

Indoor Air Quality, Energy Consumption and Building Performance: Leveraging Technology to Improve All Three

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ABSTRACT:

Building owners and occupants expect more from their buildings today – both better indoor air quality (IAQ) and less energy consumption. Many facilities strive to design and commission a ‘smart building’ – one that is healthy, environmentally conscious and operating in the most efficient way possible. However, maintaining optimum IAQ often seems to be in conflict with minimizing operating and energy costs. Conventional wisdom says the best IAQ strategy involves increasing ventilation rates. But outdoor air comes with a cost. Even with the use of heat recovery, outdoor air must be heated, cooled and dehumidified, which can cost \$2-\$4/cfm/yr. Further, increased ventilation is not always the best choice from an IAQ standpoint either. In most urban and even many suburban locations, outdoor air is actually far more polluted than indoor air. Appropriate application of air cleaning technologies and monitoring can allow many buildings to achieve both improved IAQ and lower operating costs.

INCREASING EXPECTATIONS

The function of buildings today is to provide a controlled indoor environment. If we could do things like teach school, trade stocks, and make computer chips outside in the rain, snow and sunshine, we would, and save ourselves the expense of making buildings (or at least putting walls in them). The expectations of what is considered an acceptable indoor environment have continued to increase. For millennia, it was just a fire to keep from freezing in the winter. Then roofs and walls were added to keep out sun, wind, and rain. In the middle of the last century, air conditioning was invented and is now in virtually every new building in the developed world. But still, until fairly recently, indoor air quality (IAQ) was really primarily about temperature control and comfort. Now, however, for a variety of reasons, building occupants expect that their air will not only be the proper temperature and humidity but will also be free of dangerous contaminants. And yet, outside of specialized settings, most IAQ measures are prescriptive rather than based on

actual conditions. This can result not only in poor IAQ, but also needlessly high energy consumption and operating costs. However, the technological pieces are all in place to design buildings that deliver optimum IAQ at minimum operating costs and to actually measure IAQ rather than base it on a set of assumptions that may or may not be true. The following paper discusses some of these technologies and strategies.

IAQ: A BRIEF OVERVIEW

In a paper discussing various strategies for achieving IAQ, it is important to define what IAQ is. ASHRAE Standard 62.1 2010 says:

acceptable indoor air quality: air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction.

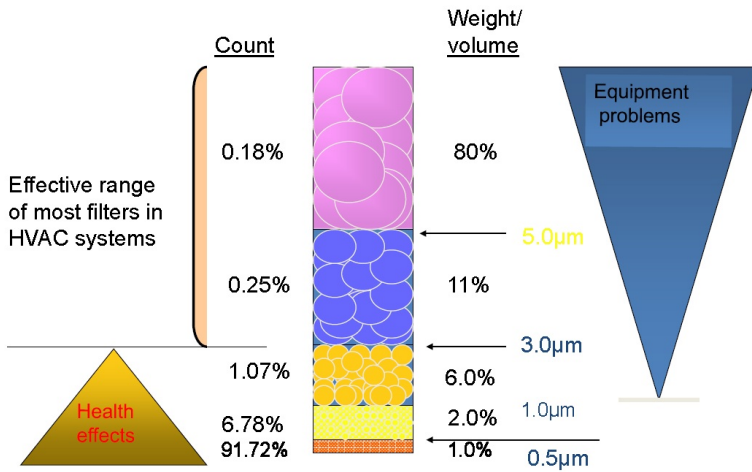
That would seem to be a reasonable starting point.

There are three major food groups of indoor contaminants: particle, biological and gas phase. All three have sources both inside and outside of buildings. The elimination of smoking from virtually all buildings has significantly decreased the generation of contaminants and particles in buildings. That said, pretty much everything we do in a building impacts the air quality in one way or another. Similarly, everything that happens outside a building also impacts the IAQ.

