Better Buildings Alliance - Laboratories Project Team

A Guide to Navigating Building and Fire Codes for Laboratories

Enabling demand-based ventilation and optimized minimum air changes per hour

1. Introduction

Chemistry laboratory[1] ventilation primarily involves exhausting air from rooms and exposure control devices such as fume hoods to contain, dilute, and remove hazardous gases as well as to remove heat generated by processes within the lab. To replace the exhausted air, conditioned outdoor air is supplied to the spaces as make up air. The objective is to maintain acceptable air quality for occupants, to prevent fires and explosions, to maintain indoor temperatures, and to maintain desired pressure differentials between building spaces. Because the process involves moving and conditioning large volumes of air, ventilation systems are often the most energy intensive systems in a lab.

Recent changes in lab ventilation technologies have created new opportunities for conserving energy while maintaining a safe work environment. This guide provides an overview of these opportunities and how they are related to building and fire codes generally used in the United States. More specifically, this document addresses safety and energy issues related to chemistry-driven lab ventilation, provides an overview of current codes and standards related to lab ventilation rates, and describes lab ventilation systems and opportunities to reduce related airflows. It then describes a process to enable airflow reductions using demand-based and optimized ventilation to ensure safe working conditions for occupants, to protect property from damage, and to do so as energy-efficiently as possible. A case study is also included to illustrate the potential energy savings from optimizing ventilation systems.

NOTE: Ventilation rates and system design must comply with mandatory provisions of related codes and standards, unless a waiver is granted. Nothing in this guide is intended to supersede requirements in codes and standards, the requirements of the authority having jurisdiction, or to replace the need to consult with a registered design professional, code official, and site EH&S staff as might be necessary to achieve a safe environment for occupants and to protect property from damage.

Laboratory Safety

Safety is a paramount consideration when using hazardous materials in a lab. There are two primary safety issues: *health* hazards (e.g., contaminant inhalation) and *physical* hazards (e.g., fire and explosion). To quantify the risks associated with these hazards and to support lab ventilation system design choices, one should carry out a hazard analysis that includes estimates of airborne contaminant concentrations and occupant exposure based on contaminant generation and removal rates, reactivity, and toxicity.

The rate of contaminant accumulation in a space (change in contaminant mass over time) can be described using a mass flow balance comprised of generation and ventilation-related terms as follows, with each term expressed as mass per unit time:

Rate of Accumulation = Generation Rate + Contaminant Inflows - Contaminant Outflows

[1] As defined by OSHA 1910.1450 (2014), a chemistry "laboratory" is a facility where chemical container manipulations can be easily and safely carried out by one person on a "laboratory scale" (excludes workplaces that produce commercial quantities of materials), multiple chemical procedures or chemicals are used, and effective "protective laboratory practices and equipment" are available and in common use to minimize the potential for employee exposure to hazardous chemicals.

The *generation* rate depends on source emissions, which include: contaminant escape from fume hoods, bench-top procedures, and unventilated equipment; leaks from chemical bottles and containers and from gas cylinders; and accidental spills. Source control techniques (e.g., closing containers when not in use, containment in a hood or by local exhaust) should be applied first to reduce the rate of contaminant accumulation in labs.

Ventilation involving general exhaust and the supply of make-up air should be used as needed for removal and dilution, respectively, of contaminants in the lab space. Contaminant *inflows and outflows* for a lab or fume hood depend on airflow (i.e., the ventilation rate), air density, and contaminant concentration at the flow path inlet. The ventilation rate is often described on a volumetric basis as air changes per hour (ach), relative to either the lab or hood volume, depending upon which is of interest. All other things being equal for a given volume, a higher ach results in quicker contaminant removal times; a lower ach results in longer times.

Simply specifying a prescriptive ach without carrying out a hazard analysis may lead to a false sense of safety or to suboptimal solutions, because such specifications do not directly address the primary metrics of concern: minimizing exposure, or in the case of fire and explosion hazards, maintaining the contaminant concentration below the explosive limits. A single prescriptive ach is also a barrier to taking advantage of energy saving opportunities such as airflow reductions during unoccupied periods. The "Industrial Ventilation Manual" (ACGIH 2013, Section 10.6.1) states that " 'Air changes per hour' or 'air changes per minute' is a poor basis for ventilation criteria. The required ventilation depends on the generation rate and toxicity, not on the size of the room in which it occurs". The goal instead should be to use the minimum amount of airflow[2] needed to keep contaminant concentrations, both in the lab and inside components such as fume hoods, below levels of concern[3] from health and fire/explosion points of view.

Energy Use and Costs

Data that represent energy use in lab buildings in the U.S. are scarce, but it is clear that labs are one of the highest energy users by building type. According to DOE (2008), extrapolating from a sample of 43 buildings, there are about 9,000 laboratory buildings in the U.S. (about 650 million square feet of floor area) with an average annual *site* energy use intensity of about 300 kBtu/ft^2. The total annual site energy use therefore is about 200 TBtu. Associated expenditures for energy are about $3 billion.

Based on benchmark data for 76 U.S. buildings with chemical labs built between 2001 and 2011 (Labs21 2012), these buildings on average use about 660 kBtu of *source* energy annually per square foot of floor area (electricity and natural gas combined). Using these data, the equivalent average *site* energy is about 350 kBtu/ft^2. Of this *site* energy, about 40 kWh/ft^2 is electricity with an energy cost of about $6/ft^2. Average building peak electrical demand is about 11 W/ft^2. Using the DOE total floor area estimate above, the electricity *site* energy cost alone translates to about $4 billion. Although the average *site* energy use for these 76 buildings is somewhat similar to that based on the DOE data above, these buildings were not in the DOE dataset and caution is needed when interpreting correlations.

Compared to DOE (2008) data for other commercial building types, as listed in Table 1, the average *source* energy use intensity (EUI) for lab buildings (660 kBtu/ft^2) is about 20% greater than the average

[2] A goal of the hazard analysis should be to identify the ventilation type (dilution and local), rate, and demand control technologies that are needed. A variety of control technologies are available (e.g., two-position control systems, occupancy sensors, schedules, contaminant sensing, and sash height sensing). Operating parameters appropriate for the technologies selected should also be identified by the hazard analysis.

[3] Levels of concern should be assessed by a qualified individual who is identified in the Laboratory Ventilation Management Plan (LVMP).

for food sales buildings, but it is much larger compared to the averages for other buildings (EUI ratios range from 1.9 to 8.6). For example, compared to a similar sized average office building, an average lab building uses about three times more energy.

Table 1: Building Average Source EUIs and Laboratory EUI (660 kBtu/ft^2) to Building EUI Ratios

Building Principal Use	Average Source EUI, kBtu/ft^2	Lab/Building EUI Ratio
Food Sales	535	1.2
Health Care	346	1.9
Office	212	3.1
Mercantile and Service	204	3.2
Lodging	193	3.4
Education	159	4.2
Warehouse and Storage	94	7.0
Religious Worship	77	8.6

Even fewer data are available to disaggregate the whole-building energy use for labs into end uses (and most are only estimates and not based on submetering). Based on data for 11 of the 76 buildings in the Labs21 dataset, Figure 1 shows the average fractions of the whole-building *site* electricity consumption and demand for these buildings. The primary electrical energy uses are for ventilation and cooling (almost 60% of whole-building electricity consumption). Related peak demand is almost three quarters of whole-building demand. Clearly, reducing ventilation-related energy use, which in turn affects the cooling energy use, is a key step toward reducing lab building energy use.

