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Laboratory Fume Hood and Exhaust Fan Penthouse Exposure Risk Analysis Using The ANSI/ASHRAE 110-1995 and Other Tracer Gas Methods

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ABSTRACT

The use of the laboratory fume hood as the primary containment device in the laboratory has been a standard practice for almost half a century. Quantitative testing of the performance of these devices, however, is a more recent discipline. The use of the ANSI/ASHRAE 110-1995, Method of Testing Performance of Laboratory Fume Hoods *(ASHRAE 1995) is becoming a standard specification in the purchase of new fume hoods, the commissioning of new laboratory facilities, and benchmarking fume hoods in existing facilities. Part I of this paper proposes a risk analysis method by which worker exposure to hazardous substances used in laboratory fume hoods may be estimated using results from the ASHRAE 110 method and formulae to extrapolate this information into potential exposure scenarios.*

Contaminated air leaking from hazardous exhaust systems located inside buildings or fan penthouses can pose a health risk to building occupants and maintenance workers. This is why prudent design practices for new buildings recommend that the fans powering these systems be located outside. In existing buildings with fans located inside or where a penthouse is required for weather conditions, however, it may be necessary to estimate potential worker exposure to hazardous agents released by these systems into the worker's environment. Part II of this paper proposes a method and formulae by which this risk may be evaluated based on measurement of leakage using a tracer gas release, capture, and detection method.

INTRODUCTION

For production areas and some clinical laboratories where the target agents are limited and well defined, personal air sampling has traditionally been the method of choice for determining exposure risks. In research and development (R&D) laboratories, however, where the potential hazards are numerous, constantly changing, and often unknown, personal air sampling is expensive, time consuming, and of questionable value. Another method, one that is less expensive and time consuming, is agent independent, and yet is quantitative, would be of great value when attempting to determine exposure risk in the laboratory.

Both of the exposure risk evaluation methods described in this paper involve the use of tracer gas technology. This is a quantitative field investigation tool used to determine leakage and flow rates of contaminants from laboratory fume hoods, ducts, or equipment by releasing a measured volume of a tracer gas, sulfur hexaflouride (SF_6) in this case, into the equipment and measuring the concentration of the tracer gas outside the equipment using a sensitive detector.

In the late 1970s Caplan and Knutson began publishing research using a new method of determining fume hood capture efficiency by using a tracer gas sampling method (Caplan and Knutson 1977, 1978). This was the precursor of *ANSI/ASHRAE 110-1985, Method of Testing Performance of Laboratory Fume Hoods* (ASHRAE 1985). Recently, this standard was revised (ASHRAE 1995). The new standard was used as the basis for the tracer gas containment testing described in Part I of this paper.

The method used to determine duct leakage and potential exposure calculations for ducts and fans, outlined in Part II of this paper, was developed by the author for use in evaluating an actual laboratory facility with the exhaust fans located in a fan penthouse.

The potential exposure calculations for laboratory fume hoods and equipment leakage were synthesized by the author from standard industrial ventilation and industrial hygiene texts and anecdotal evidence from the original research done to develop the ASHRAE 110 method (Caplan and Knutson 1976, 1977, 1978).

CAUTION

Great care should be exercised when applying these methods. As with all risk evaluation methods, these extrapolations are only made possible by making several fundamental assumptions regarding exposure routes, work practices, chemical/leak evolution methods and rates, etc. These assumptions are highlighted in the text and should be thoroughly understood by the reader before

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applying these methods to real-world situations involving potential worker exposure to hazardous agents. If the assumptions enumerated in the following methods are particularly inappropriate for a specific application, then the method should be modified accordingly or another risk model should be employed or developed.

PART I: ESTIMATING POTENTIAL EXPOSURES FROM LABORATORY FUME HOODS

Step 1: Determine the Control Level of the Fume Hood Using the ASHRAE 110 Method

A diagram of the ASHRAE 110 tracer gas containment test setup is shown in Figure 1. Tracer gas (1) is released into the fume hood using a standardized ejector (2) at the rate of 4.0 liters per minute, which creates a cloud of diluted tracer gas (3) in the fume hood. Some of the tracer gas will leak out of the fume hood and into the breathing zone (4) of the mannequin (5) used to simulate the aerodynamics of the user. Air from the breathing zone is sampled, and the concentration of tracer gas is determined by a sensitive detector (6). The control level of the hood is the highest average five-minute sample taken with the ejector and mannequin located on the left side, in the center, and on the right side of the fume hood. The recommended control level for laboratory fume hoods is 0.10 ppm according to the industrial ventilation manual of the American Conference of Governmental Industrial Hygienists (ACGIH 1995), the laboratory ventilation standard of the American Industrial Hygiene Association (AIHA 1993), and *Prudent Practices* (NRC 1995).

