The Case of the

UNVENTILATED WORKPLACE

By Mitch Ricketts

Math Toolbox is designed to help readers apply STEM principles to everyday safety issues. Many readers may feel apprehensive about math and science. This series employs various communication strategies to make the learning process easier and more accessible.

Workers in many industries are exposed to hazardous concentrations of airborne gases (Rose & Cohrssen, 2011). For example, water treatment workers may be exposed to chlorine, employees in petroleum refineries may be exposed to ammonia, auto mechanics may be exposed to oxides of nitrogen and power plant staff may be exposed to sulfur dioxide.

As another example, consider the case in Figure 1 illustrating how a small internal combustion engine produced a deadly concentration of carbon monoxide in an unventilated workplace. This example is far from being an isolated incident; workers may be exposed to hazardous combustion gases whenever fuel-fired equipment is used without proper ventilation. For example, in a separate study, Venable et al. (1995) found that airborne concentrations of carbon monoxide reached the immediately dangerous to life and health value of 1,200 ppm within 15 minutes when a small 5.5-horsepower gasoline-fueled pressure washer was operated in a closed residential two-car garage. Even with both garage doors and a window open, airborne carbon monoxide in that garage exceeded the ceiling value of 200 ppm in 3 minutes and reached 658 ppm in 12 minutes.

FIGURE 1

CARBON MONOXIDE POISONING, IOWA, 1993

A 33-year-old farmer used an 11-horsepower gasoline-powered pressure washer to clean a 3,420-cubic-ft swine farrowing room. The door was closed, and there was no other ventilation.

Soon, the farmer was overcome by carbon monoxide and died. He had used the gasoline-powered washer in the room for only 30 minutes.

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The medical examiner found the farmer's postmortem carboxyhemoglobin level to be 75.6%. Normal values are less than 2% for nonsmokers and less than 9% for smokers.

Note. Adapted from "Unintentional Carbon Monoxide Poisoning From Indoor Use of Pressure Washers—Iowa, January 1992-January 1993," by CDC, 1993, *MMWR Weekly, 42*(40), 777-779, 785.

Workplace exposures to hazardous gases can often be prevented through local exhaust ventilation. For example, automotive garages typically employ tailpipe exhaust extraction systems and industrial facilities normally enclose and ventilate their chemical process equipment. When we cannot capture and remove all contaminants at their source, it may be necessary to dilute escaping gases using general ventilation, by circulating large volumes of fresh air throughout the workplace. If contaminants take the form of gases and we know the rate at which they are being emitted, the material balance equation may help us estimate the dilution ventilation rates required.

Material Balance Equation for a Gaseous Contaminant Generated at a Uniform Rate

The material balance equation estimates the amount of fresh air required to dilute a hazardous gas in workplace air. The equation assumes that the gas is being generated at a uniform rate and reaches a steady concentration in air. The equation, uncorrected for incomplete mixing of the contaminant in air, is:

$$Q' = \frac{G}{C} \cdot 10^6$$

Corrected for incomplete mixing, the equation becomes:

$$Q = \frac{G}{C} \cdot 10^6 \cdot K$$

where:

Q' = effective dilution ventilation rate of fresh air (cubic feet per minute, cfm) that will keep the airborne concentration of a gaseous contaminant at or below an acceptable level, not corrected for incomplete mixing of the contaminant in air

Q = actual dilution ventilation rate corrected for incomplete mixing of the contaminant in air (cfm)

G = generation rate; the uniform rate at which a gaseous airborne contaminant is generated (cfm)

C = acceptable airborne concentration of a gaseous contaminant in parts per million (ppm); the acceptable concentration is usually based on recognized standards such as the recommended exposure limit (REL, published by NIOSH) or the threshold limit value (TLV, published by American Conference of Governmental Industrial Hygienists, ACGIH)

10^6 = constant to account for the use of parts per million as the metric for the acceptable airborne concentration

K = mixing factor that corrects for incomplete mixing of the contaminant in air; K is most often in the range of 2 to 5, depending on conditions such as configuration of the workplace and effectiveness of the ventilation system. Lower numbers of K correspond to good ventilation mixing conditions. Higher numbers correspond to poor mixing.