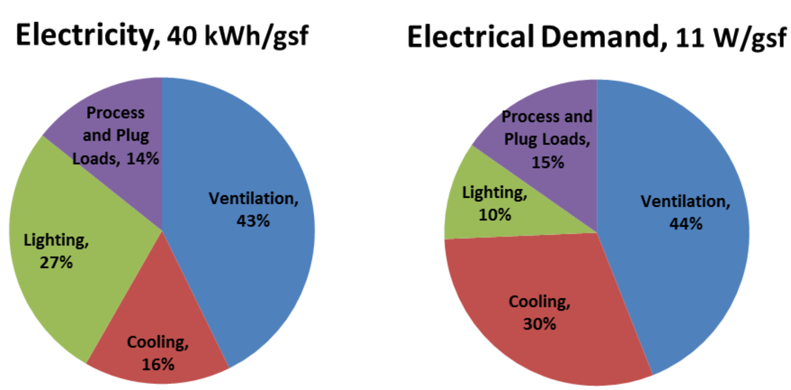

Figure 1: Lab Electrical Site Energy and Peak Demand End Use Fractions. Source: Labs 21 Data (2012)

2. Applicable Codes and Standards

Codes and standards define operational and test procedures or minimum acceptable performance, but they tend not to address best practices or enhanced performance. A *code* is a set of rules in mandatory language that can be adopted as a model by governments and enforced as a legal regulation (*mandatory* compliance). It describes *what* must be done. In contrast, a *standard* describes in detail *how* to do something. A standard involves voluntary compliance, but can be referenced by codes (if it is written in mandatory language). Some U.S. standards are accredited by the American National Standards Institute (ANSI). Such accreditation is important, because ANSI provides essential requirements for due process (e.g., openness, balance of interests, consensus) when developing ANSI-accredited documents.

It might seem that there are many regulations governing ventilation rates in U.S. labs, but in fact generally there are *no mandatory* requirements for these rates, other than the ones listed in ASHRAE Standard 62.1-2010 for educational laboratories[4] (that standard has been adopted by many codes), in Cal-OSHA Title 8 Section 5154.1 governing California laboratories, and for some particular instances in the International Mechanical Code (IMC 2012) and International Fire Code (IFC 2012). Several other documents (e.g., ANSI/AIHA Standard Z9.5 - 2012, OSHA 29 CFR Part 1910.1450, NFPA Standard 45 - 2011) make (or in the past made) recommendations about lab ventilation rates, but all are voluntary in this regard. It is important to recognize that the industry is moving toward a more performance-based approach that relies upon lab-specific engineering data and analysis to determine the specific control techniques needed to ensure safety. Table 2 summarizes ventilation rate statements in commonly referenced codes and standards. Appendix A provides a detailed discussion of the various documents.

Table 2: Summary of Lab Ventilation Rates in Codes and Standards

Document	Ventilation Rate
ANSI/AIHA Z9.5	Prescriptive ach not appropriate. Rate shall be established by owner or his or her designee. Determining rate requires engineering analysis.
ACGIH Industrial Ventilation : A Manual of Recommended Practice for Design	Ventilation required depends on contaminant generation rate and toxicity, and not on room size.
OSHA 29 CFR Part 1910.1450	1990: Appendix A stated 4-12 ach is typical. 2014: Appendix A does not state any ach.
Cal-OSHA Title 8, Section 5154.1	Requires fume hood average face velocity of 100 fpm for occupied lab (variances obtainable, however). Reduction to 60 fpm allowed when unoccupied.
ASHRAE 62.1-2010, including Addendum d; IMC 2012	Prescribes per person and per square foot outdoor airflow rates for *educational labs*. For default occupancy of 25 people/1000 ft^2 and with 9 foot high ceiling, equivalent is 2.9 ach outdoor air, but only 1.2 ach when unoccupied. For educational *science* labs (but not university or college labs, so essentially high school labs), there is also a 6.7 ach equivalent value for exhaust air. A performance-based compliance approach is also allowed.
IMC 2012, IFC 2012	Requires minimum ventilation rates equivalent to 6.7 ach for some spaces where chemicals are stored or used in "amounts exceeding the maximum allowable quantity per control area", as described by Section 5003 of the IFC 2012.
NFPA 45-2011	2004: Informative appendix stated >8 ach for occupied lab, 4 ach unoccupied. 2011: No statement regarding ach, and defers to AIHA Z9.5.

[4] ASHRAE 62.1 does not define *educational* laboratories, so it is unclear whether its requirements apply to any laboratory located on a university, college, or high school campus, or only to those labs used for instruction. Many educational laboratories have limited and controlled use of low-hazard chemicals and thus can be operated at significantly less flows than 62.1 requires.

3. Lab as a System: Ventilation System Configurations and Interactions

Fume hoods are local ventilation units designed to capture and exhaust hazardous materials. As Figure 2 shows, hoods are connected to one or more exhaust system fans, which continuously depressurize the hood interiors and in turn cause room air to enter through the sash openings to remove contaminants generated within the hoods as well as from the room containing the hoods.

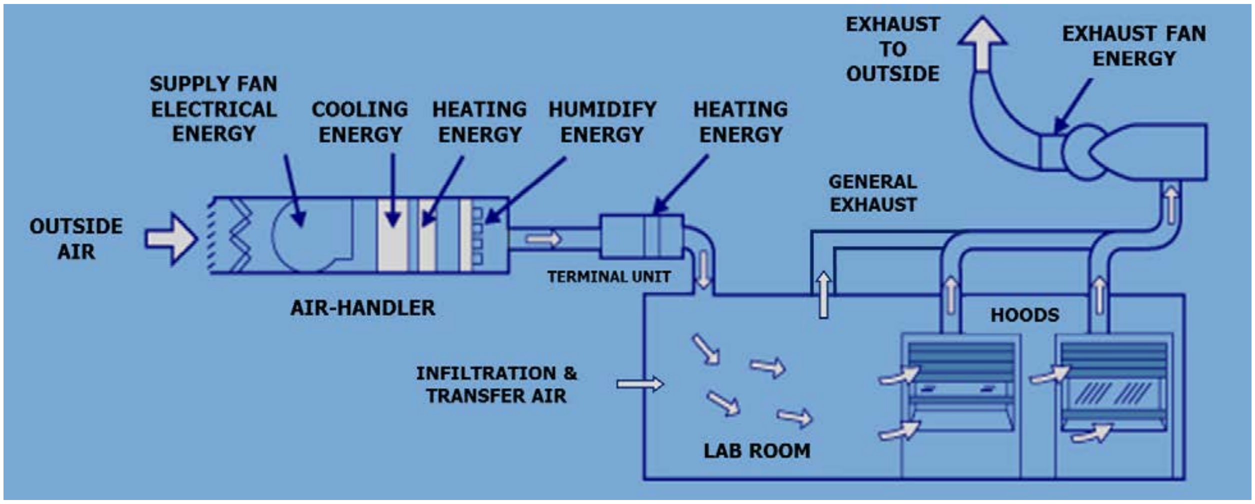

Figure 2: Schematic Diagram of Laboratory Ventilation System. Source: LBNL (2012)

Makeup air is supplied by a separate air-handling system that uses a fan to draw in outdoor air to replace the exhausted air. The supply air is filtered and then heated or cooled (and then reheated as needed) to maintain comfortable working conditions within the laboratory working space, as well as to maintain space pressure relative to surrounding spaces. Also as shown in Figure 2, general room exhaust is used to: 1) remove any contaminants that may be in the working space itself, 2) maintain required lab ventilation rates when fume hood flows are insufficient to do so, and 3) maintain negative pressure when fume hood flows are too low relative to the air supplied for space conditioning needs that are unrelated to hood exhaust (e.g., to maintain air temperature set points in the working space).

Note that space depressurization induces infiltration airflows from outdoors and transfer airflows from other spaces, and these flows constitute part of the make-up air entering the space of interest. Reducing building envelope and interzone partition leakage can reduce the thermal energy impacts of these unconditioned airflows, but more make-up air would need to be supplied to balance the exhaust flows.

There are two principal types of fume hoods used in chemical laboratories: constant air volume (CAV) and variable air volume (VAV).

- CAV hoods exhaust a constant amount of air regardless of sash position. In this case, the face velocity through the sash opening increases as the sash is closed (sometimes to the point where it can disturb or damage hood contents). To avoid this problem, some of these hoods use a bypass opening above the sash that is uncovered as the sash is closed, as well as a fixed opening at the sill, which together allow these hoods to maintain a more constant face velocity. Because flow is constant in either case, the air-handling systems (exhaust and supply) are relatively simple.

