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Nitrous Oxide as a Tracer Gas in the ASHRAE 110-1995 Standard

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ANSI/ASHRAE Standard 110 provides a quantitative method for testing the performance of laboratory fume hoods. Through release of a known quantity (4.0 Lpm) of a tracer gas, and subsequent monitoring of the tracer gas concentration in the "breathing zone" of a mannequin positioned in front of the hood, this method allows for evaluation of laboratory hood performance. Standard 110 specifies sulfur hexafluoride (SF_6) as the tracer gas; however, suitable alternatives are allowed. Through three series of performance tests, this analysis serves to investigate the use of nitrous oxide (N_2O) as an alternate tracer gas for hood performance testing. Single gas tests were performed according to ASHRAE Standard 110-1995 with each tracer gas individually. These tests showed identical results using an acceptance criterion of AU 0.1 with the sash half open, nominal 18 inches (0.46m) high, and the face velocity at a nominal 60 fpm (0.3 m/s). Most data collected in these single gas tests, for both tracer gases, were below the minimum detection limit, thus two dual gas tests were developed for simultaneous sampling of both tracer gases. Dual gas dual ejector tests were performed with both tracer gases released simultaneously through two ejectors, and the concentration measured with two detectors using a common sampling probe. Dual gas single ejector tests were performed with both tracer gases released though a single ejector, and the concentration measured in the same manner as the dual gas dual ejector tests. The dual gas dual ejector tests showed excellent correlation, with R typically greater than 0.9. Variance was observed in the resulting regression line for each hood, likely due to non-symmetry between the two challenges caused by variables beyond the control of the investigators. Dual gas single ejector tests resulted in exceptional correlation, with $R>0.99$ typically for the consolidated data, with a slope of 1.0. These data indicate equivalent results for ASHRAE 110 performance testing using either SF_6 or N_2O, indicating N_2O as an applicable alternate tracer gas.

Keywords ASHRAE 110, tracer gas, laboratory hoods

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INTRODUCTION

Sulfur hexafluoride (SF_6) is the tracer gas specified for laboratory fume hood testing by ANSI/ASHRAE Standard 110, although the standard does not prohibit use of other gases.(1) SF_6 is a near perfect choice for a tracer gas, owing to its scarcity in the environment, ease of detection, ease of delivery through the ASHRAE ejector, and desirable physical and chemical properties. SF_6 is non-toxic (Threshold Limit Value [TLV®] of 1000 ppm),(2) non-flammable, odorless, colorless, and non-corrosive.

However, the need for an alternate tracer gas arises from the high Global Warming Potential (GWP) of SF_6. With a GWP of 23,900,(3) SF_6 has the highest GWP, when compared over a 100-year period, of all gases studied by the Intergovernmental Panel on Climate Change (IPCC) in 2007. SF_6 has subsequently been subject to regulation, leading the California Air Resources Board (ARB) to limit its use to one test per laboratory fume hood.(4) Moreover, the scarcity of SF6 makes it an expensive necessity, as well as limits its availability for testing in remote locations. Finding an alternate tracer gas to address these concerns thus becomes necessary in ensuring the efficacy of ASHRAE 110 laboratory fume hood testing.

An alternate tracer gas for laboratory hood performance testing, in accordance with ASHRAE Standard 110, must be "a gas of similar molecular weight and stability, supplied from a cylinder capable of maintaining 30 psig (200 kPa [gage]) at the test release rate for at least one hour. The tracer gas release rate shall be 4.0 Lpm."(1) Further consideration of properties, not outlined in the standard, would be beneficial in determining an optimal alternate tracer gas. The gas should be nontoxic, nonodorous, detectable at an appropriately low level, usable in the ASHRAE ejector, and environmentally friendly. Furthermore, it would be advantageous if the tracer gas were economical and readily available.

