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Balancing energy conservation and occupant needs in ventilation rate standards for Big Box stores and other commercial buildings in California: Issues related to the ASHRAE 62.1 Indoor Air Quality Procedure

Author
Mendell, Mark

Publication Date
2012-07-31

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

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Mark J. Mendell and Michael G. Apte

Environmental Energy Technologies Division
Indoor Environment Group
Lawrence Berkeley National Laboratory
Berkeley, CA 94720

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California
Energy Commission

October 2010
BOA 500-99-013

Arnold Schwartzenegger, Governor

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Abstract

This report considers the question of whether the California Energy Commission should incorporate the ASHRAE 62.1 ventilation standard into the Title 24 ventilation rate (VR) standards, thus allowing buildings to follow the Indoor Air Quality Procedure. This, in contrast to the current prescriptive standard, allows the option of using ventilation rate as one of several strategies, which might include source reduction and air cleaning, to meet specified targets of indoor air concentrations and occupant acceptability. The research findings reviewed in this report suggest that a revised approach to a ventilation standard for commercial buildings is necessary, because the current prescriptive ASHRAE 62.1 Ventilation Rate Procedure (VRP) apparently does not provide occupants with either sufficiently acceptable or sufficiently health-protective air quality. One possible solution would be a dramatic increase in the minimum ventilation rates (VRs) prescribed by a VRP. This solution, however, is not feasible for at least three reasons: the current need to reduce energy use rather than increase it further, the problem of polluted outdoor air in many cities, and the apparent limited ability of increasing VRs to reduce all indoor airborne contaminants of concern (per Hodgson (2003)). Any feasible solution is thus likely to include methods of pollutant reduction other than increased outdoor air ventilation; e.g., source reduction or air cleaning. The alternative 62.1 Indoor Air Quality Procedure (IAQP) offers multiple possible benefits in this direction over the VRP, but seems too limited by insufficient specifications and inadequate available data to provide adequate protection for occupants. Ventilation system designers rarely choose to use it, finding it too arbitrary and requiring use of much non-engineering judgment and information that is not readily available. This report suggests strategies to revise the current ASHRAE IAQP to reduce its current limitations. These strategies, however, would make it more complex and more prescriptive, and would require substantial research. One practical intermediate strategy to save energy would be an alternate VRP, allowing VRs lower than currently prescribed, as long as indoor VOC concentrations were no higher than with VRs prescribed under the current VRP. This kind of hybrid, with source reduction and use of air cleaning optional but permitted, could eventually evolve, as data, materials, and air-cleaning technology allowed gradual lowering of allowable concentrations, into a fully developed IAQP. Ultimately, it seems that VR standards must evolve to resemble the IAQP, especially in California, where buildings must achieve zero net energy use within 20 years.

I. Background

Historically, the California Energy Commission (CEC) has not incorporated into Title 24 the language on recommended minimum ventilation rates (VRs) from ASHRAE Standard 62.1 (Ventilation for Acceptable Indoor Air Quality (ASHRAE 2010)). This ASHRAE standard provides two alternative methods for defining minimum VRs: the Ventilation Rate Procedure (VRP), a widely used prescriptive procedure that sets specific minimum outdoor air ventilation rates for various space uses, and the much less commonly used Indoor Air Quality Procedure (IAQP). The VRP-prescribed rates were based historically on controlling odors from occupants, and more recently have considered indoor emissions from both occupants and the building itself. The VRP rates, however, have not explicitly considered scientific knowledge on indoor emissions, indoor air quality, and health. The IAQP, in contrast, is a performance-based design approach that focuses on controlling the concentrations of selected indoor contaminants of concern to specified health-linked concentration limits and also on maintaining at least a specified level of perceived indoor air acceptability. The ASHRAE 62.1 User's Manual says the VRP is an indirect approach to achieving acceptable indoor air quality (IAQ), and the IAQP a more direct approach (ASHRAE 2007a); however, this directness requires substantial new kinds of information and judgments.

The IAQP allows the designer (the Engineer of Record) to select indoor contaminants for consideration, to select from published values a maximum concentration limit for each contaminant, and to use various methods to meet these limits, including source control, air cleaning, or the traditional dilution of indoor contaminants with outdoor air. The IAQP allows ventilation air to be reduced below rates that would have been required by the VRP, if it can be demonstrated that the resulting IAQ meets the designer-specified criteria for pollutant concentrations and occupant satisfaction (ASHRAE 2007a). Thus, the IAQP offers a potentially useful strategy for increasing energy efficiency in buildings by reducing ventilation rates through an overall approach intended to maintain occupant health and satisfaction. Given unusual indoor contaminant sources, however, the IAQP may require higher ventilation rates than those specified in the VRP in order to meet the specified limits for contaminant concentrations and occupant acceptability.

The key change in approach with the IAQP would be to consider outdoor air ventilation as *just one of multiple tools* for achieving adequate IAQ. This would be an important step towards achieving zero net energy use in buildings while maintaining or improving IAQ. Ventilation rate standards that are linked to achieving specified levels of indoor pollutants and acceptability, rather than prescribed without explicit consideration of air quality, could better provide healthful indoor environments, and also reward designers and owners who control indoor pollutants by allowing lower energy costs from reduced outdoor air ventilation. In theory, this is a win-win strategy.

But is enough information and expertise available to implement this strategy successfully and reliably? Should California consider adopting the current ASHRAE 62.1-2010 (ASHRAE 2010) into Title 24, allowing use of the IAQP for setting minimum required VRs in big box stores and other commercial buildings in California? If not suitable in this current form, are there either revisions or new data that would produce a suitable IAQP? Or, as another solution, is there some combination of elements from the current VRP and IAQP that, perhaps with additional revisions or data, would be suitable within a California ventilation standard?

Purpose of this review
The purpose of this paper is to present a broad commentary on the IAQP, based on ASHRAE documents on standard 62.1-2010, ASHRAE public review documents, the peer reviewed literature, and other available materials, in a report evaluating the appropriateness of the current ASHRAE 62.1 IAQP for adoption into California Title 24.

Purpose of overall project
The purpose of the overall project, of which this report is a part, is to provide the Nonresidential Building Standards Program of the CEC with analyses of the current IAQP, to aid in decisions about possible inclusion of the IAQP, in current or revised form, in Title 24. The focus of this work will be on "big box" retail, which is of current interest to the CEC Building Standards Program; however, the results will have application to other parts of the commercial building sector. The goal of the project is to provide the CEC with information that it needs to establish commercial building (CB) ventilation rate standards for big box stores that strike an appropriate balance between the need for decreasing energy use with the need to maintain IAQ standards that support occupant comfort, health, productivity, and performance.

