product of pressure and volume flow rate. The temperature of the gas also needs to be specified to determine the quantity or the mass of gas. However small changes in temperature may be insignificant when compared to the large changes in pressure observed usually in operating environments.

To overcome this problem the leakage is also specified in standard cubic centimeter per second, std $cm^3\ s^{-1}$, that is the leakage flow rate at a standard pressure of 101.325 kPa and a standard temperature of 293 K. Expressing leakage rates in these units provides a leakage rate valid at any temperature and pressure. In the present study we express leakage in terms of percentage of the main flow through the transport system. That is, the volumetric leakage flow rate is expressed as a percentage of the volumetric flow rate through the main transport system. As we take a ratio of two volumetric flow rates, the pressure and temperature do not have any effect.

Modes of tracer gas flow though leaks

The mode of flow through leaks can vary depending upon the size of the leak and the mean free path of the tracer gas being used for leak detection. There are three primary types of flow possible through leaks. They are viscous flow, molecular flow and transitional flow. Viscous flow may be further divided into laminar and turbulent flow. Other than these basic types of flows through leaks we also have leakage due to permeation and diffusion.

Viscous flow

Viscous flow comprises of laminar and turbulent flow. Turbulent flow is fairly uncommon in flow through leaks unless we have a fairly large sized leak. We can determine whether the flow is laminar or turbulent based on the Reynolds number, *Re* through the leak.

$$\mathrm{Re} = \frac{vd}{\nu} \qquad [1]$$

where v is the velocity through the leak, d is the cross sectional diameter of the leak and ν is the kinematic viscosity. Above a Reynolds number of 2100, the flow becomes unstable and this results in the formation of numerous turbulent eddies and vortices.

Viscous flow occurs when the mean free path of the gas, λ is significantly smaller than the cross sectional dimension of the leak. The above criterion is satisfied when the cross sectional diameter of the leak is at least a hundred times the mean free path of the gas. Viscous flow leakage is normally found to occur in high pressure systems. The

relationship between the volumetric flow rate through the leak and the pressure difference across the leak for laminar flow is given by the Hagen-Poiseuille equation:

$$Q = \frac{\pi r^4}{8\eta l}\Delta P \qquad [2]$$

where Q is the volumetric flow rate through the leak, r is the hydraulic radius of the leak, l is the length of the leak, η is the dynamic viscosity of the air-tracer gas mixture and ΔP is the pressure difference across the leak. Therefore the volumetric flow rate through the leak is a linear function of the pressure difference across the leak in the laminar flow case.

Molecular flow

Molecular flow occurs when the mean free path of the tracer gas is greater than the cross sectional dimension of the leak.

Knudsen's equation is used to describe the flow if the mean free path of the gas molecules is very large compared to the largest cross sectional dimension of the physical leak:

$$Q = 3.342\frac{r^3}{l}\sqrt{\frac{RT}{M}}\frac{\Delta P}{P} \qquad [3]$$

where Q is the volumetric flow rate through the leak, r is the hydraulic radius of the leak, l is the length of the leak, M is the molecular weight of the mixture, T is the absolute temperature, R is the universal gas constant, P is the average pressure in the leak and ΔP is the pressure difference across the leak. In this case also the relationship between the

volumetric flow rate through the leak and the pressure difference across the leak is linear, as it was in the case of laminar flow.

Transitional flow

Transitional flow occurs when the mean free path of the gas is nearly equal to the cross sectional dimension of the physical leak. Transitional flow occurs under leakage conditions intermediate between those for viscous flow and those for molecular flow. In the case of transitional flow, Knudsen's equation (Eq. 3) is modified by using a correction factor. The correction factor used depends on ratio R_t of the leakage tube radius r to the mean free path length of the tracer gas λ. The correction factor F_T is given by the following equation:

$$F_T = 0.1472 R_t + \frac{1 + 2.507 R_t}{1 + 3.095 R_t} \qquad [4]$$

The flow rate through the leak is given by the following equation:

$$Q = 3.342 \frac{r^3}{l} \sqrt{\frac{RT}{M}} \frac{\Delta P}{P} F_T \qquad [5]$$

where all the symbols have the same meaning as in Eq. 3. The mean free path is determined at the average between the upstream and downstream pressures.

Flow due to permeation

Flow can occur due to permeation through porous media. In the present study permeation may occur through gaskets or O-rings which may have become more permeable due to wear and tear. The flow through porous media is described using Darcy's law:

$$Q = \frac{k\pi r^2}{\eta l}\Delta P \quad [6]$$

where Q is the volumetric flow rate through the leak, k is the permeability of the component through which the flow is occurring, r is the hydraulic radius of the leak, l is the length of the leak, η is the dynamic viscosity of the air-tracer gas mixture and ΔP is the pressure difference across the leak.

Flow due to diffusion

There may be some flow through the leak due to diffusion. Diffusion is different from the other modes of flow in that it is driven by the concentration gradient across the leak rather than the pressure gradient across the leak. The flow due to diffusion is governed by Fick's law:

$$Q = \pi r^2 D_{AB}\frac{\Delta\omega_A}{l} \quad [7]$$

where Q is the volumetric flow rate through the leak, D_{AB} is the diffusivity of species A (tracer gas) in species B (air), r is the hydraulic radius of the leak, l is the length of the leak and $\Delta\omega_A$ is the difference in the mass fraction of the tracer gas across the leak.

Formulae used to calculate leak rate

The flow rate of sulfur hexafluoride/air mixture from the supply cylinder, required to achieve the target concentration in the mixed flow is given by:

$$Q_{SF_6} = \frac{C_T Q_D}{C_b - C_T} \quad [8]$$

Q_{SF_6} is the SF_6 flow rate in the supply line; C_T is the target concentration once SF_6 has fully mixed with the main flow, Q_D; and, C_b is the SF_6 concentration coming out of the supply cylinder.

The airflows are assumed to be incompressible as the maximum test pressure is 2.49 kPa (10 In. H_2). The leak rate, L, as a fraction of the flow through the device in the case of pressurized operation (see Fig. 5) of the device is calculated from:

$$L = \frac{Q_c}{Q_d}\frac{C_c}{C_d - C_c} \quad [9]$$

Here, C_c is the concentration of SF_6 in the flow through the chamber (Q_c) and C_d are the concentration on of SF_6 in the flow through the device and the flow rate through the device, Q_d.

The leak rate as a fraction of the flow through the device in the case of vacuum operation (see Fig. 6) of the device is:

$$L = \frac{C_d}{C_c - C_d} \quad [10]$$

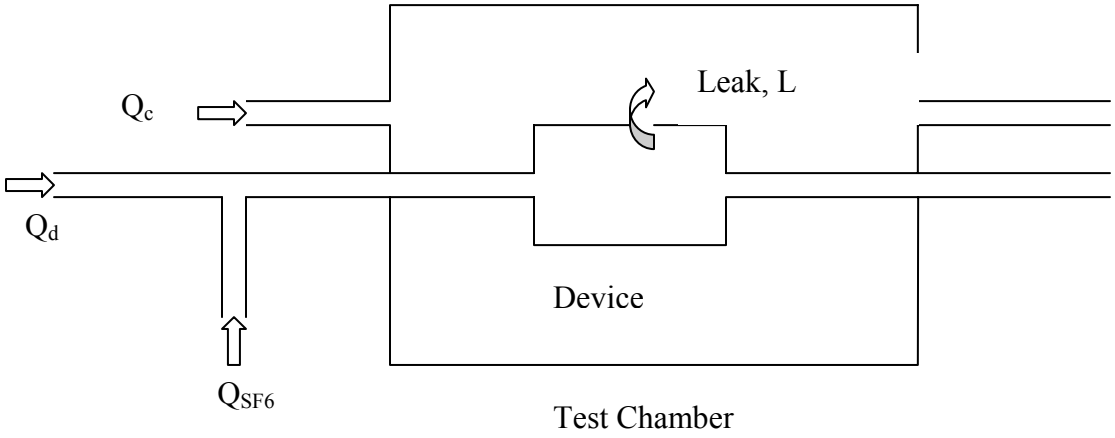

Figure 5. Flow paths through air monitoring device and chamber during pressurized operation