- For the same *maximum* sash opening area and face velocity, VAV and CAV hoods have the same flow and energy use. VAV hoods, however, can save energy by automatically reducing the exhaust flow while maintaining a constant face velocity as the sash opening is reduced (or closed). Variable-position dampers and/or variable speed drives are used to control the exhaust system pressures and flows. Because the exhaust flow varies, a VAV supply airflow system is also needed to maintain space pressure relationships, which in turn results in a more complicated system. A significant problem with VAV hoods is that most hoods are only used a few hours each day and they rely on users to manually close the sash when they finish using the hood. When users do not fully close the sash, VAV hoods do not save as much energy as they could.

For a fume hood with a 62 inch wide sash that is open 29 inches (nominally fully open) and an average face velocity of 100 fpm, the corresponding flow is about 1250 cfm. For a 700 ft^2 lab with a 9 foot high ceiling and *one* hood, this flow translates to about 12 ach. Mathew (2007) indicated that density can vary significantly from 0.5 to about 9 hoods per 5,000 square feet of lab space, depending on lab type. For the hood characteristics and room size described above, these densities correspond to a wide range of roughly 0.8 ach to 15 ach, respectively.

In the example above, if the same face velocity but a lower sash height (e.g., 18 inches) are used, the flow decreases proportionally relative to the fully-open position (i.e., to 62% of the above rates). In this case, however, if the sash is raised above 18 inches and the system has insufficient capacity to maintain the face velocity, the face velocity will decrease as the sash is opened further. An audible alarm should be provided to indicate to the user that the sash should be lowered back to a height of 18 inches or less.

Lab ventilation rates can be fume hood dominated, lab minimum ach (dilution) dominated, or thermally dominated by space heating or cooling needs. The first case occurs when there are a large number of hoods in a small lab space. The middle case occurs with fewer hoods and larger lab spaces, due to minimum ach requirements. The latter case occurs where heating or cooling loads in the lab space require large supply airflows to meet thermostat set points. Which flow regime dominates in a lab at any specific time can change as the number of hoods, chemical types, and thermal loads change, especially when variable flow supply and exhaust systems are used and controlled using a demand-based contaminant control strategy.

High performance fume hoods can use face velocities as low as 60 fpm to maintain or even reduce worker exposure to hazardous contaminants. For example, newer hoods and some retrofit kits for existing hoods use aerodynamically superior sash sills and handles, and adjustable baffle designs to reduce sash opening turbulence and optimize internal airflow patterns to prevent contaminants from spilling out of the hood into the working space. From an energy standpoint, reducing hood face velocity is important because, for a given sash opening area, a lower velocity translates to a lower exhaust airflow, which in turn reduces associated fan power and supply air thermal conditioning.

Two-state (high/low flow) control or automated sash closure technologies help to minimize exhaust flows when hoods are not in use by directly reducing flow or by reducing sash opening area, respectively. In the former case, face velocity is maintained at a low value (e.g., 60 fpm) when the hood is “unoccupied”, and is then increased (e.g., to 100 fpm) when the hood is “occupied”. The two-state control approach has the benefit that even if the sash is left open when the hood is unoccupied, flow is reduced and energy is saved. In some installations, room occupancy sensing or contaminant sensing is used instead of individual hood occupancy sensing to control the two-state flows.

4. Demand-Based Ventilation and Optimized Minimum ACH

As discussed in Section 2, except for educational labs (ASHRAE 62.1-2010), the Cal-OSHA requirements regarding fume hood face velocities (which determine a minimum flow), and some particular instances in the International Mechanical Code (IMC 2012) and International Fire Code (IFC 2012), current codes and standards do *not* prescribe minimum dilution ventilation rates (ach) for lab spaces. Because each lab differs in terms of its contaminant hazards and ventilation needs, determining what ventilation rate is "sufficient" at any given time requires analysis based on knowledge of lab operations.

Sharp (2010) discusses methods available to determine appropriate lab air change rates and to control these rates based on demand. In summary, although dilution ventilation should be provided continuously, its *rate* does not need to be constant. One demand-based control method is to simply reduce the dilution ventilation rate during *unoccupied* periods, given that occupants are not actively generating contaminants in the lab. Sufficient ventilation is still needed during those times however to deal with fugitive emissions that can lead to elevated concentrations that would need to be reduced before occupants could safely reenter the space. The goal of this method is to provide the minimum amount of dilution ventilation needed to keep occupants from being exposed to concentrations above regulatory thresholds. For this method, control band approaches (see Appendix B) can be used to characterize contaminant hazards and specific ventilation rate needs.

Alternative, but more complex, demand-based ventilation and optimized air change rate approaches can include a method for monitoring concentrations of identified chemicals. Ventilation rates can then be adjusted over time by comparing measured concentrations with desired thresholds. For example, ventilation rates might be reduced to between 2 and 4 ach during the day and to 2 ach at night (when airflows required to meet temperature set points are lower and temperature control is less important). When concentrations are too high (e.g., due to a spill), ventilation rates can be temporarily increased (e.g., to 16 ach). This additional "flushing" action thus only occurs when needed. The dilution ventilation rate also can be overridden when flows to meet fume hood make-up air requirements (pressure control) or lab space thermal requirements are greater. Note that *all* of these flows need to be reduced as much as possible within safety and comfort constraints to achieve a low minimum ach.

The contaminant sensing approach offers another advantage: data collected by monitoring concentrations can be used to identify lab practices and equipment that are causing excessive contaminant concentrations. Changes can then be made to improve source control, and to further reduce the lab ventilation rates. The monitoring also allows system degradation over time to be observed and corrected.

5. A System to Enable Demand-Based Ventilation and Optimized Minimum ACH

Depending on the state of lab systems, safety objectives, energy goals, and available funds, energy reduction projects that maintain safety and include demand-based ventilation and optimized minimum air-change rates can range from implementation of simple, low cost measures to highly complex and costly measures. Smith (2013) describes a four-step retrofit process that involves: 1) planning, 2) assessing existing performance and characterizing hazards to determine appropriate ventilation airflows, 3) optimizing and implementing selected measures to improve ventilation performance, and 4) performance management so that safe operation and savings persist over time. The following summarizes the process; Appendix B provides further details.

Step 1: Plan

Determining appropriate measures that satisfy project objectives starts with *planning* to understand needs. This step includes meeting with ALL key stakeholders to review and establish safety, comfort, productivity, energy, sustainability, and economic goals and requirements. This step also includes collecting and reviewing building documentation (e.g., as-built building and HVAC system drawings, control strategies, standard operating procedures, utility data) to prepare for the next step.

Step 2: Assess

This step involves a survey of individual laboratory spaces and evaluating lab safety and energy use, including hazards, sources, and the functional performance of ventilation system equipment. It includes assessing the demand for ventilation and benchmarking current operating conditions (i.e., hood and lab inspection, face velocity measurements, cross-draft velocity tests, VAV response and stability tests, and determining hood dilution factors).

Step 3: Optimize

Using the information obtained in Steps 1 and 2, this step involves identifying and selecting Performance Improvement Measures (PIMs) and Energy Conservation Measures (ECMs), in part using an energy and return-on-investment (ROI) analysis tool (e.g., the tool described by Sharp 2013) to prioritize measures. The step includes developing a scope of work, specifications for system characteristics and operating procedures, and identifying funding sources. It also includes actual implementation of the measures (construction, test and balance, commissioning).

Step 4: Sustain

To *sustain* safe and efficient operation, and to protect the return on energy investment after performance improvement and energy conservation measures are implemented, the process continues through definition and implementation of a Laboratory Ventilation Management Plan (LVMP), training, and ongoing testing/maintenance. It is a step required by ANSI/AIHA Z9.5-2012.

