International Institute for Sustainable Laboratories®

Best Practices Guide
Energy Savings with Demand Based Control

SEPTEMBER 2021

Executive Summary

Laboratory research facilities and vivaria are energy-intense building types due to the vast amounts of 100% outside air required to maintain a safe and healthy environment for occupants. Given pressing concerns about energy costs, carbon footprint, and indoor environmental quality, reducing energy expenses in both new and existing laboratory facilities has become a critical challenge. For many laboratories, the drivers of high energy expenses are minimum ventilation or air change settings. These drive the outside air requirements. This guide will discuss one solution, often called demand based control (DBC), a form of demand control ventilation (DCV) for labs.

This approach, referenced in the Laboratories Chapter of the ASHRAE HVAC Applications Handbook, avoids a fixed air change rate such as a value in the range of 6 to 12 air changes per hour (ACH) (ASHRAE, 2019). Instead, real-time measurements of actual indoor environmental quality are used to vary air change rates from minimum rates as low as 2 or 4 ACH up to purge values of 8 to even 16 ACH, based on detected cleanliness of the laboratory room air. By safely cutting laboratory air change rates, often by half, for nearly all of the time, this approach can often be the single largest energy conservation strategy for many laboratory facility designs.

In new facilities or major renovations, significant net reductions in first cost may also be achieved by reducing HVAC system sizing. Finally, significantly increasing air change rates when certain contaminants are sensed will improve indoor environmental quality (IEQ). This best practices guide describes the DBC concept for laboratories and vivaria and discusses one technology approach to cost-effective implementation. Case studies help demonstrate how this concept has been used successfully for more than 10 years. A sample energy analysis is also provided.

Introduction

Among strategies for reducing energy consumption for many types of laboratory facilities, use of demand based control (DBC) or centralized demand control ventilation (CDCV) has been shown to have the greatest impact. For example, DBC is a very impactful component of the highly successful Smart Labs program created at the University of California Irvine (UCI) (University of California Irvine, n.d.; Gomez & Gudorf, 2010). The energy consumption of more than a dozen campus laboratory buildings has been reduced by more than 50%. Primarily due to energy savings in laboratory facilities, UCI was able to cut its campus-wide energy consumption by 23% between 2008 and 2013. As a result, President Obama honored UCI as the nation's first university to meet his Better Buildings Challenge, which had a goal of reducing energy consumption of an organization's site-wide buildings portfolio by at least 20% by 2020.

In the past, very little objective data was available regarding the environmental and energy savings impact of reducing and varying air change rates in laboratories and vivaria using a demand based control strategy. This guide summarizes the results from a major research study that generated a significant amount of data on the indoor environmental quality (IEQ) of laboratories and vivariums using DBC. It covered more than 1.5 million hours of operations in more than 300 laboratory areas at 18 different facilities. The facilities used demand based control of air change rates, involving real-time sensing and dynamic control of laboratory air changes. More than 20 million sensor values were collected and analyzed, including data on total volatile organic compounds (VOCs), particles (size range of 0.3 to 2.5 microns), carbon dioxide, and dewpoint (absolute humidity).

This study indicated that, during the observed laboratory practices, 2 to 4 ACH provided low levels of VOCs and particulates 98 to 99% of the time. Periodic laboratory release events required the increase of air change rates up to as high as purge levels to maintain and help control IEQ for the remainder of the time.

The Drivers for Laboratory Airflow

A basic understanding of the drivers for airflow in laboratories is important. It is the foundation for a more detailed discussion of demand based airflow control.

The three main drivers of laboratory supply airflow are the laboratory hood or exhaust device flows, the airflow to manage thermal loads, and the design minimum for dilution or ACH rate, as shown in Figure 1.

Many modern research laboratories now operate with fewer fume hoods, relying more on enclosed robotics, microscale reactions, and computational chemistry. Modern laboratories may also have lower thermal needs due to reduced plug loads. As a result, the minimum dilution ventilation flow or air change rate is often the main driver of supply and general exhaust airflow volumes. However, to reduce energy use and first cost, all the airflow drivers should be minimized, since the laboratory airflow rate will be dictated by the highest instantaneous flow driver.

Reduce Fume Hood Flows

For all but very-low-hood-density laboratories (less than one fume hood per 2,000 square feet or about 200 square meters), the use of variable air volume (VAV) hoods is recommended to reduce fume hood airflow when the sash is lowered or closed. Other suggestions include:

- Consider using low-face-velocity fume hoods.
- Use an 18-inch (45-cm) or lower design opening to limit fume hood flows.
- Initiate laboratory protocols that encourage good sash-closing habits to save energy and increase safety.

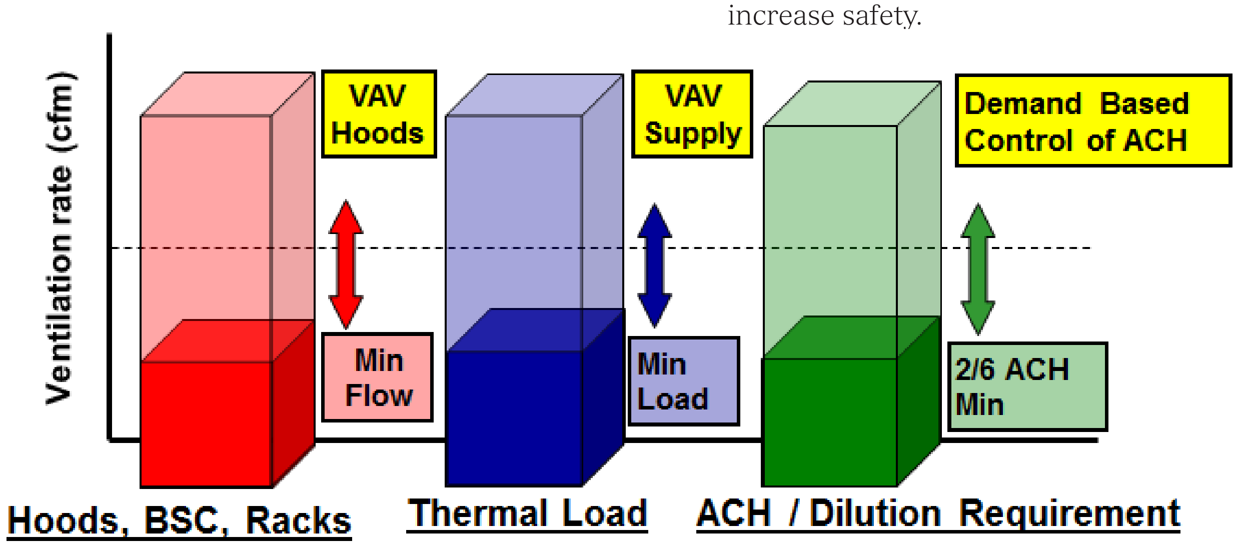

Figure 1: The three drivers of laboratory room airflow. Source for all figures unless otherwise noted: Gordon Sharp/Aircuity.

- Consider automatic sash closers or zone presence sensors to automatically set back face velocity when no user is in front of the hood.

For laboratories with moderate to high hood density (greater than one fume hood per 65 square meters), the ANSI/AIHA/ASSE Z9.5-2012 Laboratory Ventilation Standard provides guidance on the minimum (sash closed) flow of a VAV fume hood (ANSI/AIHA/ASEE, 2012). Evolutions in this guidance allow reduction in flow from previously required levels if a hazard assessment supports lower flows.

The 2003 version of Z9.5 stipulated a minimum flow for a fume hood of 25 cfm per square foot of hood bench area, or about 450 m^3/hr per square meter of hood bench area. This same requirement was also cited in NFPA 45-2004.

In 2011, a new version of NFPA 45 was released, NFPA 45-2011 (NFPA, 2011). This version and subsequent versions removed the reference to a fume hood minimum flow and replaced it with a comment to refer to ANSI Z9.5 for the fume hood minimum flow value. In 2012, ANSI Z9.5 changed as well, with the release of ANSI/AIHA/ASSE Z9.5-2012. This version contained new language that changed the guidance for fume hood minimum flow. This version (and the next version, expected to be released in 2022) do not require fixed minimum laboratory hood flows. The requirement now is that the minimum flow rate shall be sufficient to prevent hazardous concentrations of contaminants within the laboratory fume hood, supported by a hazard assessment and consideration of management of change.