Calculating Effective Dilution Ventilation Rate, Not Corrected for Incomplete Air Mixing

Let's consider the fatal incident illustrated in Figure 1. We do not know the actual amount of carbon monoxide produced by the pressure washer in this case; however, we can make a rough estimate based on pollution data published for similar equipment. For the purpose of illustration, we will estimate that exhaust of the 11-horsepower engine included 1.2 cfm of gaseous carbon monoxide. (We will ignore the generation rates of other contaminants that would also have been produced, such as nitrogen dioxide and carbon dioxide.) Based on the information in Figure 1, plus our estimate of carbon dioxide in the engine's exhaust, let's calculate the effective ventilation rate of fresh air (Q', uncorrected for air mixing) needed to keep the airborne concentration of carbon monoxide at or below the REL of 35 ppm as a time-weighted average. We will assume that carbon monoxide is being generated at a uniform rate and reaches a steady airborne concentration throughout the farrowing room, given the ventilation rate. For simplicity, we will also ignore ventilation requirements for other contaminants in the room. The data for the problem can be summarized as follows:

- It is estimated that the pressure washer's engine is exhausting carbon monoxide at the rate of 1.2 cfm. This is the value of G in the formula
- We have chosen the NIOSH REL of 35 ppm as the acceptable airborne concentration. This is the value of C in the formula

Based on these data, we calculate the effective ventilation rate (Q') in units of cfm, as follows:

Step 1: Start with the equation for effective ventilation rate:

$$Q' = \frac{G}{C}\cdot 10^6$$

Step 2: Insert the known values for contaminant generation rate (G = 1.2 cfm) and acceptable airborne concentration (C = 35 ppm). Then solve for Q', in cfm:

$$Q' = \frac{1.2}{35}\cdot 10^6 = 34{,}285.71\ cfm$$

(rounded two places past the decimal)

Note: Most calculators have a button for raising 10 to a power (often a button such as *10X* or ^). If you are using an Excel spreadsheet, the proper formula for this example is: *=1.2/35*10^6*.

Step 3: Our calculation indicates that an effective ventilation rate of 34,285.71 cfm of fresh air is required to keep the airborne concentration of carbon monoxide at a level of about 35 ppm, given the emission rate of the pressure washer's engine. If we provide more ventilation, the airborne concentration will be lower, and if we provide less ventilation, the concentration will be higher.

An effective ventilation rate of 34,285.71 cfm seems excessive for a room with a volume of only 3,420 ft^3 as described in Figure 1. To help us determine whether this rate is feasible, we may convert ventilation to room-air-changes-per-hour as follows:

$$ACH' = Q'\cdot 60 \div V$$

where:

ACH' = room air changes per hour, not corrected for incomplete mixing of the contaminant in air; ACH' is the effective ventilation rate converted to cubic feet per hour divided by the volume of the room

Q' = effective dilution ventilation rate of fresh air, not corrected for incomplete mixing of the contaminant in air (cfm)

60 = number of minutes per hour

V = volume of the room in cubic feet (ft^3)

Inserting the values of Q' (34,285.71 cfm) and V (3,420 ft^3), we calculate the effective room air changes per hour as follows:

$$ACH' = 34{,}285.71\cdot 60 \div 3{,}420 = 601.50$$

(rounded)

The calculation demonstrates that it would be impractical to provide the necessary ventilation since this would amount to more than 600 room air changes per hour (typical industrial ventilation rates rarely exceed 10 to 30 air changes per hour). Rather than relying on general dilution ventilation, we will need to consider other solutions such as switching to an electric power washer or moving the gasoline engine outdoors.

Alternate example: Let's calculate an example based on different conditions. This time, we will consider an ammonia-based refrigeration system located in a 200,000 ft^3 room at a dairy-processing facility. Ammonia is corrosive to valves and other equipment components. We will imagine our aggressive preventive maintenance program limits the release of ammonia from the system to 0.8 cfm during normal operations. Assuming that ammonia is released at a uniform rate, and the airborne concentration reaches a steady level, what effective ventilation rate (Q', uncorrected) is expected to keep the airborne concentration of ammonia at or below the NIOSH REL of 25 ppm as a time-weighted average? Again, for the sake of simplicity, we will ignore ventilation requirements for other contaminants that may be in the room. The data for the problem can be summarized as follows:

- The ammonia refrigeration system is estimated to release ammonia at the rate of 0.8 cfm. This is the value of G in the formula.
- We have chosen the REL of 25 ppm as the acceptable airborne concentration. This is the value of C in the formula.