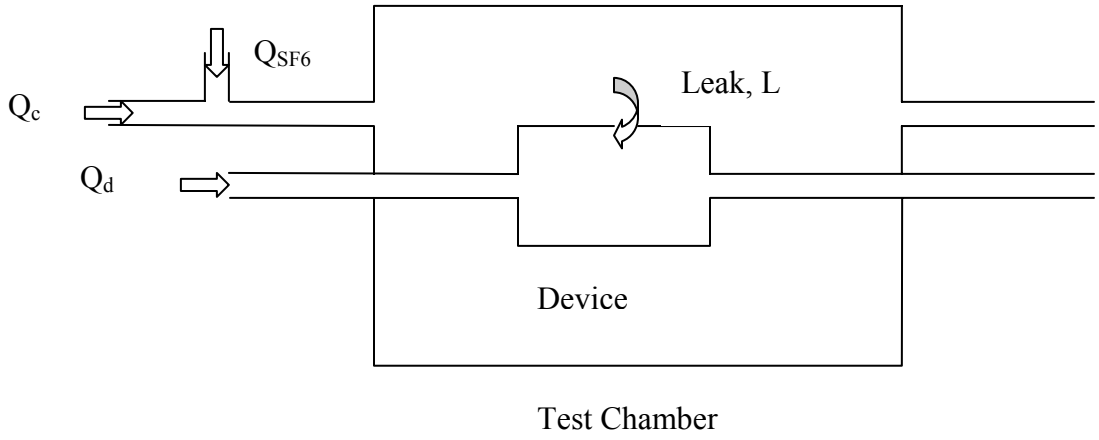

Figure 6. Flow paths through air monitoring device and chamber during vacuum operation

EXPERIMENTAL METHODOLOGY

Experimental setup

The experimental setup consists of various components and measuring instruments. The components that were used in the experiment included a test chamber, gas cylinders, pressure regulators, flow valves, flow connectors, tubes, two vacuum pumps, a high pressure air supply, syringes, a small fan, a wind tunnel, a docking board for measuring instruments and the device to be tested for leaks. Three devices were tested to determine their leakage characteristics and the devices were two types of filter holders and a prototype continuous air monitor. The instruments used for measurement in the present study included Minihelic pressure gauges (Dwyer Instruments, Inc., Michigan City, IN), rotameters (Dwyer Instruments, Inc., Michigan City, IN) and a gas chromatograph (Autotrac 101, Lagus Applied Technology Inc., San Diego, CA).

Components

The air monitoring device to be tested for leakage was housed in a test chamber. The dimensions of the test chamber are 305 mm x 305 mm x 610 mm (1 ft x 1 ft x 2 ft). The test chamber has two inlets and two outlets. One set of inlet and outlet is used for connecting to the flow through the device, the other set of inlet and outlet is used for connecting to the flow through the chamber outside the device. The test chamber is designed to hold a vacuum of around 2.49 kPa (10 In. H_2O) without leaking. Two gas cylinders were used in the experiment. The first gas cylinder was the source of SF_6 tracer gas. It contained a mixture of 100 ppm SF_6 in a high pressure air cylinder. The second

gas cylinder was the source of P5 carrier gas (5% mixture of methane in argon) required for the gas chromatograph.

Pressure regulators were used to regulate the pressure of gas from the gas cylinders to a desired level. The pressure of P5 carrier gas coming out of the cylinder was maintained at 345 kPa (50 psi) and the pressure of the SF_6 air mixture coming out of the cylinder was maintained at around 138 kPa (20 kPa). Flow valves were used to control the flow rate and pressure in the flow lines. Flow connectors were used for splitting the flow, merging two flows, connecting tubes to components, etc. Compression metal fittings (Swagelok, Crawford Fitting Company, Solon, OH) were used at most places and barbed plastic fittings were used at other places. The compression metal fittings were used because leakage through these fittings was minimal. Tubes of various flow diameters were used in the different flow paths. The individual tube diameters used in each flow path is mentioned in the discussion on flow paths.

Two vacuum pumps were used in the experiment. One vacuum pump was used to maintain the flow through the device and the other vacuum pump was used to maintain the flow outside the device but within the chamber. A high pressure air supply was used to supply air for the flow through the air monitoring device. The pressure in this line was maintained at about 35 kPa (5 psi) using a pressure regulator. Plastic syringes were used to collect the tracer gas samples, which were then analyzed using the gas chromatograph. The capacity of these syringes was 60 cc. A small fan was mounted within the test chamber. This fan was used to improve the mixing of tracer gas within the test chamber. All the flows were exhausted into the wind tunnel and the flow through the

wind tunnel was exhausted outside the building in which the tests were performed. A docking board was used to hold the Minihelic pressure gauges and the rotameters. Using a docking board provided the convenience of being able to read all the measurements at the same place.

The experimental setup includes three flow paths. The first flow path is through the air monitoring device which is being tested for its leakage characteristics. The second flow path is through the vacuum chamber which houses the air monitoring device. The third flow path brings the SF_6 air mixture from the source gas cylinder to the point where it mixes with one of the first two flows depending upon whether the air monitoring device is being tested under vacuum condition or pressure condition.

The airflow through the device is maintained constant at 56.6 L/min (2 cfm) or 28.3 L/min (1 cfm) using a vacuum pump and valves. The air for this flow is drawn from a pressurized air supply. The airflow through the chamber is maintained constant using a vacuum pump and valves and this air for this flow is drawn from the surrounding atmosphere.

Device operating in pressurized conditions

The experimental setup for pressurized operation is as shown in Figure 7. The sulfur hexafluoride/air mixture from the gas cylinder is mixed with the air flow through the device. The flow rate of sulfur hexafluoride from the cylinder is set such that a desired level of SF_6 concentration (approximately 500 ppb) is achieved in the flow through the device. The vacuum pressure in the chamber is noted. The upstream pressure in the flow through the device is varied such that the pressure differential between the

upstream pressure and the chamber pressure varies from 0.498 kPa (2 In. H_2O) to 2.49 kPa (10 In. H_2O) in increments of 0.498 kPa (2 In. H_2O). For each of these pressures SF_6 gas samples are collected from both the flow lines. For measuring the SF_6 gas samples collected from the device a 6X dilution was used.

Device operating in vacuum conditions

The experimental setup for vacuum operation is as shown in Figure 8. The sulfur hexafluoride/air mixture from the gas cylinder is mixed with the air flow through the chamber. The flow rate of sulfur hexafluoride from the cylinder is set such that a desired SF_6 concentration is achieved in the flow through the chamber. The vacuum pressure in the chamber is noted. The upstream pressure in the flow through the device is varied such that the pressure differential between the upstream pressure and the chamber pressure varies from 0.498 kPa (2 In. H_2O) to 2.49 kPa (10 In. H_2O) in increments of 0.498 kPa (2 In. H_2O). For each of these pressures SF_6 gas samples are collected from both the flow lines. For measuring the SF_6 gas samples collected from the chamber, a 6X dilution was used.

Sufficient time (3 minutes) was allowed between the start of the gas flows and collecting gas samples so that steady state operation was reached. Two sets of three samples each were collected for each pressure condition.