The non-binding section of the Z9.5 standard provides a potential range of 150 to 375 hood air changes as a minimum. This range has worked well in various situations. The range for a standard 6-ft (1.8-m) benchtop hood approximates 10 to 25 cfm per ft^2 (or about 180 to 450 m^3/hr per m^2) of benchtop area. Again, for a 6-ft (1.8-m) benchtop hood, this would represent a range of 100 to 250 cfm or 170 to 425 m^3/hr of airflow.

Figure 2 illustrates this potential range for the minimum fume hood flow vs. sash position. Note that this performance is not related to fume hood face velocity (the rate of flow, in fpm or m/sec) but only to the fume hood's minimum flow volume (in cfm or m^3/hr) when the sash is closed or nearly closed. For most laboratories with typical fume hood densities (fewer than 6 hoods per 1,000 ft^2 or about 100 m^2), this now means that the minimum fume hood flow will often translate to allowable room airflow minimums in the range of 2 to 4 ACH or even less.

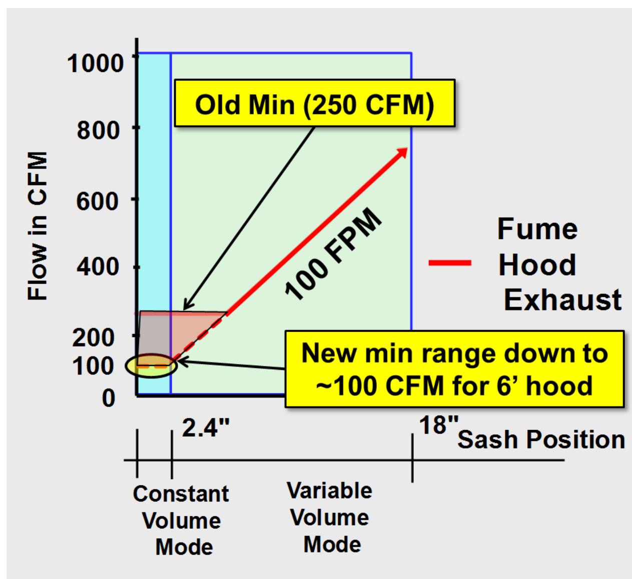

Figure 2: The ANSI Z9.5 fume hood minimum flow range.

Reduce Thermal Load Flow Drivers

As per a Labs21 and University of California Davis study (Mathew et al., 2005), average laboratory room plug and lighting loads are typically 2.5 to 3 W/ft^2 (25 to 30 W/m^2) or less. Perhaps only 20% of labs—or fewer—have loads exceeding 4 W/ft^2 (40 W/m^2). For the average laboratory room, normal daytime thermal loads require typically less than 4 ACH of conditioned supply airflow. At night, the use of a temperature setback control can reduce supply airflow demand to 2 ACH or less.

For high-thermal-load labs, and where even more energy efficient operation is desired, it is very useful to decouple the laboratory space cooling requirements from the laboratory airflow requirements by using local hydronic cooling approaches such chilled beams, chilled radiant ceilings or slabs, or fan coil units. Furthermore, these approaches in combination with demand based control can often provide significantly lower first or capital costs by reducing the supply airflow requirements and the size of the supply and exhaust fans. (For further discussion, see the sidebar on page 13.)

Vary and Reduce Average ACH Rate Using DBC

Due to the trends and design approaches mentioned above, a laboratory's dilution ventilation airflow rate is often a dominant or controlling factor. It drives average and, in many cases, design values for general supply and exhaust airflow volumes. Minimum air change rates are often set to a single value between 6 and 12 ACH, without basis in hard guidelines or dilution performance standards. No static ACH rate exists for a specific laboratory space that can meet all dilution expectations. The dynamic nature of space usage is best managed through dynamic controls. One ACH rate is not appropriate at all times or for all conditions. A non-dynamic rate will be set too high or too low at times. Rather, specific laboratory conditions will demand ACH variation.

For example, if a spill of a solvent or volatile chemical occurs, or chemists are doing hazardous work on a benchtop instead of in a laboratory hood, a higher room air change rate is desirable. In a spill situation, or even for control of fugitive emissions, a rate above 6 ACH—such as at least 8 ACH to as much as 12 to 16 ACH—can provide superior dilution performance at the time of the incident and for some time afterward (Klein et al., 2009). When the situation calls for it, a higher air change rate will more quickly reduce contaminant levels (Schuyler, 2009). However, for the great majority of the time—about 98 to 99% of time—laboratory room air has very low VOCs and particulates, and a minimum of 2 ACH will be sufficient to maintain good IEQ (Sharp, 2010). Diluting clean room air with clean supply air achieves no benefit and wastes significant amounts of energy.

Consequently, the ideal approach to minimum air change rates for laboratories is to determine the appropriate rate based on real-time air quality. Situational factors are allowed to drive airflow demand, instead of airflow being solely determined by the status of the hoods and the thermal load.

A dynamic approach to controlling minimum air change rates requires the ability to measure a unique set of indoor air parameters, such as total volatile organic compounds (TVOCs), particles, carbon dioxide, and, sometimes, humidity, and to integrate this information with the building management system. As previously discussed, this approach is commonly known as DBC (demand based control), CDCV (centralized demand control ventilation), or real-time indoor environmental quality (IEQ) monitoring and control. With demand based control, when sensors in the laboratory room or the room exhaust duct indicate that an air contaminant threshold has been exceeded, the minimum air change rate is increased. This airflow volume increase is proportional to the amount that exceeds the threshold, up to an appropriate maximum purge capacity. The purge capacity depends on the system and airflow control device capabilities but is typically recommended to be in the range of at least 8 to as high as 16 ACH (Bell & Abbamonto, 2009).

When the monitored contaminants are below the given threshold, this approach can reduce laboratory air change rates to as low as 2 ACH, or as determined by the owner's health and safety personnel. Although such ACH rates might seem too low in a laboratory, 2 ACH is still more than three times the typical outside air ventilation level for an occupied office space.

One commonly applied approach when the laboratory air contaminant levels are below the monitored thresholds is to operate at 4 ACH during the day. This can be reduced to 2 ACH at night and/or weekends, when the laboratory hood sashes are more likely to be closed, thermal loads are less, and the temperature control can be set back.

This DBC concept is similar to an approach called demand control ventilation (DCV), which is commonly applied to offices and other commercial buildings using only carbon dioxide as the controlling parameter. DCV has been known and used for more than 30 years. However, until the late 2000s, a demand-based approach to ventilating laboratories and vivaria using multiple contaminant parameters was not typically feasible or cost effective, primarily due to the quality and quantity of sensors necessary to safely implement this approach. In addition, the associated calibration and maintenance costs rendered it impractical to populate a large number of air quality sensors throughout a facility.

A Cost-Effective Implementation for DBC in Laboratories

In about 2005, to address the challenge of reliable, cost-effective sensing of multiple air parameters in a large number of spaces, an air-sampling sensing architecture began to be used for sensing air quality. It enabled a practical means of implementing DBC. This sensing architecture—sometimes referred to as a form of air sampling, or multiplexed sensing, as shown in Figure 3—changes the age-old paradigm of discrete sensing and minimizes calibration and maintenance expenses.

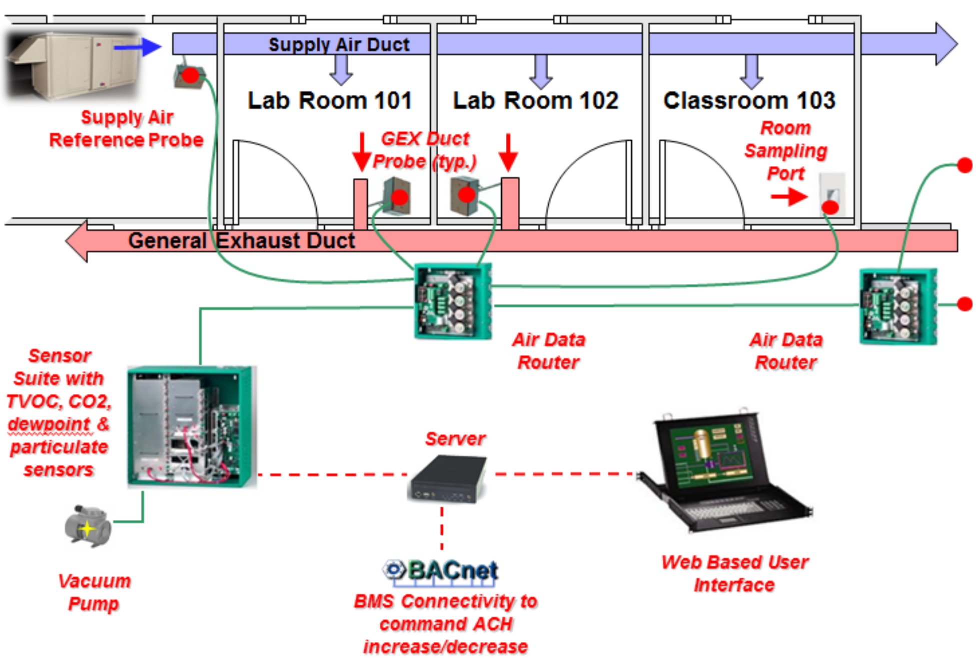

Figure 3: Multiplexed sensing architecture.