Although there is no universally used definition of big box retail, the State of California defines big box retail as a "store of greater than 75,000 square feet of gross buildable area that will generate sales or use tax (California Law AB 178)." Major types of big box stores and their merchandise include, by one type of categorization (Clanton et al., 2004):

- Discount department stores (80,000 – 200,000 ft^2) – wide variety of up to 60,000 distinct items.
- Category killers (20,000-120,000 ft^2) – specialty or niche items in a specific category.
- Outlet stores (20,000-80,000 ft^2) – discount items, often from major department stores.
- Warehouse clubs (104,000-170,000 ft^2) – limited variety of up to 5,000 products in bulk sizes to customers paying an annual membership fee.
- Supercenters (average 250,000 ft^2) – full grocery and retail services

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II. Approach

We reviewed the IAQP language in ASHRAE 62.1-2010 and other available materials related to the IAQP in multiple types of sources, including the peer-reviewed literature, relevant conference proceedings, ASHRAE journals, and the world-wide-web. Based on a synthesis of these materials, we summarize what is known or has been said about the IAQP, lay out key issues and unanswered questions raised by the current IAQP, and provide guidance for a decision on adopting the IAQP into California Title 24, in its current or in some revised form. The report also reflects input on several earlier drafts received from a Technical Advisory Committee (TAC). The 15 TAC members represented multiple sectors (State government, academia, private consulting, and various industries including retail, HVAC, filtration, and construction) and disciplines (mechanical, ventilation, and chemical engineering; industrial hygiene; chemical emissions and exposure assessment; public health; IAQ policy; and energy standards.

Ventilation rates will generally be presented here with units of cubic feet per minute (cfm) per person or per square foot (sq ft), but also in places as air changes per hour (ACH).

III. Current ASHRAE 62.1 Indoor Air Quality Procedure

In this report, we focus on ASHRAE 62.1-2010. The 2010 standard reflects a number of changes from the 2007 version, intended to reflect recently increased understanding of indoor contaminants and their health effects. (The changes in the prior standard (ASHRAE 2007) that are most relevant to this review are included in the published Addenda q and r (ASHRAE 2009, 2009a). As specified in the current standard, the IAQP is "a design procedure . . . in which the building outdoor air intake rates and other system design parameters are based on an analysis of contaminant sources, contaminant concentration limits, and level of perceived indoor air acceptability . . . (ASHRAE 2010, p. 11)." For the complete text describing the IAQP, see pages 16-17 and 25-36 in ASHRAE 62.1-2010 (ASHRAE 2010).

Applying the IAQP requires the designer (the Engineer of Record) to:

- Identify *contaminants or mixtures of concern* [abbreviated in this paper as COCs] for purposes of the design.
- Identify *indoor sources* (occupants and materials) and *outdoor sources* of each COC.
- Determine the *emission rate* of each COC from each source.
- Specify an indoor *concentration limit*, with a corresponding *exposure period* for each COC, with appropriate reference to a *cognizant authority*[1] as the source.
- Specify a *design level* of [subjective] *indoor air acceptability*, as a percentage of *occupants or visitors* expressing satisfaction with perceived IAQ.
- Determine *for each zone* the minimum required ventilation rates, equal to the *larger* of the rates that achieve
    - a *concentration within the specified limit for each COC*, as estimated in a mass balance analysis, or
    - at least the *specified indoor air acceptability*, based on either occupant evaluation of the completed building, or prior determination in a very similar building zone with similar sources and design limits for contaminant concentrations.
- Document the selected COCs and, for each, the sources, indoor and outdoor source emission rates, concentration limits, exposure periods, and related references; the analytical approach used to determine ventilation rates and air cleaning requirements; and the plans for monitoring of contaminants and for evaluation of acceptability among occupants or visitors.

In zones with unusual contaminant strengths, the IAQP and VRP may be used together, with the IAQP used to determine the *additional* outdoor air or air cleaning necessary, *beyond* that required by the VRP in that zone.

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[1] ***cognizant authority:* "**an agency or organization that has the expertise and jurisdiction to establish and regulate concentration limits for airborne contaminants; or an agency or organization that is recognized as authoritative and has the scope and expertise to establish guidelines, limit values, or concentration levels for airborne contaminants (ASHRAE, 2010)."

IV. Available Materials and Ideas on the IAQP

A. Clarification/Explanation of the IAQP

ASHRAE has produced a Users' Manual for the prior standard, Standard 62.1-2007 (ASHRAE 2007a), that provides practical advice and discussion of various issues involved in applying the IAQP. Some specific points from the Manual are summarized below:

- The IAQP requires that the overall design of the building and ventilation system create indoor environments that meet both the objective and subjective criteria, and specifies that neither criterion alone is sufficient.
- While the VRP does not allow VR rates below those specified, regardless of any use of air cleaning or low emission materials, the IAQP considers dilution of indoor contaminants with outdoor air ventilation as only one available method, along with others such as source control or air cleaning, for meeting specified COC concentration limits and acceptability levels. Thus with the IAQP, if target criteria are met, VRs might be reduced below those required by the VRP. This may allow overall lower-cost or lower-energy design solutions or operating strategies than with the VRP, although some construction and maintenance costs may be increased. In the presence of unusual contaminant sources, however, VRs with the IAQP might be higher than with the VRP.
- Determining the relevant COCs, from hundreds of contaminants and mixtures with potential for harming health or reducing acceptability, is a subjective process left to the designer (Engineer of Record). The standard does not specify how COCs should be chosen; for instance,
    - whether to select contaminants identified in prior similar buildings, or by evaluating anticipated emissions from building materials, equipment, or occupants; and,
    - among potential contaminants, whether to focus on the most common, the most abundant, or the most problematic for health or acceptability.
- COCs may be selected by review of the literature on similar buildings or, for non-office buildings for which little published information is available, by revising available information on office buildings. For existing buildings undergoing ventilation retrofitting, direct measurements of contaminants and acceptability are possible.
- The IAQP does not explicitly require post-construction verification, for the specified COCs, of their source strengths or the resulting concentrations, although this may be done. (It does require describing the plans for monitoring of contaminants and evaluating occupant/visitor acceptability.)
- Source strengths for all indoor and outdoor COCs specified by the designer must be determined. For outdoor contaminants, indoor source strength "is a function of outdoor concentration and ventilation rate" (p. 6-44), but, somewhat inconsistently, is also said to be "typically represented as a volumetric concentration (ppbv, g/m^3)" (p. 6-45). In specifying COCs with outdoor sources, designers may consider ambient criteria pollutants plus local site-specific pollutants and sources.
- For all selected COCs, the designer must specify indoor concentration limits, with a corresponding exposure period, referenced to a cognizant authority. Although the standard

does not specify limits, it lists in Appendix B some available guidelines that may be pertinent, although these do not apply for insuring acceptability of indoor air.

- Compliance with the IAQP requires that a percentage of the people exposed are satisfied with the indoor air, but it does not specify whether this is applied to occupants or visitors, and does not specify how to meet this requirement. However, a provided definition states that ***acceptable indoor air quality*** is air "with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction."
- Specific approaches for demonstrating similarity of the current building zone and prior existing building zones are not defined. Specific required approaches for either contaminant monitoring or occupant surveys are not defined and no specific time for either is prescribed, other than that they occur after all construction is complete. As the Manual points out, the IAQP does *not* require IAQ sampling prior to occupancy. Thus, occupancy immediately after construction, but monitoring of contaminants and evaluation of subjective acceptability only later, after the decay of initial high emissions, would be allowed.

