

RESEARCH ARTICLE

Assessing general ventilation effectiveness in the laboratory

The goal of a laboratory's general ventilation system is to control airborne contaminants below concentrations of concern while maintaining a comfortable environment. One concern while managing general laboratory ventilation is how uniformly the room is ventilated. We have observed that, depending on the configuration of the ventilation supply and exhaust points relative to the geometry of the room, there may be areas of a laboratory that are less well-ventilated than others. This factor must be assessed when assigning minimum general ventilation rates for that lab.

In order to determine how effective general ventilation systems are in existing laboratories on the Cornell campus, we have measured the concentration decay rates of carbon dioxide at a variety of locations in the room after raising the CO₂ level across the room above 10,000 parts per million. This paper describes the reasons for this work, the method we use, and reports our observations about this approach to assessing laboratory ventilation effectiveness.

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INTRODUCTION

General laboratory ventilation relies on dilution to prevent accumulation of significant levels of volatile chemicals while providing temperature and odor control to maintain a comfortable environment for the occupants. It is important to note that general laboratory ventilations is designed to control small sources of volatile chemicals, such as exhausts from instrumentation or bench-top use of small quantities of low hazard chemicals. More significant emission sources (as determined by a risk assessment of the process

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causing the emission) and emergencies are not expected to be controlled by the general ventilation system. Laboratory chemical hoods should be used to control large planned releases, while spills and other unexpected releases are better addressed by appropriate laboratory emergency planning and response procedures.

An emerging concern is that general ventilation represents the most energy intensive aspect of laboratory operations, thereby creating sustainability concerns for laboratory facilities. In a previous article, we described how the Cornell University Laboratory Ventilation Management Plan (LVMP) balances safety and sustainability concerns to define a laboratory ventilation program based on continuous improvement.¹ In this program, the general ventilation rate of campus laboratories is an important parameter of interest, with the goal of reducing them as much as prudently possible in order to enhance laboratory sustainability.

A complicating factor in implementing this strategy is that the pattern of air movement through a laboratory room is as important as the quantity of air moved in controlling volatile chemical concentrations. Thus, simple answers to the question of "How much general laboratory ventilation is enough?" are not readily apparent, beyond "It depends". For this reason, an important element of the Cornell LVMP is a general ventilation control banding

process.² The key factors in the control banding process are: chemistry being performed in the laboratory; house-keeping practices by the lab occupants; and the ventilation effectiveness within the laboratory. In this context, "ventilation effectiveness" refers to the relative uniformity of the decay of air contaminants within the laboratory.

In implementing this control banding system, we identified laboratories where ventilation effectiveness was a potential concern. For this reason, we needed a reproducible approach to assess this factor in laboratories. One of the challenges we faced in evaluating this concern is that laboratory ventilation systems operate at three distinct scales. Shown schematically in Figure 1, these scales are:

- air supplied and exhausted at the building-wide level occurs at the *macroscale*;
- air movement within the laboratory room itself is at the *mesoscale*; and
- air movement in the area of a local exhaust device, such as laboratory chemical hood, are at the *microscale*.

Macroscale operations are described by parameters such as pressure relationships between areas of the building and ventilation delivery and exhaust rates from the general ventilation system. These parameters are well understood and primarily managed through laboratory design standards. Similarly,