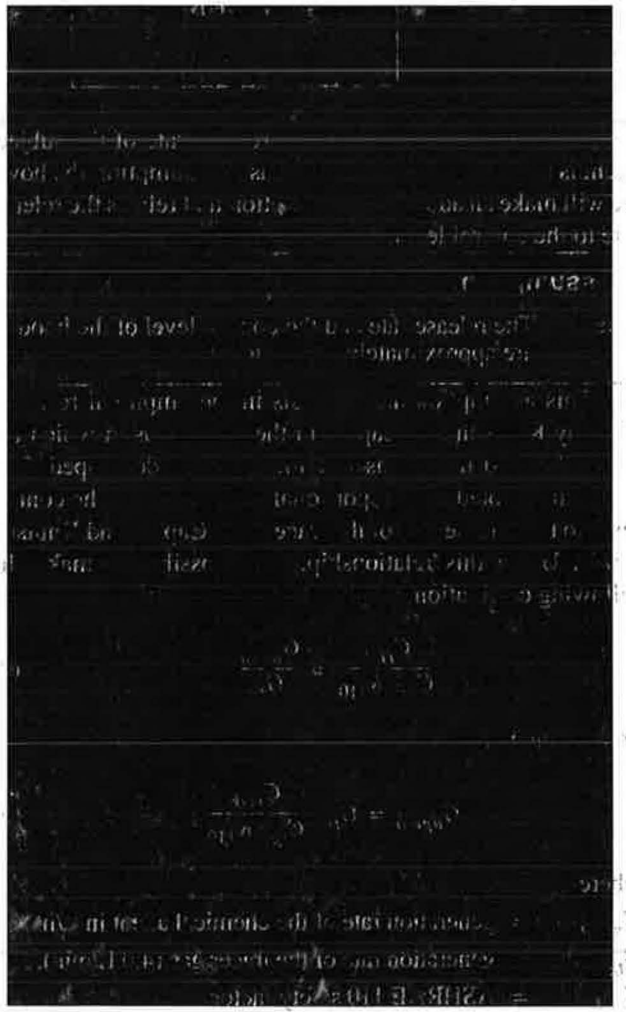

Figure 1 The ASHRAE 110 tracer gas containment test setup.

Step 2a: Determine Potential Exposures from a Particular Fume Hood

The following assumptions must be made to relate actual dynamic conditions to the static test conditions:

Assumptions

- Ia. The user and the mannequin are approximately the same height and width and are positioned the same relative to the hood opening, i.e., the user does not bring the face closer than 3 in. (75 mm) to the plane of the sash.
- Ib. The agent is released into the fume hood at the same rate and in a cloud with the same geometry and location as the tracer gas, i.e., the release occurs at least 6 in. (150 mm) behind the sash in a relatively spherical, nondirectional pattern and at a rate not exceeding 8.0 L/min, the upper limit at which the ASHRAE 110 tracer gas containment testing is known to be reliable.
- Ic. The user does not move.
- Id. The user uses prudent fume hood work practices.

The equation to determine potential exposure concentration to an agent is

$$C_{risk} = C_{tg} \cdot K_{110} \quad (1)$$

where

C_{risk} = potential exposure concentration to a chemical agent in ppm,

C_{tg} = tracer gas control level in ppm,

K_{110} = safety factor.

Since these assumptions are *never* all valid, it is prudent to employ a safety factor to account for natural arm and body movements, raising the sash quickly, and improper work practices such as having the chemical source closer than 6 inches behind the sash, etc. Field data have demonstrated, for example, that moving the tracer gas source to the plane of the sash can increase the tracer gas concentrations as much as 300 times. Although working outside the assumption envelope can cause transient exposures several hundred times the exposure found using this static method, there are other mitigating factors that lower average potential exposure. Some of these factors are:

TABLE 1
Selection of the K110 Safety Factor

Type of Agent Exposure Index	Type of Use and Operating Conditions	Safety Factor K110
TLV (Threshold Limit Value) REL (Recommended Exposure Limit)	•Periodic use •Prudent work practices •Lower release rates (<4.0 L/min)	10-20
	•Continuous use •Non-ideal work practices •Higher release rates (4.0-8.0 L/min) •Using synergistic agents	20-40
STEL (Short-Term Exposure Limit)	•Periodic use •Prudent work practices •Low release rates (<1.0 L/min)	20-40
	•Continuous use •Non-ideal work practices •Higher release rates (4.0-8.0L/min) •Using synergistic agents	40-80
CLG (Ceiling Value)	•Prudent work practices •Low release rates (<1.0 L/min)	40-80
	•Non-ideal work practices •Higher release rates (4.0-8.0 L/min) •Using synergistic agents	80-160

- The hood user is probably not in front of the hood for the entire eight-hour working day.
- The hazard in question is probably not released constantly.
- The release rate will often be lower than 4.0 L/min, etc.

Taking these factors into account, some that raise exposure potential and some that reduce it, the author recommends choosing the safety factor (K_{110}) using Table 1.

Table 1 is based on a minimum safety factor of 10 for agents with a Threshold Limit Value (TLV) exposure or Recommended Exposure Limit (REL) index representing an eight-hour time-weighted average (TWA) under favorable use and operating conditions. Statistical evaluation of the ratio of the maximum tracer gas levels to the average tracer gas levels for 1,313 actual tracer gas containment tests revealed that 95% of the observations had instantaneous maxima less than 40 times the average. Therefore, this value was chosen as the minimum safety factor when using agents with CLG (ceiling) values representing an instantaneous maximum exposure limit. The minimum safety factor for agents with a Short-Term Exposure Limit (STEL) index representing a 15-minute TWA was chosen midway between the minimum safety factors for the TLV/REL and CLG indices, respectively. The table also gives the opportunity to double the safety factor for less than favorable use or operating conditions.