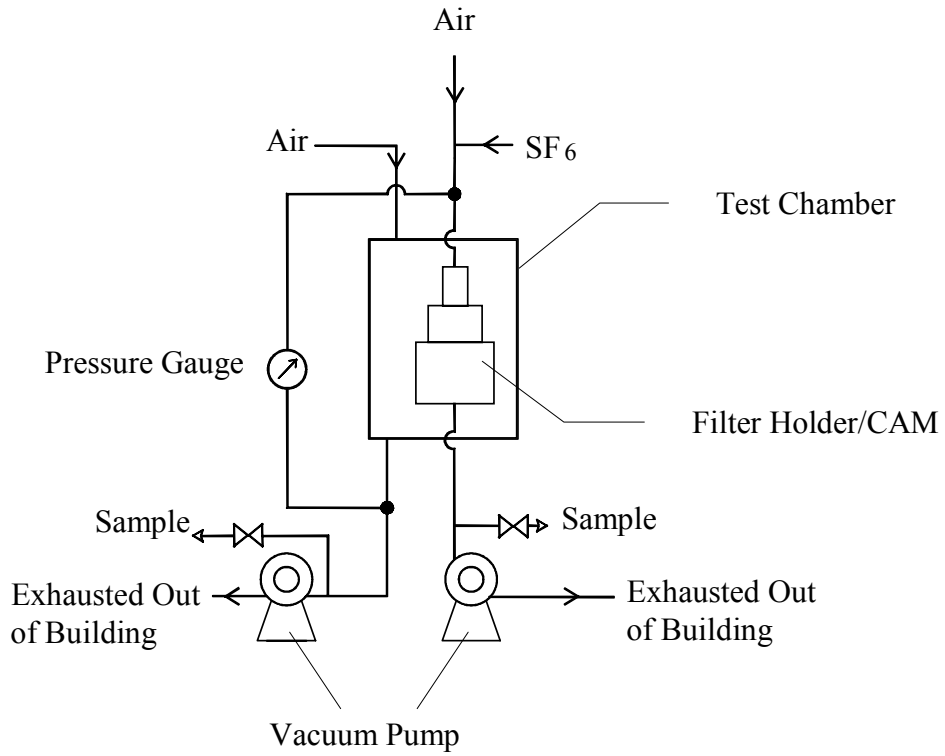

Figure 7. Schematic for leak testing during internal pressure conditions of device

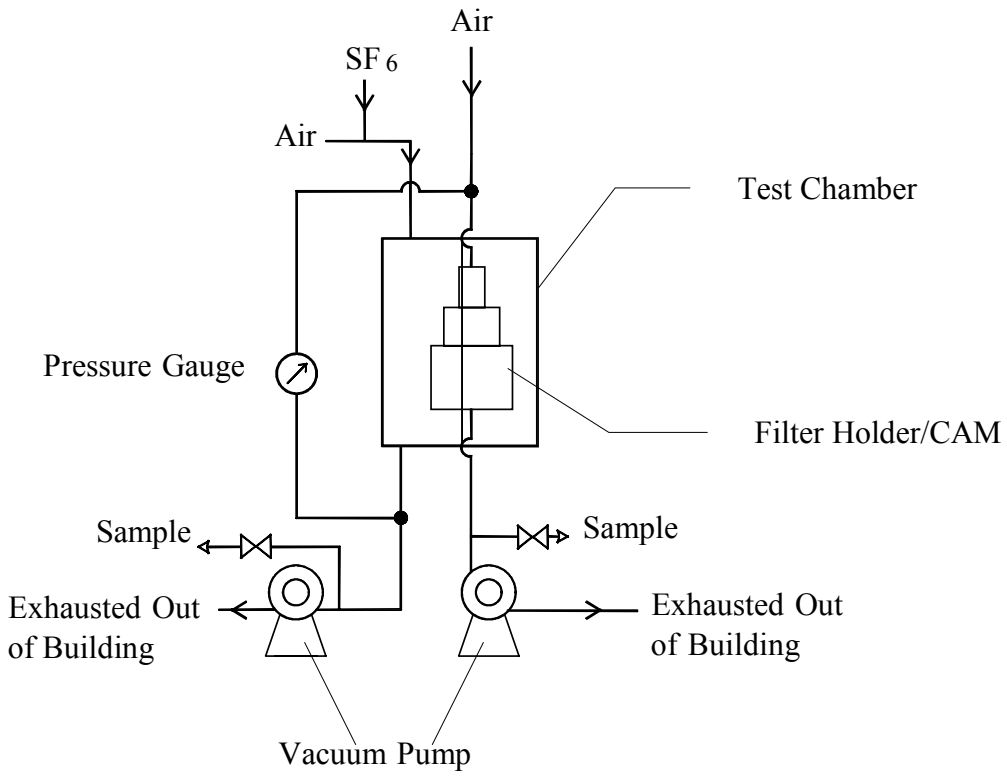

Figure 8. Schematic for leak testing during internal vacuum conditions of device

RESULTS AND DISCUSSION

The results for the continuous air monitor are shown in Figs. 9 to 13. The error bars shown in the figures represent a variation of one standard deviation about the mean of a data point. The leakage values were calculated using Eq. 9 in the case of pressurized operation and Eq. 10 in the case of vacuum operation. The leakage for the continuous air monitor at a flow rate of 120 scfh through the device for vacuum operation is shown in Figure 9. The leakage for the continuous air monitor at a flow rate of 120 scfh through the device for pressurized operation is shown in Fig. 10.

The leakage in the continuous air monitor is linear on the log-log plots shown in Figures 9 and 10, which means that the data can be represented by power functions, i.e.:

$$L \propto \Delta P^{\alpha} \qquad [11]$$

where: ΔP is the pressure differential (expressed as an absolute value) and α is a constant, which is the slope of the log-log plot. For the pressure and vacuum conditions, the values of α are 0.90 and 1.13, respectively, i.e., the leakage is approximately linear with applied pressure.

The leakage in the continuous air monitor for vacuum operation for flow rates of 30 scfh and 60 scfh through the chamber is shown in Figure 11. The flow through the continuous air monitor for both the cases is 120 scfh. The leakage in the continuous air monitor for pressurized operation for flow rates of 70 scfh and 100 scfh through the chamber is shown in Fig. 12. The flow through the continuous air monitor for both the cases is 120 scfh.