Instead of placing multiple sensors in each sensed space or area of a building, this networked system routes packets or samples of air sequentially in a multiplexed fashion to a shared set of centrally located sensors. Approximately every 30 seconds, a sample of air from a different area is routed on a common air-sampling backbone to the same set of sensors, located in what is sometimes referred to as a "sensor suite," for measurement. These sequential measurements are then "de-multiplexed" for each sampled area to create distinct sensor signals for each room, which can then be used for traditional monitoring and control. Typically, up to 30 areas can be sampled every 15 minutes with one set of sensors. Although it may seem like a long time period, for this application a 15-minute sampling time for demand based control provides dilution clearing performance that is comparable to, or even better than, a conventional fixed 6- or 8-ACH minimum ventilation approach.

Calibration and maintenance expenses are minimized due to the much-reduced number of sensors required (one set for approximately every 30 rooms). The calibration process can also be easily accomplished through an exchange program, whereby a set of factory-calibrated sensors can periodically replace the on-site sensors, perhaps every six months. The sensors can be located in equipment rooms or utility closets, where they can easily be accessed without disrupting research activity.

An important aspect of this sensing system architecture is the hollow sampling conduit or special tubing that provides the transport media through which air packets are passed one after another, similar to data packets on a communications network used in building management systems. To virtually eliminate potential contamination from one air packet to subsequent packets, the inner walls of the air sample conduit are made of an inert material, such as a fluoropolymer like Teflon or another inert material like stainless steel. Inert fluoropolymer minimizes the carryover of one sample packet to another by substantially reducing the adsorption or absorption of chemical vapors into the tubing walls.

Another requirement for the sampling conduit is that the inside walls need to be electrically conductive. This prevents the natural build-up of static charge on the interior walls caused by air flowing through the conduit or tubing. A charge build-up will attract particles to the walls of the conduit and reduce the transport efficiency for particles. However, if the conduit walls are conductive, even if not grounded, the static charge cannot build up—providing for the efficient transport of particles. Although stainless steel can again be used, a better approach involves adding a carbon-based nanomaterial, such as carbon nanotubes, to the fluoropolymer mentioned above. The carbon nanotubes are highly conductive electrically, but—unlike other forms of carbonlike graphite that can absorb and desorb chemical vapors—carbon nanotubes are relatively inert and thus do not significantly compromise the inertness of the fluoropolymer tubing.

This multiplexed sensing approach can measure almost any air parameter of interest. For laboratories, the use of a PID (photo-ionization detector) type of TVOC sensor is very beneficial for accurately detecting literally hundreds of commonly used laboratory chemicals that can volatize and become a safety concern above threshold concentrations. Combining this sensor with a laser-based particle counter to identify particulates, smoke, or aerosol vapors, plus other specialty sensors such as metal oxide semiconductor (MOS) TVOC sensors, affords detection of the great majority of airborne chemicals of concern.

Benefits of Differential Measurement with Multiplexed Sensing

In addition to dramatically reducing the number of sensors needed to implement DBC by a factor of about 30, multiplexed sensing has another advantage over individual sensors. Typically to control laboratory room's airflow and IEQ, it is important to look at the contaminant levels in the room differentially vs. on an absolute basis. In other words, we typically want to subtract the contaminant levels in the supply airflow from the exhaust or room levels to measure just the contaminants generated in the laboratory room. If the supply airflow particle levels are high, causing a high absolute number of particles in the laboratory room, we would not want the system to call for more supply flow. This would just pump even more particles into the room because the supply system is the source of the contaminant particles.

In fact, controlling airflow using absolute levels when the supply has moderate to high contaminant levels would result in commanding all laboratory rooms fed from that supply air source to maximum or purge flows. This, in turn, could create significant ventilation capacity and energy use issues. Dilution ventilation only works to dilute the contaminants generated in the room itself, not those coming in from outside!

A significant benefit of multiplexed sensing is that it can measure differential contaminant or parameter levels much more accurately and reliably than individual sensors. This is because using two different sensors, one for the room or exhaust and another for supply, can actually double the sensor drift errors since one sensor could drift negative while the other could drift positive, thereby doubling the error. With a multiplexed sensing system, the same centralized sensor is used to measure both the supply contaminant levels and the room contaminant levels. Any offset drift error of the sensor is the same for both measurements, since the sensor is the same for both measurements. Therefore, when the differential is taken and the supply level is subtracted from the room level, the offset drift error of each measurement is subtracted out. As a result, a multiplexed sensing or air sampling architecture can generate much more accurate differential measurements compared with individual sensors.

Typical Threshold Levels and Sensors for DBC

The contaminant thresholds at which the dilution ventilation rate begins to increase and the levels to which the ventilation is commanded can be set based on particular laboratory requirements. Here are some general comments and guidelines:

TVOC thresholds: Typical values for a TVOC threshold are about 0.2 ppm based on using a PID or photo-ionization detector, which is highly recommended as a TVOC sensor for this application. The basis for this 0.2 ppm minimum threshold level is that it is approximately equal to the average TVOC levels of 500 micrograms/m^3 that is used the LEED-NC (New Construction) credit for flush-out of an office building after construction (based on certain EPA and State of Washington requirements). This is a conservative threshold when used to control laboratory air changes, since laboratories primarily have infrequent short-term exposures of TVOC events vs. a constant level of VOCs from off-gassing of construction materials.

TVOC sensors: As discussed, PID sensors are very beneficial for accurately detecting hundreds of commonly used laboratory chemicals that can volatize and become a safety concern. PID sensors can also detect some non-organic compounds such as ammonia, which is of particular interest in vivarium rooms. Other TVOC sensors, such as metal oxide (MOS) sensors, are less accurate but can be used in combination with PID sensors to broaden detection capabilities to include more chemicals, such as commonly used analytical compounds like methyl alcohol, methylene chloride, and acetonitrile. Although a given TVOC sensor may not directly sense some pure compounds, many times these compounds are used in solution. The detectable solvent chemical can be the proxy to trigger an increased laboratory ventilation airflow rate.

Particle thresholds: Although there are no established regulatory requirements for indoor air particulates, particle level thresholds for DBC are typically set to increase airflow at about 1 million particles/ft^3. This number is based on guidance from the LEED-NC credit's average particulate threshold for flush-out after construction, which equates to about 1.6 million particles per cubic foot (pcf) of PM2.5-size particles (about 0.3- to 2.5-micron diameter sizes). Setting the minimum control threshold level at 1 million pcf again provides a slightly more conservative threshold level for the laboratory ACH control approach.

Particle sensors: For particle measurements, a laser-based particle counter is recommended, such as those used to monitor cleanrooms. These sensors can sense particle sizes in the PM2.5 range, from 2.5 microns all the way down to 0.3 microns or less. A laser-based particle counter also can identify particles in a size range that allows these measurements to be used as a proxy for detecting both animal allergens in a vivarium and aerosol vapors and smoke particles in a laboratory room. Particle sensors can also detect acid spills from the evolution of smoke or aerosol vapors that may not be visible to the eye but are released from the acid reacting with the countertop, flooring, or other surfaces (Gomez & Gudorf, 2010).

Other sensors: Other sensors, such as carbon dioxide sensors and accurate dewpoint or humidity sensors, can also be used to sense laboratory and vivarium rooms for general people-related ventilation and other control and monitoring purposes. Additionally, sensing humidity can be used to help maintain RH above at least 20%, which is advised to reduce the risk of viral infections.