Step 2b: Determine the Release Rate of a Particular Agent in the Hood That Will Produce an Exposure Equal to its Applicable Exposure Guideline or Limit

Instead of assuming that the release rate of the subject agent is the same as the tracer gas, as in assumption Ib above, we will make an additional assumption that relates the release rate to the control level:

Assumption

Ie. The release rate and the control level of the hood are approximately proportional.

This assumption has its basis in the empirical research done by Knutson and Caplan in the late 1970s in which the ASHRAE 110 tracer gas test method was developed. The researchers noted this proportional relationship of the control level to the release rate of the tracer gas (Caplan and Knutson 1976). Using this relationship, it is possible to make the following calculation:

$$\frac{C_{risk}}{C_{tg} \cdot K_{110}} = \frac{G_{agent}}{G_{tg}} \tag{2}$$

or, rearranging,

$$G_{agent} = G_{tg} \cdot \frac{C_{risk}}{C_{tg} \cdot K_{110}} \tag{3}$$

where

G_{agent} = generation rate of the chemical agent in L/min,
G_{tg} = generation rate of the tracer gas (4.0 L/min),
K_{110} = ASHRAE 110 safety factor.

The relationship of volume of vapor generated by an evaporating liquid to its evaporation rate is taken from the industrial ventilation manual (ACGIH 1995).

$$G_{agent} = \frac{CONV \cdot SG_{agent} \cdot ER_{agent}}{MW_{agent}} \qquad (4[IP])$$

where

G_{agent} = generation rate of agent, cfm (vapor);
$CONV$ = the volume in ft^3 that 1 pt of liquid, when vaporized, will occupy at STP, 403 ft^3/pt;
SG_{agent} = specific gravity of liquid agent;
ER_{agent} = evaporation rate of liquid agent, pt/min.;
MW_{agent} = molecular weight of liquid agent.

This equation is converted from inch-pound to SI units using the following conversions:

1 ft^3 = 28.3 $liter_{vap}$
1 pt = 473 mL_{liq}

Converting:

$$CONV = \frac{\left(403\frac{ft^3}{pt}\right)\cdot\left(28.3\frac{l_{vap}}{ft^3}\right)}{\left(473\frac{pt}{mL_{liq}}\right)}$$

$$= 24.1\frac{l_{vap}}{mL_{liq}}$$

Substituting this into Equation 4 (IP) yields

$$G_{agent} = \frac{24.1\frac{l_{vap}}{mL_{liq}} \cdot SG_{agent} \cdot ER_{agent}}{MW_{agent}} \qquad (4[SI])$$

where

G_{agent} = generation rate, L/min (vapor);
ER_{agent} = evaporation rate of liquid, $\frac{mL_{liq}}{min}$

Substituting the right side of Equation 4 (SI) into the left side of Equation 3 and substituting 4.0 L/min for the generation rate of tracer gas, G_{tg}, gives

$$\frac{\left(24.1\frac{l_{vap}}{mL_{liq}}\right)\cdot SG_{agent}\cdot ER_{agent}}{MW_{agent}} = \left(4.0\frac{l_{vap}}{min}\right)\cdot\left(\frac{C_{risk}}{C_{tg}\cdot K}\right)$$

Solving for ER_{agent} and combining terms,

$$ER_{agent} = \left(0.17\frac{moles_{liq}}{min}\right)\cdot\left(\frac{MW_{agent}}{SG_{agent}}\right)\cdot\left(\frac{C_{risk}}{C_{tg}\cdot K_{110}}\right) \qquad (5)$$

Equation 5 can be modified slightly by substituting the exposure guideline for the agent, C_{agent}, for the potential exposure concentration, C_{risk}, as in Equation 5a below.

$$ER_{agent} = \left(0.17\frac{moles_{liq}}{min}\right)\cdot\left(\frac{MW_{agent}}{SG_{agent}}\right)\cdot\left(\frac{C_{agent}}{C_{tg}\cdot K_{110}}\right) \qquad (5a)$$

This equation yields the maximum evaporation rate of an agent with properties MW_{agent} and SG_{agent} in a specific fume hood with a control level of C_{tg} and safety factor of K_{110} that will not exceed the agent exposure guideline, C_{agent}. Note that $mL_{liq/min}$ was chosen for the units in Equations 5 and 5a because this is more readily applied to scientific experiments performed in a laboratory fume hood than other possible units of measurement for this quantity.

Example 1

What is the maximum evaporation rate of gluteraldehyde in a fume hood that has an ACGIH recommended control level of 0.1 ppm, which will produce an estimated exposure level equal to the exposure guideline? What is the generation rate in L/min? The hood has periodic use, with prudent work practices and no additional synergistic chemicals.