Others have written explanations of the provisions of the IAQP for potential users. Tshudy (1998) demonstrates step-by-step application of the IAQP (as defined in ASHRAE 62.1-1989) in four typical commercial building situations, taking the perspective of the ventilation system designer. The building situations used were a hotel meeting room, a small office suite, a secretary's office, and a small conference room, each specified by size, occupants, openings, wall-coverings, and furnishings. (Note that none of these approximate the large open sales floor of a big box retail store.) The paper demonstrates the numerous decisions and judgments required, such as in selecting contaminants of concern, understanding emission behaviors of multiple sources, selecting indoor concentration limits for contaminants, and selecting a method for defining occupant acceptability. The paper also provides examples of obtaining the specific input data that are required to apply the procedure, including information on contaminant sources and emission strengths. The paper produces a range of calculated VRs for the four types of building situations. Tshudy concludes that the limited availability and quality of the data needed, combined with the large variability in calculated VRs resulting from the many judgments required in the process, allow the designer limited confidence in the successful application of the procedure. Burroughs (2009) describes the IAQP, suitable circumstances optimal for its use, advantages of its use, and examples of cost savings.

B. Benefits of the IAQP

Two types of potential benefits from the IAQP, relative to the VRP, have been mentioned:

- It *allows lower VRs* to save energy and money, while providing at least equal IAQ.
- It *allows improved IAQ, health, and satisfaction* in buildings through setting of explicit health-based and acceptability-based concentration limits.

Table 1 summarizes some potential benefits with the current IAQP, mentioned by the TAC committee or in other sources. (More complete listings of ideas and sources for the material in this table are provided in Appendix 1a, with a full listing of ideas from the TAC committee in Appendices 2 and 3.) Benefits which require IAQP-allowed VRs lower than those prescribed by the VRP are underlined in Table 1. Note that all benefits in Table 1 *not* requiring VRs below

VRP-prescribed levels (not underlined) could also be obtained under the current VRP, although incentives to do so may be absent for building owners and designers.

Table 1. **Summary of potential benefits of the current ASHRAE 62.1-2010 IAQP**
(<u>Underlined</u> = benefit requires IAQP-reduced VRs)

<table>
<tr><td>
Allows lower VRs to save energy and money, while providing at least equivalent IAQ

<u>IAQP allows, in operations, reduced total energy use, reduced operating costs, and reduced peak electrical demand, and in construction, reduced initial costs due to smaller/simpler HVAC equipment. This is because it allows lower VRs either</u>

<u>from use of reduced emissions and/or air cleaning, or</u>
<u>because the higher VRP-prescribed VRs were not necessary to achieve the specified level of IAQ (the VRP does not allow lower VRs even if indoor contaminants are reduced in other ways).</u>

<u>IAQP can help California achieve zero net energy in non-residential buildings by 2030.</u>
<u>IAQP can allow reductions in outdoor air (OA) intake rates, so that</u>

<u>where outdoor air pollutant levels are high, can reduce the amount of dirty OA needing cleaning.</u>
<u>where outdoor relative humidities are high, can help eliminate costs and challenges of removing extra humidity (less important in CA).</u>

<u>Broader use of IAQP, to the degree that allows overall reduced energy use in buildings, could improve outdoor air quality through reduced burning of fossil fuels, which would in turn improve indoor air quality, and would also reduce carbon impact of the building sector, providing additional environmental benefits.</u>

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<tr><td>
<u>Allows improved IAQ, health, and satisfaction in buildings through setting of explicit health-based and acceptability-based concentration limits</u>

IAQP allows improved IAQ and health in buildings through reduced emissions and/or air cleaning, even at VRP-prescribed rates, so solves the problem of demonstrated inadequate health protection by current VRP-prescribed rates.
<u>IAQP can provide health-protective indoor environments in buildings through reduced emissions and/or air cleaning, even at VRs lower than VRP-prescribed.</u>
<u>IAQP can reduce outdoor air (OA) intake where outdoor air pollutant levels are high, which improves indoor air quality.</u>
<u>IAQP can reduce OA intake in areas with high outdoor relative humidity, which helps with problem of either providing inadequate OA or bringing in too-humid OA</u> (less important in CA).
IAQP can define VRs for zones with unusual contaminant sources, including recently constructed or renovated, (required VRs are likely to be higher than with VRP).
IAQP can explicitly calculate needed VRs in zones to achieve selected better than minimum levels of contaminant concentrations or occupant acceptability, which may require more outdoor airflow than with VRP.
IAQP can allow designers to identify and reduce some sources of indoor pollutants.
IAQP can educate about health implications of IAQ by stimulating consideration of which

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contaminants may be of concern.
- IAQP can encourage use of low-emitting building materials and cleaning/maintenance products.
- IAQP can encourage collection and availability of standardized data on low-emitting building materials and cleaning/maintenance products.

C. Limitations of the IAQP

Four general types of limitations of the current IAQP have been mentioned most frequently:

- It may not adequately protect occupants or IAQ initially.
- It may not adequately protect occupants or IAQ in the future, even if it does initially.
- It is too imprecise, can calculate a wide range of VRs.
- Engineers/designers are reluctant to use the IAQP.

See Table 2 for a summary of potential limitations of the current IAQP. Note that the VRP has many of these same limitations, including lack of guarantee that compliance provides adequate IAQ, and lack of provision for post-construction periods of increased indoor emissions or concentrations. (More complete listings of ideas and sources for material in this table are provided in Appendix 1b, with a full listing of ideas from the TAC committee in Appendices 2 and 3.)

D. Case studies – applications of the IAQP

Muller (2008) provides example strategies for applying the IAQP, and examples of substantial savings in capital and operational costs. Muller (2008a), in a presentation on "Applying the IAQ Procedure of ASHRAE 62.1-2007 at K-12 Educational Facilities," summarizes the IAQP, provides an example of application in a school, and discusses new applications of the IAQP in new or renovated schools, using gas and particulate phase filtration to reduce VR and save money. The presentation mentions that with the IAQP, there were no complaints about IAQ from teachers, and use of medical inhalers by asthmatic students was apparently reduced as much as 50% from the prior year.

Bayer (2009) reports data from six commercial buildings with both gas phase and particle phase filtration systems. The aim of the study was to provide data to assist in selecting COCs, to assist in estimating costs and benefits of applying the IAQP, and to demonstrate that the IAQP can be applied effectively in retrofitting buildings. The paper reports, for six commercial buildings retrofitted with gas phase and higher efficiency particulate filtration systems, the removal effectiveness of the filtration systems, the IAQ improvements, and operational cost savings. Buildings included a hotel, conference center, sports arena, archival storage facility, and specialty museum. Reductions in TVOC from before (VRP without enhanced air cleaning) ranged from 38-74%; removal efficiencies for 0.5 um particles ranged from 28-95%; and removal efficiency for ozone was 100%. Various VOCs identified indoors were described. Low indoor levels of contaminants at high levels outdoors demonstrated applicability of the IAQP in areas of poor ambient air quality. [This benefit of enhanced air cleaning would have occurred with the VRP also, although direct cost incentives to motivate this would have been lacking.]