6. Example: University of California, Irvine

Approach

Even though many of their laboratories are more efficient than required by California’s energy code (Title 24 Part 6), the University of California Irvine recognized that their labs have the potential to be even more efficient without sacrificing occupant safety. Increased efficiency could be achieved if laboratory variable air volume features and digital controls could be integrated with advanced air quality and occupancy sensors driving smarter control logic (Brase 2012). Many lab buildings now use real-time air quality sensing and vary ventilation rates on a zone-by-zone basis, from 4 ach under normal occupied conditions to 2 ach when unoccupied, and peaking to 12 ach when threshold levels of particulates, volatile organic compounds, or carbon dioxide (CO_2) are sensed. This demand-based feature is part of their integrated “Smart Labs” package of measures to reduce laboratory energy use.

Results

UC Irvine's “Smart Labs” program, which involves reducing air change rates by utilizing centralized demand-controlled-ventilation (demand-based ventilation, as described in Section 4) and exhaust stack discharge velocity reduction as key attributes, has resulted in average HVAC-related energy savings of 58% across several laboratory buildings (Table 3). The electricity savings average 55% while natural gas savings average 76%. UC Irvine attributes the large gas savings to more closely matching the air change rate to the actual load of the space, thus eliminating almost all reheat. More information about UC Irvine's "Smart Labs" program is available at: http://www.ehs.uci.edu/programs/energy/index.html.

Table 3: Savings from "Smart Lab" retrofit, reducing air change rate to 4/2 ACH (occupied/unoccupied)

Laboratory Building		BEFORE "Smart Labs" Retrofit			AFTER "Smart Labs" Retrofit		
Name	Type	Estimated Average ACH	System Type	More Efficient Than Code?	HVAC Electricity Savings	HVAC Gas Savings	Total Energy Savings
Croul Hall	P	6.6	VAV	20%	41%	60%	55%
McGaugh Hall	B	9.4	CAV	No	40%	66%	47%
Reines Hall	P	11.3	CAV	No	70%	76%	72%
Natural Sciences 2	P, B	9.1	VAV	20%	48%	62%	50%
Biological Sciences 3	B	9.0	VAV	30%	45%	81%	60%
Calit2	E	6.0	VAV	20%	46%	78%	62%
Gillespie Neurosciences	M	6.8	CAV	20%	58%	81%	61%
Sprague Hall	M	7.2	VAV	20%	58%	82%	71%
Hewitt Hall	M	8.7	VAV	20%	58%	77%	69%
Engineering Hall	E	8.0	VAV	30%	59%	78%	61%
Averages		**8.2**		**20%**	**55%**	**76%**	**58%**

Type: P = Physical Sciences, B = Biological Sciences, E= Engineering, M = Medical Sciences

7. Summary: Key Takeaways

The following are a few key takeaways based on the information contained in this guide and the related references:

1. Safety is paramount when using hazardous materials in a chemical lab. Source control techniques should be applied first to reduce the rate of contaminant accumulation in labs. Ventilation involving general exhaust and the supply of make-up air should be used as needed for removal and dilution, respectively, of contaminants in the lab space. Because lab ventilation involves substantial energy use, the goal should be to use just the right amount of airflow (either increasing or decreasing it as needed over time) to keep contaminant concentrations, both in the lab and inside components such as fume hoods, below levels of concern from health and fire/explosion points of view.

2. It might seem that there are many prescriptive regulations governing ventilation rates in U.S. chemical labs, but in fact generally there are no mandatory requirements for these rates. The industry is moving toward a more performance-based approach that relies upon lab-specific engineering data and analysis to determine the specific control techniques needed to ensure safety.

3. Lab ventilation rates can be fume hood dominated, lab minimum ach (dilution) dominated, or thermally dominated by space heating or cooling needs. Which flow regime dominates in a lab at any specific time can change as the number of hoods, chemical types, and thermal loads change, especially when variable flow supply and exhaust systems are used and controlled using a demand-based contaminant control strategy. As a result, designing, retrofitting, and maintaining lab ventilation involves a systems approach.

4. Depending on the state of lab systems, safety objectives, energy goals, and available funds, energy reduction projects that maintain safety and include demand-based ventilation and optimized minimum air-change rates can range from implementation of simple, low cost measures to more complex and costly measures. This guide provides an example four-step retrofit process that involves: 1) planning, 2) assessing existing performance and characterizing hazards to determine appropriate ventilation airflows, 3) optimizing and implementing selected measures to improve ventilation performance, and 4) performance management so that safe operation and savings persist over time.
5. As described in the example case study, dramatic energy savings (about 60%) can be achieved without sacrificing occupant safety by implementing demand-based and optimized ventilation.

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APPENDIX A: Codes and Standards - Detailed Discussion

This appendix discusses nine commonly referenced codes and standards, focusing on their statements related to laboratory ventilation rates. These documents include:

- ANSI/AIHA Standard Z9.5
- OSHA 29 Code of Federal Regulations(CFR) - Part 1910.1450
  (including Cal-OSHA Title 8 Section 5154.1 differences)
- ANSI/ASHRAE Standard 62.1
- NFPA Standard 45
- U.S. "International" Model Codes (including IMC, IBC, IFC, and IECC)

It is important to note that the provisions of codes and standards change over time and it may take several years in some cases before adopted codes are updated to use the most current model code or standard. For simplicity here, we refer only to the most recent versions of the codes and standards listed above. Current versions of applicable locally adopted codes should always be consulted for specific details.

A1. ANSI/AIHA Standard Z9.5

Standard Z9.5-2102 is entitled "Laboratory Ventilation", and is published by the American Industrial Hygiene Association. Its primary purpose is to establish minimum requirements and best practices for laboratory ventilation systems to protect personnel from physical harm and overexposure to potentially harmful airborne contaminants generated within the laboratory. That said, Z9.5 does *not* use a prescriptive approach. Instead, its requirements should be considered minimum criteria that can be adapted to the needs of the "user establishment". Z9.5 allows and encourages innovative approaches provided that exposure to airborne contaminants is *demonstrably* controlled.

In terms of laboratory ventilation rates, Section 2.1.2 of Z9.5 requires that "The specific room ventilation rate shall be established or agreed upon by the owner or his or her designee." Section 2.1.3 requires that: "Dilution ventilation shall be provided to control the buildup of fugitive emissions and odors in the laboratory. The dilution rate shall be expressed in terms of exhaust flow in negatively pressurized laboratories and supply flow in positively pressurized laboratories."

Commentary for Sections 2.1.2 and 2.1.3 expands upon these requirements to describe the philosophy behind them (in the form of recommendations):

> "Ventilation is a tool for controlling exposure. Contaminants should be controlled at the source. Potential sources should be identified and exposure control devices should be specified as appropriate to control emissions at the source. (See Sections 3 and 4). All sources and assumptions should be clearly defined and documented.
>
> An air exchange rate (air changes per hour) cannot be specified that will meet all conditions. Furthermore, air changes per hour is not the appropriate concept for designing contaminant control systems.
>
> Excessive airflow with no demonstrable safety benefit other than meeting an arbitrary air change rate can waste considerable energy.

Control of hazardous chemicals by dilution alone, in the absence of adequate laboratory fume hoods, is seldom effective in protecting laboratory users. It is almost always preferable to capture contaminants at the source, than attempt to displace or dilute them by room ventilation. Nevertheless, dilution or displacement may remove contaminants not captured by a specifically applied device.

The quantity of dilution (or displacement) ventilation required is a subject of controversy. Typical dilution ventilation rates can range from 4 to 10 air changes per hour depending on heating, cooling, and comfort needs and the number and size of exposure control devices."

It is important to recognize that the text above provides a range of air change rates typically used by industry versus providing any strict guidance as to what should be used as a minimum or recommended ach level. In fact, the above commentary clearly states that setting a fixed ach rate for a laboratory for all conditions is not an appropriate design approach.

