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Demand-Based Control of Lab Air Change Rates

By Gordon P. Sharp, Member ASHRAE

Labs and vivarium facilities typically consume large amounts of energy and have high carbon emissions[1] because of the large volumes of outside air that are conditioned, supplied to, and exhausted from these facilities. With many modern laboratories operating with fewer fume hoods and more energy-efficient equipment and lighting,[2,3] the labs' minimum air exchange rate requirement is often the dominant energy use driver. Achieving the safe reduction or variation of air change rates in labs and vivariums can represent the greatest single approach for reducing their energy consumption and carbon footprint.

Unfortunately, little objective data has been available on the environmental and energy savings impact of safely reducing and controlling air change rates in labs and vivariums. This article attempts to address this data gap with the results of a major research study that generated a significant amount of objective data on the indoor environmental quality (IEQ) conditions of labs and vivariums that are using a dynamic or demand-based control approach to lower air change rates.

Before reviewing this study, it is important to first understand how air changes can be safely reduced in labs and vivariums. One successful approach[4] is by dynamically varying air change rates with a demand-based concept that uses the air quality level or "air cleanliness" of the lab or animal room to control its air changes or minimum dilution ventilation airflow.

As noted earlier, in a majority of labs and vivariums, the airflow often is dictated by the minimum air change rate for the space, which might be up to 12 ach in

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a lab room or up to 20 ach in a vivarium. Although high thermal loads or the heavy use of fume hoods or high density animal racks also can drive a room's airflow, often it is the minimum ventilation rate that determines the airflow.[5]

The purpose of this minimum ventilation rate is for rapidly clearing the lab room of fugitive emissions, lab spills and vapors generated by bench top lab work. The dilution ventilation provided by this airflow is no substitute for the containment performance of a laboratory fume hood or other local containment devices. Any work with hazardous chemicals should be done in a fume hood or other containment device no matter the room ventilation rate. Additionally, when it comes to determining the "right" ventilation rate level for clearing a room of fugitive emissions or spills, no single correct value exists for all situations. Instead, the airflow amount required to rapidly clear the room after an event or release of chemical vapors varies significantly based on the amount of the release, the chemical's evaporation rate, and the level of hazard of the chemical.

In general, increased airflow rates generate a significantly greater impact on clearing a lab room after a chemical vapor release, at least for airflow rates below about 15 ach. For example, one recent CFD study presented at the 2009 ASHRAE Winter Conference showed a greater than 10-to-1 reduction in lab room background concentrations resulted from increasing the air change rate in a lab from 4 ach to 8 ach.[6] Another study[5] at Yale University (where lab spills were performed with room air change rates from 6 to 16 ach) similarly concluded that, "The greatest relative improvements in room air quality (both in chemical concentration and clearance time) occurred between about 6 and 8 ach, with diminishing returns beyond about 12 ach…." This information supports the contention that lowering a fixed minimum air change rate to save energy from, for example, 8 ach to 4 ach or even to 6 ach, can have a significant impact on the efficacy of clearing the lab room air of contaminants and may not be a prudent approach for many labs.

Another approach that has been proposed to save energy in labs with respect to lowering air change rates is to reduce the minimum air change rate during nighttime or unoccupied periods. The reasoning behind this is that if no one is in the lab then it is less likely to have vapors in the lab room air. Additionally, even if vapors are in the air, no one will be in the room to be exposed. However, there are potential issues with this reasoning. First, chemicals typically are stored in the lab, and lab operations are conducted 24 hours a day in hoods or even on the bench top using various equipment and apparatus that may emit contaminants at any time. As a result, although with less frequency than during occupied hours, fugitive vapors and lab room air contaminants can still build up and become present during unoccupied times. Although not studied in detail, data from the study described later in this article clearly showed chemical and particle releases occurring in many labs at all times of the day and night.