Gluteraldehyde:

MW = 100
SG = 1.1
C_{agent} = 0.2 ppm (NIOSH CLG)
K_{110} = 40 (chosen from Table 1 using the information above)

Substituting into Equation 5,

$$ER_{agent} = \left(0.17\frac{moles_{liq}}{min}\right)\cdot\left(\frac{100\frac{g}{mole}}{1.1\frac{g}{mL}}\right)\cdot\left(\frac{0.2_{ppm}}{0.1_{ppm}\cdot 40}\right)$$

$$= 0.77\frac{mL_{liq}}{min}$$

The generation rate is calculated using Equation 4 (SI).

$$G_{agent} = \frac{24.1\frac{l_{vap}}{mL_{liq}}\cdot 1.1\cdot 0.77\frac{mL_{liq}}{min}}{100}$$

$$= 0.2\frac{l_{vap}}{min}$$

Example 2

What is the estimated exposure concentration for acrylonitrile released at a rate of 10 mL/min in a fume hood that has an ASHRAE 110 control level of 0.1 ppm? What is the generation rate in L/min? The hood has periodic use, with prudent work practices and no additional synergistic chemicals.

Acrylonitrile:

MW = 53
SG = 0.81
C_{agent} = 1.0 ppm (NIOSH REL)
K_{110} = 10 (chosen from Table 1 using the information above)

Rearranging Equation 5a and substituting values,

$$C_{agent} = \left(\frac{ER \cdot SG \cdot C_{tg} \cdot K_{1.10}}{MW \cdot 0.17 \frac{moles_{liq}}{min}} \right)$$

$$= \frac{10 \frac{mL}{min} \cdot 0.81 \frac{g}{mL} \cdot 0.1_{ppm} \cdot 10}{53 \frac{g}{mole} \cdot 0.17 \frac{moles_{liq}}{min}}$$

$$= 0.9 \text{ ppm}$$

Note that this is just slightly under the exposure guideline of 1.0 ppm, and care should be taken to limit the release rate to 10 mL/min.

Again, the generation rate is calculated using Equation 4 (SI):

$$G = \frac{24.1 \frac{l_{vap}}{mL_{liq}} \cdot 0.81 \cdot 10 \frac{mL_{liq}}{min}}{53}$$

$$= 3.6 \frac{l_{vap}}{min}$$

PART II: ESTIMATING POTENTIAL EXPOSURES FROM DUCT AND EQUIPMENT LEAKS IN HAZARDOUS EXHAUST SYSTEMS

When using a chemical agent at the generation rate that will result in a potential exposure equaling the exposure guideline, an exhaust system concentration may pose a health hazard to those working in enclosed fan penthouses, where fan and duct leaks allow exposure to this contaminated air.

Step 1: Determine the Actual Leakage Rate from the Specific Component in Question

This can be done by creating a physical control volume around the component as shown in Figure 2. In practice, the control volume is an enclosure fabricated from plastic sheeting around the component to be tested. Tracer gas is injected enough upstream of the fan to ensure adequate mixing. The duct concentration of tracer gas is measured, and this is assumed to be the concentration of tracer gas in the air leaking into the "bag." An air sample is drawn from the bag through a flowmeter using a small fan or sampling pump. The steady-state concentration of tracer gas in the sample is measured and allows the volume of the leak to be determined using the following simple relationship:

$$Q_{leak} = Q_{sample} \cdot \left(\frac{C_{sample}}{C_{leak}} \right) \quad (6)$$

This relationship is only valid for a steady-state condition, which happens only after about 10 air changes occur in the enclosure (bag). At low leak/sample/infiltration flow rates, it can take quite some time to reach steady state. It is advisable to monitor the sample concentration graphically in real time using a computer or strip chart recorder to ensure that equilibrium has been reached before recording the sample concentration, C_{sample}. It is also necessary that Q_{infilt} be greater than zero. If C_{sample} is less than C_{duct}, this is ensured. Care must also be exercised when fabricating the enclosure and performing

Key

Q_{tracer}	=	Volume of tracer gas injected into the duct upstream of the control volume
C_{duct}	=	Concentration of tracer gas in duct (measured)
C_{sample}	=	Concentration of tracer gas in sample (measured)
Q_{sample}	=	Volume flow rate of sample (measured)
C_{infilt}	=	Concentration of tracer gas in ambient air drawn into control volume by sample pump (assumed, see below)
C_{leak}	=	Concentration of tracer gas in leak (assumed, see below)
Q_{leak}	=	Volume flow rate of equipment leak into control volume

Assumptions

Control volume pressure is ambient: do not draw a vacuum on the sample bag.

$Q_{leak} + Q_{infilt} = Q_{sample}$ (control volume mass balance)

$C_{leak} = C_{duct}$

C_{infilt} = Zero. This may not actually be true as tracer gas leaks into the area during testing and background concentrations build up. But, if the background concentration does not exceed 10% of the sample concentration, and the infiltration into the control volume does not exceed 100% of the leak volume, then the error will not exceed 10%. The actual formula for the error is as follows:

$$\text{error (\%)} = \frac{C_{ambient}}{C_{leak}} \times \frac{Q_{ambient}}{Q_{leak}} \times 100$$

Figure 2 - Control volume concepts.

the sampling so that the enclosure bag does not collapse and create a negative pressure around the leak area. This will increase the differential pressure across the leak and give erroneously high results.

Step 2: Calculate System Leakage

In this case, an exhaust fan system, the principal leakage sources would be the fan housing, fan shaft seal, discharge/flex connection, fittings, and ductwork. Leakage from each of these components can be individually determined using the control volume method.