Section 3 contains recommendations and specifications for laboratory fume hoods, including:

- Design and construction, which must conform with guidelines in the current ACGIH "Industrial Ventilation: A Manual of Recommended Practice for Design".
- Face velocity, with the requirement that "the average face velocity of the hood shall be sufficient to contain the hazardous chemicals for which the hood was selected". No specification is provided but related commentary states that operation below 60 fpm is not recommended, that higher velocities might be required, and that other factors such as hood design, lab layout, and cross drafts also need to be considered to achieve acceptable hood performance.
- The commentary also describes fume hood containment characteristics and operating cost impacts for various face velocity ranges (60-80 fpm, 80-100 fpm, and 100-120 fpm) that provide "effective" operation. It notes that, although most hoods can operate effectively with face velocities of 120-150 fpm, performance is not significantly better with these velocities than at lower ones, and the operating cost penalty imposed by the higher velocities is "severe". It also notes that operating above 150 fpm can cause turbulence inside the fume hood, which in turn creates more potential for spillage from the hood.
- Minimum flow rate to ensure that contaminants *within* a hood are properly diluted and exhausted to address *flammability and corrosion* issues. Here, flow is based on hood internal air changes per hour. The commentary indicates that typical flows are in the range of 150 to 375 hood ach. 375 ach is equivalent to about 25 cfm per ft^2 of hood work surface area, which is a value that was described in NFPA 45-2004; 150 ach is equivalent to about 10 cfm per ft^2 of work surface area.
- Section 3.3.3 requires that each hood be equipped with a flow measuring device to alert users to improper flows (high or low by 20% relative to the set point value).

Section 4 addresses other containment devices, such as glove boxes, ductless hoods, and "special purpose" hoods (e.g., for use with analytical balance, histology processing, atomic absorption, or gas chromatography equipment).

A2. OSHA 29 Code of Federal Regulations(CFR) - Part 1910.1450

The U.S. Occupational Safety and Health Administration (OSHA) provides relatively little specific guidance regarding lab ventilation. The only reference it has is in "Occupational Exposures to Hazardous Chemicals in Laboratories; Final Rule", which was initially published in 1990 as 29 CFR Part 1910.1450.

In particular, this OSHA document addresses exposure limits, training programs for fume hood users, and requires (like Z9.5) that employers create a written Chemical Hygiene Plan (CHP) that “sets forth procedures, equipment, personal protective equipment and work practices that are capable of protecting employees from the health hazards presented by hazardous chemicals used in that particular workplace”.

An example CHP is provided in Appendix A of the document to help employers create their own document, but that Appendix is specifically described in 1910.1450(e) as being non-mandatory. The Appendix presents recommendations from the National Research Council's (NRC) 2011 edition of "Prudent Practices in the Laboratory: Handling and Management of Chemical Hazards”. As Appendix A states: “Prudent Practices” deals with “both general laboratory safety and many types of chemical hazards”, while the OSHA document is “concerned primarily with chemical health hazards as a result of chemical exposures”.

In 1990, Appendix A contained statements related to lab air change rates and fume hood face velocities in Subsections 4(a), 4(f), and 4(g) of “Section C. The Laboratory Facility”. However, these statements were not mandatory nor were they even recommendations:

- “(a) General laboratory ventilation. This system should: Provide a source of air for breathing and for input to local ventilation devices (199); it should not be relied on for protection from toxic substances released into the laboratory (198); ensure that laboratory air is continually replaced, preventing increase of air concentrations of toxic substances during the working day (194); direct airflow into the laboratory from non-laboratory areas and out to the exterior of the building (194).”
- “(f) Performance. Rate: 4-12 room air changes/hour is normally adequate general ventilation if local exhaust systems such as hoods are used as the primary method of control [194].”
- “(g) Quality. General airflow should not be turbulent and should be relatively uniform throughout the laboratory, with no high velocity or static areas (194, 195); airflow into and within the hood should not be excessively turbulent (200); hood face velocity should be adequate (typically 60-100 lfm) (200, 204).”

The 4 to 12 ach range stated above is broad (factor of three variance from the lower bound) and there is no guidance on when to apply the higher rates. As such, this information is not very useful as a guide to designers who seek to limit contaminant exposures and doses, and as written, does not even preclude the use of lower rates.

Currently, Section C of Appendix A no longer says anything specific about air change rates or hood face velocities, but still does address ventilation related issues: “A laboratory ventilation system should include the following characteristics and practices:

(a) Heating and cooling should be adequate for the comfort of workers and operation of equipment. Before modification of any building HVAC, the impact on laboratory or hood ventilation should be considered, as well as how laboratory ventilation changes may affect the building HVAC.

(b) A negative pressure differential should exist between the amount of air exhausted from the laboratory and the amount supplied to the laboratory to prevent uncontrolled chemical vapors from leaving the laboratory.

(c) Local exhaust ventilation devices should be appropriate to the materials and operations in the laboratory.

> (d) The air in chemical laboratories should be continuously replaced so that concentrations of odoriferous or toxic substances do not increase during the workday.
>
> (e) Laboratory air should not be recirculated but exhausted directly outdoors.
>
> (f) Air pressure should be negative with respect to the rest of the building. Local capture equipment and systems should be designed only by an experienced engineer or industrial hygienist.
>
> (g) Ventilation systems should be inspected and maintained on a regular basis. There should be no areas where air remains static or areas that have unusually high airflow velocities."

It is important to recognize that some state OSHA requirements with respect to ventilation (e.g., California Code of Regulations, Title 8, Section 5154.1) differ somewhat from federal requirements. In particular, Subsection (c)(1) of Section 5154.1 sets stricter limits for minimum face velocities:

> "The exhaust system shall provide an *average face velocity of at least 100 fpm* with a minimum of 70 fpm at any point, except where more stringent special requirements are prescribed in other sections of the General Industry Safety Orders, such as Section 5209. The minimum velocity requirement excludes those measurements made within 1 inch of the perimeter of the work opening."

Subsection (e)(10) requires that the velocity in (c)(1) be "obtainable with the moveable sash full opened". Subsection (c)(2) allows reductions to 60 fpm when "no employee is in the immediate area of the hood opening". Variances to allow velocities lower than 100 fpm can and have been obtained, however, when engineering analysis and tests have demonstrated equivalent or better performance using the lower velocities. One example is Genetech, Inc., which obtained a variance in December 2001 to use 80 fpm during occupied periods. San Diego State University also obtained a similar variance in May 2006.

A3. ANSI/ASHRAE Standard 62.1

Standard 62.1-2010 is entitled "Ventilation for Acceptable Air Quality", and is published by ASHRAE. Its purpose is to "specify minimum ventilation rates and other measures intended to provide indoor air quality that is acceptable to human occupants and that minimizes adverse health effects. … This standard is intended for regulatory application to new buildings, additions to existing buildings, and those changes to existing buildings that are identified in the body of the standard. … This standard is intended to be used to guide the improvement of indoor air quality in existing buildings."

Other than for *educational*[5] laboratories, there are *no* prescriptive requirements in 62.1 for lab ventilation rates. For *science*[6] *and university/college laboratories*, using the prescriptive "Ventilation Rate Procedure" in Section 6.2 of 62.1, Table 6-1 requires that a minimum of 0.18 cfm/ft^2 of occupiable floor area[7] *plus* 10 cfm per person of outdoor air be delivered to the breathing zone. With an assumed

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[5] ASHRAE 62.1 does not define *educational* laboratories, so it is unclear whether its requirements apply to any laboratory located on a university, college, or high school campus, or only to those labs used for instruction. Many educational laboratories have limited and controlled use of low-hazard chemicals and thus can be operated at significantly less flows than 62.1 requires.

[6] ASHRAE 62.1 also does not define *science* laboratories, but because these laboratories are listed separately from university and college laboratories, one can likely assume that science laboratories are located in high schools.

[7] The area-based flow is to be provided at all times, regardless of occupancy. This flow requirement was added to 62.1 in the 2004 version of the standard (Stanke 2006).

occupant density of 25 people per 1000 ft^2 and an assumed 9 foot high ceiling[8], this total airflow requirement translates to about 2.9 ach of outdoor air when at the default full occupancy and about 1.2 ach when unoccupied. If the zone air distribution effectiveness is less than 1.0 (e.g., due to short circuiting of air from a supply to an exhaust grille, or due to excessively warm air supply at the ceiling), then the flow will need to be increased accordingly.