Energy cost savings with the IAQP compared to the VRP due to reduced outdoor air supply ranged from $10K to $1.3 M annually, with one building also saving $2.5M in chiller

Table 2. Potential limitations of the current IAQP

IAQP may not adequately protect occupants or IAQ even initially • Specification of contaminants and mixtures of concern and selection of health-based limits and exposure time periods from specific cognizant authorities are all left entirely to designer, who as mechanical engineer traditionally has not been trained to make these judgments; no comprehensive minimum set of contaminants and limits; no standardization and no oversight of this process. • Inability to specify truly health-protective VRs, because of limited current ability to define healthy indoor air; we can now define healthy concentration levels only for the few air contaminants that are both measurable and have health-based exposure limits. • The IAQP should, but does not, explicitly consider the HVAC system including filters as a source of pollutants, based on current scientific findings. • Recent scientific findings suggest specific exposures that might need consideration in the IAQP, but for which limits have not yet been set – chemicals such as formaldehyde, phthalates, TXIB, other plasticizers, glycol ethers, and fire retardants; and biological exposures such as dampness/mold related, and infectious airborne agents from occupants. • California health-related agencies (CalOSHA, CDPH) and the health community worry that reducing VRs will reduce occupants' margin of safety without adequately reducing sources of risk; while VRP-prescribed VRs may not have a solid scientific basis, they have a history and track record. • The IAQP does not address specific issues of different occupancy types, and therefore may fail to address these differences; for instance, whether customers or workers in retail environments, students or teachers in schools, and visitors or workers in public buildings should be considered most critical regarding acceptability and health effects of indoor air; or, the need for additional emphasis on the diverse and changing materials that may be present as products in retail environments, with relatively less contribution from building surface materials (lower surface-to-volume ratios), relative to other types of commercial building uses. • Designers using the IAQP will usually specify VRs adequate for the *worst single indoor contaminant*, ignoring potential combined effects of multiple chemicals each at low, sub-limit concentrations. If multiple chemicals are present that have effects on the same organ system, effects may be at least additive; total concentrations of these related compounds may thus exceed an acceptable level but not be evaluated as a total. • IAQP allows assessment of contaminant concentrations and IAQ acceptability at an unspecified time; i.e., could assess after occupation and after emissions have declined, even though occupants moved in during initial high emissions from materials.
IAQP may not adequately protect occupants or IAQ in the future • One-time measurement to determine all future indoor concentration of contaminants in a

building is inadequate; adequate protection would require ongoing periodic monitoring or real-time sensors, or even implementation of demand-controlled VRs based on multiple key contaminants.

- Title 24 doesn't include continued maintenance over time. Poor compliance and maintenance are apparently common with current VRP standards. Thus, lowering VRs even further with IAQP, if low maintenance/compliance is predictable in many buildings, provides less margin of error, especially for sensitive populations.
- Ventilation systems designed with the IAQP can rely on untested technologies or systems with unknown filter life for air cleaning.
- IAQP does not consider later periods of increased indoor concentrations and adverse exposures; i.e., emissions in buildings from renovation, or indoor build-up after short periods of no ventilation such as over weekends and vacations.
- If IAQP is used, new chemical emissions from new indoor materials (buildings, furnishings, surfaces, products) introduced later may increase unrecognized health risks at previously lowered ventilation rates.
- A reduced-capacity HVAC system designed per IAQP calculations may not be adequately sized to provide increased future ventilation rates needed due to any new pollutant sources or activities.

IAQP too imprecise, can calculate wide range of VRs

- Calculated VR rates for a design can vary broadly, either randomly or with intentional manipulation, so this process needs more detailed guidance. LEED criteria do not allow use of the IAQP for this reason.

Reluctance of engineers/designers to use IAQP

- Engineers, who traditionally certify that an HVAC system meets engineering specifications that they understand well, have been reluctant to make the non-engineering judgments required to use the IAQP, because most engineers do not possess much of the required knowledge, and making these judgments without specific training seems risky:
    - Issues with the requirement to select COCs – the standard doesn't stipulate whether to select based on experience, analysis of similar buildings, documented contaminants indoors or outdoors, or findings from others, nor does it include any comprehensive list of contaminants. The identification of an appropriately complete set of COCs requires non-engineering judgment and, while possible, may seem daunting to engineers, and would pose risks of error and liability.
    - Issues with *identifying sources* for each initially selected COC, or conversely *selecting COCs* based on initial knowledge about indoor or outdoor sources -- this requires new cooperation of the engineer with the architect and other experts, and new knowledge about material emissions.
    - Issues with determining *source strengths* for each COC for all identified indoor and outdoor sources -- determinations of types and rates of emissions may require literature searches or materials testing in areas involving non-engineering judgment.
    - Issues in *specifying relevant acceptable concentration limits and exposure times* for COCs (for each of all relevant human outcomes/responses) and the corresponding

cognizant authorities – all these determinations require non-engineering judgments.
    - Issues in selecting a time point for prediction /determination of future indoor concentrations and indoor air acceptability.
    - Issues of increased burden from detailed documentation, relative to the VRP.
- IAQP not likely to be widely used by building designers because it fails to provide a well-defined path to compliance. The building designer has no clear, indisputable definition of acceptable indoor air quality. Appendix B provides selected standards and guidelines from various cognizant authorities, but says that a) meeting even all of the listed values does not ensure acceptable IAQ; b) no quantitative definition of acceptable IAQ can necessarily be met by measuring contaminants; and c) even if the known and specifiable contaminants listed are controlled to the established concentration levels, indoor air quality still may not be satisfactory. Consequently, many designers choose to use the VRP, in which the requirements are clearer and compliance to requirements is more easily demonstrated.
- IAQP requires designer to design a system that adequately controls contaminants to a level that will be judged acceptable in later subjective evaluation. Because evaluation can only occur <u>after</u> system installation and building occupancy, a designer cannot comply with the standard without a successful subjective evaluation of the <u>completed</u> system. Since a positive subjective evaluation is a system design requirement, it is unclear how a building can be occupied before the system design is completed.
- Limited current use of the IAQP is partly due to lack of data demonstrating use, effectiveness, and lifetimes of air cleaning technologies.
- There is limited availability and quality of the data needed on emissions. The resulting large variability in calculated VRs (by a factor of up to 26), resulting from the many judgments, assumptions, and estimates required in the process, allow limited confidence in the successful application of the procedure (from an engineering or legal point of view).
- Needed improvements include improved and expanded materials emission data from standardized protocols, estimated emissions over time from well-characterized products, increased information on human responses to key indoor pollutants, expanded availability of authoritative guidelines on acceptable human exposures to indoor contaminants, development of more sophisticated procedures for VR calculations that reflect the variety and time-dependence of indoor sources, and improved methods for evaluating acceptability of indoor air quality.
- Engineers for the IAQP must specify building contents so as to achieve future sensory acceptability by occupants, but even the limited available emissions data in the U.S. do not evaluate products for this purpose; designers do not have this needed information available for selecting products that will ensure a successful design.
- Fear of liability with the IAQP: use of the VRP, although not science-based, takes much of the liability risk off the engineer; although VRP says that it may not provide adequate indoor air quality (a caveat included to protect ASHRAE), most designers using the VRP never consider whether any atypical sources are present.
- If an engineer initially tries the IAQP, finds higher VR than with VRP, and then applies the VRP instead, any resulting liability may be a disincentive to even trying the IAQP.
- The IAQP is too complex, time-consuming, and expensive for designers to use in singly-designed buildings, because it's hard to get owners to pay for cutting edge design. Engineers using the IAQP conscientiously may price themselves out of the market.
- Engineering fee is usually a % of costs, and IAQP is likely to being construction costs *down*

(because smaller HVAC equipment will be required to supply the lower VRs, although cost of air cleaning equipment may partly compensate), making it even less attractive for engineers to use.

construction costs. Large potential savings in construction cost were evident from use of *smaller system equipment* in original designs due to projected lower VRs.