As with any laboratory room and its controls and operating practices, an engineer should work with the owner's health and safety personnel to determine the chemicals being used in the space and the maximum permissible levels. Sensors under consideration should be evaluated for their ability to detect the significant and relevant chemicals present or projected for use. Sensors should measure within acceptable tolerances, and provide long-term reliability and recalibration capability. *Note also that since particles cannot be allowed to flow out of a BSL-3 or BSL-4 (P3 or P4) Biological Safety Level room, demand based control is not suitable for these types of laboratory rooms.*

Application Considerations

Demand based control can be applied to both new buildings and to retrofits of existing laboratory facilities. By far the best location for sensing a laboratory room is in the exhaust duct from the room since this gives a better average measurement of the room's environment. If sensing in the duct is not possible for some reason, then a location should be picked that will be at least 2 meters or more from any laboratory bench or fume hoods since the work done there could unduly affect the measurement of the total average room environment. For both new construction and existing laboratory retrofits, it is important to use air valves or VAV boxes with a low minimum flow rate, so that the desired minimum air change rate such as 2 or 4 ACH can be achieved. Similarly, rooms with a high density of fume hoods, such as more than six 6-foot fume hoods in 1,000 ft^2 (100 m^2), may not provide significant energy savings due to the high minimum flow required by the fume hoods even when their sashes are closed.

For rooms with high thermal loads, use of local room cooling devices such as chilled beams or fan coil units is recommended to decouple the room's cooling requirements from the outside airflow requirements. This strategy provides both significant energy savings and lower capital costs, as mentioned later in this guide (box, page 13). Finally, demand based controls can be used with almost any of the many variable air volume (VAV) laboratory airflow control systems that are available, including older installed systems, whether analog or DDC based. Although BACnet is most often used to connect demand based systems to these laboratory airflow or building control systems, simple analog interfaces can also be used.

Research Study on Lab Room IAQ

To scientifically validate assumptions on how often a laboratory room's air is relatively clean, a research study was conducted using 1.5 million hours of environmental data obtained from the previously described multiplexed sensing system using sensor data from 18 different laboratory and vivarium sites (Sharp, 2010). Collectively, these sites represented over 300 laboratory and vivarium rooms across the U.S. and Canada where dynamic control of air change rates was employed. These sites consisted primarily of life sciences and biology-related spaces as well as a smaller number of chemistry and physical sciences labs. Three of the above sites involved animal facilities, which are not addressed in this guide in the interests of brevity as the

Comments on Laboratory Ventilation Standards and Guidelines

In the U.S. and Europe, there are no prescriptive requirements for air change rates in laboratories other than the ASHRAE 62.1 (ASHRAE, 2019) fresh air requirements for university/college laboratories, corresponding to about 1.2 ACH (0.18 cfm/ft^2, or 0.9 l/s/m^2). However even this and other fresh air and exhaust requirements of ASHRAE 62.1 are not applicable to labs, due to an exemption in ASHRAE 62.1, if those laboratories follow the requirements of the ANSI/AIHA/ASEE Z9.5 Laboratory Ventilation Standard (ANSI/AIHA/ASEE, 2012).

In terms of recommended levels, standards are also moving away from the prescribed values of the past to a more performance-based approach based on the specific requirements of a given laboratory space. Chapter 17 of the 2019 ASHRAE HVAC Applications Handbook has guidance and recommendations on minimum levels for laboratory air changes and control approaches for ventilation (ASHRAE, 2019). The handbook recommends demand based control of air changes or, as the handbook puts it, "real-time sensing of contaminants."

The 2019 ASHRAE Applications Handbook, Lab Chapter 17, states that: "Reducing ventilation requirements in laboratories and vivariums based on real-time sensing of contaminants in the room environment offers opportunities for energy conservation. This approach can potentially safely reduce lab air change rates to as low as 2 ACH when the lab air is clean and the fume hood exhaust or room cooling load requirements do not require higher airflow rates."

Another relevant performance-based standard that concerns animal facilities or vivara but is also relevant to laboratories is from the CCAC (Canadian Council on Animal Care). Their 2019 document "Heating, Ventilation, and Air Conditioning: Addendum to the CCAC Guidelines on Laboratory Animal Facilities – Characteristics, Design and Development" provides quantitative yet performance-based guidelines on what constitutes contaminant levels for clean air, as well as setting guidelines regarding the parameters and threshold levels for the use of demand based control in a vivarium (CCAC, 2019).

vivarium room results were reasonably similar to the laboratory room data.

Research Study Results

Figure 4 shows a graph of the average TVOC levels across all of the laboratory locations representing about 1.5 million hours of operating data. This is a cumulative graph, so that for example, the value of 0.84% at 0.10 ppm means that, on average, this is the amount of time that a laboratory location has a TVOC value greater than or equal to 0.1 ppm. Similarly, the value of 0.08% at 1 ppm means that, on average, the TVOC values in laboratory rooms for this study exceeded 1 ppm about 0.08% of the time. Since this represents the average, some locations can be much higher than this and others potentially near zero. However, the average gives a good idea of the potential energy savings across all these different locations.

The blue shaded region starting at 0.2 ppm and ending at 1.6 ppm represents a typically used range of TVOC values where DBC will vary the minimum ventilation rate. In other words, the lower edge at 0.2 ppm represents the TVOC value at which the minimum airflow will start to increase above a minimum of, for example 2 ACH, with proportionally increasing minimum airflows up to a maximum purge rate of 16 ACH corresponding to a TVOC value of 1.6 ppm.

As seen in Figure 4, measured TVOCs were below the threshold of 0.1 ppm (representing a "clean" condition for the purposes of this study) about 99.2% of the time. This means that energy can be saved by operating at reduced minimum air change rates up to about 99.2% of the time in labs, at least with respect to the TVOC sensor. Looking at the same data in another light, on average, TVOC events greater than 0.1 ppm in magnitude occur for about 1.5 hours a week in a given laboratory room, or over 3% of a typical 40-hour work week.

To show the variations in this data among different sites, Figure 5 shows the same TVOC graph

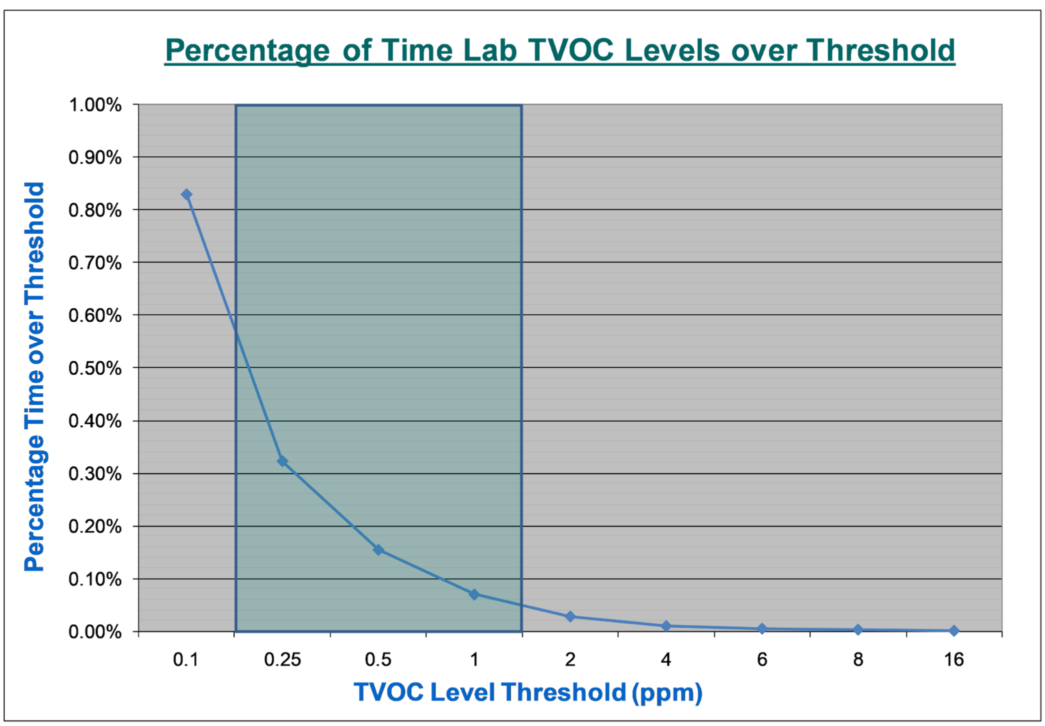

Figure 4: Average TVOC level percentages over threshold (1.5M hours of laboratory operation).