To calculate the effective ventilation rate for the refrigeration room in units of cfm, we use the original equation to solve for Q':

$$Q' = \frac{G}{C}\cdot 10^6$$

Next, we insert the values of values for contaminant generation rate (G = 0.8 cfm) and acceptable airborne concentration (C = 25 ppm) to obtain the following result:

$$Q' = \frac{0.8}{25}\cdot 10^6 = 32{,}000\ cfm$$

The calculation indicates an effective ventilation rate of 32,000 cfm of fresh air is necessary to keep the airborne concentration of ammonia at a level of about 25 ppm. In this case, the room is quite large (200,000 ft^3) so it may be feasible to provide this rate of ventilation. To help us decide, we will calculate the room air changes per hour:

$$ACH' = Q' \cdot 60 \div V$$

Inserting the values of Q' (32,000 cfm) and V (200,000 ft^3), we find the ventilation rate in a room of this size equals 9.6 effective room air changes per hour as follows:

$$ACH' = 32{,}000 \cdot 60 \div 200{,}000 = 9.6$$

A ventilation rate of 9.6 effective air changes per hour is feasible in many industrial workplaces, so we conclude that dilution ventilation (in connection with an effective preventive maintenance program) is likely to keep airborne concentrations of ammonia at acceptable levels under normal working conditions. Additional controls, such as local exhaust ventilation and PPE may be required if more serious leaks occur.

You Do the Math

Apply your knowledge to the following questions. Answers are on p. 54.

1. Dry ice (solid carbon dioxide) is used for blast cleaning of process equipment in a food manufacturing facility. During blast cleaning, small pellets of dry ice are propelled by compressed air from a nozzle to clean residues from the equipment. The pellets sublimate and release carbon dioxide gas in the process. Imagine that engineers have determined that 70 cfm of carbon dioxide may be released in the 100,000 ft^3 manufacturing area during routine cleaning, which takes place continuously throughout the workday. This rate of carbon dioxide release includes all sources known to be present in the manufacturing area, including sublimation of dry ice, human respiration and more. Answer the following:

a. Assuming carbon dioxide is released at a uniform rate and the airborne concentration reaches a steady level, what effective ventilation rate (Q', uncorrected) is expected to keep the airborne concentration of carbon dioxide at or below the NIOSH REL of 5,000 ppm as a time-weighted average? To keep the calculation manageable, ignore ventilation requirements for other contaminants that may be present in the manufacturing area. Use the equation for effective ventilation rate (Q', uncorrected), and solve in units of cfm.

b. Calculate the effective room air changes per hour. Use the equation for ACH'.

2. In a 300,000 ft^3 warehouse, a fleet of propane-fueled forklifts were found to emit carbon monoxide at a total steady rate of 2 cfm throughout the workday. Answer the following:

a. Assuming that carbon monoxide is released at a uniform rate and the airborne concentration reaches a steady level, what effective ventilation rate (Q', uncorrected) is expected to keep the airborne concentration of carbon monoxide at or below the NIOSH REL of 35 ppm as a time-weighted average? Use the equation for effective ventilation rate (Q', uncorrected), and solve in units of cfm. Again, ignore ventilation requirements for other contaminants that may be present.

b. Calculate the effective room air changes per hour. Use the equation for ACH'.

Calculating Actual Dilution Ventilation Rate, Corrected for Incomplete Air Mixing

Our calculations thus far have assumed perfect mixing of ventilation air with contaminants throughout the work space. In reality, ventilation air will not mix uniformly with contaminants. Instead, there will be localized areas of imperfect dilution due to turbulence, room partitions, the configuration of equipment, the location of air vents and more.