Particles range from the very small to very large. Particles are typically measured in microns; a micron is one 25,000th of an inch. A human hair is about 150µm; the smallest thing that we can see is about 10 µm; ultrafine particulate from combustion processes smaller than 0.1 µm. There is an inverse relationship between count and size. By weight and volume, over 95% of what’s in the air is bigger than 3.0 µm. By count, over 95% of what’s in the air is smaller than 0.5 µm.

Historically, most filters were in most HVAC systems to capture the larger particles that form visible dust, can build up in duct work and on coils and affect heat transfer. However, from a health standpoint, it is the submicron particles that matter. They can bypass the respiratory system’s defenses and be drawn deeply into the lungs.

Typical Atmospheric Dust Sample



There are a myriad of sources of particles in buildings, from both indoors and outdoors. From inside the building, there are ceiling tiles, carpet fibers, clothing fibers, copy machines, printers, etc. And from the outside there are things like vehicle exhaust, mold spores, pollen, and atmospheric dust. Again it is the smaller particles, and in particular the ultra-fines, that are generally of greater concern from a health standpoint. The primary sources of these are combustion processes, especially combustion of diesel fuel and other hydrocarbons, and are typically outside the building.

Biological contaminants also range in size and source. There are three primary categories here: molds, bacteria, and viruses. Mold spores are ubiquitous and tend to be fairly large, 3.0 to 5.0 μm in diameter. The primary source of these is outdoor air. The challenge in a building is to not have circumstances (moisture and food) that allow mold spores to get a foothold. Nor should the HVAC system become a means of distribution. Bacteria

comes in a range of sizes but tends to be from 0.5 μm to about 2.5 μm . There are a variety of sources of bacteria, but people are a major contributor. Viruses can be extremely small, 0.02- μm to 0.3 μm in diameter. However, as a practical matter, they tend to be attached to larger formations. Here again the primary sources of viruses are typically people.

Reactive gas phase contaminants come from furnishings, paints, perfume, vehicles, kitchen exhaust, and a wide range of other sources. With the banning of smoking and the move towards low emitting furnishings and finishes, it is interesting to note that some of the major indoor sources of gas phase contaminants are cleaning products.

To achieve acceptable IAQ, all three categories of contaminants must be dealt with and controlled.

Contaminant Control

The three basic tools for dealing with indoor contaminants are:

- 1) source elimination/exhaust,
- 2) dilution, and
- 3) air cleaning.

All three should be employed to the extent practical.

Obvious examples of number one are the banning of smoking and exhaust fans in kitchens and bathrooms. But this can only take you so far in that most sources are not so easily identified and dealt with.

“Dilution is the solution to pollution”. While this has become the mantra and guiding principle of many for achieving IAQ, most do not realize that the origin of the phrase was actually the black humor of big industry, i.e. dump pollution in the ocean where concentrations will rapidly dissipate. Regardless, the concept of replacing relatively dirty air with relatively clean air is a sound one. Problems arise when the “clean” air is not clean.

Air cleaning systems exist that can remove virtually any contaminant to any concentration desired. It is not that we do not know how to clean air, we do. It is more that no one thought it was necessary in other than specialized situations. The other challenge is in identifying what

contaminants are present and what levels are acceptable. However, when properly employed, air cleaning can be an extremely effective and cost-effective means of achieving IAQ.

From an air cleaning perspective, both biologicals and particles are a subset of particles, both are solid things in the airstream. Gas phase contaminants can be removed a number of ways. Many are adsorbed onto the surface of ultra-fine particles.

Professor Gunter Oberdorster in various studies has found that important characteristics of UFPs include a high pulmonary deposition efficiency, magnitudes higher particle number concentration than larger particles, and thus a much higher surface area. The UFPs surface can carry large amounts of adsorbed or condensed toxic air pollutants (oxidant gases, organic compounds, transition metals). Removing the ultra-fines from the air will remove the gas phase toxins as well.