Outdoor air supply flows can also be determined using the "Indoor Air Quality Procedure" (Section 6.3). This performance-based rather than prescriptive design procedure relies upon an "analysis of contaminant sources, contaminant concentration limits, and level of perceived indoor air acceptability". A "Natural Ventilation Procedure" is also available for use, but it is unlikely this strategy would be appropriate for laboratory ventilation.

Regardless of which procedure above is used, Table 6-4 in 62.1-2010 initially also required a minimum design exhaust rate of 1.00 cfm/ft^2 of floor area for *educational science laboratories (not including ones in universities and colleges, so essentially high school labs)*, which translates to about 6.7 ach assuming a 9 foot high ceiling. With the publication of Addendum d in 2011, this prescriptive option is still present, but more flexibility is now provided by allowing a demand-controlled-ventilation "Performance Compliance Path" as well:

> "6.5.2 Performance Compliance Path. The exhaust airflow shall be determined in accordance with the following:
>
> 6.5.2.1 Contaminant Sources. Contaminants or mixtures of concern for purposes of the design shall be identified. For each contaminant or mixture of concern, indoor sources (occupants, materials, activities, and processes) and outdoor sources shall be identified, and the emission rate for each contaminant of concern from each source shall be determined.
>
> Note: Appendix B lists information for some potential contaminants of concern.
>
> 6.5.2.2 Contaminant Concentration. For each contaminant of concern, a concentration limit and its corresponding exposure period and an appropriate reference to a cognizant authority shall be specified.
>
> Note: Appendix B includes concentration guidelines for some potential contaminants of concern.
>
> 6.5.2.3 Monitoring and control systems shall be provided to automatically detect contaminant levels of concern and modulate exhaust airflow such that contaminant levels are maintained at no greater than the specified contaminant concentration limits."

In Section 6.5, the standard allows makeup air for exhaust to be any combination of outdoor air, recirculated air, and transfer air.

The 62.1 requirements described above are not necessarily all encompassing, however, even for educational laboratories. Section 2.3 states: "Additional requirements for *laboratory*, industrial, health care, and other spaces may be dictated by workplace and other standards, as well as by the processes occurring within the space."

[8] The occupancy assumption is from Table 6-1 in 62.1. Actual occupancy and room volume must be used when applying the standard.

A4. NFPA Standard 45

NFPA 45-2011 is entitled "Standard on Fire Protection for Laboratories Using Chemicals", and is published by the National Fire Protection Association. Its purpose is to "provide basic requirements for the protection of life and property through prevention and control of fires and explosions involving the use of chemicals in laboratory-scale operations".

This standard applies to laboratory buildings, units, and work areas in which chemicals are handled or stored, except where "low hazard "chemicals in Categories 0 or 1 with respect to health, flammability, and instability are used (as defined by NFPA 704 "*Standard System for the Identification of the Hazards of Materials for Emergency Response*"), the lab is a manufacturing plant, or chemicals are only used incidentally such as in electronic labs.

Hazard categories 0 and 1 correspond to materials that under emergency conditions do not cause incapacitation, residual or serious injury or death; that will not burn during a fire or that must be "considerably" preheated under all temperature conditions to ignite; and that do not undergo "violent" or explosive chemical reactions at normal or elevated temperatures and pressures.

Labs that have radioactive or explosive-only hazards are covered instead by NFPA 801 "*Standard for Fire Protection for Facilities Handling Radioactive Materials*" and NFPA 495 "*Explosive Materials Code*", respectively

Regarding ventilation rates, the only references to such in the body of the 2011 version are as follows (same as in 2004):

> "8.2.2* Laboratory units and laboratory hoods in which chemicals are present shall be continuously ventilated under normal operating conditions."

> "8.4.7* The hood shall provide containment of the possible hazards and protection for personnel at all times when chemicals are present in the hood."

The asterisks above denote that there is explanatory material in Appendix A of the standard. Note that Appendix A is *informative* rather than normative and thus statements there are *NOT requirements.*

In the 2004 version, A.8.2.2 in Appendix A stated: "A minimum ventilation rate for unoccupied laboratories (e.g., nights and weekends) is four air changes per hour. Occupied laboratories typically operate at rates greater than eight room air changes per hour, consistent with the conditions of use for the laboratory." Some people have interpreted this *statement* as a mandatory requirement. It is not even a recommendation, and was removed in the 2011 version.

A.8.4.7 in the 2004 and 2011 versions states …"Face velocities of 0.4 m/sec to 0.6 m/sec (80 ft/min to 120 ft/min) generally provide containment if the hood location requirements and laboratory ventilation criteria of this standard are met." The 2011 version of this section also now states "The chemical fume hood exhaust airflow should not be reduced to less than the flow rate recommended in ANSI/AIHA Z9.5". Because Appendix A remains an informative part of the Standard, this deferral to Z9.5 is only a recommendation and not a requirement, however.

A8.4.7 also stated in the 2004 version that the "chemical fume hood exhaust airflow should not be reduced to less than 127 L/sec/m^3 (25 ft^3/min/ft^2) of internal hood work surface even when the sash is fully closed except where a written hazard characterization indicates otherwise." This recommendation was removed in the 2011 version.

A5. U.S. "International" Model Codes

The International Code Council (ICC) has developed several model codes that contain provisions related to lab ventilation rates. Four codes of particular interest in this regard include the International Mechanical Code (IMC), the International Building Code (IBC), the International Fire Code (IFC), and International Energy Conservation Code (IECC). Most have been adopted statewide with no limitations by about a half or more of the states (IMC: 30 states; IBC: 36 states; IFC: 23 states; IECC: 35 states), and to some extent by many other states or local governments. Some states have not adopted one or more of the codes: IMC (4 states) - California, Hawaii, Maine, and Vermont; IFC (8 states) - Florida, Hawaii, Maine, Maryland, Massachusetts, Rhode Island, Vermont, and West Virginia; IECC (3 states) - California, Indiana, and Minnesota.

As stated at the beginning of Appendix A, it is important to note that an adopted code is not always up to date relative to the most current model code. For example, the 2012 version of the IMC has been adopted statewide without limitation in 13 states and to some extent by four other states. The rest of the 23 statewide IMC adoptions are based on older versions: 2009 (19 states), 2006 (Indiana and New York), 2003 (Connecticut), and 2000 (Minnesota). For simplicity here, we refer only to the 2012 versions of the model codes. Current versions of applicable locally adopted codes should always be consulted for specific details.

The purposes of the IMC, IBC, and IFC broadly speaking are to provide minimum standards to safeguard life or limb, health, property, and public welfare (including occupants, as well as fire fighters and emergency responders during emergency operations) from fire, explosion, and other hazards attributed to the built environment in part by regulating and controlling the design, construction, installation, quality of materials, location, and operation and maintenance or use of building systems (ventilation being only one aspect). For the IECC, its purpose is to regulate "the design and construction of buildings for the effective use and conservation of energy over the useful life of the building".

Chapter 4 of the 2012 IMC specifically addresses ventilation. Traditionally, the IMC follows but does not reference ASHRAE Standard 62.1, and it typically lags a revision or two behind the current version of 62.1 (nominally about 5 years). As a result, the 2012 IMC follows 62.1-2007 and even reprints Tables 6-1 and 6-4 from 62.1 together as Table 403.3.

In particular, Table 403.3 of the 2012 IMC includes the 62.1-2007 references to *educational science laboratories* that require: 1) a minimum of 0.18 cfm/ft^2 of floor area PLUS 10 cfm per person of outdoor air be delivered to the breathing zone, and 2) a minimum design exhaust rate of 1.00 cfm/ft^2 of floor area.

Note that commentary for Section 415.10.1.6 "Ventilation" of the 2012 IBC and Section 5705.3.7.5.1 of the 2012 IFC also refers specifically to this same design exhaust rate. In the IBC, this reference is mostly for semiconductor facilities, but it is also applicable to labs classified as Group H-5 occupancies (i.e., ones that utilize hazardous materials in excess of the maximum allowable quantities and that are considered unique high-hazard occupancies). In the IFC, the reference is specifically for Group H-2 or H-3 occupancies where dispensing, use, mixing and handling of flammable liquids occurs (i.e., Group H-2 is one that uses or stores "Class I, II or III" liquids in open containers and systems, or in closed containers or systems with a pressure exceeding 15 psig; Group H-3 is similar, but the pressure is 15 psig or less). Some labs are classified as having such occupancy types.