To account for areas of limited circulation, we normally include a mixing factor, K, in the material balance equation. A mixing factor of one ($K = 1$) would be used when ventilation air is expected to mix with contaminants uniformly throughout the workspace. Values higher than 1 ($K > 1$) are used when air mixing is not uniform. Since perfect circulation is not expected in work environments, OSH professionals typically employ values between $K = 2$ and $K = 5$. For example, a value of $K = 2$ may be used in open work areas where air supply and return vents are distributed effectively and few impediments to circulation exist. In contrast, a value of $K = 5$ may be used where mixing is expected to be poor because of factors such as high ceilings, numerous partitions, poor distribution of vents and air turbulence. For a discussion of realistic mixing factors, see Feigley et al. (2002).

Example: Let's recalculate our first problem, this time with a mixing factor of $K = 2.5$. Recall that our first problem involved the use of an 11-horsepower gasoline-powered pressure washer emitting 1.2 cfm of carbon monoxide in a room with a volume of 3,420 ft^3. A moderately low mixing factor of $K = 2.5$ seems reasonable because the room is open, with supply and exhaust vents placed opposite one another to circulate air across the relatively small room (if the room was larger, we might select a mixing factor of greater magnitude).

We now have the data necessary to calculate the actual ventilation rate of fresh air (Q, corrected for air mixing) needed to keep the airborne concentration of carbon monoxide at or below the NIOSH REL of 35 ppm as a time-weighted average. Again, we will assume that carbon monoxide is generated at a uniform rate and the airborne concentration reaches a steady level. We will also ignore the generation rates of other contaminants. Since we are calculating the actual (corrected) ventilation rate, we use the equation for Q, which incorporates the mixing factor, K:

$$Q = \frac{G}{C} \cdot 10^6 \cdot K$$

Inserting the values outlined above for contaminant generation rate ($G = 1.2$ cfm carbon monoxide), acceptable airborne concentration ($C = 35$ ppm) and mixing factor ($K = 2.5$), we find the required actual ventilation rate (Q) is 85,714.29 cfm:

$$Q = \frac{1.2}{35} \cdot 10^6 \cdot 2.5 = 85{,}714.29\ cfm$$

(rounded)

Since the value of the mixing factor (K) is 2.5, the value of the actual (corrected) ventilation rate (Q) is 2.5 times the value of the effective (uncorrected) ventilation rate (Q') that we obtained in our first problem.

Next, we will calculate the actual number of room air changes per hour by inserting the value of the actual ventilation rate (Q, corrected for incomplete mixing) and the volume of the room (V) in the following equation:

$$ACH = Q \cdot 60 \div V$$

where:

ACH = room air changes per hour, corrected for incomplete mixing of the contaminant in air; ACH is the actual (corrected) ventilation rate converted to cubic feet per hour divided by the volume of the room

Q = actual dilution ventilation rate corrected for incomplete mixing of the contaminant in air (cfm)

60 = number of minutes per hour

V = volume of the room in cubic feet (ft^3)

Since $Q = 85{,}714.29$ cfm and $V = 3{,}420$ ft^3, as demonstrated, we solve the equation as follows:

$$ACH = 85{,}714.29 \cdot 60 \div 3{,}420 = 1{,}503.76$$

(rounded)

With a mixing factor of $K = 2.5$, the ventilation rate of 1,503.86 actual air changes per hour is 2.5 times the value of the effective (uncorrected) air changes per hour we calculated in our initial problem. Again, such a high rate of ventilation would not be feasible.

Alternate example: Let's recalculate our second example with a mixing factor included. Recall that in the second example, the ammonia-based refrigeration system emitted 0.8 cfm of ammonia in a 200,000 ft^3 room at a dairy-processing facility. Refrigeration rooms such as this tend to have poor mixing of ventilation air due to the presence of large machines and other partitions that interfere with air flow. Additionally, substantial turbulence may be expected due to the motion of machine parts, the presence of hot and cold surfaces, and more. In this case, we will assume a high mixing factor of $K = 5$.