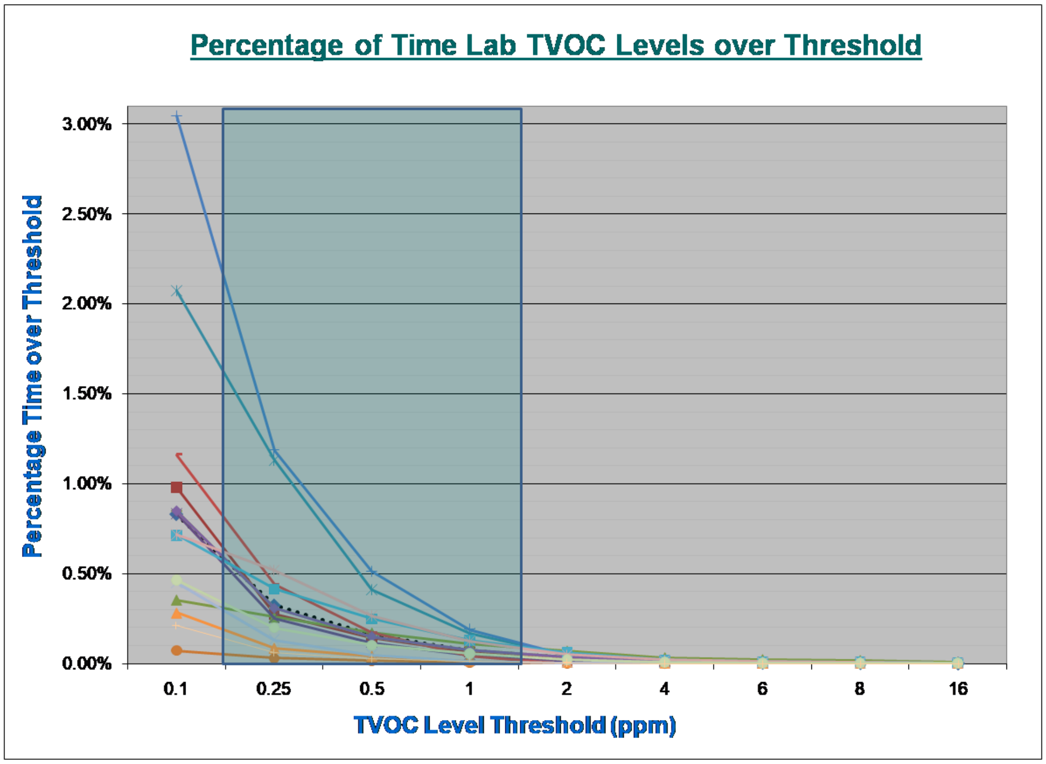

Figure 5: Average TVOC level percentages for multiple laboratory sites where each line represents a different laboratory site's averaged TVOC levels in ppm. The black dotted line represents the average of all laboratory sites.

but with each of the laboratory sites shown as a separate line. The average curve is shown by the black dotted line. Note that even at the site with the greatest amount of TVOC activity, the DBC concept can still save energy about 97% of the time. For almost six hours per week the minimum room ACH rates were safely increased. These ACH increases quickly purged the TVOC releases to the desired air quality below the TVOC threshold.

It is interesting to note that the laboratory rooms with the highest regular contaminant levels are often cell culture or tissue life science laboratory rooms, where researchers frequently spray alcohol on samples in a biosafety cabinet. However, these biosafety cabinets are often recirculating cabinets, so the alcohol vapors pass right into the room. The typical alcohol vapor concentration in these rooms should not be hazardous, but it is still a good idea to clear them quickly. A DBC system does that by purging the room at high air change rates when alcohol vapors are detected. Note that even in rooms with typically high amounts of purging time, the air is still clean of these vapors and other contaminants 90 to 95% of the time, enabling significant energy savings even in typical "worst case" rooms.

Particle increases are another parameter that can trigger an increase in the minimum air change rate. Examples are an out-of-control reaction or perhaps an acid spill that causes smoke or an aerosol to evolve in the laboratory room. Figure 6 shows a graph of the average level of 0.3- to 2.5-micron particle counts (PM2.5) that exceeded a background level of the laboratory room supply air for all the different sites of the study. Typically, about 1.0 million particles a cubic foot (pcf) is used as the threshold for increasing the minimum air change rate.

As can be seen in Figure 6, the average laboratory room, indicated by the dotted black line, was above

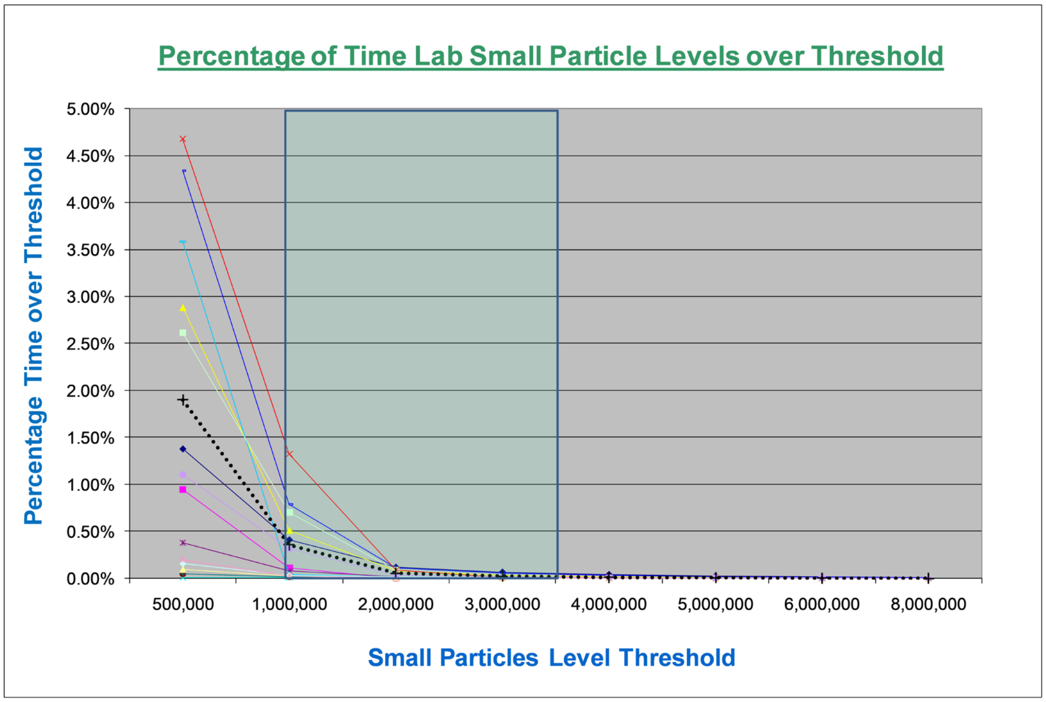

Figure 6: Percentage of time that small particle levels exceed threshold for multiple laboratory sites where each line represents a different laboratory site's averaged particle levels in particles per cubic foot (pcf). The dotted black line represents the average curve of all sites.

the 1M pcf threshold about 0.5% of the time (about 30 minutes a week on average). The individual sites showed a range of values when air flow should be increased based on a particle event, from near zero up to about 1.5% of the time. Adding this amount of time to the time that TVOCs exceed the control threshold yields an average total of about 1.2% of the time, or, for some sites, 2 to 3% of the time. In other words, minimum air change rates of between 2 to 4 ACH could be achieved from 97% to more than 99% of the time, with TVOC and/or particle events occurring on average up to about 5 hours a week.

In summary, this 2010 research study indicated that, with higher airflows required only about 1 to 2% of the time, very significant energy savings can be achieved with DBC.

Boston Energy Savings Analysis Example

A sophisticated laboratory energy analysis tool has been developed to analyze the savings of DBC plus many other energy efficient design approaches for labs, such as chilled beams, multiple types of heat recovery, variable exhaust fan exit velocity control, and so on. This non-proprietary tool, which has been presented in the past in workshops at the International Institute for Sustainable Laboratories' (I^2SL) annual conference and by some I^2SL chapters, allows the analysis not only of these energy savings approaches alone but also in combination, to provide a more accurate view of the potential interaction of these approaches.