Laboratory Ventilation System Elements

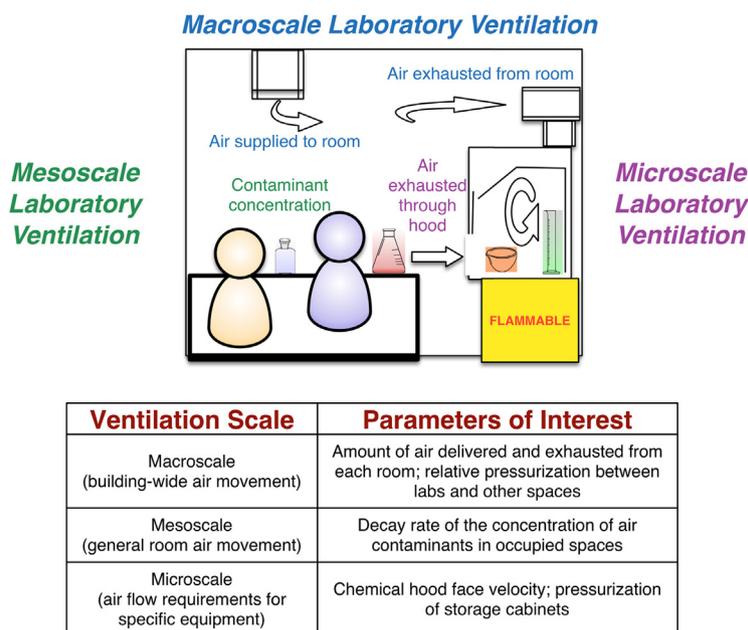


Figure 1. Elements of the laboratory ventilation system.

microscale parameters, such as laboratory chemical hood face velocity or pressure differentials of flammable storage cabinets, are generally specified in the design process and then maintained by ongoing certification of this equipment. Mesoscale issues were harder to define. In this paper, we describe work we have done with carbon dioxide decay rates to evaluate this issue.

EVALUATING EXISTING LABORATORY VENTILATION

There are a number of factors involved in determining the effectiveness of a laboratory ventilation system. These include the specific location of the supply and exhaust diffusers in the room; the layout of the laboratory furniture and equipment; and the location of doors and windows in the lab and their relative leakiness to adjoining areas. While mathematical models of these spaces can be used to estimate contaminant concentration patterns,³ there is often inadequate room design information to use computational fluid dynamics models of the airflow in the room for this purpose. This is the result of changes in laboratory operations and room layout. This can result in

facility staff increasing a laboratory's ventilation rate to address odor complaints or in order to create a "margin of safety" rather than being able to address ventilation system design parameters.

Ventilation effectiveness of existing spaces has been examined in a variety of ways, including qualitatively with neutral bubble visualizations and quantitatively with tracer gas work.⁴ For example, recent work used organic solvents as tracer gases to determine effective air exchange rates in a laboratory with varying ventilation rates.⁵ This approach has two advantages: first, solvents are commonly used in laboratories so their use as a tracer simulates a release which is reasonably expected to occur; second, air monitors are available which make real time solvent concentrations easy to measure. The results reported from this work were found to be in general agreement with computational fluid dynamic modeling of these concentrations done on the same laboratory. But, more interestingly, these approaches demonstrate that the control of volatile chemicals depends on the *effectiveness of air movement patterns* at removing the airborne chemicals within the laboratory at least as much as the *quantity*

of air the ventilation system provides to the laboratory.

In order to support recommendations for minimum air exchange rates within our control banding system at Cornell, we have investigated how ventilation effectiveness varies within and between laboratory rooms. We were interested in developing a process that can be routinely used at the laboratory room level, but were concerned that the risks of working with flammable chemicals were too high for routine use.

As an alternative, we decided to work with carbon dioxide released from fire extinguishers. By raising the CO₂ level throughout the room to the same level, we are able to simultaneously measure the contaminant decay rate as several locations. Using CO₂ avoids the hazards associated with solvent use. It is significantly cheaper (less than \$100 per assessment, after labor and equipment is in place) than conducting computational fluid dynamic modeling of specific laboratory rooms, which can cost as much as \$10,000 per room.

METHOD OVERVIEW

The decision to use carbon dioxide as a tracer gas was inspired by work found in several professional presentations on the Internet; particularly work conducted in a hospital in Peru.⁶ The method involves discharging the contents of a carbon dioxide fire extinguisher into the room to reach concentrations above 10,000 ppm throughout the room. Mixing of the CO₂ within the lab is enhanced by release of the gas from the extinguisher in a sweeping pattern across the top portion of the room.

The decay rate is determined in multiple locations in the room through the parallel measurement of the decay of CO₂ concentrations using between three and six data-logging CO₂ sensors. These data are analyzed using standard regression functions provided by spreadsheet software. The findings are then compared with the air exchange rate calculated from the flow rate measured in the ventilation ductwork.