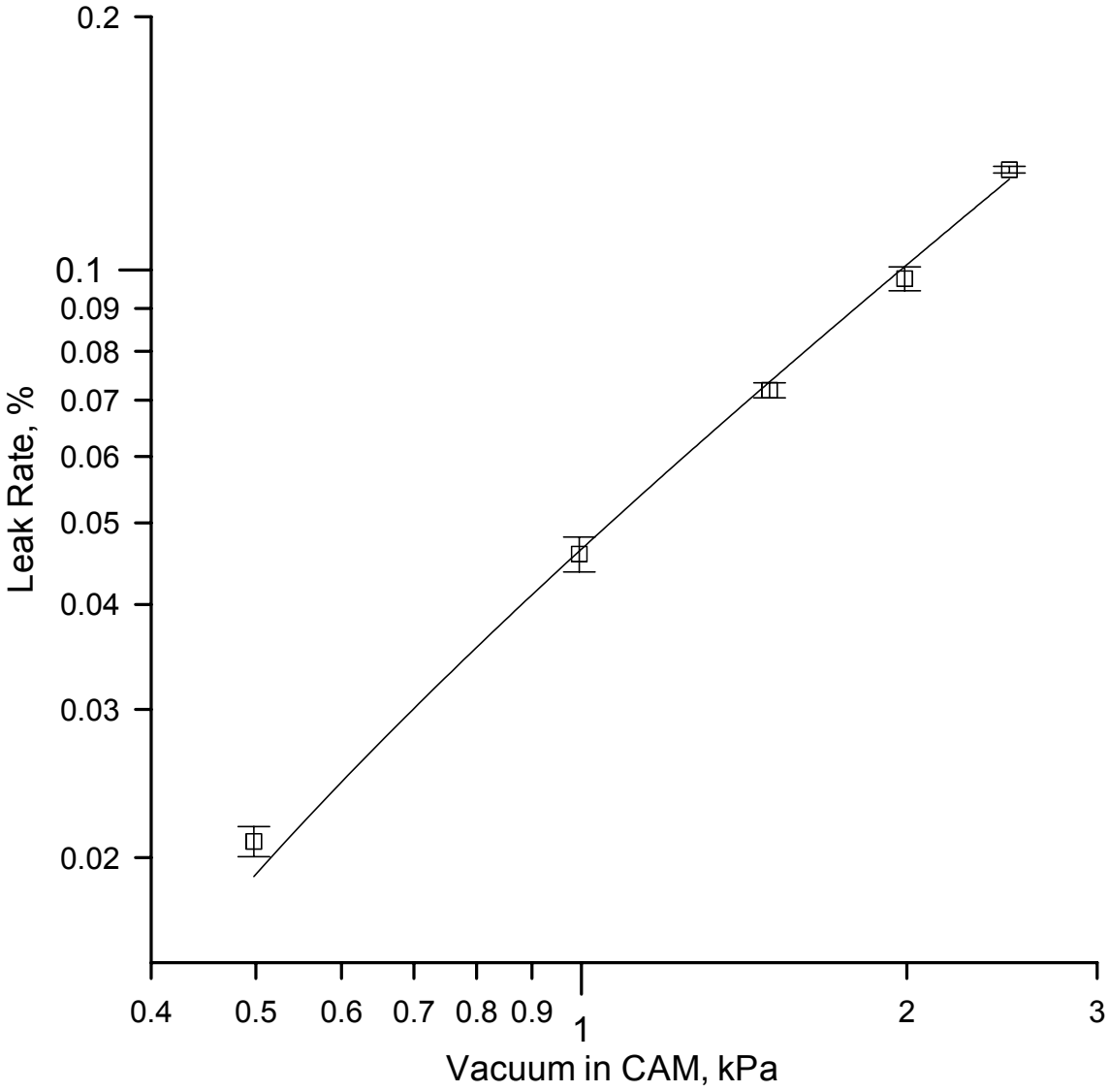

Figure 9. Percentage leakage in continuous air monitor for vacuum operation

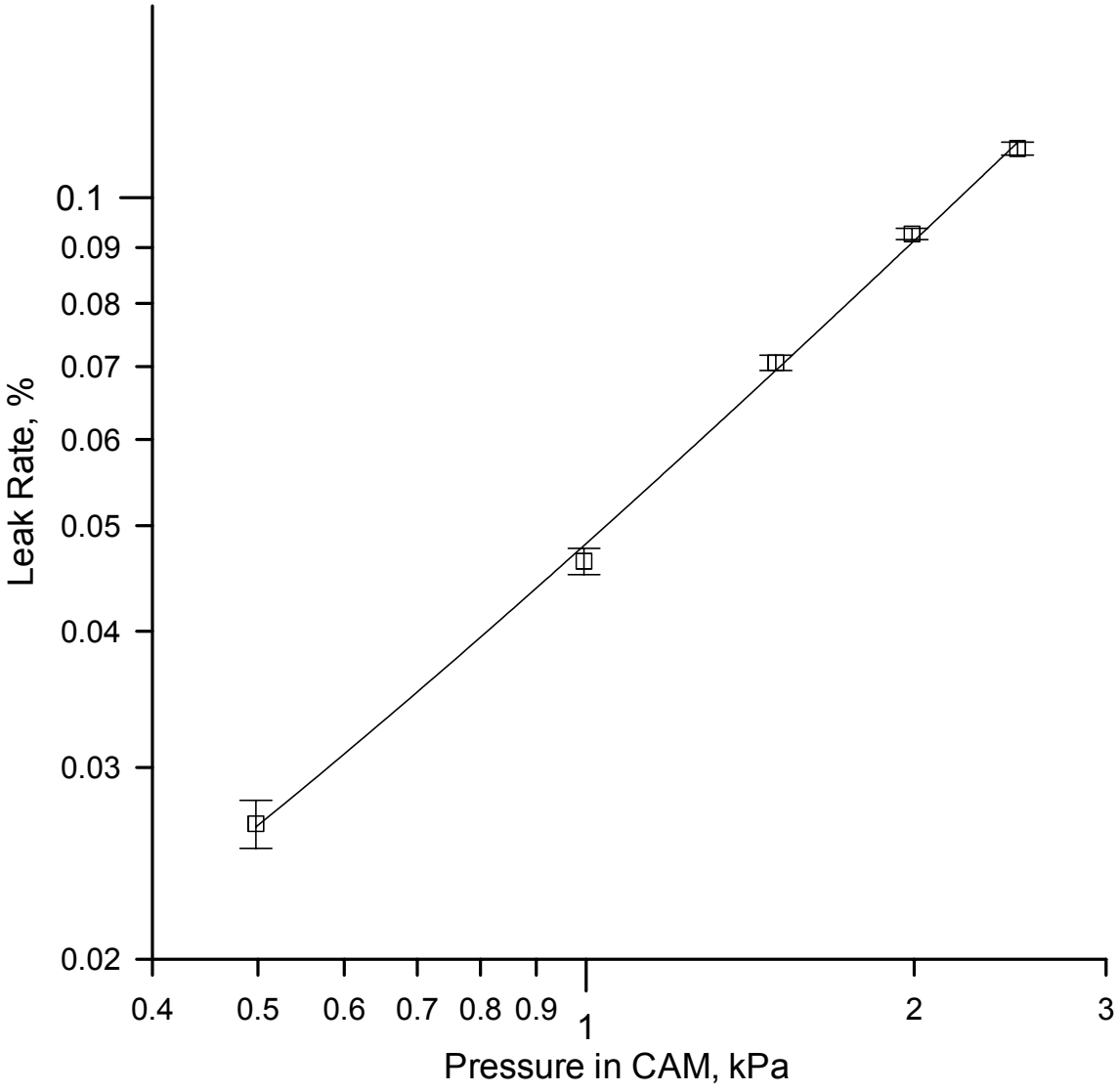

Figure 10. Percentage leakage in continuous air monitor for pressurized operation