Additionally, the reasoning behind unoccupied times equating to no personal exposure has potential problems as well. For example, occupancy sensors can be used to detect when someone returns to the lab room to immediately increase the air change rate. However, even when increasing room airflow to an occupied air change rate of 8 ach, a lab room with typical ventilation effectiveness and air distribution can still take over an hour or more to significantly reduce the ambient contaminant levels. As a result, during this initial occupancy time the lab room occupant will be exposed to potential lab air contaminants.

A different approach to saving energy in labs that solves these aforementioned problems and has been shown to effectively and safely reduce air change rates in labs and vivariums is a demand based approach that directly senses the quality of the air for such contaminants as volatile organic compounds (VOCs), ammonia, other sensed chemical vapors, and particulates. When the level of contaminants sensed in the room air is below a given threshold, indicative as noted below of "clean" conditions, then the air change rate in a lab room can be reduced. In other words, when the lab air quality is already very good, there is no reason to dilute clean air with more clean air.

For example, in a "clean" lab the ach rates can be reduced to between 4 and 2 ach during the day and 2 ach at night (when thermal loads are less and temperature control is less important), and for vivariums to 6 ach or potentially lower. When contaminants are sensed above the threshold, higher dilution ventilation levels can be used proportionally, such as up to 15 ach. The ability, when needed, to use higher dilution ventilation rates instead of the typical minimum ventilation rates, also can help increase the safety of the lab versus using fixed lower minimum ach rates blindly. Rather than flush the room with a moderate amount of air all of the time, this concept only increases the quantity of dilution ventilation to potentially higher levels based on whether there are contaminants to flush out or dilute.

Additionally, the information that becomes available from this approach on which labs are commonly having releases or fugitive emissions also can be used to understand and improve equipment operation and lab practices to eliminate contaminants through better source control. If there is occasionally an undetectable contaminant in the lab room air, however, since the far majority of commonly present contaminants are sensed, this concept will still deliver, on average, greater dilution air to the lab when contaminants are present.

This demand-based approach to dilution ventilation typically operates with a variable air volume lab airflow control system set to a low minimum airflow of between 2 to 4 ach. The control system typically overrides this low minimum flow based on fume hood makeup air requirements, cooling load requirements, or the previously mentioned IEQ-based minimum ventilation override signal.

The contaminant thresholds at which the dilution ventilation rate begins increasing and the levels to which the ventilation are commanded can be set based on the particular requirements of the lab. However, typical values for a total VOC (TVOC) threshold are about 0.2 ppm based on using a PID or photoionization detector type of TVOC sensor. The basis for this 0.2 ppm minimum threshold level is that it is approximately the average limit value for the LEED-NC (New Construction)

EQ 3.2 credit for flush-out of an office building after construction, which is based on certain EPA and Washington state requirements. This is a conservative threshold when used with labs for control of air changes since the study data in this article shows primarily infrequent short-term exposures of VOC events versus a constant level of VOCs from off-gassing of construction materials.

Typical values for the particle level threshold are about 1 million pcf or particles per cubic foot (35.3 million particles/m^3), and similarly this particle requirement was also set with guidance from the LEED EQ 3.2 credit's average value threshold for flush-out after construction, which is about 1.6 million pcf (56.5 million particles/m^3). Setting the minimum control threshold level at 1 million pcf (35.3 million particles/m^3), again provides a slightly more conservative threshold level for the lab ach control approach.