Section 414.3 "Ventilation" of the 2012 IBC also requires compliance with the mechanical ventilation provisions of the IMC and IFC for "rooms, areas or spaces of Group H in which explosive, corrosive, combustible, flammable or highly toxic dusts, mists, fumes, vapors or gases are or may be emitted due to the processing, use, handling or storage of materials".

Clearly, a hazard analysis needs to be conducted to determine whether a lab should be classified as a Group H facility. For example, per Section 304 of the IBC, some labs, such as those in "laboratories that are located in colleges, universities and academies for educating students above the 12th grade and that have an occupant load of less than 50" can be classified instead in Group B (business occupancies with "low fuel loads").

The 2012 IMC does not include the specific language from Addendum d to 62.1-2010, which allows a "Performance Compliance Path" to be used. However, Section 403.2 essentially allows such an option when a registered design professional can demonstrate that their design will "prevent the maximum contaminant concentration from exceeding that obtainable" based on Table 403.3. In that case, the minimum airflow can be reduced to a lower ventilation rate in accordance with this design. As a result, demand-based ventilation control strategies that meet these requirements can be used to provide an accepted means of compliance.

Section 510.3 "Design and Operation" in the IMC provides further requirements for exhaust systems for some laboratories. The included labs are non-manufacturing ones where contaminants have a health-hazard rating of 1-4 (per NFPA 704) and with "concentrations exceeding 1 percent of the median lethal concentration of the substance for acute inhalation toxicity" (LC50). In particular, Section 510.3 states: "The design and operation of the exhaust system shall be such that flammable contaminants are diluted in non-contaminated air to maintain concentrations in the exhaust flow below 25 percent of the contaminant's lower flammability limit" (LFL). This requirement implicitly means that the flow will depend on the contaminant characteristics and that engineering analysis needs to be used to determine the exhaust airflow that can achieve the stated performance goal: provide sufficient ventilation in these labs to maintain health hazard related concentrations below 1% of the LC50 and to maintain flammability related concentrations below 25% of the LFL.

The IMC 2012 and IFC 2012 (as well as some other codes, such as the FCNYS 2010) require minimum ventilation rates of 1 cfm/ft^2 of floor area for some spaces where chemicals are stored or used in "*amounts exceeding the maximum allowable quantity per control area*", as described by Section 5003 of the IFC 2012. This ventilation rate is identical to the minimum design exhaust rate required by ASHRAE 62.1-2007 for educational *science* labs (which is about 6.7 ach with a 9 foot high ceiling). Allowable amounts depend on material type and whether it is stored or used in an open or closed system. These amounts range widely (e.g., from 3 pounds for highly toxic materials used in an open system to 500 pounds for less toxic materials in storage). Anecdotal reports have indicated that some consultants specify this ventilation rate "across the board" for all spaces with hazardous chemical storage and use to avoid having to justify a conflicting interpretation to the multitude of "Authorities Having Jurisdiction" (AHJs) that they encounter.

Section C403.2.5 in the *commercial* provisions of the 2012 IECC addresses ventilation. It requires compliance with the Chapter 4 provisions of the IMC. It also requires demand controlled ventilation for spaces larger than 500 ft^2 and with an average occupant load of 25 or more people per 1000 ft^2 of floor area that are served by systems with one or more of the following characteristics:

- Air side economizer
- Automatic modulating control of the outdoor air damper; or
- Design outdoor airflow exceeding 3,000 cfm.

Exceptions to the DCV requirement in the IECC are too numerous to describe here, but the most pertinent one for modern labs involves the presence of an energy recovery system compliant with Section C403.2.6 (numerous exceptions are listed there too). If such an energy recovery system is used, then DCV is not required. However, this exception does not apply to all labs, because Section 514.2 of the IMC prohibits use of energy recovery for exhaust systems conveying hazardous contaminants as defined in Section 510 of the IMC.

APPENDIX B: A System to Enable Demand-Based Ventilation and Optimized Minimum ACH

Laboratory buildings vary in size, age, function and type of systems. Depending on the state of the systems, safety objectives, energy goals, and available funds, energy reduction projects that maintain safety and include demand-based ventilation and optimized minimum air-change rates can range from implementation of simple, low cost measures to highly complex and costly measures. Smith (2013) describes a four-step retrofit process that involves: 1) planning, 2) assessing existing performance and characterizing hazards to determine appropriate ventilation airflows, 3) optimizing and implementing selected measures to improve ventilation performance, and 4) performance management so that safe operation and savings can be sustained over time. Section 5 summarizes the process; this appendix provides further details.

Step 1: Plan

1. Determining appropriate measures that satisfy project objectives starts with *planning* to understand needs. This step includes meeting with ALL key stakeholders to review and establish safety, comfort, productivity, energy, sustainability, and economic goals and requirements. Stakeholders include building owners and managers, lab users, facilities and EH&S staff, fire marshal, code officials, and sustainability officers.
2. This step also includes collecting and reviewing building documentation (e.g., as-built building and HVAC system drawings, control strategies, standard operating procedures, utility data) to prepare for the next step.

Step 2: Assess

This step involves a survey of individual laboratory spaces and evaluating lab safety and energy use, including hazards, sources, and the functional performance of ventilation system equipment. It includes assessing the demand for ventilation and benchmarking current operating conditions (i.e., hood and lab inspection, face velocity measurements, cross-draft velocity tests, VAV response and stability tests, and determining hood dilution factors).

1. Determine Performance
   a) Use ANSI/ASHRAE 110 “Method of Testing Performance of Laboratory Fume Hoods” to carry out hood-related flow visualization smoke tests and tracer gas containment tests.
   b) Conduct system operating mode test (SOMT) on each hood to assess VAV response and stability.
      - Data collection includes two hood operating modes (sashes closed in unoccupied mode, sashes open in occupied mode): measure total airflow and static pressure, and obtain building automation system (BAS) trends for fan airflows, and terminal box airflows, set points, and damper positions.
      - Evaluate airflow change response time and stability after change; compare airflows to set points; look for stuck dampers; compare unoccupied and occupied airflow sums.
2. Determine Generation “Emission” Scenarios
      - Address contaminant type, quantity, vapor pressure, heat, energy, reactivity, and corrosiveness aspects.
      - Where possible, consider opportunities to capture hazards at source.
      - Consider filtration, where appropriate.

3. Apply Control Band Matrix to Determine Minimum ACH

- To avoid the need to carry out complex contaminant generation and transport analyses for every lab, the control banding concept offers a simplified system for grouping labs into categories for which a small range of air change rates have been predetermined to be able to control the associated exposure and physical hazards by dilution. It uses a risk-based scoring system that considers the types of chemicals involved, how they are used, and how their associated hazards are controlled. Table A1 provides an example "scoring system" (Smith 2013) that can be modified to meet the unique needs and hazards of specific facilities. The control bands, parameters, scores, and applicable air change rates can vary depending on the type of laboratory, hazards, processes, dynamic nature of research, and degree of risk avoidance. The table refers in part to exposure control devices (ECDs), which are system components such as fume hoods or snorkel exhausts.
- Table A2 describes example control-band-based air change rates and the extent to which recirculation of lab air can be allowed (Smith 2013). Recirculation air can be used with low risk categories (1) to save energy without compromising safety, can be used sometimes for moderate risk categories (2 and 3) if further additional control measures are implemented (i.e., filtration or demand-controlled ventilation) when analyses indicate that safety will not be compromised, but needs to be avoided completely for the higher risk categories (4 and 5). Table A2 also provides information about the lab depressurization needed to avoid transferring lab air to surrounding spaces and to ensure safety. Greater depressurization (as well as monitoring for verification purposes) is needed as the risk category increases.