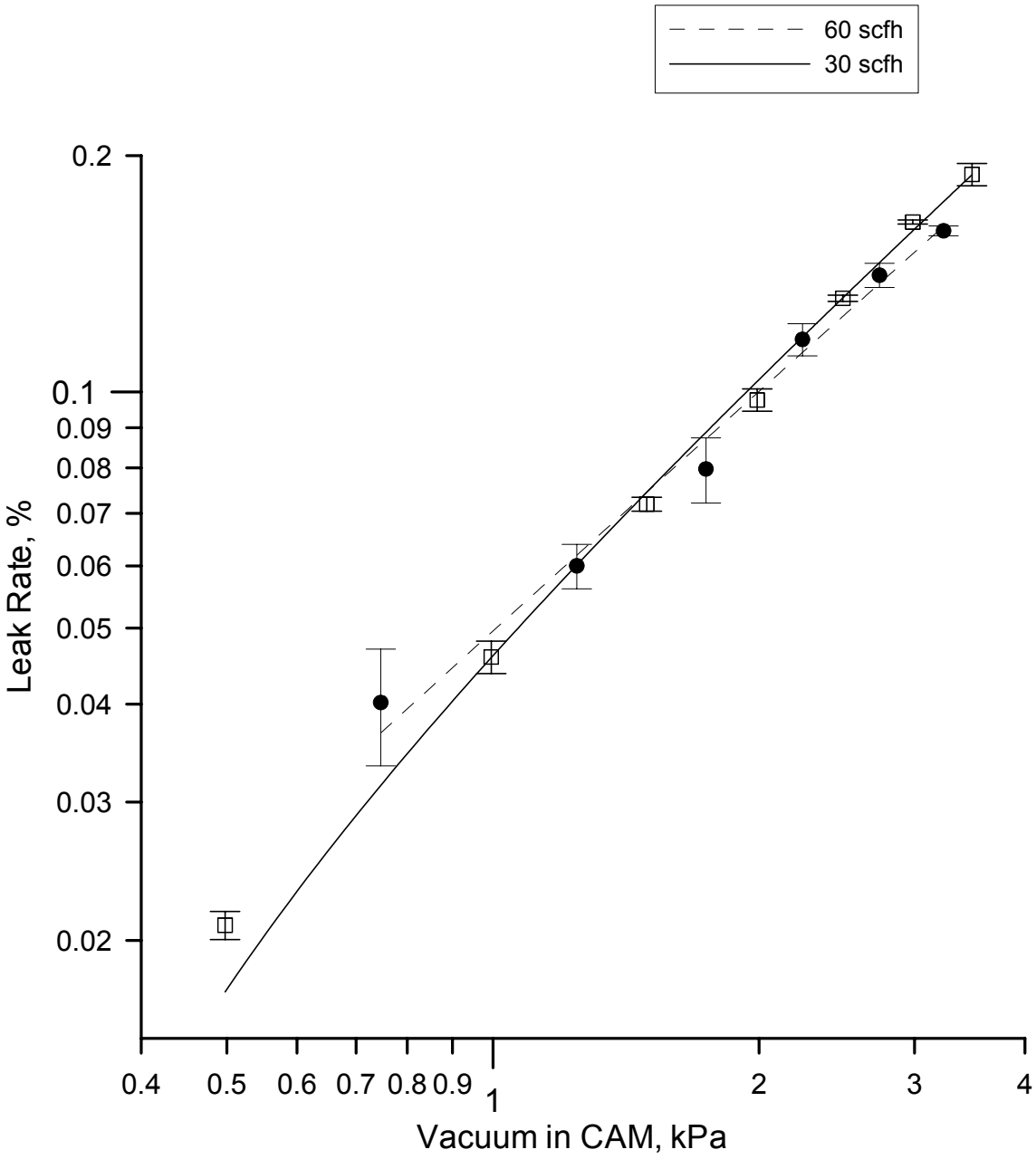

Figure 11. Percentage leakage in continuous air monitor for vacuum operation for flow rates of 60 scfh and 30 scfh through the chamber. The flow rate through the device is 120 scfh for both cases

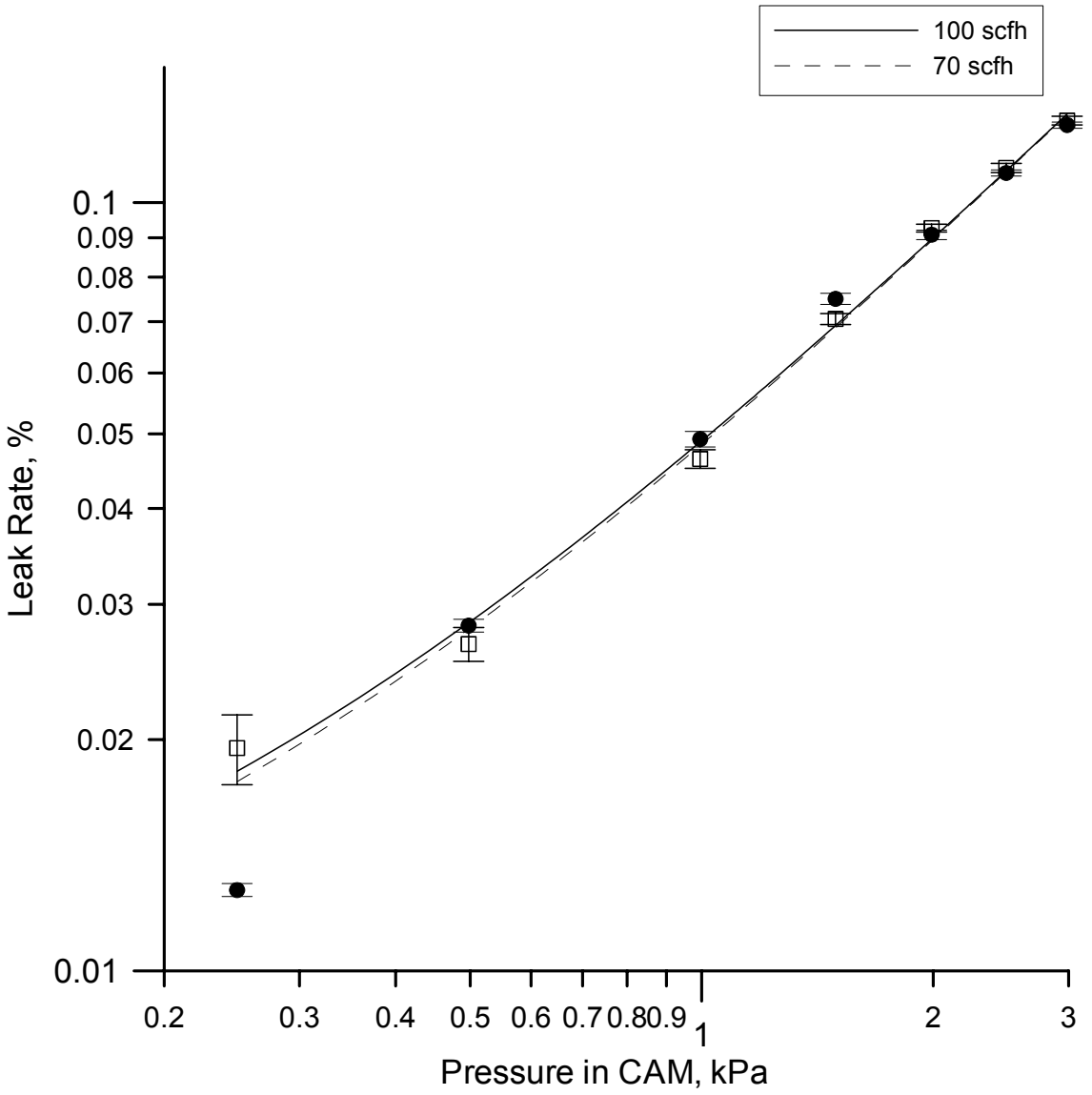

Figure 12. Percentage leakage in continuous air monitor for pressurized operation for flow rates of 100 scfh and 70 scfh through the chamber. The flow rate through the device is 120 scfh for both cases