Figure 7 shows a holistic view of multiple laboratory energy savings approaches. One of the key messages of this figure is that the foundation for significant laboratory energy savings is a VAV control system. By itself, VAV may not enable significant savings, but it enables other approaches for reducing laboratory airflows and lowering capital costs. Next most important is DBC and the related use of low VAV fume hood minimums and, if needed, automatic sash closers (at least for those laboratories with a moderate to high density of

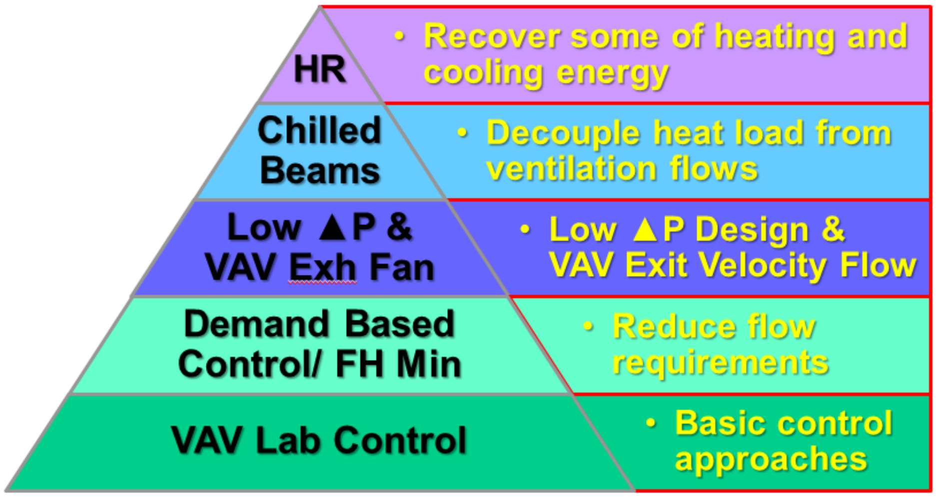

Figure 7: Holistic view of relative impact of multiple energy efficient approaches.

fume hoods). The other approaches listed higher than DBC in the figure can further increase savings, as has been mentioned for chilled beams and fan coil units.

Note that heat recovery (HR) is shown as having a smaller impact since its savings will vary significantly based on climate, with the greatest impact for both cold or very hot climates. For humid climates, enthalpy wheels, which have the highest efficiency levels, may have a good energy savings benefit. However even in climates favorable to heat recovery, this strategy will typically save significantly less energy than a DBC approach. Being able to safely reduce laboratory flows to at least 2 ACH at night and 4 during the day will typically save three or more times as much as an enthalpy wheel or other heat recovery systems. Again depending on the climate, a good strategy may be to use both DBC and heat recovery, particularly since the use of DBC will reduce the size and cost of the heat recovery system. Enthalpy

Demand Based Control Improves Chilled Beam Use

When chilled beams or fan coil units are used in laboratory rooms having a 6 or 8 ACH minimum dilution ventilation flow, the cool (55°F or 13°C) supply air volume requires a large amount of reheat energy to achieve the desired room air temperature. Even though design requirements can be in the range of 10 to 15 ACH of airflow, in actuality, most laboratories only need 2 to 4 ACH of airflow to meet typical cooling loads (Mathew, et al., 2005). Not only does this create a large amount of required reheat, but the chilled beams or fan coil units are rarely needed, producing an inefficient result with a duplication of equipment for cooling.

If demand based control is used to bring the room minimum flow down to 3 to 4 ACH during the day and 2 ACH at night, the amount of overcooling and required reheat energy is drastically reduced. If further cooling is required above 2 to 4 ACH, the chilled beams or fan coil units can now appropriately meet this peak cooling requirement without impacting the required outside airflow. As a result, the HVAC system can be downsized since the laboratory room's temperature management is decoupled from airflow. The air system can be sized to as low as 2 to 4 ACH of outside air capacity, based only on the dilution ventilation and fume hood exhaust requirements combined with a greater diversity factor enabled by room-level DBC.

continued on page 14

Demand Based Control Improves Chilled Beam Use, Cont.

Occasionally designers provide “neutral air” or air at about 68°F (20°C) to the laboratory for ventilation purposes so that the chilled beams or fan coil units provide all the cooling. However, reheat will often still be needed, though now it must be accomplished at the supply air handler. This is because some cooling at the air handler is still necessary to dehumidify the outside air in climates that can at least occasionally have moderate to high humidity. Various heat recovery technologies such as dual-wheel designs or “wraparound” coils may be used at the air handler to reduce this cooling load. These systems typically still require some reheat energy and, importantly, capital costs are significantly increased due to the required sizes of both the air handlers and the chilled beams or fan coil units.

Again, the complexity of adding heat recovery systems, as well as increasing the size of chilled beams and supply and exhaust fans, can all be eliminated by using DBC. DBC matches airflow with actual cooling requirements. This is a good example of a situation where the combination or “whole” (demand based control and chilled beams or fan coil units) has greater advantages than would result from the sum of the parts.

wheels, if employed, should not be used with the laboratory rooms’ general exhaust if any fume hood exhaust air is being mixed into the room exhaust. Per ANSI/ASHRAE 62.1-2019, the laboratory room and fume hood exhaust flows (class 3 and 4 air respectively) should be separated so the enthalpy wheel is used with just the room exhaust flows (ANSI/ASHRAE, 2019).

With the above-mentioned analytical tool, a typical energy savings analysis can be performed to gauge the energy savings impact of a DBC system. Using Boston as the location of a hypothetical laboratory energy retrofit, we created a baseline set of assumptions, including a fixed 6-ACH minimum airflow and energy costs of $0.105/kWh for electricity and $0.80/therm for heating. The model assumes typical cooling loads, Boston weather, and a facility of 125,000 ft^2 or 11,600 m^2, of which 50,000 ft^2 or 4,650 m^2 is laboratory space and is the subject of the analysis. This theoretical laboratory space consists of 75 laboratory rooms of an average size of 675 ft^2, each containing an average of one fume hood.

Figure 8 shows the results of the laboratory energy analysis. The base case using 6 ACH shows an HVAC energy use of $281,000 for 50,000 ft^2 of laboratory space, distributed among supply and exhaust fan power, reheat, heating, and cooling as shown.

The figure also shows that DBC with a minimum “clean” air change rate of 4 ACH during the day and 2 ACH at night reduced the energy use by about 50%, to $141,000. The cost of implementing a demand based system will vary based on local conditions and the type of project, such as new vs. retrofit. However, using reasonable assumptions of these costs yields a payback of about 2.5 years and a net 10-year savings of slightly over $1 million dollars.

Capital Cost Reduction Impacts of DBC

In addition to very significant reductions in energy use, the reduction of the laboratory airflow rates by demand based control can also lower HVAC first or capital costs, as mentioned earlier. Even though a single laboratory may go to higher flows when contaminants are detected, this typically only happens about 1 to 2% of the time. As a result, there is considerable diversity in the system, and peak flow can often be significantly reduced,

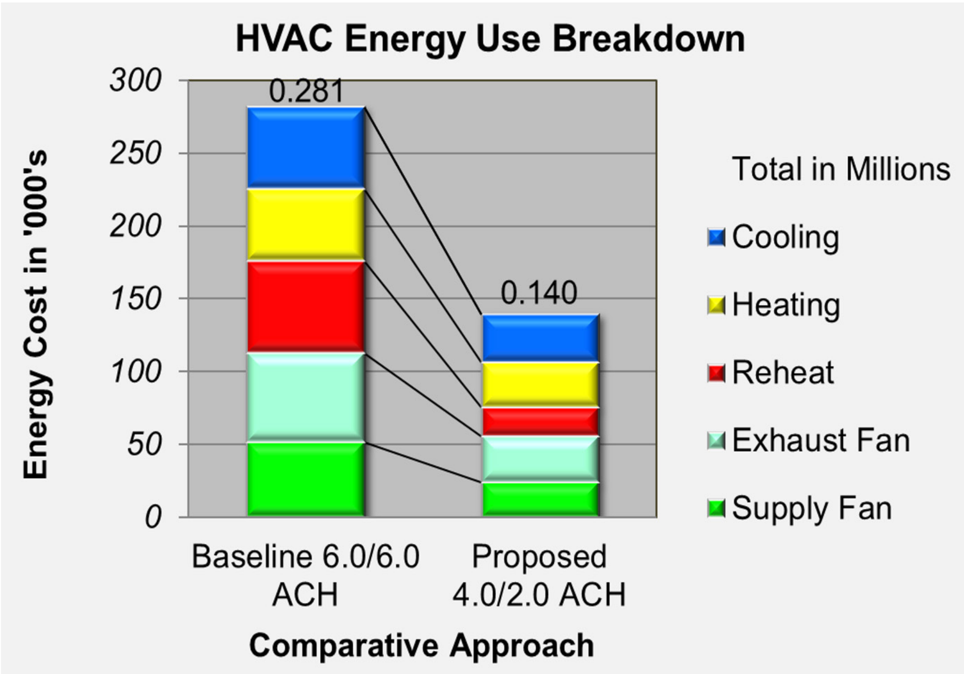

Figure 7: Holistic view of relative impact of multiple energy efficient approaches.

particularly when cooling load is decoupled from supply airflow. These savings can sometimes more than pay for the cost of the added controls, creating a net first cost savings as well as significant energy use reductions.