Table A1: ACH Control Band Parameters and Scoring (ECD: exposure control device)

Parameter	Score	Score Description
Chemical Hazard Rating	0-15	Summation of multiple parameters based on material types and process (e.g., based on empirical data on generation rates; considers reactivity, toxicity, LEL)
Chemical Generation Source Location	0-5	0 - Inside approved ECD 5 - Outside approved ECD
Chemical Generation Potential Outside ECD	0-5	Lower value - In sealed container Higher value – Open container
Number of Generation Locations	0-5	0 - Outside of ECD and sealed 1-2 - Outside and open, 1 location 2-5 - Outside and open, >1 location
Duration of Chemical Generation	0-5	Weighted factor for length of time for chemical generation outside ECD
ECD Availability	0-5	0 – ECD available for use 5 – ECD necessary but not available or used
ECD Appropriateness	0-5	0 – ECD appropriate for use 5 – ECD inappropriate for use
Sufficient Number of ECDs	0-5	0 - Sufficient number of ECDs available 5 – Insufficient number of ECDs available
Lab Practices and Housekeeping	0-2	0 – Good lab practices 2 – Less than desirable lab practices
Ventilation Effectiveness	0-5	0 – Adequate Sweep through Room 5 – Poor Mixing & Stagnation

Table A2: ACH, Recirculation, and Depressurization Based on Control Bands

Total Score from Table A1	Control Band	ACH	Recirculation of Lab Air	Lab Depressurization
0-5	1	< 4	Yes	Neutral
6-11	2	4-6	Filtered or DCV	< 0.005 in.w.g.
12-21	3	6-8	Investigate	< 0.01 in.w.g.
22-31	4	8-10	No	< 0.05 in.w.g., w/Monitor
>31	5	> 10	No	>= 0.05 in.w.g., w/Anteroom (airlocks) & Monitor

4. Determine Room Volume and Specify Minimum Airflow
   - Base airflow rates on hood exhaust requirements, control band, and comfort (temperature).
   - Consider demand-controlled-ventilation (DCV).
5. Assess compliance with codes and standards.

Step 3: Optimize

Using the information obtained in Steps 1 and 2, this step involves identifying and selecting Performance Improvement Measures (PIMs) and Energy Conservation Measures (ECMs), in part using an energy and return-on-investment (ROI) analysis tool (e.g., the tool described by Sharp 2013) to prioritize measures. The step includes developing a scope of work, specifications for system characteristics and operating procedures, and identifying funding sources. It also includes actual implementation of the measures (construction, test and balance, commissioning).

1. Consider opportunities to modify systems to meet stakeholder demands and codes and standards requirements, such as:
   a) Remove or Hibernate Unnecessary Hoods.
   b) Modify Inefficient Hoods (problems include: poorly designed hoods, under-utilized hoods, hoods that operate continuously at high flows).
   c) Replace or Retrofit Traditional Fume Hoods:
      - Includes bench top types (traditional bypass hoods, low velocity – high performance hoods, VAV – restricted bypass hoods); distillation types; floor-mounted walk-in types).
      - “High Performance” Fume Hoods include the following:
        - o Low flow constant volume (60 to 80 fpm face velocity),
        - o Low flow constant volume retrofit kits (60 to 80 fpm face velocity),
        - o Variable air volume with automated sash closure, or two state (high/low flow) control based on occupancy sensing.
      - Retrofits (upgrade critical components: airfoil sill, sash handle, baffle):
        - o Candidates include traditional / standard CAV or VAV bench-top hoods with good existing integrity.
        - o Cost effective: Retrofit payback for 400 cfm reduction from pre-retrofit 1000 cfm hood flow ($2,000 saving) is about 2.5 years (assuming $5 per cfm-year); replacement with high-performance hood about 7 years.
   d) Upgrade CAV & Dysfunctional VAV Controls:
      - Component upgrades include replacing VAV terminal actuators and pressure transducers with more accurate components.
   e) Optimize Temperature & Humidity Controls.

f) Install Demand-Based Control or Demand Control Ventilation:
   - Use measuring devices on each hood to monitor flow, velocity, and pressure.
   - Flow control types include: through the wall velocity, sash position, occupancy, and manual operation.
   - VAV modes: two state, full VAV, VAV hybrid, DCV.

g) Reduce / Reset System Static Pressure.
h) Optimize Exhaust Fan (including discharge) and AHU Operation.
i) Decouple Heat Load from Ventilation Flows (e.g., Chilled Beams)
j) Implement Energy Recovery.

2. Select and prioritize PIMs and ECMs
   - Key metrics and weighting factors include: size and space allocation, energy use and operating costs, state of the systems, project complexity, and energy reduction potential.
   - Suggested building classification system:
     - A: ROI < 3 years; *no major* engineering; *no* retrofits, component upgrades or replacement; *no new equipment* installation.
     - B: ROI < 5 years; *same as "A",* but requires retrofits and component upgrades or replacement.
     - C: ROI < 10 years; same as "B" but requires *major* engineering.
     - D: ROI > 10 years; same as "C" but requires *new equipment* installation.

3. If needed, provide report to client or to senior management with assessment and recommendations
   - Includes building classification, energy reduction assessment, and estimated project costs and payback.

4. Project Implementation
   a) Phase 1 – Project Engineering
      - Develop scope of work
      - Develop specifications for:
        - AHUs and exhaust fans
        - Manifolds (redundancy, emergency power)
        - Maximum and minimum flows and associated system static pressures
        - Duct transport velocity
        - Exhaust stack discharge
        - Control capabilities (VAV diversity and sensitivity)
      - Identify funding sources (e.g., utility rebate programs)
      - Design new systems or upgrades and system modifications
      - Develop test and balance (TAB) and commissioning plans

   b) Phase 2 – Construction, TAB, and Commissioning
      - Install equipment
      - Verify performance and energy savings using TAB and measurement and verification (M&V) techniques, following defined plans.

Step 4: Sustain

To sustain safe and efficient operation, and to protect the return on energy investment after performance improvement and energy conservation measures are implemented, the process continues through definition and implementation of a Laboratory Ventilation Management Plan (LVMP), training, and ongoing testing/maintenance. It is a step required by ANSI/AIHA Z9.5-2012.

1. Develop System Management and Sustainability Plan that addresses:
    - Organization and Responsibilities, including Lines of Communication (Reporting)
    - Standard Operating Procedures (SOPs) for Surveys, Testing, and Maintenance
    - Metrics, Monitoring, and BAS Utilization
    - Comparison to Ventilation Standards
    - Management of Change
    - Personnel Training (lab users, facility maintenance staff, building operators)
2. Develop LVMP Documents:
    a) Component 1 – Program Management
        - Section 1 – LVMP Program Description
            - Coordinate efforts (management, facilities engineering and maintenance, EH&S, lab staff, contractors)
            - Standardize operations (lines of communication, management of change, document control, personnel training)
        - Section 2 – Design Guide and Specifications
        - Section 3 – Test Requirements for Laboratory Hoods
        - Section 4 – Standard Operating Procedures (SOPs)

    b) Component 2 - Building Operation Plan
        - Mechanical systems and controls
        - Lab fume hood and related equipment inventory
        - As-built drawings and documents, including flow and operating specifications
        - Tasks and schedules (reference applicable SOPs)
        - Reporting requirements
3. Coordinate repair and preventative maintenance task documents with system and lab/hood tests, and monitoring/reporting to make best use of available resources. A suggested timeline to effectively utilize resources is as follows:
    - Weeks 1-4: AHU and exhaust fan repairs and preventative maintenance
    - Weeks 5-7: System operating mode tests (SOMTs)
    - Weeks 8-9: Carry out repairs if problems found in SOMTs and redo SOMTs as needed
    - Weeks 10-13: Lab environment tests(LETs) and lab hood performance tests (LHPTs)
    - Weeks 14-15: Carry out repairs if problems found in LETs or LHPTs and redo LETs and LHPTs as needed
    - Ongoing: repairs and preventative maintenance as needed; analyze trends from BAS monitoring