Tshudy (1998) demonstrates in a paper (described earlier) the step-by-step application of the IAQP (as defined in ASHRAE 62.1-1989) to four typical but hypothetical building situations, the decisions and information required, and problems encountered in finding information and making decisions.

Grimsrud et al (2009), in a presentation titled "Ventilation Requirements in a Retail Store," describe several ventilation-related projects at multiple locations of a "Big Box" retailer in the U.S. Implementation of these projects involved application of the IAQP (but not use of enhanced air cleaning) to reduce ventilation below VRP minimum rates. One project, completed in 1997, involved altering ventilation rates in a single store (>90,000 ft^2) for one week during each quarter, and measuring ventilation rates with several methods, along with IAQ, during that period. Pollutants measured at multiple sites included formaldehyde, VOCs, CO_2, CO, PM_3, and PM_{10}. Nine VOCs were measured at levels above limits of detection. Based on thresholds mostly not specified in the presentation slides, the project found that the total VOCs (TVOC, maximum/target concentration 1,000 $\mu g/m^3$) was the critical contaminant determining required VR. The required VR was 0.56 ACH or 0.15 cfm/ft^2.

In another project, Grimsrud et al. (2009) reported one-week measurements, spaced at three-month intervals during one year, in 3 other U.S. stores of approximately 100,000 ft^2 or greater, using at least 8 different VRs in each store. Continuous multi-point indoor and outdoor CO_2 monitoring, plus knowledge about CO_2 sources, was used with mass balance models to estimate VRs. These estimates were compared to VRs estimated by two other methods: measurements using tracer decay and "tab" settings on the roof-top units. Six contaminants plus temperature and relative humidity were measured at multiple locations in each store. Untrained panels evaluated perceived IAQ on four occasions in each building. In one store for which more detailed results were reported, total VR was not consistently related to percent satisfied, with ≥80% satisfaction (80, 84%) achieved at 0.061 and 0.105 cfm/ft^2, but not at intermediate VR values (75, 79%). Fourteen VOCs were detected, with major sources identified (with a portable photoionization detector) as cleaning materials plus merchandise in the shoe, sporting goods, and seasonal portions of the store. Key observed pollutants, with concentration limits selected, are listed in Table 3.

Table 3. Pollutants observed, and concentration limits used, in a large U.S. retail store (Target) (Grimsrud 2009)

Contaminant	Concentration Limit Chosen	Cognizant Authority and Time Period
Formaldehyde	100 μg/m^3	WHO -- 30 minute
PM 2.5	15 μg/m^3	NAAQS – 1 year
Carbon monoxide	10 mg/m^3	NAAQS -- 8 hour
TVOC	1,000 μg/m^3	(not specified)

Formaldehyde concentrations in the 3 stores (48 hour averages) ranged from about 35-95 μg/m^3, and were apparently not consistently reduced at higher VRs within the approximate range of 0.05-0.10 cfm/ft^2. Formaldehyde concentrations were almost entirely under Target's stated limit of 100 μg/m^3 (81 ppb), (22 of 23 measurements, with a max of 106 μg/m^3), with mean store values ranging from about 50 to 75 μg/m^3. Interquartile ranges for TVOC concentrations in the 3 stores (48 hour averages) ranged from about 190-925 μg/m^3, and were somewhat more consistently reduced at higher VRs within the approximate range of 0.05-0.10 cfm/ft^2. CO concentrations were not consistently reduced with higher ventilation rates, but were almost all below 2 ppm. $PM_{2.5}$ concentrations showed an apparent increase with VRs above approximately 0.09 cfm/ft^2. The maximum observed indoor concentrations for all four selected pollutants – formaldehyde, TVOC, CO, and $PM_{2.5}$ – somewhat exceeded the chosen target level, including by 38% for TVOC. Based on estimated normalized source strengths for each of the four pollutants, critical ventilation rates and dilution factors necessary to meet COC targets were estimated.

For formaldehyde, the concentration limit Target uses for customers is 81 ppb, the WHO 30-min exposure guideline, which is based on preventing irritation in sensitive people. For employees, Target reports that they use the OSHA 8 hour occupational formaldehyde limit, but among several OSHA-listed concentrations, they use not the 8-hour TLV of 750 ppb or the 500 ppb action level, but the 100 ppb trigger level for hazard communication, hazard warning labels, provision of material safety data sheets, and employee training on formaldehyde hazards. Target's formaldehyde concentration limit for their ventilation studies, and presumably for their store operations, is the lower of these two levels, the *81 ppb* set for customers. They thus selected a higher concentration limit for employees (100 ppb, from a different cognizant authority) than for customers, although the employees are exposed for longer periods.

In Grimsrud (2009), Williams, manager of Mechanical Engineering at Target Corporation, notes that the IAQP has been successfully implemented in over 800 Target stores, with "10 years of proven performance," and that Target would not have used the IAQP to lower ventilation rates if it interfered with their "guest friendly store environment." His company reports that in their big box stores, the IAQP (apparently involving reduced VRs, but no reduced emissions or extra air cleaning) reduces cooling by 46 tons per store, saving in the years 1999-2007 amounting to $27 M in total energy costs, $24M in capital costs, 84 MKwh in electricity use, 37,000 kW in electricity demand reduction, 17 M therms of gas use, and 150,000 metric tons of reduced CO_2 emissions.

We should point out that informal evaluation of building operation strategies that does not include formal assessment of occupant satisfaction and health, but relies on complaints of odors or irritant symptoms, does not provide information than can be relied upon. Both any acute symptoms and chronic health effects actually caused by lower VRs are not likely to be linked by occupants or visitors with these VRs or the building. There are well-used scientific methods for obtaining data on VR and symptoms or other health outcomes, and these have not been used yet to evaluate the IAQP.

E. Opinions on suitability of the current IAQP for inclusion in ventilation standards
We have encountered a range of opinions on whether the IAQP in its current form or some revised form is appropriate for inclusion in ventilation standards. The opinions range from approval of the current form, through recommending various revisions before inclusion, to thinking it is inherently ill-advised.

In Grimsrud (2009), Williams, from Target Corporation, suggests that the IAQ procedure should be better defined (although recognizing that the basis for the prescriptive rates in the VRP is not well-defined). He suggests, however, that any changes in the IAQP should not add unattainable requirements such as validation by contaminant monitoring. Changes, he says, should not limit design options that have proven successful in similar buildings, as many standards are based on proven performance in like buildings, and Target Stores has had 10 years of success with their approach.