In this method, we measure concentrations between 10,000 and 2500 ppm of carbon dioxide. It is important to note that this range includes levels above the recommended Occupational Safety and Health Administration (OSHA) eight-hour Time Weighted Average for CO₂ exposure of 5000 ppm. However, in the laboratory setting, where air change rates can be expected to be above 5 air exchanges per hour (ACH), concentrations above the OSHA Permissible Exposure Limit exist for 15 min or less and conservative calculations indicate that levels identified as Immediately Dangerous to Life and Health (50,000 ppm) can be avoided by limiting the size of the fire extinguishers (5 or 10 pounds, depending on the room size). In addition, once the carbon dioxide is released, the space being assessed is left unoccupied. Therefore, we do not consider carbon dioxide toxicity to be a concern with this approach in most laboratory settings. In those situations when we have conducted this work in locations with lower ventilation rates, we have reduced the amount of CO₂ released accordingly.

Prior to the extinguisher release, carbon dioxide meters (Table 1) are placed at locations of interest in the room. In our work, we have used a variety of meters for this purpose; all are specific for measuring carbon dioxide and are calibrated for each use using an outdoor air value of 400 parts per million using the manufacturers' recommendations. The meters we have used have varying measurement ranges and sampling frequencies, but sample readings are recorded at least every other second. All the meters we use have the capability to record the readings electronically for analysis. The various models used gave good agreement in the decay rates calculated.

The selection of sampling locations depends on the scenario being



Figure 2. A simple lab layout with typical sampling locations illustrated.

considered, the specific questions, which need to be answered, and the professional judgment of the people conducting the test. For example, in cases when labs are assessed prior to occupancy, minimal furniture and equipment were in the room (Figure 2). For these tests, sensors are distributed evenly across the room to compare decay rates in areas where ventilation rates are expected to be similar. Occupied rooms are significantly more complicated, with a variety of laboratory islands, storage cabinets, laboratory chemical hoods and large equipment situated in the laboratory according to the history of the room's use. In this situation, the sensors are placed in locations in the laboratory where volatile chemicals are most likely to be used or human exposure to them is reasonably expected to occur, such as on lab benches or at the operator's position at a laboratory chemical hood or biosafety cabinet. We also found that floor level decay rates can be significantly lower than those in breathing zones.

This can be important in considering emergency spill scenarios.

After the carbon dioxide is released, the tracer concentrations are allowed to decay by normal operation of the lab's ventilation system. CO₂ levels in the room are logged between 10,000 ppm and 2500 ppm of carbon dioxide. The collected data are used to calculate exponential regression decay curves associating concentrations of CO₂ levels with time. Following the Concentration Decay Test Method and using the Regression calculation for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution described in ASTM E741 Standard,⁷ the time constant of the regression equation is used as a measure of the air exchange rate in the sampled locations. Figure 3 shows a sample of the results of one run using this method of analysis. The calculations are done using standard functions available in the Excel spreadsheet application.

Measurements below 2500 ppm are not used because they could be significantly affected by background concentrations of CO₂ in the air, violating the mathematical assumptions of the regression model.⁸ We examined this concern by extending the range of data analyzed to 1000 ppm. We found that using the data between 2500 and 1000 ppm significantly lowered the correlation coefficient of the calculated regression curve. This is because the input of about 400 ppm carbon dioxide from outdoor air is not accounted for in the simple regression equation.

This work was conducted in a variety of Cornell laboratories, including BSL-3 rooms, small (less than 750 square feet) laboratories containing laboratory chemical hoods, as well as rooms with single pass air, but no chemical hoods. The ventilation rates in these rooms varied between 5 and 38 ACH. In all cases, the supply air was directly fed from outside sources and no recirculation of air in the room existed. While collecting and reviewing the data collected in these rooms, we have made several procedural observations:

- The release of CO₂ gas from the fire extinguisher can generate static

Table 1. CO₂ meters used for measuring room ventilation effectiveness.