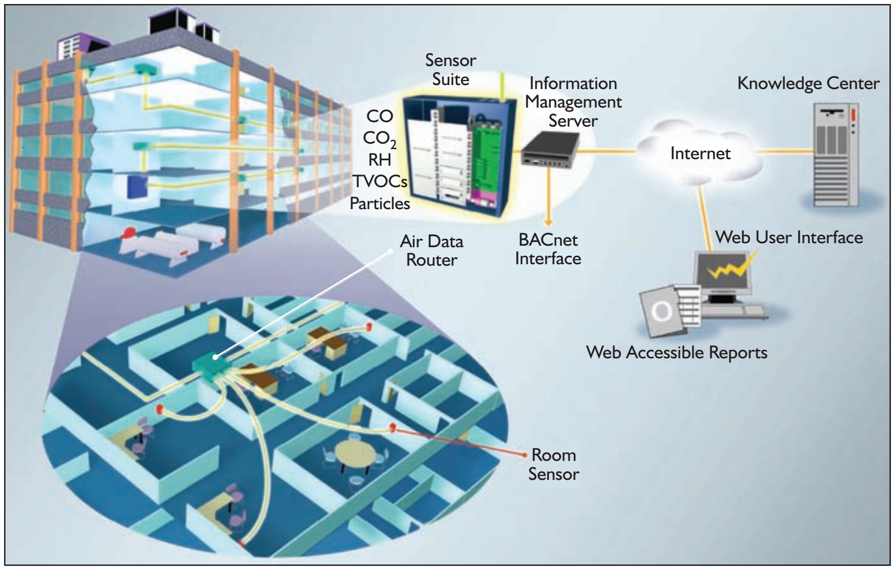

Figure 1: Facility-wide multiplexed sensing architecture.

One approach to economically and reliably sense environmental conditions in many labs and vivarium rooms of a facility is to use a novel sensing architecture known as multiplexed sensing. With this approach, one central set of sensors is used in a multiplexed fashion to sense not one but many different rooms or areas. Instead of placing multiple sensors in each room, this networked system routes packets, or samples of air, sequentially in a multiplexed fashion to a shared set of sensors.

Every 40 to 50 seconds a sample of air from different areas is routed through a common air sampling backbone consisting of a hollow structured cable to the centralized set of sensors (known as a sensor suite) for measurement. These sequential measurements are then "de-multiplexed" for each sampled area to create distinct sensor signals that can be used for monitoring and control. Typically, 15 to 20 areas can be sampled with one set of sensors approximately every 15 minutes, which theoretical and empirical spill testing[7] has shown meets the time requirements for the safe, demand-based control of these spaces.

This multiplexed sensing approach (*Figure 1*) can measure many different air parameters. For laboratories, the use of a PID type of TVOC sensor is beneficial for accurately detecting hundreds of commonly used laboratory chemicals that can volatize and become a safety concern. Additionally, other nonorganic compounds (such as ammonia, which is of interest in vivarium rooms) can be detected with a PID sensor. Other TVOC sensors such as metal oxide (MOS) sensors are used in addition to the PID sensor for broader detection of chemical contaminants. Combining these sensors with a laser-based particle counter allows the identification of particles, which can be used as a proxy for animal allergens in a vivarium, as well as for detecting aerosol vapors and smoke particles in a lab room. Carbon dioxide sensors and accurate dew-point or humidity sensors also can be used to sense the lab and vivarium rooms for other control and monitoring purposes.

Methodology of the Study and Data Analysis

In addition to being used for control purposes, the multiplexed sensing system of *Figure 1* also sends its sensing data to a password-protected Web site to be archived and made available for review and analysis purposes by facilities and other qualified personnel. One use of this information is to assess the environmental and energy savings impact of demand-based control of air changes in a specific facility. To get a broader view of the efficacy of this concept across not just one, but many facilities, a comprehensive research study was undertaken to analyze the archived data from many different lab and vivarium sites.

This study was conducted using environmental data from 18 different lab and vivarium sites across the U.S. and Canada. Of these sites, six were from the East Coast, seven from the Central U.S., three from the West Coast, and two from Canada. These sites consisted primarily of life sciences and biology-related areas, as well as a smaller amount of chemistry and physical sciences lab areas. Three of the above sites involved animal facilities that were broken out as a separate group. Almost all of the lab facilities involved spaces with a moderate or low density of fume hoods. In total, more than 300 lab and vivarium rooms were involved in the study, representing a large cross-section of different lab room environments.