Under certain conditions, a random sampling of duct and fittings can be tested to determine average leakage. Several lengths of ductwork can be tested in a similar way and averages can be determined so that every fitting and foot of duct do not have to be tested. Leakage from different sizes of fittings of similar construction is directly proportional to the diameter. It is helpful to normalize (divide) the leakage from fittings by the diameter of each, and then the leakage from similar fittings can be determined by multiplying the average of the normalized leakage by the number and diameter of the fittings in a particular system.

Duct leakage may be estimated similarly. For spiral duct, the leakage is proportional to the diameter and the square root of the duct static pressure. Normalize the duct leakage by the diameter, length tested, and the square root of the duct static pressure measured near the fan; then determine leakage from the straight ductwork in a particular system by multiplying the average of the normalized leakage by the diameter, the length of straight duct on the discharge side of the fan system, and the square root of the duct static pressure measured near the fan. If the duct systems are similar in length and resistance, this is a relatively reliable method of estimation since the duct is produced by a machine and variability is lower than with handmade duct.

For snaplock duct or duct with pittsburgh joints, the leakage is proportional to the length and the square root of the duct static pressure. Normalize the duct leakage by the length tested and the square root of the duct static pressure measured near the fan. Then multiply the average of the normalized leakage by the length of straight duct on the discharge side of the fan system and the square root of the duct static pressure measured near the fan. Since there may be great variability between sections of rectangular duct, this method may yield erroneous results even if the duct systems are similar in length and resistance, and caution is recommended.

In all cases, careful visual inspection of every inch of the duct system is advised. This will catch gross leaks caused by faulty fittings, unplugged test holes, holes caused by corrosion, or nonuniform application of duct sealants.

Step 3: Determine the Concentration of the Leak in the Enclosed Space

Knowing the flow rate of the leak, the concentration of the leak, and the ventilation rate, you can determine breathing zone concentration of the agent using the standard steady-state dilution ventilation equation (ASHRAE 1995) and several fundamental assumptions:

Assumptions

IIa. The area ventilation is equally distributed among all the hazardous exhaust systems in the area ventilated.

IIb. The concentration of leaking contaminant is uniform throughout the imaginary near-field control olume surrounding the equipment.

$$Q_{vent} = \left(\frac{G_{agent}}{C_{resp}}\right) \cdot K_{vent} \qquad (7)$$

where

Q_{vent} = actual ventilation rate, cfm;

G_{agent} = generation rate of pure agent (contaminant), cfm;

C_{resp} = near-field respirable concentration of gas or vapor, ppm;

K_{vent} = mixing factor (range: 1-10).

Rearranging Equation 7 and solving for C_{resp},

$$C_{resp} = \left(\frac{G_{agent}}{Q_{vent}}\right) \cdot K_{vent} \qquad (8)$$

The generation rate, G_{agent}, assumes a pure contaminant. If the contaminant is dilute, it can be determined as follows:

$$G_{agent} = Q_{leak} \cdot C_{leak} \qquad (9)$$

Substituting Equation 9 into Equation 8 yields

$$C_{resp} = \left(\frac{Q_{leak} \cdot C_{leak}}{Q_{vent}}\right) \cdot K_{vent} \qquad (10)$$

Based on assumption IIa, we have the following relationship:

$$Q_{vent} = \frac{Q_{total}}{n} \qquad (11)$$

where

Q_{total} = total penthouse evangelization rate (cfm);

n = total number of exhaust systems in the penthouse

Rearranging Equation 10 and solving for Q_{leak} and substituting Equation 11 for Q_{resp} yields

$$Q_{leak} = \frac{C_{resp} \cdot Q_{total}}{C_{leak} \cdot K_{vent} \cdot n} \qquad (12)$$

The duct/leak concentration is calculated as follows:

$$C_{duct} = \frac{\left(\frac{ER_{agent} \cdot SG_{agent}}{MW_{agent}}\right) \cdot 10^6}{\left(\frac{Q_{hood}}{SV_{air} \cdot MW_{air}}\right) \cdot \left(454\frac{g}{lb}\right)} \quad (13)$$

where

C_{duct} = duct concentration, ppm;

ER_{agent} = evaporation rate of agent, $\frac{mL}{min}$

AG_{agent} = specific gravity of agent;

MW_{agent} = molecular weight of agent;

Q_{hood} = hood flow rate, cfm;

SV_{air} = specific volume of air @ STP, 13.3 $\frac{ft^3}{lb}$;

MW_{air} = molecular weight of air, 28.9.

Substituting the known values for air and the assumption that $C_{duct} = C_{leak}$,

$$C_{leak} = \left(\frac{ER_{agent} \cdot SG_{agent}}{MW_{agent} \cdot Q_{hood}}\right) \cdot \left(0.85 \times 10^6 \frac{ppm \cdot ft^3}{mole}\right) \quad (14)$$

Substituting Equation 14 into Equation 12 yields the leak rate that will produce an exposure concentration of C_{resp} in the penthouse:

$$Q_{leak} = \frac{C_{resp} \cdot MW_{agent} \cdot Q_{hood} \cdot Q_{total}}{ER_{agent} \cdot SG_{agent} \cdot \left(0.85 \times 10^6 \frac{ppm \cdot ft^3}{mole}\right) \cdot K_{vent} \cdot n} \quad (15)$$