Model	Software	Type of sensor
pSense Plus	Handheld Meter Data Logger	CO ₂ non-dispersive infrared sensor
ToxicRae Pro II CO ₂	ProRAE Studio II	CO ₂ non-dispersive infrared sensor

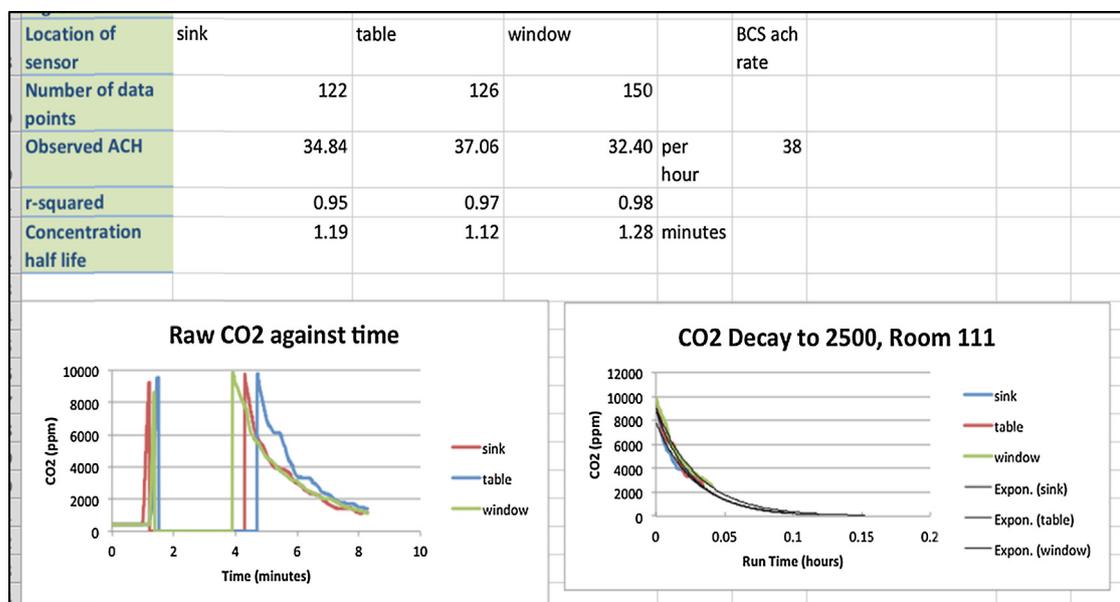


Figure 3. Typical carbon dioxide decay data for three locations in the same laboratory.

electricity that can be felt by the person operating the extinguisher. Placing the extinguisher on the floor during the release usually mitigates this problem.

- Some smoke detection systems can be triggered by the release of a carbon dioxide extinguisher. This concern must be assessed before releasing the extinguisher's contents.
- A significant amount of solid dry ice flakes are released from the extinguisher. These dry ice particles can impact the observed decay patterns if they land in the area of the sensors by increasing the concentrations of the CO₂ near the sensor. To address this issue, the areas of the sensors should be checked for dry ice particles after the release. Any solid CO₂ particles near the sensor should be swept away from the sensor.
- Similarly, electronic lab equipment can be vulnerable to dry ice particles. We protect such equipment by placing plastic sheets over the equipment. In some cases, these sheets could impact airflow more than the equipment itself. This concern is taken into account when determining the locations in which the sensors are placed.
- We found that it can be difficult to achieve a smooth regression curve in large rooms when people are moving around the room. This is due to

turbulence associated with air movement in the wake of people's travels. In order to maintain consistency in the data collection process and due to the health concerns mentioned above, people leave the room as soon as possible after the extinguisher is released. They return after an appropriate time for the general CO₂ levels to be below 5000 ppm.

RESULTS OVERVIEW

We have conducted this work in about 40 laboratories at Cornell. We have found that for this type of data analysis to be helpful, the regression curve must be smooth and have a high coefficient of determination. In our work, coefficients above 0.9 were found 75% of the time, particularly in unoccupied laboratories with simple layouts. In simple, small laboratories, horizontally dispersed sensors generally found decay rates within 10% of each other. In larger and more complicated labs that contain various equipment, decay rates can vary significantly, both vertically and horizontally.