Approximately 1.5 million operating hours of lab data and about 100,000 hours of vivarium data were analyzed. If only one lab room was studied versus more than 300, the number of operating hours would have spanned over 18 decades. The data from the various sites was for different lengths of time depending on when the site came online. Data was analyzed for lab operation in a range starting in the early fall of 2006 and continuing until early January 2009. In total, more than 20 million sensor values were collected and analyzed including data on TVOCs, particles of a size range of 0.3 to 2.5 microns, carbon dioxide, and dew point (absolute humidity). This article will focus only on the data collected on TVOCs and particulates since this data is most directly related to the demand-based control of air change rates.

For particles and TVOCs, most measurements were taken as differential measurements of the room conditions compared to the environmental conditions of the supply air feeding the lab or vivarium. This was done to significantly reduce potential effects of any sensor drift, as well as to subtract out any impact of the outdoor conditions on the measured room conditions. Since all measurements were taken using a multiplexed sensing system, the measurements of the room conditions and the supply air feeding these rooms were taken with the same sensor, thereby creating very accurate differential measurements.

To simplify the analysis, all sensor data was placed into bins representing the number of counts or times that a parameter exceeded a specific threshold level corresponding to that bin. The data was then normalized based on the total number of data points or counts to generate the percent of time the data exceeded the bin value thresholds. A cumulative graph was created showing the percent of time that each bin value was exceeded.

Regarding the average air change rates of the labs involved, generally the typical "clean" or minimum rate was between 2 and 6 air changes based on the specific site involved. When significant levels of TVOCs or particles were sensed, the commanded purge rates of airflow typically were between 12 and 16 ach based on the site involved. Regarding the vivariums, the reduced flow rates varied between 6 and 10 ach when the rooms were sensed to be clean and the commanded purge rates, when significant contaminants were sensed, varied between 15 and 20 ach. Note that airflow rates higher than the minimum flow rates mentioned previously may have also occurred occasionally, even if the lab rooms were clean due to VAV fume hoods that may have been opened or cooling loads that demanded additional airflow.

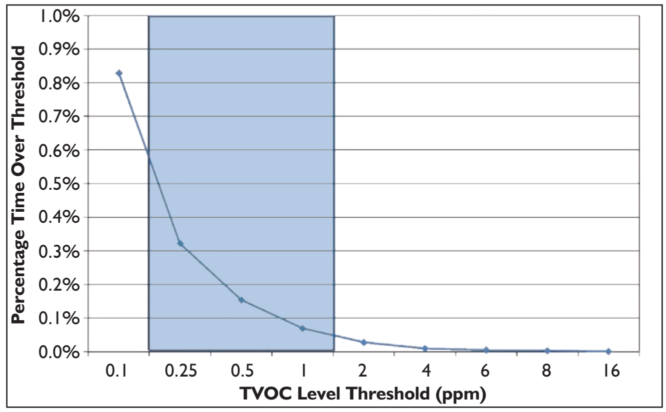

Figure 2: Average TVOC level percentages over threshold (1.5 million hours of lab operation).

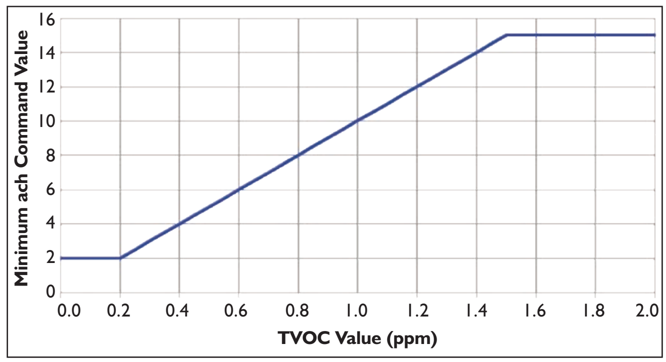

Figure 3: Typical control relationship between TVOC values and commanded airflow.