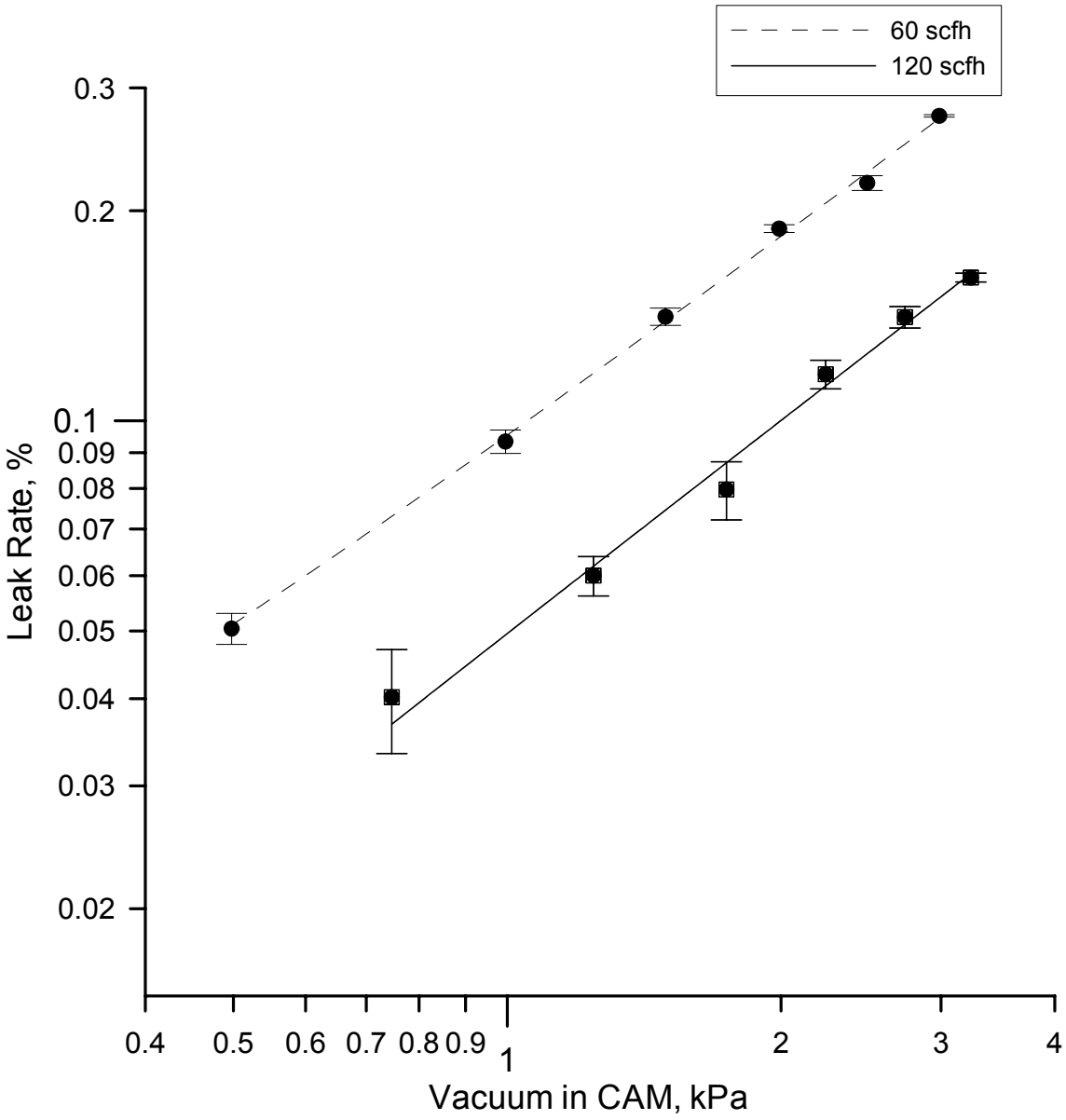

Figure 13. Percentage leakage in continuous air monitor for vacuum operation for flow rates of 60 scfh and 120 scfh through the device. The flow rate through the chamber is 60 scfh for both cases

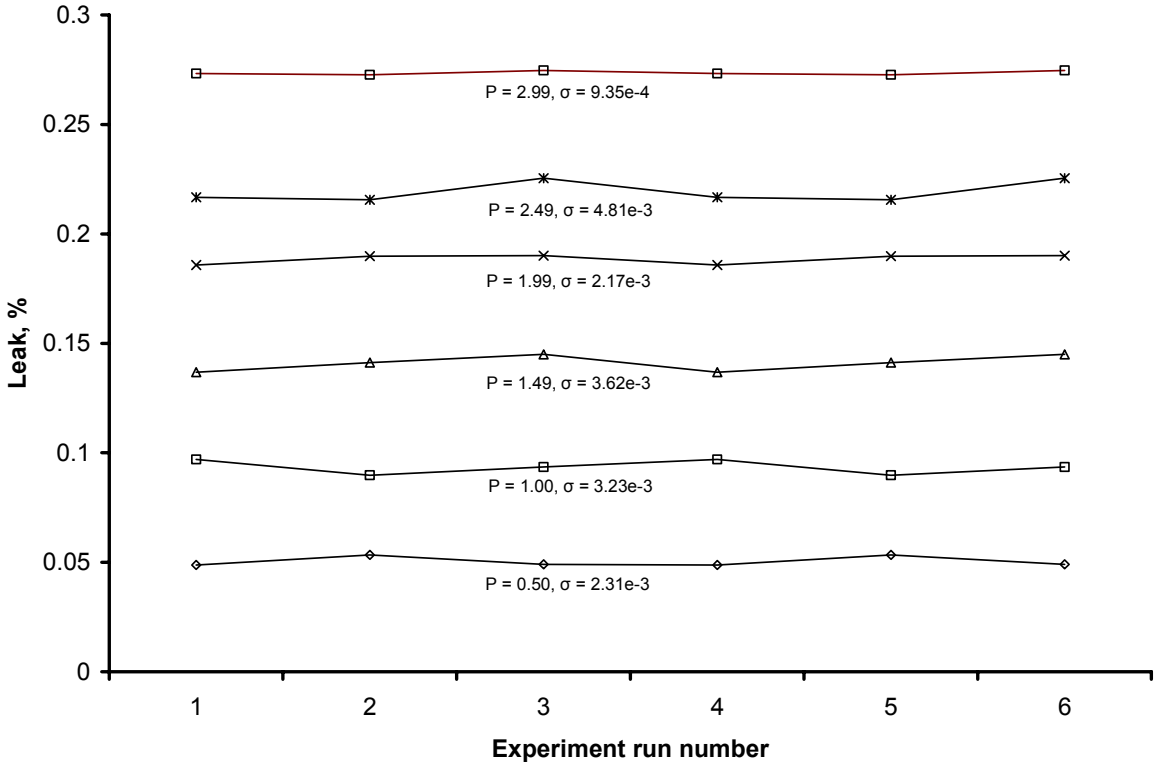

Figure 14. The comparison of data from six experimental runs for the case where flow rate through the chamber and device is 60 scfh. The pressure, P and standard deviation, σ are shown for each data series.

As can be seen from the figures the leakage rate is same for both the flow rates through the chamber. This shows that the leakage is independent on the flow rate through the chamber.

The leakage through the continuous air monitor for vacuum operation for flow rates of 60 scfh and 120 scfh through the device is shown in Fig. 13. The flow rate through the chamber is 60 scfh in both the cases. The leak rates appear different because we represent the leak rates as a percentage of the nominal flow rate through the device. The actual volumetric flow rate through the leak for both the cases is still the same. From this we can see that the leak flow rate is not affected by the flow through the device.

The reproducibility of test results is an important consideration in any experimental study. The leakage values obtained for six different experimental runs at a flow rate of 60 scfh through the device and chamber is shown in Fig. 14. The standard deviation at various pressure differences across the leak is also shown. The relative error in repeatability is defined as the ratio of the standard deviation over the mean. The maximum relative error is 4.6% at a pressure of 0.50 kPa. This shows that the experimental methodology has good repeatability.

The leakage for all the three devices tested has been tabulated in Appendix A. The leakage values at different flow rates through the chamber and device for the three devices are tabulated in Tables 3 to 11. The leakage in the filter holder FH_1 for a flow rate of 120 scfh through the device is tabulated in Tables 3 and 4. The leakage in the filter holder FH_2 for a flow rate of 120 scfh through the device is tabulated in Tables 5

and 6.For the two filter holders FH_1 and FH_2 we do not see any trend in the change of leakage values with respect to the change in pressure. This is because the values of leakage in these filter holders are less than what can be measured accurately with the present experimental setup.

The leakage values at ± 2.49 kPa (± 10 In. H_20) in the device are listed in Table 1. It may be noted from Table 1 that the leakage values are 0.11% at 2.49 kPa pressure and 0.13% at 2.49 kPa of vacuum. These values are both considerably lower than the ANSI standard limit of 5%.