In order to determine the maximum duct/equipment leak rate that will produce an ambient concentration in the penthouse at the exposure guideline, simply substitute the exposure guideline, C_{agent}, for the ambient concentration, C_{resp}. This gives

$$Q_{leak} = \frac{C_{resp} \cdot MW_{agent} \cdot Q_{hood} \cdot Q_{total}}{ER_{agent} \cdot SG_{agent} \cdot \left(0.85 \times 10^6 \frac{ppm \cdot ft^3}{mole}\right) \cdot K_{vent} \cdot n} \quad (15a)$$

In Equation 15a above, all the variables are easily determined, either by measurement or by the use of the tables herein, except the agent evaporation rate, ER_{agent}. This is extremely difficult to determine quantitatively. Even the laboratory personnel, in most cases, have no idea what is the generation/evaporation rate of the materials with which they work. So, two final assumptions, IIc and IId, are required.

Substituting Equation 5a into Equation 15a gives the following:

$$Q_{leak} = \left(\frac{C_{tg} \cdot Q_{hood}}{0.14 \times 10^6 (ppm \cdot cfm)}\right) \cdot \left(\frac{K_{110}}{K_{vent}}\right) \cdot \left(\frac{Q_{total}}{n}\right) \quad (16)$$

Assumptions

IIc. The fume hoods served by the enclosed exhaust systems have a control level of C_{tg}.

IId. The release rate of the agent in the fume hood is the rate at which the potential exposure concentration at the fume hood, C_{risk}, is equal to the exposure guideline for the agent, C_{agent}.

Note that by assuming the release rate in the hood will produce a breathing-zone concentration at the hood equal to the exposure guideline, C_{agent}, and the duct/equipment leak rate in the penthouse will produce the same exposure level, C_{agent}, all the agent-related components (C_{agent}, SG_{agent}, MW_{agent}, ER_{agent}) cancel because the evaporation rate and the duct leak rate are both dependent upon these figures.

Equation 16 should be used when determining the maximum average leak rates for fume hood exhaust systems in enclosed spaces when the exposure is expected to occur in the near-field area around the fan/leak. If, however, the general area concentration is of concern, assumption IId may yield very conservative numbers since the maximum release rates may not occur in all fume hoods simultaneously. This is especially true in research and development facilities, where fume hood utilization is often relatively low and work in different laboratories is uncoordinated. The assumption is less conservative in quality control laboratories, where hood usage is usually more intensive than in R&D. The assumption is least conservative in teaching, production, or clinical laboratories, where fume hood utilization is high or identical operations are conducted in many hoods simultaneously.

Therefore, $K_{diversity}$, or the hood release diversity factor, is introduced and is applied by modifying Equation 16 as follows:

$$Q_{leak} = \left(\frac{C_{tg} \cdot Q_{hood}}{0.14 \times 10^6 (ppm \cdot cfm)}\right) \cdot \left(\frac{K_{110}}{K_{vent} \cdot K_{diversity}}\right) \cdot \left(\frac{Q_{total}}{n}\right) \quad (16a)$$

where

$K_{diversity}$ = fume hood release diversity.

Choose $K_{diversity}$ using Table 2.

TABLE 2

Recommended Fume Hood Release Diversity Factor

Type of Laboratory Facility	$K_{diversity}$
Research and Development	0.1-0.5
Quality Control	0.25-0.75
Clinical,Production,Teaching	0.5-1.0

In all cases, the choice of $K_{diversity}$ should be made only after carefully examining the type of usage for a particular facility.

Example 3

An exhaust fan penthouse has 5,000 cfm (2,360 L/s) of general exhaust divided among 50 exhaust fan systems. The air in the penthouse is poorly distributed. Agents with TLVs are used with prudent work practices in 6 ft (1.8 m) fume hoods with recommended control levels of 0.1 ppm and sized for 100 fpm (0.5 m/s) at 50% open. Each hood is served by a single fan. What is the maximum leakage per system that can occur and not exceed the exposure guideline of the hazard?

Assigning a value of 10 to K_{vent} to account for poor air distribution in the penthouse, a value of 10 to K_{110} in accordance with Table 1, a value of 0.1 to $K_{diversity}$, and a nominal Q_{hood} of 625 cfm (295 L/s) into Equation. 16 yields

$$Q_{leak} = \left(\frac{0.1\text{ppm}\cdot 625\text{cfm}}{0.14\times 10^6\text{ppm}\cdot\text{cfm}}\right)\cdot\left(\frac{10}{10\cdot 0.1}\right)\cdot\left(\frac{5,000\text{cfm}}{50}\right)$$

$$= 0.45\text{cfm}(0.21\text{L/s})$$

Example 4

A mitigation program has reduced the maximum leakage from 2.0 cfm (0.94 L/s) to 1.0 cfm (0.47 L/s) per fan system in the penthouse described in Example 3. What is the amount of additional ventilation that needs to be added to dilute the duct leakage to the exposure guideline?