Review of the Lab Room Data

Figure 2 shows a graph of the average TVOC levels over all of the lab locations representing about 1.5 million hours of operating data. As mentioned previously, this is a cumulative graph so that the value of 0.84% at 0.10 ppm means that, on average, this is the amount of time that a lab location has a TVOC value greater than or equal to 0.1 ppm. 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 highlighted blue area on the graph in *Figure 2* represents a typical set of values for where the dynamic control of air changes operates in a proportional control fashion. For the indicated example, below about 0.2 ppm, there is no override of the room airflow. At 0.2 ppm and above, the override of the minimum air change rate starts to occur with a maximum command value of 15 ach reached when the sensed TVOC value reaches 1.5 ppm. This typical control relationship between the sensed TVOC values in a room versus the generated command for the minimum ventilation rate is shown in *Figure 3*.

As can be seen in *Figure 2*, labs are, on average, typically clean of most chemical contaminants more than 99% of the time at least to a background level of less than about 0.2 ppm. This means that energy can be saved by using a reduced minimum air change rate of down to 2 ach for more than 99% of the time in labs with respect to at least the TVOC sensor.

Looking at this same data in another light, *Figure 4* takes the data of *Figure 2* and displays it in terms of approximately how many TVOC events occur in an average week in one of the lab room locations. Most TVOC events where chemical vapors are sensed in a lab room typically vary in duration from about 15 minutes to 90 minutes, although the more common small events are often 15 to 30 minutes long. For the purposes of the graph, the total amount of time that the average TVOC event lasts was assumed to be 15 minutes. For events over about 0.2 ppm, there are about four of these events or about one hour of total time per week, on average, that the TVOC sensor senses over 0.2 ppm.

Based on this data and a lab building with 50 lab rooms, on average, there may be events occurring almost every hour of at least the occupied and potentially some part of the unoccupied schedule somewhere in the building. This provides further evidence for the relatively common need to use higher airflow

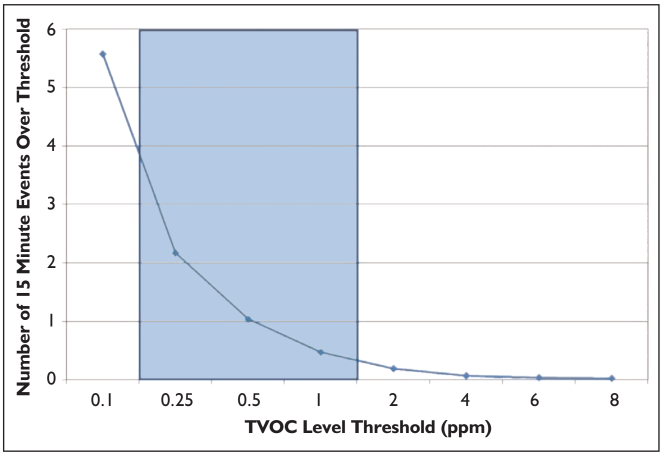

***Figure 4:** Number of short TVOC events per week for an average lab area.*

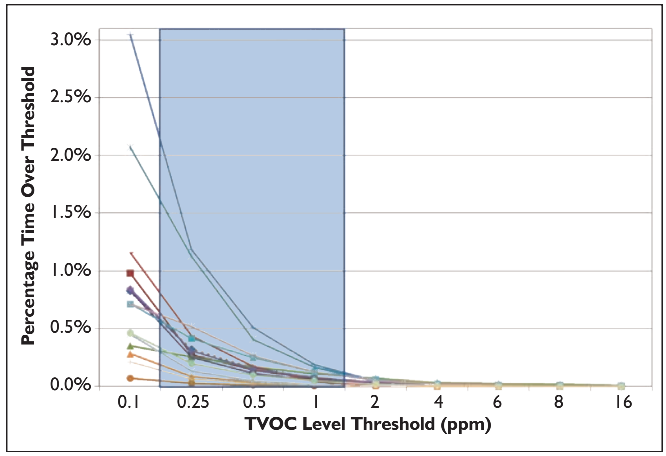

***Figure 5:** Average TVOC level percentages for multiple lab sites (1.5 million lab hours).*

rates to purge the rooms during these events versus trying to use a fixed, but likely lower ach rate that may not be as effective during these events.