TABLE I. Properties of Tracer Gases

Property	Sulfur Hexafluoride	Nitrous Oxide
CAS	2511-62-4	10024-97-2
Molecular weight	146 gm/mole	44 gm/mole
ACGIH® TLV®	1000 ppm	50 ppm
NIOSH REL	1000 ppm	25 ppm
Toxicity	Non-Toxic	Toxic at high concentration
Stability	Stable	Stable
Odor	None	None at moderate concentration
Corrosivity	Non-corrosive	Non-corrosive
Minimum Detection Level	0.01 ppm	0.01 ppm
Background	Negligible	0.32 ppm and variable
Global Warming Potential (GWP)	22,200	296

Nitrous Oxide

Nitrous oxide (N_2O) has the necessary characteristics for an alternate tracer gas as specified by ASHRAE Standard 110. N_2O is also cost-effective and easily acquired, with beneficial qualities for an alternate to SF_6. Comparison of the physical properties of SF_6 and N_2O is presented in Table I.

Molecular Weight

The molecular weight of the gas used in ASHRAE Standard 110 testing affects the mass flow through the ejector, and the behavior of the plume subsequently generated. As the tracer gas exits the orifice, it entrains air into the ejector. The air-gas mixture forms a plume that exits the ejector top. Intuitively, the size of the plume is critical to the test because grossly different plumes could result in different hood challenges.

This investigation used 0.025-inch (0.63 mm) orifices as specified by Standard 110, and a calibrated piston meter to measure the flow through the orifice at a range of pressures. An upstream pressure of about 30 psig (200 kPa [gage]) is required to achieve 4.0 Lpm for SF_6. N_2O required approximately 9 psig (62 kPa [gage]) for the same flow.

Although it is easy to measure the flow through the orifice alone, it is difficult to measure the total flow of the tracer gas and the entrained air. A flow box, as seen in Figure 1, was used to measure the total flow. The flow box was used for measurement of the air entering the ejector through a long, straight entry tube. A rotary vane anemometer was used to measure the flow through the tube. The differential pressure between the test lab and flow box was monitored to determine any significant reduction in airflow due to the box. Such losses were negligible and the results allowed for determination of the size of the ejector plumes. As shown in Figure 2, 4.0 Lpm of tracer gas produced a total volumetric flow of approximately 700 Lpm and 400 Lpm, for SF_6 and N_2O, respectively. The flow box confirms a difference in the volume of the plumes. The lower volume of the N_2O plume implies a higher concentration of N_2O in its smaller plume when compared to SF_6.

Toxicity

N_2O has been in use as an anesthetic gas for over 150 years with limited noted adverse effects, beyond its association with asphyxiation. Anesthetic applications of N_2O are often 50%–80% by volume (500,000 ppm to 800,000 ppm). Recent studies have shown high, but not anesthetic, levels of N_2O are associated with spontaneous abortions, neuropathy, and embryo toxicity/fetotoxicity when N_2O anesthetic waste gas is released into the workspace. Based on available literature, ACGIH®[2] has established an N_2O TLV® of 50 ppm.

All tests performed in this study showed no leakage into the laboratory itself; however, there is a possibility of exposure to others in the building. Therefore, when using N_2O as a tracer gas, it is critical to understand the building ventilation system, and the interaction of the fan systems. For example, any fume hood exhaust system exceeding 5,600 acfm (2.6 actual m^3/s) will dilute the tracer gas to less than 25 ppm in the exhaust while the ejector is operating at 4.0 Lpm. For low volume systems, it is important to coordinate with facilities staff at or near the exhaust fan discharge to minimize potential exposure. Likewise, in buildings with reentry potential, the extent of potential exposure should be discussed with the health and safety staff to reduce potential exposure.

To minimize potential exposures to N_2O, certain administrative controls are recommended. Testing should be coordinated with the client, laboratory staff, EH&S, and facilities departments prior to conducting tests. The detectors should be operated with the audible alarm active at all times. If the face velocity or smoke visualization tests do not conform to the design parameters, or if the instrument alarms, the test should be terminated. Consider the use of additional tracer gas detectors as needed to monitor any areas where the concentration of N_2O may increase.