In the continuous air monitor the cam lever needs to be rotated in the clockwise direction to provide better sealing integrity. If the cam lever is rotated in the counterclockwise direction it can leave a small a gap in the O-rings seals, which will increase the leakage.

The leakage in the filter holders is too low to be quantified using the present measurement system. Nevertheless we can prescribe an upper limit for the leakage in the filter holders. With reference to Table 1, the maximum leakage in both the filter holders in either pressure or vacuum operations is less than 0.007% of the nominal flow rate, which is much below the 5% limit set by ANSI.

The gas chromatograph that was used in the experiment can measure tracer gas concentrations as high as 150 ppb, but by diluting the gas before measurement we can increase that upper limit. The lowest concentration is controlled by the SF_6 background, which in the laboratory where the experiments were conducted was typically 10 ppt to 30 ppt.

Table 1. Maximum leak rates in the filter holders and continuous air monitor

Component	Pressure (kPa)	Leak Rate, %
CAM	2.49 (Pressure)	0.11
	2.49 (Vacuum)	0.13
Filter Holder – 1	2.49 (Pressure)	0.004[a]
	2.49 (Vacuum)	0.007[a]
Filter Holder -2	2.49 (Pressure)	0.006[a]
	2.49 (Vacuum)	0.007[a]

[a] Value below threshold level

Table 2. Hydraulic radius of the leak as a function of length of leak

Length of Leak (m)	**Hydraulic radius of leak (µm)**	
	CAM	Filter Holders[a]
1×10^{-5}	21	11
1×10^{-4}	38	19
1×10^{-3}	68	33
1×10^{-2}	120	59
1×10^{-1}	214	105
1	381	187

[a] The leak radius is calculated for a leak rate of 0.007% of a nominal flow of 120 scfh

The lowest possible leak rate that can be measured using the present setup is about 0.002%, so this is also the minimum error in measurement. For the given nominal flow rate this corresponds to a leak rate of 1.8×10^{-2} mL/s.

Determination of the nature of flow and characteristic dimension of the leak

There are different possible modes of flow through the leak. The flow through the leaks may be laminar, turbulent, molecular or transitional. In addition to this we may flow due to diffusion and permeation through porous media. The data obtained from the leakage tests on the three devices was used to determine the nature of flow through the leaks. The nature of the leak path across the device is pretty complex. The leak flow typically follows a tortuous path across the device. The length of flow path can be assumed to be approximately equal to the thickness of the device. Nevertheless analysis was done assuming the length of the leak to vary through a wide range.

Calculations were performed to determine the characteristic dimension of the leak using Eqs. 2 to 6 assuming a certain length of leak. The hydraulic radius of the leak thus obtained was compared with the mean free path of the tracer gas air mixture. From this comparison it was determined that the nature of flow through the leak is laminar. The hydraulic radius of the leak for different lengths of the leak path for laminar flow has been tabulated in Table 2. We can see from Eq. 2 that the amount of flow through the leak does not depend on the amount of flow through the device or chamber. This was what was observed from experiments.

The flow through the leak due to diffusion and permeation through porous media was also calculated. For this analysis the gaskets and O-rings were assumed to be porous

and a certain permeability was assigned to them. The calculations were done assuming that the length of the leak path is of the order of 1 mm. The leak rates due to these two mechanisms were found to of the order of 1 x 10^{-10} %. So these modes of leak flow can be neglected when compared to the laminar flow through the leaks.

SUMMARY AND CONCLUSIONS

Methodology has been developed for measuring leakage in air monitoring elements (filters and CAMs), which is based on the use of sulfur hexafluoride as a tracer. The methodology involves enclosing the air monitoring element in a leak tight test chamber that is fitted with connections to allow an air flow through the air monitoring device and an air flow through the chamber itself. The two air flows are independent of each other, the only connection between the two flow paths being the leak in the element. The tracer gas is introduced in the flow through the element or the flow through the chamber depending upon whether there is pressure in the element or vacuum in the element. If there is a leak in the element, some amount of the tracer gas escapes into the other flow. By measuring the concentration of sulfur hexafluoride in this flow we can quantify the leak through the air monitoring element.

To demonstrate this leak testing methodology, the leakage through two filter holders and a CAM was studied. The percentage leakage in CAM was found to be less than 0.2 % of the nominal flow rate and the percentage leakage in the filter holders was less than 0.07 % of the nominal flow rate. These leak rates are much smaller than the 5% leakage limit prescribed by ANSI standards. Because the leakage rates are more than an order of magnitude less than the ANSI limit, we suggest the ANSI N13.1 committee review the limit to ascertain whether or not it is too high.

Testing using sulfur hexafluoride provides an easy and accurate means to quantify even very minute leaks of the order of 10^{-2} mL/s. Even lower leak rates can be

measured provided the nominal flow rate is less than the 56.6 L/min (2 cfm) used in testing the devices in this study.

The measurement time for leak detection is also considerably less than that needed for pressure decay testing. Therefore sulfur hexafluoride leak detection technique provides fast as well as safe, easy and accurate means of checking the leak rates of components under flow conditions.

REFERENCES

Baron PA, Bennett JS. Calculation of leakage and particle loss in filter cassettes. Aerosol Science and Technology 36:632-641; 2002 a.

Baron PA, Khanina A, Martinez AB, Grinshpun SA. Investigation of filter bypass leakage and a test for aerosol sampling cassettes. Aerosol Science and Technology 36:857-865; 2002 b.

Bley WG. Helium leak detectors: from a laboratory device to dedicated industrial leak test units. Vacuum 44: 627-632; 1993.

Bloomer RN. Leak detection and measurements by vacuum bubblers. Vacuum 23:239-244; 1973.

Health Physics Society (HPS) / American National Standards Institute (ANSI). Sampling and monitoring releases of airborne radioactive substances from the stacks and ducts of nuclear facilities. ANSI/HPS N13.1-1999, Health Physics Society; 1999.

Intergovernmental Panel on Climate Change (IPCC). Climate change 2001: Synthesis report. A contribution of working groups I, II, and III to the third assessment report of the intergovernmental panel on climate change [Watson RT and the core writing team (eds.)]. Cambridge University Press. New York; 2001.

Nelson KH. Gas chromatographic detection of leaks in microelectronic packages. Microelectronics and Reliability 8:313-318; 1969.

Reich G. Leak detection with tracer gases; sensitivity and relevant limiting factors. Vacuum 37:691-698; 1987.

Sheen S, Chien H, Raptis AC. Ultrasonic techniques for detecting helium leaks. Sensors and actuators B 71: 197-202; 2000.

Tingey DT, Waschmann RS, Phillips DL, Olszyk DM. The carbon dioxide leakage from chambers measured using sulfur hexafluoride. Environmental and Experimental Botany 43:101-110; 2000.

Turner WJ, Mudford NR. Leak detection, timing, location and sizing in gas pipelines. Mathl Comput Modeling 10: 609-627; 1988.

Supplemental sources consulted

American Society for Nondestructive Testing. Nondestructive testing handbook, second edition: Vol. 1, Leak Testing. Columbus, OH; 1982.

Chandra S, McFarland AR. Leakage in filter holders. Presentation THAM-C.4, Health Physics Annual Meeting, Cleveland, OH; 2001.

Fox RW, McDonald AT. Introduction to fluid mechanics, fifth edition. John Wiley & Sons, Inc. New York; 2001.

Gupta R. Turbulent mixing and depositional studies for single point aerosol sampling. College Station, TX: Department of Mechanical Engineering, Texas A&M University; 1999. Dissertation.

Martinez JT. A rugged continuous air monitor for sampling. College Station, TX: Department of Mechanical Engineering, Texas A&M University; 2002. Thesis.