To show the variations in this data between different sites, *Figure 5* shows the same TVOC graph but with each of the lab sites shown as a separate line with the average curve shown by the black dotted line. Note that even at the site with the greatest amount of TVOC activity, the dynamic control concept can still save energy about 98% of the time with almost four hours of time during which the minimum room ach rate is increased to safely respond to TVOC-based events.

Another parameter that can cause an increase in the minimum air change rate is an increase in particles in the lab due to a reaction that may go out of control or an acid spill that causes

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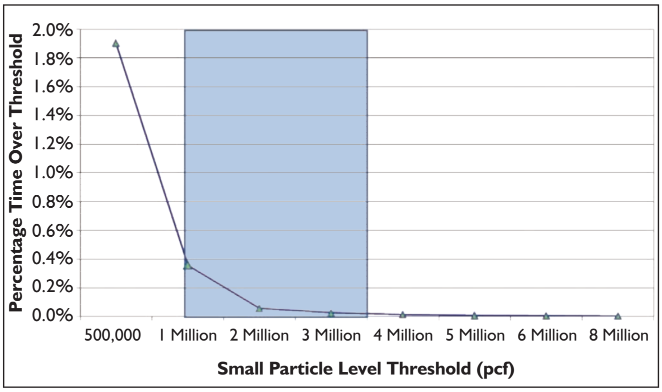

Figure 6: Percentage of time that small particle levels exceed threshold (1.5 million lab hours).

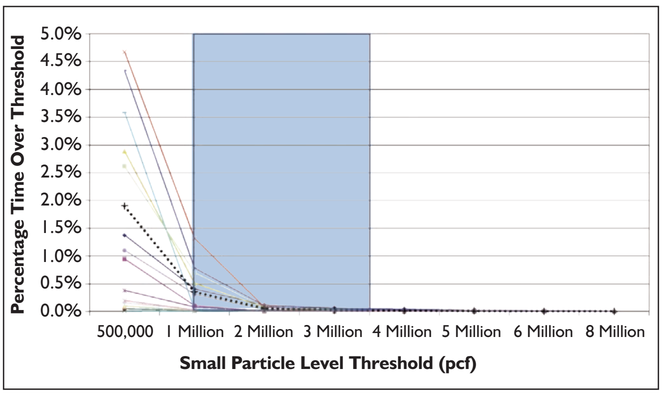

Figure 7: Small particles graph for multiple lab sites (1.5 million operating hours).

an evolution of smoke or an aerosol into the lab room. *Figure 6* shows a graph of the average level of 0.3 to 2.5 micron particles that exceeds a background level of the lab room's supply air. Typically, about 1 million pcf is used as the threshold for increasing the minimum air change rate.

As can be seen in *Figure 6*, the average lab room is above the 1 million pcf threshold about 0.4% of the time or about 30 minutes a week on average. If this amount of time is added to the average amount of time that TVOCs are above the control threshold, this comes to a total of about 1.0% of the time. Thus, the labs can be operated at the lowest minimum flow, on average, about 99% of the time taking into account both TVOC and particles.

To provide more detail on the variation in particle data across sites, *Figure 7* shows the same data but with the individual sites represented by separate lines. The average value across all sites is shown as the black dotted line for reference. This data shows a similar level of variation compared to the TVOC data. Both sets of data show about a 3-to-1 variation between the average site and the worst case site measured. Based on this data, even if the worst-case site for particles and TVOCs were the same site, this site would still operate at the lowest minimum ach rate about 96.5% of the time. The average lab room's minimum ach rate would then need to be increased for almost six hours a week to help maintain safe lab conditions. Note that individual room data can show even greater variations resulting in rooms with higher

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percentages of time when purge airflows are needed. However, these rooms will be balanced out across a site by other rooms that have less activity.

Review of the Vivarium Room Data

For vivariums, a smaller, more preliminary set of data was collected on three sites that potentially had near worst-case conditions for demand-based control of air changes. These consisted of one site with open, unventilated rodent cages, another with ventilated rodent cages that were exhausted into the vivarium room, and a site with nonhuman primates (NHP) housed in open cages. The total data of these three sites consists of about 100,000 operating hours.