Offerman (2008) recommends, because of our limited current ability to define healthy air, that we should not reduce minimum VRs in buildings using the IAQP in order to save energy. Instead, we should pursue heat recovery strategies with current VRP-prescribed VR levels until our measurement capabilities and knowledge of health effects of exposures is sufficient to allow lower VRs in conjunction with reduced indoor air emissions and improved air cleaning technologies.

Shaw (1997) recommends that standards specify minimum levels for multiple modes of VR in each building. He recommends that first, a *normal* ventilation mode is specified for everyday operations, used in two ways – for an occupancy cycle during the week, and for a pre-occupancy flushing cycle after regular and long weekends with no ventilation, for enough extra hours to remove contaminant build-up during unventilated periods. Then, an additional *enhanced* ventilation mode specified to speed up the removal of contaminants in spaces where renovations are taking or have taken place and to control the migration of contaminants to other spaces without renovations. The engineer should know when, by how much, and for how long to increase the ventilation rate for the flushing cycle in normal mode, and in the enhanced mode. The current IAQP, in allowing single VRs lower than allowed by the VRP throughout a building's initial post-construction occupancy, renovations, and on/off cycling, may periodically allow excessive exposures and occupant dissatisfaction, even if meeting target criteria during general operation. [This, of course, is also true of the VRP.] Thus, Shaw says, providing multiple VR specifications in the initial design, for these inevitable periods of increased indoor emissions during the lifetime of a building, would be an improvement.

Additional comments on this issue, from TAC members or other sources:

- Lack of consideration of mixtures may result in VRs potentially too low to protect occupants against additive effects of multiple chemicals with the same mechanisms of biologic action, such as aldehydes, but each at relatively low concentrations considered to be safe. We should define "impact groups" of compounds with similar modes of biologic effect; then set limits for individual COCs, calculate the needed VR to keep each below its limit by a safety factor, and then add the required VRs for all COCs in each impact group to incorporate additivity into the standard. To achieve this, we could add, in 62.1 Appendix B, Table 3, a column for assigning contaminants to groups, within which their effects might add (for instance, odors or other specific mechanisms of action).

- While the IAQP is a useful procedure for encouraging improvements in material emissions and air cleaners, it is too flexible to be very useful as part of a building code in California or elsewhere. In all jurisdictions covered by either the IMC or UMC, it can only be used when the code authority grants a code variance, as it is not an accepted, explicit alternative approach. For CEC to save energy without risking occupants' health/comfort, consider revising currently prescribed rates which may be too high or too low, instead of using the IAQP. Designers don't like the time or risks involved, and it produces a wide range of VR, and thus energy and IAQ, outcomes. Because the VRP rates and calculations are not universally used throughout the U.S., and don't seem to have been used in California in the past, it should be easy to set big box rates lower than in the current VRP without adopting the IAQP.

- Target is lowering VRs and keeping IAQ within acceptable limits, without using air cleaning or changed/reduced sources. Suggests that California create a board; people would apply and receive approval to use the IAQP if the design meets certain specifications.

- It's hard to interest owners/designers in using the IAQP, as it's too expensive. If California wanted to encourage lower VRs to save energy, they may need to offer incentives to get the IAQP used. And maybe focus the incentives on lowering emissions rather than on air cleaning.

- The IAQP is not practical or economical to use in singly designed buildings, and for many retail and commercial settings, owners can't easily spend the time and money to make the IAQP work for them. Owners with large numbers of buildings of essentially similar design, contents, and contaminants, however, could use the IAQP reasonably. These owners, such as big box stores, can afford to invest in the necessary research to use the IAQP in a cost-effective way.

V. Indoor contaminants of concern in commercial buildings -- sources, emissions, concentrations, and effect levels

In selecting COCs for determining IAQP-based VRs in commercial buildings for a specific type of building, or for inclusion more broadly in policy guidelines, one reasonable approach would consider those compounds found in indoor air either at high levels, or at levels of concern for health or IAQ. We summarize below available information on indoor concentrations of contaminants in stores and other commercial buildings, and on indoor contaminants of potential concern for health or IAQ. We also refer to current lists in the informational Appendix B of ASHRAE 62.1-2007 (ASHRAE 2007).

A. indoor contaminant concentrations in retail stores and other commercial buildings – current knowledge

We identified only two studies with data on indoor concentrations of VOCs in U.S. retail stores, plus one review of indoor VOCs in offices and residences.

Loh et al. (2006) used personal samplers in retail store, restaurant, and transportation environments to evaluate a set of VOCs including hydrocarbons, several chlorinated compounds, and aldehydes. Nine types of retail store were included: hardware, multipurpose, grocery, drug, sporting goods, furniture, housewares, department, and electronics. Stores, especially some types, had higher concentrations of formaldehyde, toluene, ethylbenzene, xylenes, and styrene than other locations. Houseware and furniture stores had the highest geometric mean (GM) formaldehyde levels (53 and ~37 $\mu g/m^3$), while multipurpose stores had the highest GM toluene levels (76 $\mu g/m^3$). Ethylbenzene, xylenes, and styrene had highest concentrations in hardware, houseware, and multipurpose stores. Methylene chloride was relatively much higher in hardware and multipurpose stores. 1-4-dichlorobenze was much higher in houseware, multipurpose, and drug stores. These levels in stores were several times higher than those in transportation environments, indicating strong local sources – some sources seemed clear, such as moth repellents and deodorizers with 1,4-dichlorobenzene, and paint removers and solvents with methylene chloride. Stores did not have relatively increased levels of benzene. Some store samples (each a composite of three stores) had extremely high values of specific compounds – the maximum value of trichloroethene was over 100 times the GM value, and the maximum value for m,p-xylene was over 40 times the GM value.

Hotchi et al. (2006) reported on indoor VOC concentrations in a Target store in the San Francisco Bay Area, with some information on concentration changes during a period of lower ventilation. In a preliminary walkthrough, with 34 compounds quantified, the highest concentrations (>10 $\mu g/m^3$) in the sales area included formaldehyde, 2-butoxyethanol (2-BE), toluene, and decamethylcyclopentasiloxane, and also acetaldehyde, acetone, ethanol, and di(propylene glycol)methyl ethers (DPGME). VRs measured during two periods of regular ventilation were 0.71 and 0.95 ACH, relative to the ASHRAE guideline of 0.99 ACH and the Title 24 guideline of 0.86 ACH. A 30% reduction in VR, from 0.71 to 0.50 ACH, was associated with increased concentrations of most VOCs, with the median increase somewhat higher than the relative decrease (29%) in the ventilation rate. Concentrations of 22 of the 34 quantified VOCs increased by more than 10%, with fractional increases ranging from 0.11 to 1.28 and a median increase of 0.41. Formaldehyde increased by a factor of 1.12 (from 11.5 to 25 ug/m^3), but the article pointed out that concentrations were still below a 33 $\mu g/m^3$ (27 ppb) guideline of the California Air Resources Board intended at that time to protect the general population, including sensitive individuals, from acute health effects. [Note, however, that the current OEHHA Chronic Relative Exposure Level (CREL) is 9 $\mu g/m^3$.] In a second experiment, the predominant compounds measured were formaldehyde, 2-BE, DPGME, and toluene. The 2-BE (contained in cleaning products) and DPGME (source unknown) decreased during the day.