Scheidegger AE. The physics of flow through porous media, third edition. University of Toronto Press. Toronto; 1974.

APPENDIX

DATA TABULATION

Table 3. Leakage in the filter holder FH_1 for pressured operation at a flow rate of 120 scfh through the device and 35 scfh through the chamber

Parameter	Flow Path	Units	Value
Flow Rate	Device	*scfh*	120.00
	Chamber	*scfh*	35.00
	SF6	*cc/min*	180.00
SF6 Concentration	Device	*ppb*	317.30
Vacuum (gage)	Chamber	*kPa*	0.75

Pressure (gage)		SF6 Concentration	% Leak
Device	Difference	Chamber	
kPa	*kPa*	*ppt*	
-0.25	0.50	44.00	0.004
0.25	1.00	51.00	0.005
0.75	1.49	61.00	0.006
1.24	1.99	35.00	0.003
1.74	2.49	42.00	0.004

Table 4. Leakage in the filter holder FH_1 for vacuum operation at a flow rate of 120 scfh through the device and 40 scfh through the chamber

Parameter	Flow Path	Units	Value
Flow Rate	Device	*scfh*	120.00
	Chamber	*scfh*	40.00
	SF6	*cc/min*	85.00
SF6 Concentration	Chamber	*ppb*	465.50
Vacuum (gage)	Chamber	*kPa*	0.75

Vacuum (gage)		SF6 Concentration	% Leak
Device	Difference	Device	
kPa	*kPa*	*ppt*	
1.25	0.50	454.20	0.007
1.75	1.00	448.20	0.006
2.24	1.49	466.80	0.004
2.74	1.99	473.40	0.006
3.24	2.49	485.40	0.005

Table 5. Leakage in the filter holder FH_2 for pressured operation at a flow rate of 120 scfh through the device and 60 scfh through the chamber

Parameter	Flow Path	Units	Value
Flow Rate	Device	*scfh*	120.00
	Chamber	*scfh*	60.00
	SF6	*cc/min*	280.00
SF6 Concentration	Device	*ppb*	506.70
Vacuum (gage)	Chamber	*kPa*	1.49

Pressure (gage)		SF6 Concentration	% Leak
Device	Difference	Chamber	
kPa	*kPa*	*ppt*	
-1.00	0.50	56.00	0.006
-0.50	1.00	47.00	0.005
0.00	1.49	59.00	0.006
0.50	1.99	55.00	0.005
1.00	2.49	14.00	0.001

Table 6. Leakage in the filter holder FH_1 for vacuum operation at a flow rate of 120 scfh through the device and 40 scfh through the chamber

Parameter	Flow Path	Units	Value
Flow Rate	Device	*scfh*	120.00
	Chamber	*scfh*	40.00
	SF6	*cc/min*	90.00
SF6 Concentration	Chamber	*ppb*	472.00
Vacuum (gage)	Chamber	*kPa*	0.75

Vacuum (gage)		SF6 Concentration	% Leak
Device	Difference	Device	
kPa	*kPa*	*ppt*	
1.25	0.50	31.00	0.007
1.75	1.00	33.00	0.007
2.24	1.49	24.00	0.005
2.74	1.99	18.00	0.004
3.24	2.49	12.00	0.003

Table 7. Leakage in the continuous air monitor for pressured operation at a flow rate of 120 scfh through the device and 70 scfh through the chamber

Parameter	Flow Path	Units	Value
Flow Rate	Device	*scfh*	120.00
	Chamber	*scfh*	70.00
	SF6	*cc/min*	260.00
SF6 Concentration	Device	*ppb*	491.40
Vacuum (gage)	Chamber	*kPa*	1.49

Pressure (gage)		SF6 Concentration	% Leak
Device	Difference	Chamber	
kPa	*kPa*	*ppt*	
-1.24	0.25	107.33	0.013
-1.00	0.50	237.00	0.028
-0.50	1.00	414.33	0.049
0.00	1.49	630.33	0.075
0.50	1.99	763.67	0.091
1.00	2.49	918.67	0.109
1.49	2.99	1060.00	0.126

Table 8. Leakage in the continuous air monitor for pressured operation at a flow rate of 120 scfh through the device and 100 scfh through the chamber

Parameter	Flow Path	Units	Value
Flow Rate	Device	*scfh*	120.00
	Chamber	*scfh*	100.00
	SF6	*cc/min*	260.00
SF6 Concentration	Device	*ppb*	491.40
Vacuum (gage)	Chamber	*kPa*	1.49

Pressure (gage)		SF6 Concentration	% Leak
Device	Difference	Chamber	
kPa	*kPa*	*ppt*	
-1.24	0.25	115.00	0.020
-1.00	0.50	157.00	0.027
-0.50	1.00	273.33	0.046
0.00	1.49	415.67	0.071
0.50	1.99	545.67	0.093
1.00	2.49	653.33	0.111
1.49	2.99	752.67	0.128

Table 9. Leakage in the continuous air monitor for vacuum operation at a flow rate of 120 scfh through the device and 30 scfh through the chamber

Parameter	Flow Path	Units	Value
Flow Rate	Device	*scfh*	120.00
	Chamber	*scfh*	30.00
	SF6	*cc/min*	50.00
SF6 Concentration	Chamber	*ppb*	374.40
Vacuum (gage)	Chamber	*kPa*	0.25

Vacuum (gage)		SF6 Concentration	% Leak
Device	Difference	Device	
kPa	*kPa*	*ppt*	
0.75	0.50	78.33	0.021
1.24	1.00	172.00	0.046
1.74	1.49	269.33	0.072
2.24	1.99	365.50	0.098
2.74	2.49	492.33	0.132
3.23	2.99	615.67	0.165
3.73	3.48	707.67	0.189

Table 10. Leakage in the continuous air monitor for vacuum operation at a flow rate of 120 scfh through the device and 60 scfh through the chamber

Parameter	Flow Path	Units	Value
Flow Rate	Device	*scfh*	120.00
	Chamber	*scfh*	60.00
	SF6	*cc/min*	100.00
SF6 Concentration	Chamber	*ppb*	346.80
Vacuum (gage)	Chamber	*kPa*	1.49

Vacuum (gage)		SF6 Concentration	% Leak
Device	Difference	Device	
kPa	*kPa*	*ppt*	
1.74	0.25	72.00	0.021
2.24	0.75	139.33	0.040
2.74	1.24	208.00	0.060
3.23	1.74	276.33	0.080
3.73	2.24	404.00	0.117
4.23	2.74	487.67	0.141
4.73	3.23	555.33	0.160

Table 11. Leakage in the continuous air monitor for vacuum operation at a flow rate of 60 scfh through the device and 60 scfh through the chamber

Parameter	Flow Path	Units	Value
Flow Rate	Device	*scfh*	60.00
	Chamber	*scfh*	60.00
	SF6	*cc/min*	100.00
SF6 Concentration	Chamber	*ppb*	346.80
Vacuum (gage)	Chamber	*kPa*	1.49

Vacuum (gage)		SF6 Concentration	% Leak
Device	Difference	Device	
kPa	*kPa*	*ppt*	
1.99	0.50	174.67	0.050
2.49	1.00	323.67	0.093
2.99	1.49	488.33	0.141
3.48	1.99	652.67	0.189
3.98	2.49	758.67	0.219
4.48	2.99	946.00	0.274

VITA

Vishnu Karthik Vijayaraghavan was born in Trichy, India. He received his Bachelor of Technology degree in mechanical engineering from the Indian Institute of Technology, Madras, India in May 2001. The author may be contacted at C-8-2, 5th Cross Road, IIT Madras, Chennai-600036, India.

The typist for this thesis was Vishnu Karthik Vijayaraghavan.