Stability

Nitrous oxide itself is stable, and effectively non-reactive, at room temperature and any elevated temperature expected in a laboratory hood. Although nitrous oxide is an oxidizer

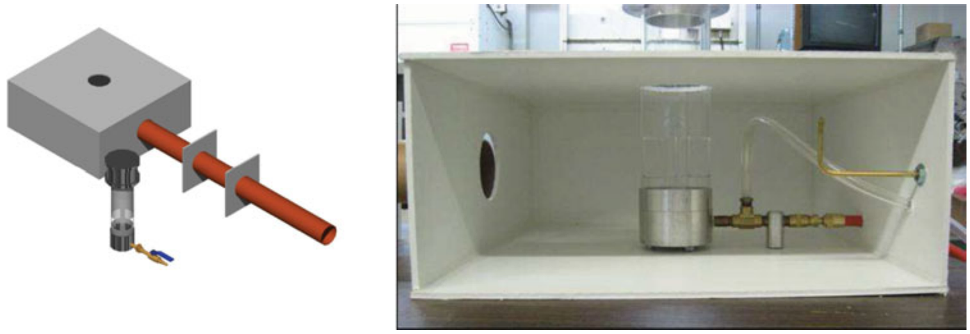

FIGURE 1. Flow Box.

at elevated temperature, it is not flammable. At the 4.0 Lpm release rate, it does not affect the lower explosive level of the local air envelope.

Background Concerns

N_2O is always present in air. It is generated by several human and natural activities. The background level depends on location and varies throughout the day. Major sources of N_2O include agriculture practices, especially the use of commercial and organic fertilizers, fossil fuel combustion, nitric acid production, and biomass burning. Although the background level fluctuates by region and throughout the day, the average global background level is approximately 0.32 ppm.(5)

The background was high enough that it cannot be ignored. However, if the variability is small relative to the acceptable level, the effect of background can be neglected. Figure 3 presents the N_2O background level for one representative hood at the site of testing in Riverside, California, on April 27, 2010.

Over the nearly four hours of testing, the change in background was greater than the acceptance level (AU 0.1) required by Cal/OSHA.(6) However, since the test takes less than 6 min at each position, variation was observed over a 10-min period. A relative frequency histogram for the variation in N_2O levels of the representative hood presented in Figure 3, during the observed 10-min periods, is presented in Figure 4. The data show nearly all 10-min periods had a variation of less than 0.03 ppm.

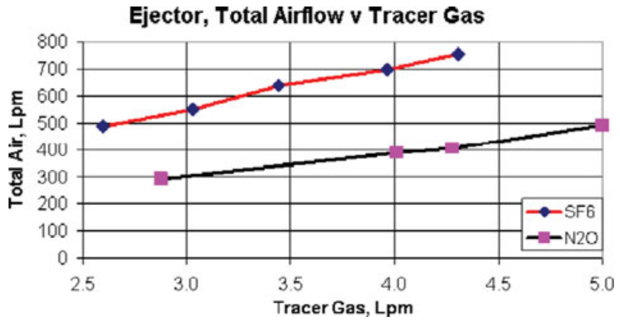

FIGURE 2. Total flow through the ejector.

Minimum Detection Level

The infrared spectrophotometer used for testing has a minimum detection level (MDL) of 0.03 ppm, as published by the instrument manufacturer. Based on the background data tests, it is clear that the MDL claim is conservative. Infrared spectrophotometers used in the tests are “portable;” however, the instruments were used in a stationary mode during testing. This improved the MDL. Based on the data collected for background, it was found that the MDL for performance testing with N_2O should be 0.01 ppm.

FIELD TESTS

Single Gas Tests

Methods

Single gas tests were conducted on thirty bench top hoods with a vertical sash using SF_6 and N_2O tracer gases. Each hood was tested with the sash at a nominal 18 inches (0.46 m) above the work surface, and the face velocity set at a nominal 60 fpm (0.3 m/s) according to ASHRAE Standard 110-1995. The face velocity of each hood was measured, and smoke visualization methods were used as described in Standard 110. The performance tests for each hood were conducted once using 4.0 Lpm of SF_6 and once using 4.0 Lpm of N_2O. The tracer gases were released from the three positions prescribed by Standard 110.