High levels of gas phase contaminants can be removed from the airstream with adsorptive or chemisorptive technologies where required.

AIR CLEANING TECHNOLOGIES: AN OVERVIEW

Passive filters

This is an oversimplification for the sake of brevity, but passive filters are essentially sieves: the smaller the holes in the media, the more efficient the filter is. The trade-off is efficiency for resistance to airflow. Therefore, as passive filters get more efficient, they also get bigger with deeper beds of pleated media. Passive filters are by far the most common technology in use in buildings today. They come in a range of efficiencies, from \$1.98 furnace filters that keep leaves off the coil to \$400 ULPA filters in Class 1 clean rooms. As passive filters load with contaminants, they increase in efficiency (to a point) and also in resistance to airflow. When the filter is dirty, it is changed and thrown away.

Passive electrostatic filters are a variation of passive filter where the fibers of the media have a slight static charge imparted on them in production. This gives them initially a better efficiency than they would have based on the density of the media and therefore a lower resistance to airflow v. a purely passive filter. However, with time, humidity, loading and other factors, the passive charge dissipates and efficiencies can drop significantly.

In North America and other places, passive filters are tested using the AHSRAE Standard 52.2 which yields the MERV ratings. There are a few considerations to be noted when applying and using passive filters:

1) Until a MERV rating of 14 or higher, sub-micron removal performance and efficiency is not taken into account.

2) Loading: Loading is a critical aspect of ongoing performance and cost, i.e. how long will a filter last and how much energy will it use. Because loading was for a few years not part of the 52.2 test per se, many manufacturers did not report loading data. This has resulted in MERV 13 filters, for example, with very shallow beds (2" - 4") that in operation will last a matter of weeks before they need to be replaced. (Ironically, these are typically targeted for use in LEED projects.) A typical deep-bed passive filter will last 6-12 months before it needs to be changed.

3) Seal: Holes and gaps in filter banks and ductwork can result in far worse performance than anticipated.

4) Over 90% of the cost filtration is the energy to push air through the filter, the labor to change it, and its disposal. It is not the cost of the filter itself.

Electrostatic Precipitators

Electrostatic precipitators (ESPs) do not work at all by the density of a media, rather they rely solely on electrostatic attraction: the principle that opposite charges attract. ESPs typically have an ionizing section wherein a high DC voltage (~10+kV) is applied to an array of thin wires or sharp points. This creates a corona spray of ions that attach themselves to particles in the air, giving them a charge. Downstream of the ionizing section there are collection plates that are charged in the opposite polarity of the particles. The positive (e.g.) particle is attracted to the negative plate and deposits on it. ESPs have very low resistance to airflow, (you could roll a quarter through one), but they are extremely effective at capturing small particles when clean. However, as ESPs load, their efficiency drops, eventually to the point where there is no effect at all. This can happen quickly in a very dirty environment. In an HVAC setting, this can cause problems: charged particles will also want to stick to grounded surfaces such as walls, ceilings, people, and ductwork. The collection plates must then be cleaned with strong chemicals. Because of the efficiency loss, the need for

cleaning, and the fact that they generate Ozone as a byproduct of the ionization process, ESPs are rarely used in HVAC applications at this point. They are widely and effectively used in industrial applications, where there is room for large collection plates and automatic spray washing systems.

Non-Ionizing, Active-Field Polarized Media

This technology combines elements of both passive filters and ESPs. Polarized media air cleaners utilize an active high DC voltage to create an electrostatic field inside a disposable media pad. There is no ionization or charging of particles and no Ozone production. Rather the field reorganizes and polarizes the surface charge of the fibers of the media pad, giving each a negative side and a positive side. As particles enter the air cleaner and the field, they too become polarized. The particles are then drawn to the fibers of the media pad. The polarized particles are also attracted to each other, agglomerating and forming larger groupings. The advantages of polarized media are:

- a better efficiency than the density of the media alone would yield (and therefore a lower resistance to airflow). This not only saves energy on fan horsepower but also can allow for use on smaller types of equipment (e.g. VRF and fan coils) that cannot handle high pressure drops
- a superior loading profile. The particles will load uniformly around the entire diameter of the fibers versus primarily on the upstream side, as with a purely passive filter. This yields a maintenance cycle that be as long as a few years.
- no loss in efficiency with loading
- a superior ability to capture ultrafine particles. Ultra fine particles tend to move somewhat randomly in the airstream. By polarizing the surface charge of the larger particles, it makes them, in essence, stickier to the ultra fine particles.
- a proven ability to reduce gas phase contaminants that have adsorbed onto the surface of the smaller particulate. Typically this can reduce ambient VOC levels by 40-90%.

Carbon and Specialty Media for Gas Phase Removal

In applications with harmful or nuisance levels of gas phase contaminants, activated carbon can be used alone (in various types) or in conjunction with

other medias (e.g. potassium permanganate) to effectively remove virtually any contaminant at virtually any concentration. While this is an old and proven methodology, high operating costs (due to increased static pressure and media replacement) make this practical generally in only industrial and other high-impact settings. However, there have been some recent developments in creating carbon/ceramic honeycomb materials that have proven effective with far lower static (no need for a post filter) and a longer service life.

UVC

Ultra-Violet light at 254 nm wavelength (UVC) will inactivate biological contaminants. Since UVC requires contact time and intensity to work, care must be taken in the application of UVC to make it effective. However, UVC can be successfully applied to a range of applications where airborne biologicals are a concern.

Photocatalytic Oxidation (PCO)

PCO is a promising technology for reduction and destruction of VOCs. UV light is used to activate a catalyst (typically titanium dioxide) creating hydroxyl radicals. These react with gas phase contaminants and over time break them down to carbon dioxide and water vapor. PCO is not a single pass technology: upstream/downstream reductions are relatively small. However, since in most HVAC applications, the same air will be seen again and again, PCO has proven effective at reducing ambient levels of gas phase contaminants in non-critical environments.

General Application Principles

The above panoply of air cleaning technologies is not meant to be exhaustive or deep. Its purpose is to show that there is a range of technologies that can be brought to bear in a given application to clean the air. We can create Class 1 cleanrooms; we can create odor-free areas in the middle of a sewage treatment plant. We know how to clean air. Air cleaning is a about having a contaminant removal rate that is greater than the generation rate. This boils down to identifying contaminant strengths and sources, air cleaner efficiencies, air change rates (re-circulated air), air exchange rates (outdoor air), and airflow patterns.

Generally, the biggest challenge with the application of air cleaning is knowing what the "challenge levels" are. People are often certain of what the desired outcome is, i.e. the maximum

allowable levels of certain compounds, but they rarely know what the challenge levels are. Filter efficiency, whether particle or gas phase, is fairly constant, challenge levels, however, are not. Contaminant levels can vary by factors of 10 routinely and factors of 100 not infrequently. This is particularly true of outdoor sources: ambient outdoor particle levels vary widely with wind direction and proximity to sources. Further, there can be significant micro-bursts from things like diesel generators, buses, helicopter and kitchen exhausts. The obvious (but often overlooked) point being that downstream levels will vary with upstream levels: 95% of 100 is different than 95% of 10,000. One of the best specifications that I have seen came from a museum application in Singapore: it called for two weeks of monitoring at the proposed site and to design a system based on the maximum levels found.

THE UNDERUTILIZED ROLE OF MONITORING

Technology for direct monitoring and measurement of IAQ parameters and contaminants is now readily available and reliable. Its use in actual buildings curiously lags behind. From an IAQ standpoint most buildings are designed like an HVAC system with no thermostat. There is rarely any actual data collected. Demand control ventilation with CO₂ sensors is a bit of an exception and one way sensors are becoming more widely used. But CO₂ is really an indirect measurement of IAQ. CO₂ is not a contaminant of concern in and of itself, rather it is an indicator of human occupancy and from that we infer a certain contaminant level.