For example, a 189,000-ft^2 laboratory project for Cal Poly's Warren J. Baker Center for Science and Mathematics in San Luis Obispo, CA, in 2013, used a combination of demand based control and chilled beams to reduce the first cost of the project by about $716,000, despite the cost of the chilled beams and DBC system.

Another example was the 167,000-ft^2 (15,500 m^2) Health and Biomedical Sciences Center at the University of Houston, TX, in 2013. Value engineering was applied when the project appeared to be going over budget. The idea of using DBC to reduce the cost of the building—which was initially designed to have a 12 ACH minimum ventilation level in the laboratory areas and a 15 ACH minimum flow in the vivarium areas—was suggested and evaluated.

After an analysis and redesign using the DBC approach, the laboratory minimum ventilation level was reduced from 12 ACH to 4 ACH, and the vivarium minimum air change level was reduced from 15 ACH to 9 ACH. These changes reduced the size, and thus the cost, of the HVAC system by more than $1.5 million. The cost of the controls to implement DBC was about $500,000, so the net first (capital) cost reduction was about $1 million. Additionally, DBC saved about $250,000 of annual operating energy costs, resulting in an energy payback of two years beyond even the net first cost savings.

We can also use the laboratory energy analysis tool mentioned above to calculate the required peak HVAC airflow capacity reduction from using demand based control, such as with the previously mentioned Boston project. In this example, we have not only a lower base case of 6 ACH as a minimum, vs. the 12 ACH minimum of the Houston project, but also no added use of chilled beams or fan coil units to decouple the cooling requirements from the airflow requirements as was done at Cal Poly. Even so, we can still achieve an HVAC capital cost reduction of about 13%, which roughly translates to a first cost reduction of about $200,000. These savings reduce the expected payback from 2.5 years to about 1.1 years.

Finally, many utilities will provide sizable rebates and incentives for the use of energy savings systems and approaches such as DBC. For example, the Mortimer B. Zuckerman Research Center, a large 22-story laboratory building of the Memorial Sloan Kettering Cancer Center in New York City, used DBC in a 2016 retrofit project to reduce laboratory energy use by about $4 million annually. The project received an up-front utility incentive of $3.8 million, or about one year's worth of expected savings, from Con Edison.

Conclusions on Demand Based Control in Laboratories

Demand based control uses sensing of laboratory room indoor air quality to dynamically vary laboratory airflow rates as needed from as low as 2 ACH to purge rates as high as 16 ACH. This approach often has the single largest impact on responsibly reducing laboratory building energy use, sometimes by as much as 50%. Decoupling thermal loads from ventilation, at least when combined with DBC, is another important step to reduce laboratory energy use. Even more significantly, this decoupling and DBC strategy can reduce first or capital costs enough to more than pay for the required equipment and installation.

While heat recovery approaches alone can provide good paybacks in certain climates, reducing ACH rates with demand based control usually has better paybacks and energy savings impacts. When heat recovery systems are used in combination with DBC system for additional savings, the size and cost of the heat recovery system can be reduced due to the lower outside air flow rates. Low-ACH laboratory design with approaches such as DBC has become a proven and safe paradigm. It serves as a solid foundation for both the energy and capital efficient design of new laboratories, as well as for retrofitting existing laboratories to significantly reduce energy use and carbon footprint. With today's laboratory owners and designers being challenged to improve laboratory IEQ, save energy costs, and cut greenhouse gas emissions, demand based control can be a valuable tool to help achieve these goals.

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Case Study 1: Arizona State University's Biodesign Institute

An installed example of demand based control and multiplexed sensing can be seen at the Biodesign Institute at Arizona State University in Tempe, AZ: a LEED Platinum facility that was *R&D Magazine's* Lab of the Year in 2006. The building was initially designed with a minimum ventilation rate of 12 ACH. Stakeholders later decided to reduce the air change rate by a factor of three down to 4 ACH when the laboratory air is clean. Demand based control increases the airflow to about 16 ACH when sensed contaminants are detected in the lab.

This strategy was successfully tested in a pilot project in 2007 and then implemented in 2009 in more than 200 laboratory spaces and another 90 vivarium spaces throughout the ~350,000 gross ft^2 building. The net result of this 2009 retrofit was a measured and verified energy savings of approximately $1 million annually.

Not only was energy saved, but, as shown in Figure C1, the indoor environmental quality (IEQ) also improved overall. When contaminants were present, airflow rates of up to 16 ACH purged contaminants more quickly from laboratory areas, vs. the previous non-dynamic 12 ACH setting. This can be seen in the lower amounts of time that various TVOC thresholds were exceeded when DBC was used, compared with the prior constant ACH rate. Demand based control provided both significant energy savings and improved IEQ for this facility.

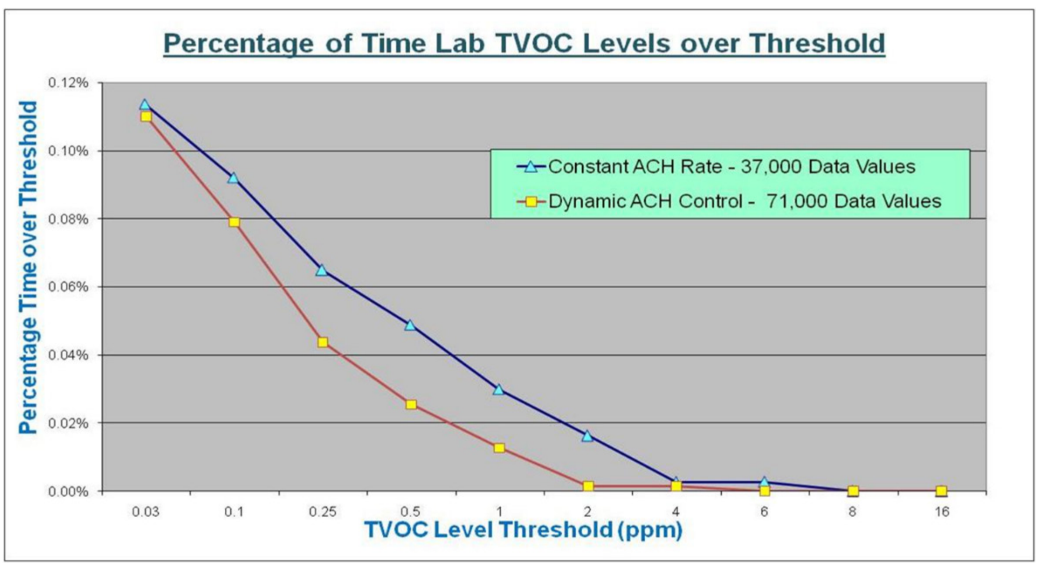

Figure C1: Improved IEQ via lower TVOC levels from demand based control vs. a constant airflow.

Case Study 2: Masdar Institute of Science and Technology (MIST)

The Masdar Institute of Science and Technology (MIST) is located in Masdar City in Abu Dhabi, UAE. Designed to be one of the world's most sustainable facilities with a near-net-zero carbon footprint, the MIST 1A and 1B buildings comprise mixed-use lab, office, classroom, and residential space over about 150,000 square meters (1.6 million ft^2).

The MIST 1A facility (Figures C2, C3, and C4) was completed in about 2010, and MIST 1B was completed around 2012. The region experiences a severe climate with very high temperatures and relative humidity, so achieving near net zero energy use was challenging to say the least.

Figure C2: MIST 1A, Masdar Institute of Science and Technology.