Distribution of sampling points vertically rather than horizontally resulted in low coefficients of determination and more variation between locations in the lab. This variance is likely due to a lack of vertical

homogeneity of the tracer gas as the cold extinguisher gas settles in the room, vertical stratification of air movement patterns in the room occur, and/or because of the short-circuiting of ventilation patterns within the laboratory. For this reason, we focus on horizontal variation at breathing zone levels and other point source locations in observing air exchange rates in a laboratory.

Based on these observations, we have developed three key "lessons learned" from our work to date:

1. There can be significant variation in the observed decay curves at different locations in the same laboratory. This is more pronounced in laboratories with complicated layouts, such as those that contain a variety of laboratory furniture and equipment.
2. Observed decay rates depend on the even distribution of the source and the degree to which the contaminant is mixed throughout the space. Rooms in which the amount of carbon dioxide released did not completely fill the room had inconsistent results between runs.
3. Describing these decay rates to laboratory workers and Environmental Health and Safety (EHS) support staff, is most useful when done in terms of the contaminant's

half-life, described later in this paper, in specific locations within the laboratory. This is because it gives them a sense of how quickly contaminants can be expected to return to background levels. This is in contrast to facility designers and operators, who used air supply and exhaust rates to calculate room air change rates. These parameters are simple reciprocals of each other.

VARIATION WITHIN A ROOM

Our results indicate that there can be as much as 50% variation in contamination decay rates within the same room. This variation reflects a potential inability of the ventilation system to control contaminant concentrations in specific locations, depending on where the source of the contaminants is located. Review of the runs where this variation was found indicate that it is likely related to a variety of factors including: the physical shape of the room, including ceiling height; the location of laboratory furniture and equipment; and the location and type of supply and exhaust diffusers and the airflow throw patterns they create. In smaller, simpler rooms, horizontal variation in the observed ventilation rates was low; however, in even moderately complex rooms, the variation between similar locations can be significant. This observation reinforces the importance of considering factors beyond the overall room air exchange rate in using general ventilation as a protective strategy, as well as the value of using specific local exhausts to manage known chemical sources in the room.

When considering the variation within rooms, the type of and configuration of diffusers supplying air to the room played a significant role. This observation is supported by results of computational fluid dynamic modeling of airflow in laboratories. Therefore, this design element should be a key consideration during the design and construction of a laboratory building or renovation, and on an ongoing basis as laboratories are remodeled or when equipment usage in the lab changes.

IMPACT OF THE STRENGTH OF SOURCE

There are not many routine laboratory situations in which a contaminant will be spread instantaneously throughout the room as is done by the fire extinguisher with carbon dioxide. A more typical laboratory source will be a point source, such as a leak or equipment exhaust, or area source, such as a puddle. These sources have more localized impact on air quality. With this in mind, we informally investigated measuring carbon dioxide decay curves from small sources such as dry ice in warm water baths. We found that generating a consistent quantity of CO₂ was not feasible using this technique.

However, we noted that in these situations, the decay rates near a small spill were higher than expected from the ventilation rate provided by the building. This is because dispersion of the tracer gas away from the source also contributes to decay of the CO₂ concentration. Thus, the actual decay rate depends on the amount of material being emitted and how much free space there is in the area of the source for the material to disperse from the source, as well as how quickly air in the lab is moving.

We believe that this observation reinforces that the careful planning of the mechanics of chemical work, combined with good housekeeping, is a valuable factor in leveraging the safety value of the laboratory's ventilation system. Fortunately, these aspects of laboratory work reinforce other

prudent laboratory safety practices, particularly proper storage of hazardous chemicals and maintenance of a neat and clean lab.

DESCRIBING GENERAL LABORATORY VENTILATION

It is our overall goal to use the results of this procedure to help inform laboratory workers about the effective use of general ventilation as a safety measure while identifying opportunities to lower general laboratory ventilation rates. We believe that it is important to emphasize that the observed decay of the concentration of gases in the space is exponential rather than linear. In other words a room with 6 ACH will not replace contaminated air in the room in 10 min. The exponential decay of chemical concentrations in a location with 6 ACH has a half-life about 7 min (see Table 2). In this example, it will require about 70 min for the concentration of chemicals in the laboratory air to be reduced to 10% of the original concentration. Figure 4 demonstrates that the impact of this distinction occurs primarily at the later stages of the decay curve. This explains why laboratory odors often linger longer than the laboratory occupants expect.