Results and Discussion

An acceptance level of AU 0.1 ppm was set for all single gas tests. Two of the 30 hood tests performed exceeded this acceptance, and 28 were below the acceptance level for both tracer gases. Twenty-seven of the hood tests were at, or below, the MDL for each tracer gas. Using this acceptance criterion of AU 0.1 ppm, the results of the single gas tests were typical of laboratory hoods designed and set to operate near 60 fpm and identical for both tracer gases Due to the preponderance of tests at the limit of detection, comparison data needed to evaluate N_2O against SF_6 could not be collected via single gas testing. To overcome this issue, two dual gas test methods

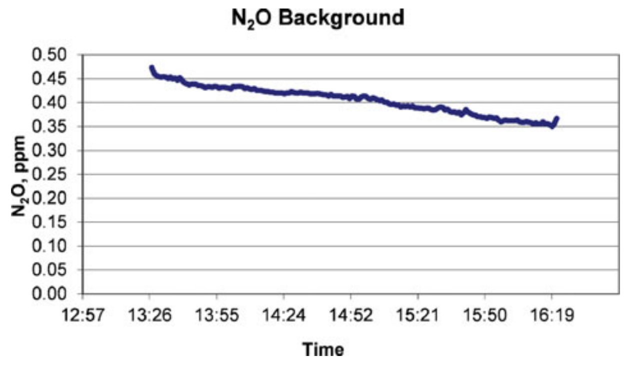

FIGURE 3. N_2O Background of one representative hood in Riverside during testing on April 27, 2010.

were devised, allowing for sampling of both tracer gases simultaneously. The conditions were slightly modified for dual gas testing, with the sample probe placed closer to the sash opening to provide measurements over a range of concentrations to have a robust comparison of N_2O and SF_6.

Dual Gas Dual Ejector Tests

Methods

Dual gas dual ejector tests were performed on 10 hoods. A 50-min test was conducted on each hood, and the data parsed into 10 5-min sets. Two ejectors were placed side by side. One ejector discharged 4.0 Lpm of SF_6, the other discharged 4.0 Lpm of N_2O. To increase the challenge to the hood, dual gas dual ejector tests were performed with the sash full open, 28.5 in (0.72 m). The VAV system modified the airflow to achieve a nominal face velocity of 60 fpm (0.3 m/s). The low face velocity and the larger opening contributed to increased control levels (decreased performance).

Using two ejectors necessarily modified the geometry of the test. The ASHRAE Standard 110 specifies the distance for both the mannequin and the ejector from the plane of the hood. The investigators held these dimensions. The Standard also specifies the position of the mannequin and the ejector relative to the sidewall. All tests were conducted in the center position. Consequently, the mannequin and ejector should be in the center (left to right) of the hood opening. Clearly, with two ejectors, this is not possible. The ejectors were placed with the bonnets (top screen) touching at the centerline of the hood. One ejector was to the left and one to the right (the relative positions varied during the testing). With the bonnets touching, the centerline distance between the two ejectors was 5 inches (0.13 m). Figure 5 shows the test arrangement.

Two infrared spectrophotometers sampled air through a single probe at the "breathing zone" of the mannequin. A Y-adapter connected to the two detectors was used to split the probe. The flow rate through the detectors was balanced. A third detector was used as an area monitor for N_2O, and was placed on a test cart remote from the hood. Data loggers collected the voltage output from the detectors.