Again, we will assume that ammonia is released at a uniform rate and the airborne concentration reaches a steady level. We will ignore ventilation requirements for other contaminants that may be in the room. With these assumption in mind, what actual ventilation rate (Q, corrected for incomplete mixing) is expected to keep the airborne concentration of ammonia at or below the NIOSH REL of 25 ppm as a time-weighted average? We begin with the formula for actual (corrected) ventilation rate:

$$Q = \frac{G}{C} \cdot 10^6 \cdot K$$

Next, we insert the values of values discussed for contaminant generation rate ($G = 0.8$ cfm), acceptable airborne concentration ($C = 25$ ppm) and ventilation mixing factor ($K = 5$) to obtain the result:

$$Q = \frac{0.8}{25} \cdot 10^6 \cdot 5 = 160{,}000\ cfm$$

The calculation indicates an actual ventilation rate of 160,000 cfm (corrected for incomplete mixing) is necessary to keep the airborne concentration of ammonia at a level of about 25 ppm. Given the mixing factor of $K = 5$, this result is 5 times the result we obtained when we calculated the effective (uncorrected) ventilation rate for this same problem. Let's now calculate the actual room air changes per hour, using the following formula:

$$ACH = Q \cdot 60 \div V$$

Recalling the volume of the room ($V = 200{,}000\ ft^3$) and the actual ventilation rate ($Q = 160{,}000$ cfm), we will calculate the actual room air changes per hour as follows:

$$ACH = 160{,}000 \cdot 60 \div 200{,}000 = 48$$

A ventilation rate of 48 actual air changes per hour is rather high, but it may be achievable. If an engineering study determines that this rate of ventilation is not feasible, we may need to redistribute vents, add fans to improve circulation or enclose some machinery with local exhaust ventilation to lower the required mixing factor. As before, additional controls may be required if emergency conditions result from more serious leaks.

You Do the Math

Apply your knowledge to the following questions. Answers are on p. 54.

3. Let's incorporate a mixing factor and reexamine the first scenario from You Do the Math, Problem 1. Recall that 70 cfm of carbon dioxide may be released in the 100,000 ft^3 manufacturing area from dry ice blast cleaning, human respiration and other activities. The manufacturing area is generally open, but it does have rather high ceilings and some large equipment that may interfere moderately with air circulation. For this area, we will select a mixing factor of $K = 3$. Answer the following:

a. Assuming that carbon dioxide is released at a uniform rate and the airborne concentration reaches a steady level, what actual ventilation rate (Q, corrected for incomplete mixing) is expected to keep the airborne concentration of carbon dioxide at or below the NIOSH REL of 5,000 ppm as a time-weighted average? As before, ignore ventilation requirements for other contaminants that may be in the room. Use the equation for actual ventilation rate (Q, corrected) and solve in units of cfm.

b. Calculate the actual room air changes per hour. Use the equation for *ACH*.

4. We will now incorporate a mixing factor to reexamine You do the Math, Question 2. Recall that the fleet of propane-fueled forklifts emitted carbon monoxide at a total steady rate of 2 cfm throughout the workday within a 300,000 ft^3 warehouse. The warehouse has high ceilings, tall racks of materials and the vents may not be ideally located. With these limitations in mind, we select a mixing factor of $K = 3.5$. Answer the following:

a. Assuming that carbon monoxide is released at a uniform rate and the airborne concentration reaches a steady level, what actual ventilation rate (Q, corrected) is expected to keep the airborne concentration of carbon monoxide at or below the NIOSH REL of 35 ppm as a time-weighted average? Use the equation for actual ventilation rate (Q, corrected) and solve in units of cfm. Again, ignore ventilation requirements for other contaminants that may be in the room.

b. Calculate the effective room air changes per hour. Use the equation for *ACH*.

Important Considerations

Several important issues must be examined when we apply the material balance equation to actual workplaces. First, the equation is most appropriate for general (dilution) ventilation of open work spaces. Ventilation of this nature is normally used after local exhaust and other engineering controls have reduced emissions to the lowest feasible levels. In addition, dilution ventilation is most appropriate for relatively low toxicity contaminants produced at slow, steady emission rates in areas where there is plenty of space between emission sources and workers' faces. Dilution ventilation may not be appropriate in work areas that do not meet these requirements.

It is also important to note that our simplified scenarios have focused on the control of a single contaminant in the workplace. When other contaminants are present, we must ensure that the total ventilation rate is sufficient to control all contaminants that may be present, including consideration of any combined health effects.