Figure 8 shows the individual TVOC data for the three sites. As might be expected, the highest TVOC levels were for the rodents in the nonventilated cage racks. Interestingly, the NHP rooms were the cleanest in terms of TVOCs and ammonia. Note that the multiplexed sensing system and PID TVOC sensor is calibrated with isobutylene and responds to ammonia with a response factor or effective calibration constant of between about 10 to 20. With respect to sensing just ammonia, if the PID TVOC sensor reads a value of 1 ppm, this would equal an actual ammonia level in the animal room of between about 10 to 20 ppm. A typical control range for vivariums would range from about 0.4 ppm to 1 ppm corresponding to a command for about 6 ach and 15 ach, respectively. This shows the opportunity to save energy in these vivariums is high, with the worst site of the study, the non-ventilated rodent cages potentially requiring extra airflow on average only 1.5% of the time, at least based on TVOC levels seen in this study.

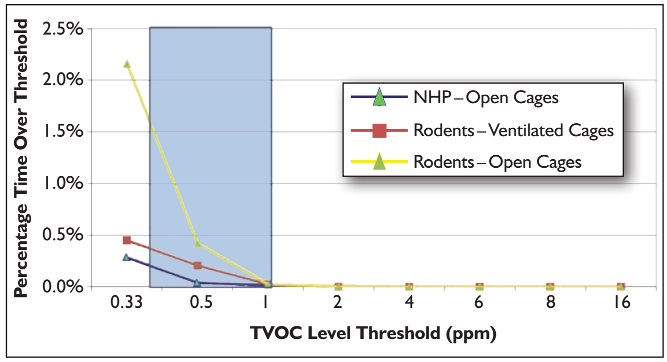

Figure 8:** **Average TVOC level percentages for multiple vivarium sites (100,000 hours).

Specific TVOC data for a few of the rooms with rodents in nonventilated cages is shown in *Figure 9*. The difference between the blue supply air line and the red, green and black room TVOC lines represents the TVOC/ammonia levels in those rooms created by the animals. (Note that the nonzero supply

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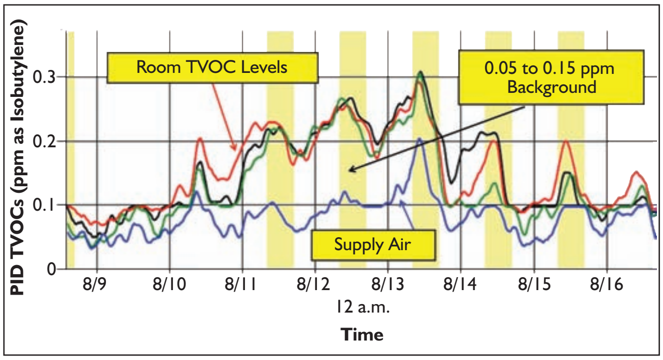

Figure 9: Typical background TVOC/ammonia levels for nonventilated rodent cage rooms. (The figure shows one week during the period between July 30 and Sept. 2, 2008.)

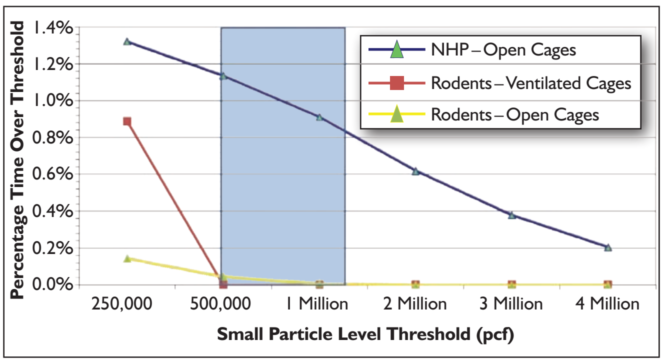

Figure 10: Percentage of time that particles exceed threshold for multiple vivariums (100,000 hours).

levels in this graph indicate system and sensor background levels, not outside air entrainment.)