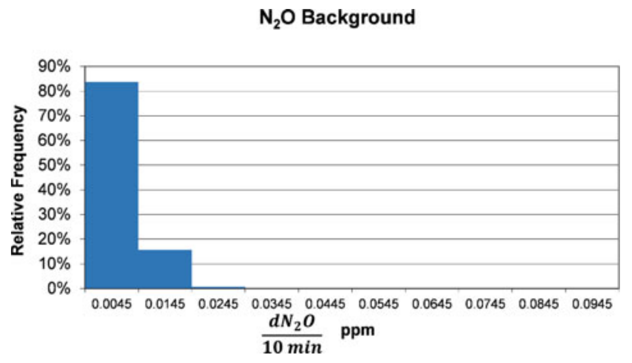

FIGURE 4. Corresponding histogram for the N_2O background data of the representative fume hood presented in Figure 3.

Results

Typical results of the 50-min tracer gas dual gas dual ejector tests are shown in Figure 6. Eight of ten sets of hood test data show excellent correlation, with R typically greater than 0.9. High variability was seen in the slope of the best-fit line, with a range from 0.43 to 1.57. For the consolidated data, R was found to have slightly lower correlation, with a value of $R = 0.86$. A substantial range of data was collected for each hood. There was some truncation of the data due to the method of data collection.

The voltage collected by the data loggers exceeded 1 volt (the upper limit of the data logger) at times during testing. When the SF_6 concentration exceeded about 5.1 ppm, the recorder truncated the data at 5.1 ppm. Likewise, the maximum N_2O recorded was about 6.2 ppm. This had little effect with an acceptance level of 0.1 ppm; however, with significant spillage, it affected the average concentrations. In some 5-min tests, there was no effect. In some tests, the effect was minimal. In some tests, significant truncation occurred. In these cases, the truncation occurred at 50 times the Acceptance Level, and consequently had little significance in data analysis.

The relation between the SF_6 and N_2O results for each hood was examined through comparison of the ten pairs of airborne concentrations for a given fume hood. This correlation was calculated in the form of the correlation coefficient R, given by Equation 1

$$R = \frac{n\sum x_i y_i - \sum x_i \sum y_i}{\sqrt{n\sum x_i^2 - \left(\sum x_i\right)^2} - \sqrt{n\sum y_i^2 - \left(\sum y_i\right)^2}} \qquad \textbf{(1)}$$

The Coefficient of Determination, R^2, describes the amount of variation of one variable that is accounted for by the variation in the second variable. Calculated values for R and R^2 are presented in Table II.

Discussion

The full open sash (nominal 62 in by 28.5 in [1.57 m by .72 m]) and the low face velocity (60 fpm [0.3 m/s]) resulted

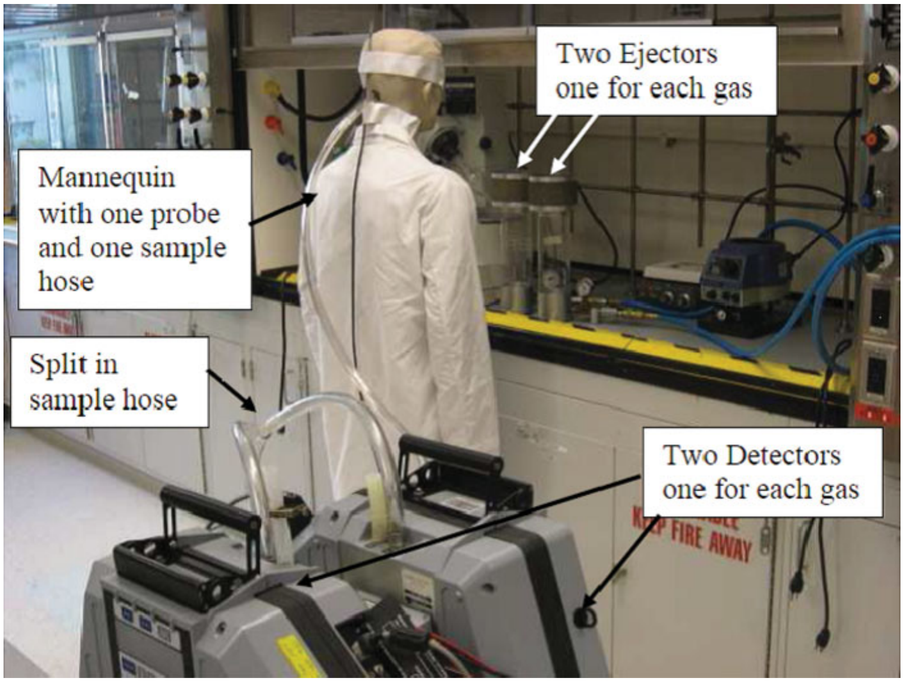

FIGURE 5. Dual Ejector test set up.