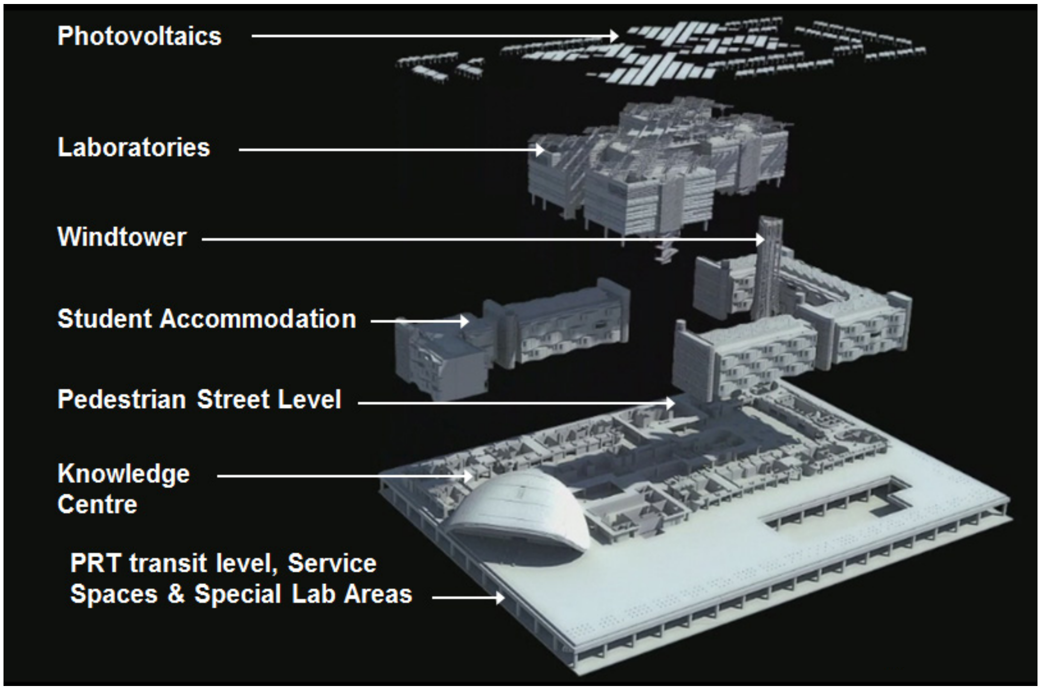

Figure C3: MIST 1A layout and laboratory spaces. Source: RFD.

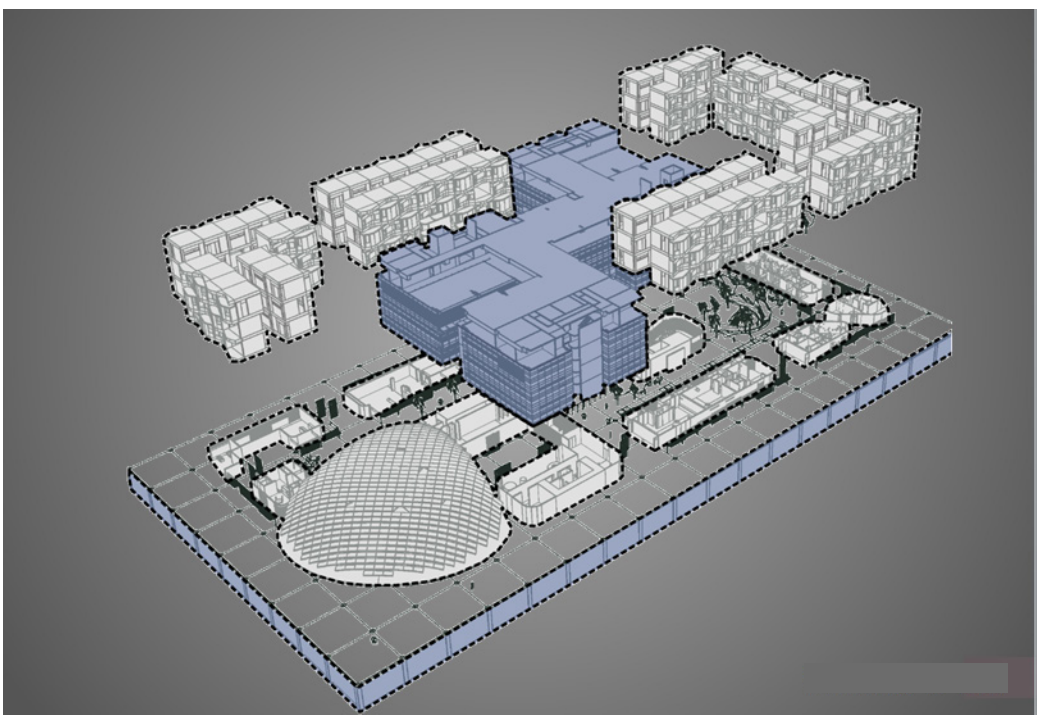

Figure C4: Further detail of MIST 1A laboratory spaces (blue). Source: RFD.

To significantly reduce laboratory energy use and carbon footprint, MIST used DBC in conjunction with either chilled beams (in larger laboratory rooms) or fan coil units (in smaller laboratory rooms) to reduce minimum laboratory air change rates to 2 ACH day and night when sensors indicated laboratory air to be clean. When sensors indicate the presence of contaminants, the system demands purge airflow rates of as high as 14 ACH to provide dilution and clearance. DBC purges faster than a fixed minimum ventilation rate of, for example, 8 ACH.

The lab's VAV fume hoods with closed sashes were initially intended to operate at 300 cfm or 150 l/s. However, the revised ANSI Z9.5-2012 standard recommendations helped guide an implementation of a VAV fume hood minimum of 90 cfm or 45 l/s that was implemented to further increase energy savings. Finally, multiplexed sensing was also applied in the office and classroom areas of MIST. Demand control ventilation achieved lower energy use in those areas as well.

The estimated energy savings of DBC for both the MIST 1A and 1B facilities was approximately 9,000 MWh per year. Additionally, the airflow reductions in the lab, office, and classroom areas reduced the project's HVAC capacity requirements, creating a significant reduction in first or capital costs. This was achieved though downsizing the main HVAC equipment such as air handlers, exhaust fans, chillers, heat recovery systems, and so on.

Finally, the roughly 9,000 MWH/year of avoided energy use also meant that 4 MW less of solar photovoltaic panels were required for the facility to approach net zero energy use. Capital savings on solar PV panels alone exceeded $20 million! This very large first cost savings in renewable energy equipment, which is typical for net zero or near net zero projects using DBC, is due to reduction in project capital requirements, including the cost of generating a lower amount of renewable power in addition to the building construction costs. In other words, if the facility will use less power, the renewables requirements, such as photovoltaic panels, can be reduced.

Case Study 3: UCI

A third case study concerns the University of California Irvine (UCI), which, as previously discussed, has implemented demand based control as part of its Smart Labs program in more than a dozen laboratory buildings. Figure C5 shows the results of 10 of these "Smart Lab" retrofit projects, where the average savings in electrical power was 57% and the average gas savings was 72%, for a total average non-process building energy savings of 61%. Of note is that many of these buildings were already significantly exceeding the California Energy Code even before the retrofit.

Laboratory Building		BEFORE Smart Lab Retrofit			AFTER Smart Lab Retrofit		
Name	Type[1]	Estimated Average ACH	VAV or CV	More efficient than code?	kWh Savings	Therm Savings	Total Savings
Croul Hall	P	6.6	VAV	~ 20%	48%	40%	40%
McGaugh Hall	B	9.4	CV	No	57%	66%	59%
Reines Hall	P	11.3	CV	No	67%	77%	69%
Natural Sciences 2	P,B	9.1	VAV	~20%	48%	62%	50%
Biological Sciences 3	B	9.0	VAV	~30%	45%	81%	53%
Calit2	E	6.0	VAV	~20%	46%	78%	58%
Gillespie Neurosciences	M	6.8	CV	~20%	58%	81%	70%
Sprague Hall	M	7.2	VAV	~20%	71%	83%	75%
Hewitt Hall	M	8.7	VAV	~20%	58%	77%	62%
Engineering Hall	E	8.0	VAV	~30%	59%	78%	69%
Averages		**8.2**	**VAV**	**~20%**	**57%**	**72%**	**61%**

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

Figure C5: Results of the UCI Smart Labs program, of which demand based control is a significant component.

The UCI Smart Labs program also includes other energy efficiency measures, such as sustainable lighting design, dynamic static pressure reset, and more efficient exhaust fan operation. However, DBC, which allows UCI to operate laboratories at a minimum of 4 ACH occupied and 2 ACH unoccupied vs. a previous campus average of 8.2 ACH, was estimated to be responsible for 50 to 75% of the total savings shown in Figure C5.