ASHRAE 62.1 Addendum f:

“ASHRAE Standard 62-1989 has contributed to several misunderstandings regarding the significance of indoor carbon dioxide levels. The standard previously led many users to conclude that CO₂ was itself a comprehensive indicator of indoor air quality and a contaminant with its own health impacts, rather than simply a useful indicator of the concentration of human bio-effluents.”

The CO₂ levels will be the same in a space if the occupants are sitting at their desks typing or sitting at their desks pouring toluene onto rags and laying them on the floor. Obviously, there is very different IAQ in the two situations. Similarly, besides occupancy, outdoor air levels are typically varied with the temperature rather than the quality of the air. The Economizer does not know if there

is a bus idling under the outdoor air intake, it is told that the outdoor air is the right temperature and it should open up.

And yet we can monitor broadly (Total VOCs) or narrowly (toluene, e.g.) and anywhere in between. We rarely do this in other than specialized applications. Though it would seem to make sense from both an IAQ and energy standpoint.

DESIGN PRACTICES AND STANDARDS

ASHRAE Standard 62 Ventilation Rate Procedure and LEED

The currently dominant design standards rely heavily --almost exclusively, in fact-- on outdoor air dilution of indoor contaminants. The ASHRAE Standard 62 Ventilation Rate Procedure (VRP) assumes that there is no air cleaning whatsoever and requires a certain level of outdoor air per square foot of floor space plus a certain level per person. While it does not necessarily assume that the outdoor air quality is good, in practice that is how the Standard generally is used. If the VRP is followed properly, then outdoor air contaminants are measured and taken into account. If their levels exceed acceptable maximums, then air cleaning is used to bring the contaminants in line.

LEED takes this a step further: the only way to get an additional point for IAQ under the IEQ section is to bring 30% more outdoor air than the Ventilation Rate Procedure requires. In many climates, there is a not insignificant energy penalty associated with this. Every cfm of outdoor air must be heated, cooled, and dehumidified. This can cost \$2-\$4/cfm/year. Further, in any urban or dense sub-urban environment, the result can be worse IAQ. With low-emitting building materials, finishes and furnishings and no smoking, outdoor contaminant levels are often far higher than those found in indoor air. This leads to my favorite inconsistency in LEED: one cannot use air cleaning to clean the indoor air, but one can get an extra point for bringing in 30% more outdoor air that is dirty as long as one uses air cleaning to clean it first. I am sure this will be addressed in subsequent LEED versions.

I will interject an anecdotal comment here. In cases where my company is asked to help identify and fix an IAQ problem, 95+% of the time, it is because of an outdoor air problem-- most often some sort of exhaust from vehicles, kitchens, or generators.

Example: A LEED EB Gold building in a large Eastern US city. The building brings in 30% more outside air than the Ventilation Rate Procedure requires. Adjacent to the building, there is a code-compliant kitchen exhaust from a steakhouse. The outlet of the exhaust is at the same height as the outdoor air intakes in the office building. When the wind is out of the right direction, smoke from the kitchen exhaust travels directly into the outside air intakes. CO₂ levels in the building are barely above ambient outdoor levels. Because of occupant complaints, the building engineers have hung chemical odor eating/generating canisters on coat hangers inside the air handlers. The entire building smells like a cross between a men's room and burnt food.

I use this not as a sample of a LEED Gold Building, as clearly proper design and engineering practices according to any standard were not implemented. Rather it is an extreme example of a not atypical problem that one finds in urban areas.