in hood instability and frequent spillage of tracer gas. These parameters may not depict typical laboratory operations. There is considerable variability in the SF_6 and N_2O tracer gas levels over time. Airborne concentration of SF_6 and N_2O track reasonably well. Although there are differences in the two tracer gases, the two concentration levels tend to rise and fall at the same time. There appears to be more variability between the 5-min SF_6 tests than between the SF_6 and N_2O tests (see Figure 6). The acceptance decision, based on the 5-min segments of each 50-min test of either tracer gas, appears to be the same. Since the parsed data for each hood consisted of ten pairs of data, each can be analyzed as a separate set of data. A two-tailed analysis of a correlation coefficient was used to determine the validity of correlation in the found results.

Eight degrees of freedom occur within the collected data, with n = 10, and n-2. Consequently, the probability of accepting the hypothesis that the tracer gas results are correlated when they are not is less than 0.01 (i.e., less than 1% of the time) when the correlation coefficient, R, is at or greater than 0.765. In nine of the ten hoods, R exceeds, and usually substantially exceeds, the critical value. Consequently, the probability for Type 1 error (accepting the null hypothesis—that the two tracer gas results are correlated—when it is incorrect) was found to be well less than 0.01 for nine of ten data sets and less than 0.05

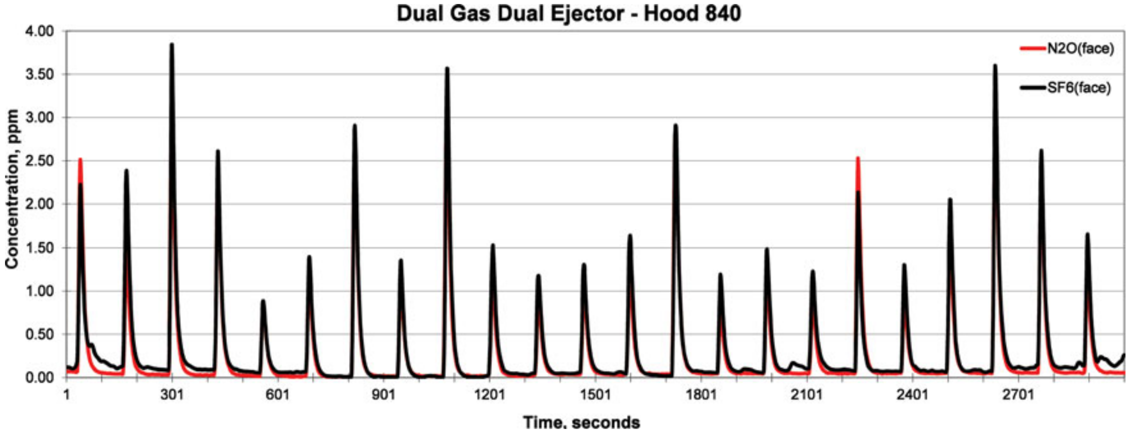

FIGURE 6. Typical full open sash tracer gas results for dual gas dual ejector tests.