The measured concentrations of formaldehyde and acetaldehyde were reported to be similar to those found in office buildings in the EPA BASE study (Apte and Erdmann, 2002).

Hodgson and Levin (2003) reviewed the published data on indoor concentrations of VOCs in residential buildings (existing and new) and office buildings (primarily large) in North American from 1990 on. The review excluded some compounds, such as very volatile compounds and compounds with low occurrence. Thirty-five of the compounds summarized are classified as hazardous air pollutants (HAPs). VOCs with maximum concentrations of 50 ppb or more included: in existing residences, acetic acid, formaldehyde, toluene, m/p-xylene, 1,4-dichlorobenzene, dichloromethane, 1,1,1-trichloroethane, and 2-propanone; in new houses, acetic acid, formaldehyde, acetaldehyde, hexanal, toluene, ethylene glycol, 1,2-propanediol, 2-propanone, and alpha-pinene; and in office buildings, ethanol, 2-propanol, n-octane, toluene, dichloromethane, 1,1,1-trichloroethane, and 2-propanone.

Levels of VOCs in the new homes were more than three times those in existing homes. Mean concentrations of several compounds were more than three times higher in office buildings than in residences: 1,1,1-trichloroethane, trichloroethene, and tetrachloroethene (all chlorinated solvents that may be used in office and janitorial products). N-dodecane, similarly elevated, was once commonly used in wet-process photocopiers. Mean concentrations of several compounds were more than three times higher in residences than in office buildings: pentanal, alpha-pinene, and d-limonene (all probably due to fewer wood products in offices than residences), 1,4-dichlorobenzene (once widely used in residences for moth control), and dichloromethane.

The authors point out that published data on indoor concentrations are available for only a fraction of the VOCs that are known or suspected to occur in indoor air. The unmeasured compounds are likely to include a number that have important effects on health, sensory irritation, and odor, but that are inadequately characterized by conventional collection or analysis methods (Wolkoff and Nielsen 2001).

Limited information is available on indoor chemical concentrations in retail stores, and in big box stores in particular. To the extent that building materials, furnishings, cleaning products, etc. in retail stores, and in particular large retail stores, may be similar to those in these residences and offices, this information may provide useful information for big box stores.

<u>B. Concepts for health-related limits for indoor contaminants of concern</u>

Hotchi et al. (2006) reported measured indoor VOC concentrations in a Target store in the San Francisco Bay Area, at normal ventilation conditions, and also at a reduced outdoor air supply rate. For the 11 compounds measured that had general population exposure guidelines available at that time, measured concentrations of formaldehyde, acetaldehyde, naphthalene, and tetrachloroethene were within a factor of 10 of any existing guideline value at that time. The maximum formaldehyde concentration measured during the period of lower VR was below the more restrictive of two existing population guidelines, 50 $\mu g/m^3$, but approached the more recent recommended guideline from CARB at that time for 8-hour exposures in residences and schools, 33 $\mu g/m^3$. [Again, note that the current OEHHA CREL is 9 $\mu g/m^3$.] Although the GM formaldehyde and acetaldehyde concentrations exceeded the chronic RELs, the RELs assume continuous lifetime exposures rather than the short term or work-time exposures in these buildings. Also, the formaldehyde chronic REL is near concentrations found in urban outdoor air, so the formaldehyde and possibly acetaldehyde concentrations in many indoor environments exceed their chronic RELs.

Offerman (2008) proposes a set of contaminants and concentration limits for "safe" air (i.e., healthy, but not for "acceptable IAQ"), appropriate to use with the IAQP for non-industrial indoor environments, based on health endpoints of non-cancer effects (including irritation), cancer, and reproductive toxicity. For non-cancer health effects, he suggests using criteria from the California OEHHA CREL's for VOCs, and the EPA NAAQS for outdoor criteria air pollutants. For cancer effects, he suggests using California Proposition 65 No Significant Risk Levels (NSRLs), the EPA AHERA limits for asbestos, and the EPA limits for radon gas. For reproductive effects, he suggests using California Proposition 65 Maximum Allowable Dose Levels (MADLs). Offerman suggests constructing a list of indoor air contaminants and exposure limits, consisting of frequently encountered indoor air contaminants and the lowest associated health-based concentration limit. An example list is provided in Table 4. Offerman emphasizes that buildings with indoor air contaminant concentrations all below selected health-based limits do not guarantee safe/healthy air, because of the previously mentioned limits in our knowledge and measurement capabilities.

Offerman also suggests consideration of additional "risk factors" whose presence in a building he says has been shown to increase the risk of unsafe building air, although not to demonstrate unsafe air. These risk factors, Offerman suggests, include inadequate outdoor air supply, evident moisture/mold, concentrations of mold genera higher (statistically significantly) indoors than outdoors, odors (such as mold, chemicals, ETS), carbon monoxide concentration higher indoors than outdoors, and surface accumulations of dust.

Table 4. Example list of indoor air contaminants, indoor concentration limits, and median measured levels (all in µg/m^3) in California residences* and U.S. offices** [Offerman 2008]

	OSHA 8-hour PEL	**OEHHA CREL (NC)**	**NSRL (C)**	**MADL (R)**	**Minimum Criteria**	**Residential Median**	**Office Median**
Acetaldehyde	360,300	140	**4.5**	--	4.5	20	7.2
Benzene	3,200	60	**0.7**	--	0.7	1.1	3.6
Formaldehyde	920	9	2	**1.2**	1.2	36	15
d-Limonene	--	--	--	--	--	11	7.1
Naphthalene	52,400	9	**0.3**	--	0.3	0.2	0.7
a-Pinene	36,000	--	--	--	--	11	0.6
Styrene	426,000	**900**	--	--	900	0.9	0.9
Toluene	753,700	**300**	--	350	300	8.5	8.7
Xylene	434,200	**700**	--	--	700	5.4	7.2

Note: NC=Noncancer; C = Cancer; R = Reproductive toxicity.
* Residential data from California Air Resources Board 2006 Study of 108 New Homes.
** Office data from the US Environmental Protection Agency's 1994-1998 BASE study of 100 office buildings.

In the article that was the source for Table B-3 (added to ASHRAE 62.1 by Addendum q), Hodgson and Levin (2003a) examined the potential for odor, sensory irritation, and noncancer health effects for VOCs identified in a review of indoor VOC concentrations in North American residences and offices since 1990 (Hodgson and Levin 2003). The initial review excluded cancer, immunologic effects, reproductive toxicity, lower respiratory effects, allergies, hypersensitivity reactions, and subtle neurologic effects such as headache, drowsiness, and memory loss. The authors followed a clearly described algorithm for choosing reference concentration levels for each type of effect for each evaluated compound. They then considered these reference levels together with the range of indoor concentrations compiled in their prior review (Hodgson and Levin 2003), in order to focus on compounds with effect levels within the observed range of indoor chemical concentrations. Because maximum VOC concentrations found in residences and office buildings were uniformly below 1 ppm, they focused on compounds with effect levels equal to or less than approximately 1 ppm, for the effects being considered. They calculated indoor effect, or hazard or odor quotients, by comparing their best estimates of a) odor thresholds, b) protective sensory irritation levels, and c) protective noncancer chronic health levels for the general population to the VOC concentrations measured in residences and office buildings. These calculations involved dividing maximum concentrations by the selected values.