Finally, we must consider that selection of appropriate mixing factors is highly subjective. Indeed, different safety professionals may choose significantly different mixing factors based on their training and experience. Routine air sampling will always be required after controls are in place to verify their effectiveness.

How Much Have I Learned?

Try these problems on your own. Answers are on p. 54.

5. Imagine that chlorine is used in a water treatment room. The room has a volume of 75,000 ft^3. Further imagine that even with enclosed processes and an aggressive preventive maintenance program, engineers estimate that 0.004 cfm of chlorine may be released into the room from fugitive emissions during normal operations. Answer the following:

a. Assuming that chlorine is released at a uniform rate and the airborne concentration reaches a steady level, what effective ventilation rate (Q', uncorrected) is expected to keep the airborne concentration of chlorine at or below the NIOSH REL of 0.5 ppm as a ceiling value? Use the equation for effective ventilation rate (Q', uncorrected) and solve in units of cfm. Ignore ventilation requirements for other contaminants that may be in the room.

b. Calculate the effective room air changes per hour. Use the equation for ACH'.

6. Let's now incorporate a mixing factor and reexamine the chlorine emissions in the 75,000 ft^3 water treatment room discussed above. Recall that 0.004 cfm of chlorine may be released during normal operations. The room has a high ceiling, numerous storage tanks and reaction vessels. Furthermore, the supply and return air vents are not ideally located. Based on these factors, we select a mixing factor of $K = 4$ to account for incomplete mixing of ventilation air with the contaminant. Answer the following:

a. Assuming that chlorine is released at a uniform rate and the airborne concentration reaches a steady level, what actual ventilation rate (Q, corrected for incomplete mixing) is expected to keep the airborne concentration of chlorine at or below the NIOSH REL of 0.5 ppm as a ceiling value? Use the equation for actual ventilation rate (Q, corrected) and solve in units of cfm. Ignore ventilation requirements for other contaminants that may be in the room.

b. Calculate the effective room air changes per hour. Use the equation for ACH.

For Further Study

Learn more from the following source: *ASSP's ASP Examination Prep: Program Review and Exam Preparation*, edited by Joel M. Haight, 2016. **PSJ**

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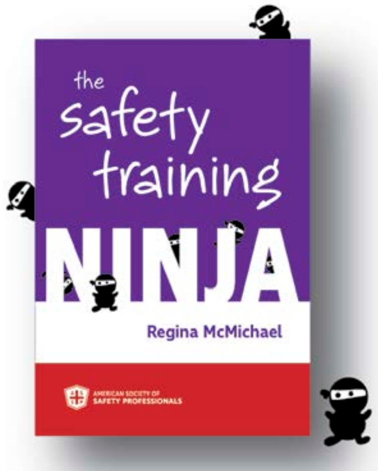

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Math Toolbox, continued from pp. 47-51

Answers: The Case of the Unventilated Workplace

You Do the Math

Your answers may vary slightly due to rounding.

1.a. $Q' = \frac{70}{5{,}000} \cdot 10^6 = 14{,}000\ cfm$

1.b. $ACH' = 14{,}000 \cdot 60 \div 100{,}000 = 8.4$

2.a. $Q' = \frac{2}{35} \cdot 10^6 = 57{,}142.86\ cfm$

2.b. $ACH' = 57{,}142.86 \cdot 60 \div 300{,}000 = 11.43$

3.a. $Q = \frac{70}{5{,}000} \cdot 10^6 \cdot 3 = 42{,}000\ cfm$

3.b. $ACH = 42{,}000 \cdot 60 \div 100{,}000 = 25.2$

4.a. $Q = \frac{2}{35} \cdot 10^6 \cdot 3.5 = 200{,}000\ cfm$

4.b. $ACH = 200{,}000 \cdot 60 \div 300{,}000 = 40$

How Much Have I Learned?

5.a. $Q' = \frac{0.004}{0.5} \cdot 10^6 = 8{,}000\ cfm$

5.b. $ACH' = 8{,}000 \cdot 60 \div 75{,}000 = 6.4$

6.a. $Q = \frac{0.004}{0.5} \cdot 10^6 \cdot 4 = 32{,}000\ cfm$

6.b. $ACH = 32{,}000 \cdot 60 \div 75{,}000 = 25.6$