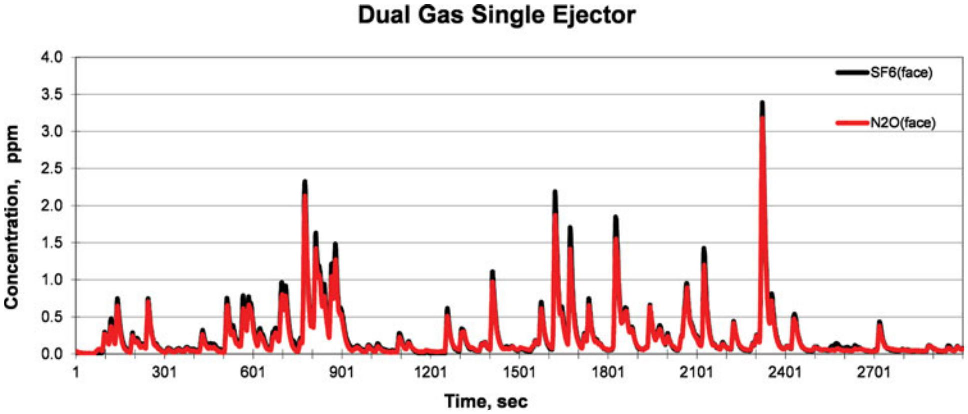

FIGURE 7. Typical dual gas single ejector test results.

for the remaining data set (Hood 4816). Hood 4816 appeared abnormal. It had the highest control levels of the parsed tests (the highest average, with all data in the highest quartile). This peculiarity was not investigated in field tests.

Two types of variability were observed. First, the parsed data (using either the SF_6 or the N_2O data) were found to be highly variable. Second, the behavior of the relative tests (comparing SF_6 and N_2O) varied as shown by the range of slopes form 0.43 to 1.57. In hood testing that was conducted over the past 30 years, significant variability has been observed in tracer gas concentration during testing. Discounting the very low tests, where variability may be obscured by the limit of detection, and the very high tests, in which catastrophic hood failure could obscure the data by exceeding the range of calibration on the instrument, typically a periodic variability on the test results is observed. As shown by both the parsed SF_6 and N_2O data, hood ratings have considerable variability. Although there are many theories, the true cause of this variability remains unknown. Several factors are believed to play a role, however.

A major factor that contributes to hood variability is the formation of a vortex in front of the mannequin that builds up and breaks off into the hood. This vortex shedding may be related to tracer gas spillage at the leading edge of the

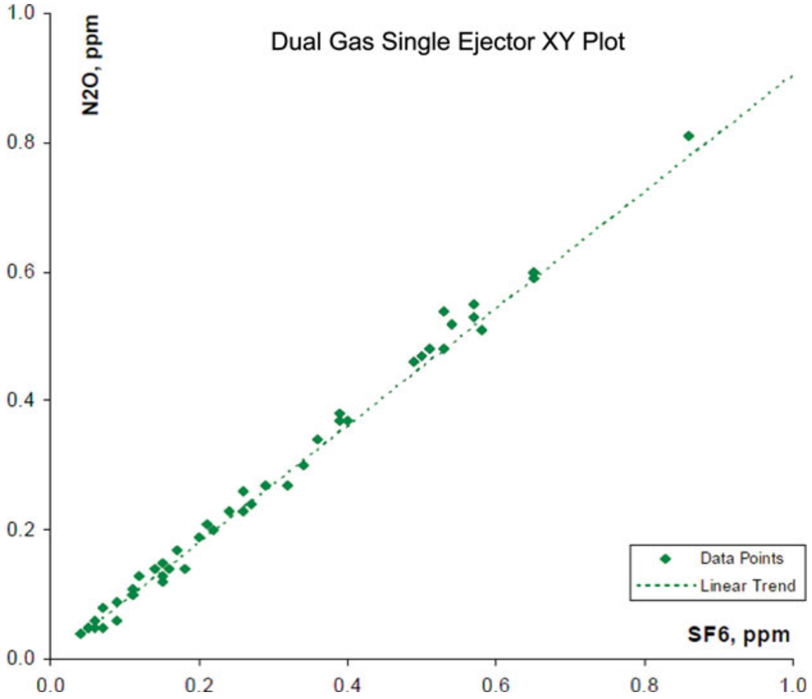

FIGURE 8. Summary of five dual gas single ejector tests.