Rearranging Equation 16 and solving for Q_{total} gives

$$Q_{total} = \frac{Q_{leak}\cdot n}{\left(\frac{C_{tg}\cdot Q_{hood}}{0.14\times 10^6(\text{ppm}\cdot\text{cfm})}\right)\cdot\left(\frac{K_{110}}{K_{vent}\cdot K_{diversity}}\right)}$$

$$= \frac{1.0(\text{cfm}\cdot 50)}{\left(\frac{0.1(\text{ppm}\cdot 625\text{cfm})}{0.14\times 10^6(\text{ppm}\cdot\text{cfm})}\right)\cdot\left(\frac{10}{10\cdot 0.1}\right)}$$

$$= 11,200\text{ cfm }(5,290\text{ L/s}) \qquad (17)$$

The additional ventilation is calculated by subtracting the existing ventilation capacity from the total required ventilation calculated above:

11,200 cfm - 5,000 cfm = 6,200 cfm of additional ventilation

(5,290 L/s - 2,360 L/s = 2,930 L/s of additional ventilation)

Example 5

The exhaust system connected to the hood in Example 1 is found to be leaking a total of 1.0 cfm (0.47 L/s) from the shaft seal, the flex connections, and duct fittings. If the system is located in the fan penthouse described in Example 3, what is the estimate of the near-field concentration of gluteraldehyde?

The actual area concentration is directly proportional to the ratio of the actual leak rate to the leak rate at the exposure guideline; therefore:

$$C_{actual} = \left(\frac{Q_{actual}}{Q_{leak}}\right)\cdot(C_{agent})$$

$$= \left(\frac{1.0\text{cfm}}{0.45\text{cfm}}\right)\cdot(0.2\text{ppm})$$

$$= 0.44\text{ppm}$$

This figure exceeds the CLG value of 0.2 ppm for gluteraldehyde and indicates that some type of source reduction or additional dilution should be implemented.

In Example 3 there are 50 exhaust systems with a capacity of 625 cfm (295 L/s) each for a total of 31,250 cfm (14,750 L/s) and a required ventilation rate of 11,200 cfm (5,290 L/s). The 1.0 cfm (0.47 L/s) leakage rate per fan system used in Examples 4 and 5 is very low, and even at this low leakage rate, the amount of ventilation required by this model is 36% of the fume hood volume.

This is why the five most widely referenced standards and guidelines on laboratory facility design and operation, i.e., the industrial ventilation manual (ACGIH 1995), the laboratory systems chapter of *ASHRAE Applications* (ASHRAE 1995), the ANSI/AIHA laboratory ventilation standard (AIHA 1993), NFPA 45 (NFPA 1986), and *Prudent Practices* (NRC 1995) all recommend that laboratory fume hood exhaust fans be located outside the building and not in an enclosed space.

Even after explaining this clearly to certain architects and building owners, one may be forced into the unenviable position of violating this extremely important recommendation and designing an enclosed laboratory exhaust fan system. In this case, one must specify the exhaust components in such a way as to minimize possible leakage.

Here are some guidelines. Use welded duct with flanged and gasketed fittings. Eliminate the flex connections at the fan altogether or use one-piece double-clamped flexible "hose" on the fan inlet and outlet. Specify fans with shaft seals and breaker tabs (small radial blades on the back side of the fan wheel), which maintain the shaft opening at a negative pressure. And, once the system has been running for about a month and is broken in, test each system qualitatively using a tracer gas technique, such as injecting a small amount of tracer gas upstream of each fan and probing the fan and fittings to reveal any leaks.

Applying The Risk Model

This model was applied in 12 different laboratory fume hood exhaust fan penthouses. Leakage measurements were taken at the shaft seal, the fan housing, the fan discharge and flex connections, duct fitting connections, and the ductwork itself for a sample population of the fan systems. Table 3 shows these data for an actual penthouse. Several of the duct

TABLE 3
Leakage Calculations for an Actual Fan Penthouse

System	Shaft Leakage cfm (L/s)	Housing Leakage cfm (L/s)	Discharge & Flex Leakage cfm (L/s)	Fitting Leakage cfm (L/s)	Duct Leakage cfm (L/s)	SYSTEM LEAKAGE cfm (L/s)
1	1.0 (0.47)	0.00 (0.00)	0.98 (0.46)	0.14 (0.07)	0.28 (0.13)	2.4 (1.1)
2	0.52 (0.24)	0.32 (0.15)	0.03 (0.01)	0.18 (0.09)	0.28 (0.13)	1.3 (0.62)
3	0.62 (0.29)	0.00 (0.00)	0.26 (0.12)	0.18 (0.09)	0.38 (0.18)	1.4 (0.68)
4	0.00 (0.00)	0.00 (0.00)	1.0 (0.47)	0.11 (0.05)	0.25 (0.12)	1.4 (0.64)
5	0.03 (0.01)	0.00 (0.00)	0.08 (0.04)	0.14 (0.07)	0.28 (0.13)	0.53 (0.25)
6	0.21 (0.10)	0.10 (0.05)	1.0 (0.47)	0.25 (0.12)	0.34 (0.16)	1.9 (0.90)
7	0.23 (0.11)	0.00 (0.00)	0.80 (0.38)	0.25 (0.12)	0.34 (0.16)	1.6 (0.77)
8	0.17 (0.08)	0.26 (0.12)	1.0 (0.47)	0.14 (0.07)	0.38 (0.18)	2.0 (0.92)
9	0.00 (0.00)	0.00 (0.00)	0.29 (0.14)	0.14 (0.07)	0.38 (0.18)	0.82 (0.38)
10	1.0 (0.47)	0.04 (0.02)	1.0 (0.47)	0.25 (0.12)	0.51 (0.24)	2.8 (1.3)
11	0.00 (0.00)	0.00 (0.00)	0.15 (0.07)	0.25 (0.12)	0.42 (0.20)	0.82 (0.39)
12	0.01 (0.00)	0.00 (0.00)	1.0 (0.47)	0.22 (0.10)	0.42 (0.20)	1.7 (0.78)
Averages	0.31 (0.15)	0.06 (0.03)	0.63 (0.30)	0.19 (0.09)	0.36 (0.17)	1.6 (0.73)