IAQ procedure: A Common Sense Approach

Thankfully, ASHRAE Standard 62.1 also has the IAQ Procedure (IAQP). This allows for outdoor air levels to be potentially reduced based on design factors such as the use of air cleaning, banning of certain activities, use of low-emitting materials, good airflow patterns, good air change rates, etc. The IAQ Procedure is slightly harder work to implement in that it requires identifying and predicting contaminant levels with mass balance equations. (However, it would be no more work if engineers applied the VRP properly and actually measured outdoor air contaminants.) But the IAQP is being used increasingly as it provides a path forward to both improved IAQ and energy savings.

Further, at this point, as partly outlined above, there is a particularly fortuitous confluence of technologies:

- air cleaning systems that can remove virtually any contaminant,
- sensors for monitoring in real time actual IAQ and outdoor air quality parameters beyond temperature and humidity and to give this information to,
- sophisticated building automation systems that can vary airflow and ventilation air depending upon actual conditions, and
- computer systems and programs that can perform the mass balance equations in a matter of seconds.

I would argue that the best IAQ – and the least energy intensive – is achieved in a design and HVAC system based on the use IAQP coupled with air cleaning and either continuous monitoring of indoor and outdoor air that interfaces with the building automation system or in less sophisticated systems, periodic monitoring to confirm the system settings.

CASE HISTORIES

The following are a few buildings where the IAQP and monitoring has been implemented either before during the design phase or after the fact.

Example 1: The owners and occupiers of a North Carolina office building installed polarized media air cleaners in the rooftop air conditioning units. The outdoor air level was reduced from 20 cfm/person to 5 cfm/person. An Aircuity monitor was used to measure IAQ parameters before and after the reduction. CO₂ levels increased slightly and with a peak of about 800 ppm. Every other IAQ parameter (PM 10, PM 2.5, and TVOCs) got much better. See addendum A.

Example 2: Endeavor Elementary School in Lakota, Ohio is, according to a USA Today report based on EPA data, in an area that is in the 94th percentile of bad outdoor air. The school is a new building and was designed using the IAQP. Schools are often a good application of the IAQ Procedure due to such factors as no smoking, intermittent occupancy, and that they are often located near roadways. Polarized media air cleaners were installed in the air handlers to help ensure acceptable IAQ. Prior to construction, analysis was performed of potential contaminant levels in the building based on occupancy, anticipated uses and other design parameters. The calculations were run at a constant minimum of 5 cfm per person of outdoor air. For the analysis, children were counted as adults (the primary impact would be on Carbon Dioxide levels). The

Aircuity Optima was placed in a classroom and measured temperature, humidity, CO₂, small particles, large particles, CO, Ozone, and Radon constantly over the period of the test and compared the measured values to accepted target levels for the parameters. Endeavor Elementary received an overall score of four stars (the highest rating) and both the Air Cleanliness Index and Building Pollutants indices had the highest possible absolute score (100).

Example 3: Perhaps a better example of a LEED building than the one cited above is the LEED Platinum renovation of ASHRAE Headquarters. It has exemplary indoor air quality. It also has a sophisticated polarized media air cleaning system. In addition, it has continuous monitoring of both the indoor air and the outdoor air. At any given time, indoor levels of particles and TVOCs will be a fraction of those found in the outdoor air. In the case of particles, the indoor levels are generally about 1/10th the level of the outdoor air. The building is adjacent to one of the major freeways in Atlanta. The building is designed to be a living laboratory and I am sure will produce much useful data.

CONCLUSION

While the overarching goal in building design is the indoor environment and air quality, energy use cannot be ignored. Buildings account for over 40% of our energy use. However, IAQ and energy conservation can go hand in hand. We are now in a position where we can design systems that provide IAQ the same way we provide temperature and humidity control: based on actual measured conditions. Engineers do not build HVAC systems that assume the outdoor air is always the same temperature and humidity. But that is essentially what is done with IAQ. Further, the underlying assumption has been Outdoor Air: Good / Indoor Air: Bad. This was probably a lot closer to the truth when there was smoking in buildings. The ETS issue skewed and hijacked the process of providing clean air in buildings for many years. But now, it is largely a non-issue. (In fact, most ETS in buildings comes from people huddled *outside* smoking.)