TABLE II. Correlation Analysis

Test	Coefficient of Determination	Correlation Coefficient	Best fit straight line
Hood	R^2	R	Slope
4806	0.88	0.94	0.43
4807	0.69	0.83	0.46
4808	0.91	0.95	0.57
4809	0.99	0.99	0.99
4810	0.93	0.96	1.10
4811	0.97	0.98	1.00
4814	0.81	0.90	1.21
4815	0.97	0.98	0.91
4816	0.50	0.70	0.78
4817	0.87	0.93	1.57
All	0.75	0.86	0.78

hood. A second major factor is the roll in the upper portion of the hood, sometimes referred to as a vortex. As this roll changes in size and speed of rotation, it may relate to control at the sash pull. In addition, air entering the hood under the sash pull demonstrates flow separation resulting in turbulence, and occasionally reverse flow, under the sash. Another factor may be the face velocity, which varies temporally, as with any ventilation system. Total flow can also contribute to variability, as it changes through the hood due to changes in other hoods, fluctuations in the system static pressure, and variation in the exhaust fan. Other factors include supply air, temperature, and volumetric flow to the room, which vary with time. These factors affect the control level of the hood.(7)

The large correlation coefficients for the parsed data indicate that the two tracer gases track very well with these (unknown and unmeasured) fluctuations. Although the parsed data indicate very high correlation, unity was not achieved for the slope of the best-fit line, nor was the slope constant. Slope variation occurred from 0.43 to 1.57. The linear relationships with different slopes indicate conditions at each hood may have had a systematic bias, believed to be attributable to variable symmetry.

In ASHRAE testing, the positioning of ejectors, mannequin, and probe is critical. Small variations can affect the test results. Often, observed deviations from expected results through examination of the challenge and the mannequin occur due to small deviations from the specified geometry. This is especially exacerbated in the dual ejector challenge. If the mannequin is slightly to the left of centerline, it now resides closer to the left ejector and farther from the right ejector. If the room air currents, hood design, or hood balance induce a slight left to right motion, the probe will be more influenced by the tracer gas released through the left ejector than the right ejector. Thus, if the mannequin is not perfectly symmetric, in design and positioning, one ejector could have a greater influence than the other. Consequently, variations in slope for best-fit lines are expected.

Dual Gas Single Ejector Tests

Methods

Additional dual gas tests were conducted on five hoods of the same model and manufacturer. The discharge from two gas cylinders was connected to a single line feeding the ejector. The flow rates for each of the two tracer gases were the same, but less than the 4.0 Lpm specified in Standard 110. To determine the total flow rate, the flow box (Figure 1) was used. The induced total flow was matched to the 4.0 Lpm SF_6 challenge. Through simultaneously increasing the flow rate of both tracer gases, the "equivalent" plume was obtained with a flow rate of 2.66 Lpm for each gas, a total flow of 5.32 Lpm.

Results and Discussion

Of the 50 time intervals observed, the results are nearly indistinguishable. Figure 7 presents the data from testing of one hood, which can be taken as representative of all fifty tests performed on the five total hoods. The fifty points in Figure 8 show the result of these tests. The correlation coefficient for the data of 0.997 demonstrates the nearly linear relationship of the dual tracer gas tests. This indicates the two gases behave similarly once they leave the ejector, and that airflow in the hood has a more significant effect than gaseous diffusion. Therefore, it can be disregarded in further analysis. The variability in tracer gas concentration was negligible.

CONCLUSION

The results of testing indicate N_2O is a viable candidate for an alternative to SF_6 for laboratory fume hood testing according to ASHRAE Standard 110. Thirty single gas tests result in essentially indistinguishable results for both tracer gases. For the ten dual gas dual ejector tests with full open sash, there was greater variability within the 50-min test than between the 5-min paired tracer gas results. For each hood, the correlation coefficient for the two tracer gasses was typically greater than 0.90. For the five tests with dual gas with a single ejector, the correlation coefficients for each hood were greater than 0.997 and the slope of the best fit line was about 0.99.

ACKNOWLEDGMENTS

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