For this reason, for laboratory workers and EHS staff, who are primarily interested in the environmental conditions within the room (i.e. at the mesoscale), the most appropriate way to describe ventilation within the general laboratory is in terms of the half-life of chemical concentrations at specific

Table 2. Comparison of contaminant concentration half-life with ventilation rate.

Ventilation rate (air exchanges per hour)	Concentration half-life (min)	10 half- lives (h)
2	20.79	3.47
4	10.40	1.73
6	6.93	1.16
8	5.20	0.87
10	4.16	0.69
12	3.47	0.58
15	2.77	0.46
20	2.08	0.35
25	1.66	0.28
30	1.39	0.23
35	1.19	0.20

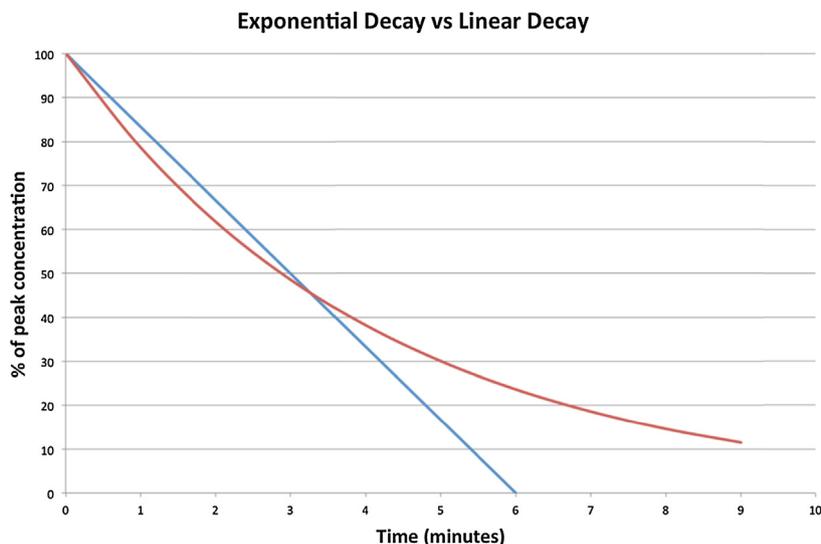


Figure 4. Exponential decay versus linear decay.

locations. An additional advantage is that this parameter is likely to be familiar to this audience, as the half-life concept describes the decay of a variety of other natural phenomena, such as radioactive decay or the clearance of chemicals from the body.

This terminology is in contrast to that of other stakeholders who are likely to focus on other parameters associated with laboratory ventilation. For example, facility engineers who design and operate laboratory buildings at a building wide (macroscale) level are most interested in the air exchange per hour or cubic feet per minute descriptions of ventilation rate, as these more directly describe the mechanical requirements and energy costs of moving, heating and cooling laboratory air. On the other hand, EHS staff or facility mechanics tasked with assessing the function of equipment such as laboratory chemical hoods or ventilated enclosures (microscale) will consider ventilation parameters specific to the equipment, such as face ve-

locity of the laboratory chemical hood or flow rate of the ducted enclosure or the exhaust ductwork. An integrated overview of how these parameters interact is one of the key goals of the Laboratory Ventilation Management Plan.

CONCLUSIONS

The use of carbon dioxide as a tracer gas to measure and compare contaminant decay rates in existing laboratories can be a useful tool in assessing ventilation effectiveness. In simple, well-characterized laboratories, computational fluid dynamic models of these labs can provide similar information, but at significantly higher cost. Our work with this technique has demonstrated that variations of ventilation effectiveness within a laboratory can be significant, particularly across vertical cross sections and in complex room layouts.

It is important that this information be provided in a way that it can be

readily understood by laboratory occupants so that they can make use of the information to prudently use the general laboratory ventilation in managing chemical hazards in their specific work place. For this purpose, we suggest that the concentration half-life of contaminants at specific locations within the room is a more appropriate description than the air exchange rate expressed in room volume per hour. This term emphasizes the non-linear nature of contaminant decay in the laboratory while describing the inhomogeneity of ventilation provided to the room.

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