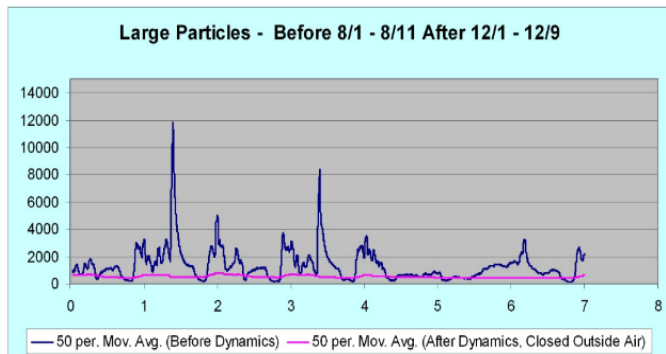
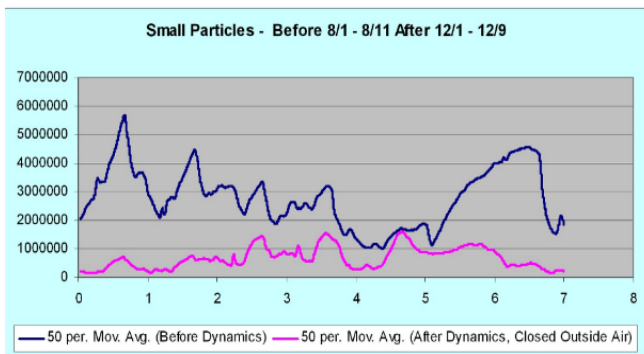
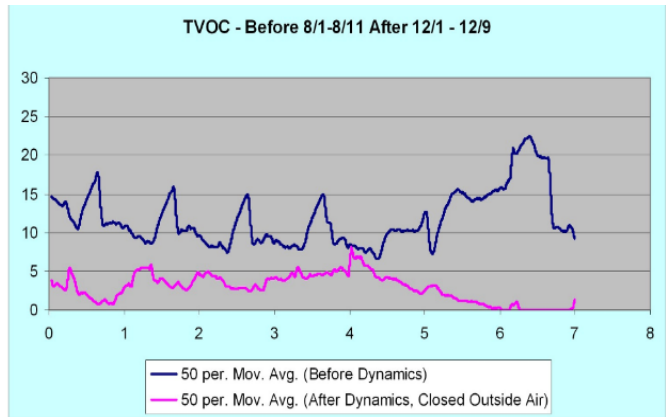
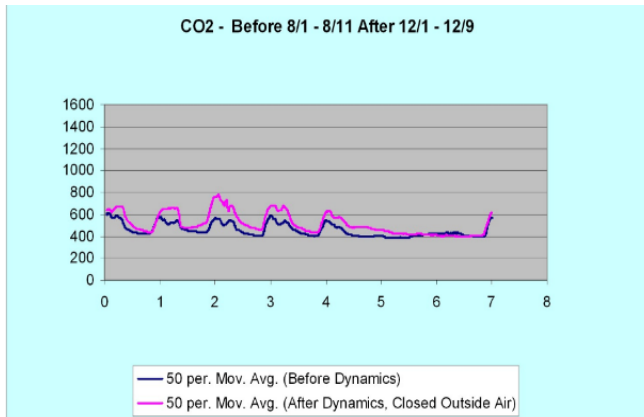
Going forward our challenge as designers is to bring appropriate technology to bear to provide systems that give people what they assumed they had: quality indoor air. Further, we must do this in the larger context of energy use and climate

change. To do otherwise is both negligent and irresponsible.

REFERENCES:

ASHRAE 2010. *ANSI/ASHRAE Standard 62.1. Ventilation for Acceptable Indoor Air Quality*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE 2007. *ANSI/ASHRAE Standard 52.2. Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.



Addendum A. Red lines above represent the “after” test.