The gradually increasing TVOC/ammonia level in these rooms starting at about August 9 followed by a decrease in the levels at about August 14 and 15 shows the increase in TVOC and ammonia levels between cage changes. If the increase with respect to the supply air levels was solely related to ammonia, this might correspond to a variation in the sensed ammonia levels in the room exhaust of up to about 1.5 to 3 ppm.

The next set of data shown in *Figure 10* is for particles across the different vivarium sites. Overall, the average levels are low for all cases at no more than about 1.2% for the NHP rooms, so the ability to reduce air changes when the air is clean and has low levels of particulates occurs about 99% or more of the time on average, providing a significant opportunity for energy savings from lower air change rates.

Figure 11 shows some of the specific site data from the nonhuman primate rooms that points out the reason for the high particle levels in this facility. Note how the indicated particles spikes match up in time and in room location (different colors) with the large dew-point/humidity spikes. This information indicates that the cages were being cleaned during these periods, throwing a lot of particulates into the air as a result. Automatically increasing the air change rates during the cage cleaning process helps keeps particle levels lower and clears the room more quickly of excess particles, animal dander/allergens and moisture. Additionally,

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this also allows lower air change rates for the majority of time that the cages are not being cleaned.

Summary and Conclusions

The largest and most comprehensive study to date of the impact of demand based control of air change rates on lab and vivarium IEQ conditions and energy savings was completed in January 2009. This study involved about 1.6 million operating hours of recorded data representing more than 20 million sensor values from more than 300 lab spaces and 18 sites. For laboratories, on average, the lab IEQ conditions of low TVOCs and low particulates permitted the substantial reduction of minimum air change rates approximately 99% of the time.

Across the sites reviewed, the average laboratory room saw about 1.5 hours a week of IEQ conditions that required increasing the room airflow from its minimum value. There was some significant variability across sites with the worst-case sites for TVOCs and particles having about three times the average of all the sites. As such, the worst-case sites saw conditions requiring increased flow on average of about four hours a week per each lab room.

For the three types of vivariums studied, similar to labs, the IEQ conditions of low TVOC and particulate levels occurred about 98.5% of the time or less, safely allowing for substantial energy savings for all but about 2.5 hours a week when higher flows were required.

With the current challenges many organizations are facing concerning reducing their carbon footprint and their use of energy, this study provides ample evidence of the significant contribution that the demand-based variation of lab and vivarium air change rates can make towards safely meeting these goals.

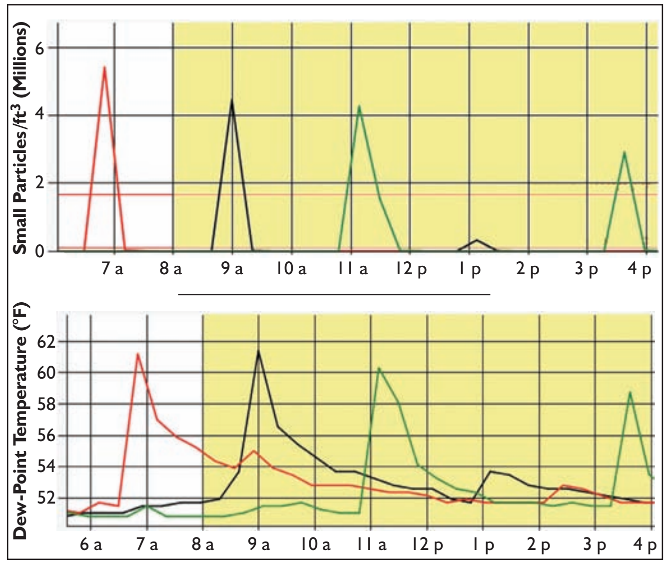

Figure 11: Impact of NHP cage cleaning on room particle and dew-point/humidity levels. Data recorded on September 8.

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