TABLE 4
Penthouse Ventilation Rate vs. Recommended Allowable Average System Leakage

No. of Hood Fans:	Penthouse Vent. Rate - cfm (L/s)	Allowable System Leakage in cfm (L/s) at Acceptable Level of Risk				
		Model	2 x Model	5 x Model	10 x Model	20 x Model
66	2,500 (1,180)*	0.17 (0.08)	0.33 (0.16)	0.83 (0.39)	1.7 (0.79)†	3.3 (1.6)
	5,000 (2,360)	0.33 (0.16)‡	0.67 (0.31)**	1.7 (0.79)	3.3 (1.6)	6.7 (3.1)
	7,500 (3,540)	0.50 (0.24)	1.0 (0.47)	2.5 (1.2)	5.0 (2.4)	10 (4.7)
	10,000 (4,720	0.67 (0.31)	1.3 (0.63)	3.3 (1.6)	6.7 (3.1)	13 (6.3)
	15,000 (7,080)	1.0 (0.47)	2.0 (0.94)	5.0 (2.4)	10 (4.7)	20 (9.4)
	20,000 (9,440)	1.3 (0.63)	2.7 (1.3)	6.7 (3.1)	13 (6.3)	27 (12.6)
	25,000 (11,800)	1.7 (0.79)	3.3 (1.6)	8.3 (3.9)	17 (7.9)	33 (15.7)

* Indicates existing amount of penthouse ventilation.
† The black cell with white numbers indicates (as close as possible) actual system leakage.
‡ The shaded cells indicate reasonable leakage/ventilation/risk scenarios.
** The cell with bold border indicates recommended leakage/ventilation/risk scenario.

and fitting leakages shown are identical because the number of fittings and duct lengths were identical and an averaging technique was used to determine them. The average leakage per fan system in this penthouse was determined to be 1.6 cfm (0.73 L/s). Data from the owner revealed that the penthouse had a total of 66 fan systems and 2,500 cfm (1,180 L/s) of penthouse ventilation.

Using these data, and the formulae above, one can build a risk model to determine a reasonable mitigation plan. Table 4 shows the allowable leakage rates (per fan system) at different penthouse ventilation rates and different levels of risk. The column labeled "Model" shows permissible leakage rates at different penthouse ventilation rates assuming a level of risk equal to the model with the assumptions previously described, and the numbers in each cell are calculated using Equation 16a with Q_{total} equal to the penthouse ventilation rate at the left of the row, n equal to the number of fan systems in the penthouse, $K_{110F} = 10$, $K_{vent} = 10$, and $K_{diversity} = 0.1$. The columns to the right represent higher levels of risk above that assumed by the model and are calculated by multiplying the leakage rates in the "Model" column by the multiplier shown, i.e., 2x, 5x, 10x, etc.

Table 4 shows that at an average fan system leakage rate of 1.6 cfm (0.73 L/s) and the current ventilation rate of 2,500 cfm (1,180 L/s), the risk level is approximately nine times higher than the model. If the owner feels that this risk level is too high (and the author believes it is) then a decision has to be made about increasing the ventilation in the penthouse and/or reducing the leakage rate per fan system. Economic analysis of several of these systems revealed that controlling the leakage rate is almost always cheaper (using a life-cycle type of analysis) than adding ventilation. Ventilation costs are high for installation and operation, especially if you must temper the make-up air for freeze protection in the penthouse. However, real-world experience shows that certain types of leaks can only be reduced so much. Based on this knowledge, a range of reasonable approaches to this problem were targeted and are shown in the shaded cells in Table 4. The author's specific recommendation for this particular client/site/penthouse combination was to reduce the average system leakage from 1.6 cfm (0.73 L/s) to 0.67 cfm (0.31 L/s), which is an ambitious, but reasonable, goal and add an additional 2,500 cfm (1,180 L/s) of ventilation for a total of 5000 cfm (2,360 L/s).

CONCLUSION

The method cited in Part I of this paper outlines the extrapolation of quantitative fume hood containment testing results to real-world potential exposures to laboratory chemicals. Using the equations provided and knowing the exposure guideline for a particular agent and the tracer gas control level for the hood, one can estimate the release rate at which the exposure guideline will be exceeded. Conversely, knowing the release rate of the agent and the control level, it is possible to estimate exposure.

The tracer gas method of determining the leakage from fan systems, described in Figure 2, has been successfully used in actual facilities. Potential exposure to hazardous substances leaking from equipment located inside a facility can be estimated using the methods described in Part II once the leak rate is determined using this or other methods.

A final caution is warranted here. This method should only be used by those who fully understand the engineering and industrial hygiene implications of the method and the assumptions made herein.

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