The most odorous compounds (odor threshold (OT) <10 ppb) were 1-octanol; the aldehydes 3-methylbutanal, hexanal, heptanal, octanal, and nonanal; acetic acid; and hexanoic acid. The next most potent odorous compounds (OT=100 ppb) included phenol, propionaldehyde, benzaldehyde, naphthalene, dichlorobenzenes, and carbon disulfide. For sensory irritation, acrolein was by far the most potent irritant, followed by butylated hydroxytoluene, diethyl phthalate, formaldehyde, acetic acid, and 2-ethyl-1-hexanol. For noncancer chronic toxicity, compounds with high toxicity, and thus low chronic toxicity exposure levels (<10 ppb), included acrolein as the most potent, along with formaldehyde, acetaldehyde, 1,3-butadiene, naphthalene, 1,2,4-trichlorobenzene, bromomethane, carbon tetrachloride, tetrachloroethene, and acrylonitrile.

For the selected compounds with effect levels equal to or less than approximately 1 ppm, VOCs with odor quotients exceeding one were, for residences, hexanoic acid and the aldehydes hexanal, heptanal, octanal, nonanal, and acetic acid. Compounds with odor quotients between 0.1 and 1 were, for residences and office buildings, 1-butanol, formaldehyde, acetaldehyde, propionaldehyde, 3-methylbutanal, m/p-xylene, naphthalene, and 1,4-dichlorobenzene. No quotient could be calculated for 1-octanal, although highly odorous, because of limited building data. Of the VOCs with available indoor concentration values, 11 were considered to be relatively potent sensory irritants. Acrolein had the highest quotient in residences, followed by formaldehyde and acetic acid, and the other 8 all had quotients 0.06 or below. The maximum sensory irritation quotient for office buildings was 0.06 for 2-ethyl-1-hexanol, providing little evidence of likely sensory irritation from chemicals in these buildings (when chemicals are considered individually, as by Hodgson and Levin (2003a)). For noncancer chronic toxicity, hazard quotients were approximately one or more for acrolein (by far the highest), formaldehyde, and acetaldehyde, and were less than one but 0.1 or greater for the aromatic hydrocarbons benzene, toluene, and naphthalene, and the chlorinated solvent tetrachloroethene.

Hodgson and Levin (2003a) point out limitations of their process, which: excluded compounds known or suspected to be in indoor air that were not included in the literature or not even measurable by conventional methods; excluded various important health effects such as cancer and reproductive outcomes; and relied on a very incomplete literature. The authors suggest that future research to bolster these kinds of estimates focus on compounds most likely to have adverse effects on occupants, including the compounds identified in their article, along with other chemicals with similar physiochemical properties, such as reactive aldehydes and carboxylic acids.

Hodgson and Levin (2003a) also note the lack of obvious identified sensory irritants in office environments, despite the common reporting of sensory irritation in offices, and attribute this potentially to the little understood but demonstrated phenomenon of indoor chemical oxidation processes producing short-lived reaction products that are potent irritants not detected by standard methods (Wolkoff 1997; Buchanan et al. 2008; Destaillats et al. 2006; Weschler 2004; Weschler 2006). Note that *if* this process is the cause of sensory irritation in offices, it is probably reduced by ventilation because this reduces the concentration of reaction precursors such as terpenes and also reduces the time for reaction, even if more ventilation brings in more outdoor ozone (Weschler and Shields 2000). Thus, lowering VRs below current levels may increase sensory irritation unless reduced indoor concentrations of these precursor chemicals are insured in other ways (despite their not being irritants themselves). These same precursor chemicals create a similar problem through their reaction to form indoor particles (Wainman et al. 2000).

A recent paper has demonstrated a comprehensive approach to hazard evaluation, risk ranking, and mitigation prioritization for indoor chemicals in residences (Logue et al. 2010). Their approach synthesized findings in available studies to identify indoor pollutants with estimated acute or chronic exposure concentrations of concern, relative to available health standards. Contaminants of concern for chronic health effects were identified, fifteen of concern in a large fraction of homes, nine in a substantial minority of homes, and nine in a very small percentage of homes. Nine priority hazards identified were acetaldehyde, acrolein, benzene, 1,3-butadiene, 1,4-dichlorobenzene, formaldehyde, naphthalene, nitrogen dioxide, and PM2.5. Potential acute, activity based hazards were found for $PM_{2.5}$, formaldehyde, carbon monoxide, chloroform, and nitrogen dioxide. For some chemicals, chronic exposures even exceeded acute standards: nitrogen dioxide, formaldehyde, and acrolein. This approach by Logue et al. (2010) provides a model for evaluating exposure hazards in commercial buildings. Also, some compounds found to be of concern in homes may also be of concern in commercial environments.

ASHRAE 62.1-2010 (2010) includes three tables within Informative Appendix B, which is not part of the formal standard. These tables, provided for use as “background” information, list substances with concentration limits issued by cognizant authorities. Table B-1 provides some common air contaminants along with “selected standards and guidelines used in Canada, Germany, Europe, and the U.S. for acceptable concentrations of substances in ambient air, indoor air, and industrial workplace environments.” The substances listed include carbon dioxide, carbon monoxide, formaldehyde, radon, lead, nitrogen dioxide, ozone, $PM_{2.5}$, PM_{10}, total particles, and sulfur dioxide. Table B-2 in Appendix B lists some common air contaminants of concern in nonindustrial environments, with “concentration values of interest . . . as general guidance for building design, diagnostics, and ventilation system design using the IAQ procedure." The substances listed include carbon monoxide, formaldehyde, radon, lead, nitrogen dioxide, ozone, $PM_{2.5}$, PM_{10}, sulfur dioxide, VOCs, TVOCs, and odors. This list differs from those in Table B1 in omitting carbon dioxide and total particles, and adding VOCs, TVOC, and odors. .

Table B-3 in Appendix B includes a list of 32 VOCs found in offices or residences, in peer-reviewed studies between 1990-2000, at levels of potential concern, along with Reference Exposure Levels (RELs), which are general population exposure guideline levels from the California Office of Health Hazard Assessment (OEHHA), and Minimal Risk Levels (MRLs), which are set by the U.S. Agency for Toxic Substances and Disease Registry (ATSDR). The included compounds are, from among the set of compounds listed by Hodgson and Levin (2003a), the subset that has available exposure guidelines for general populations developed by cognizant authorities. The text notes that chemicals of potential concern but without available guidelines from these two cognizant authorities, or not identified in indoor environments in the review cited, have not been included. (Thus, omission of specific VOCs from Table B-3 does not suggest evidence for lack of health effects.)

VI. Current Conditions in Commercial Buildings

A. Ventilation rates

Limited information is available on current outdoor air VRs in commercial buildings in California. This is partly because VRs are difficult and expensive to measure accurately. A number of available studies used tracer gases to accurately estimate VRs in surveys of U.S commercial buildings (Turk et al. 989; Persily 1989; Lagus Applied Technologies 1995), as summarized by Thatcher et al. (2001), but only one included data from California.

Lagus Applied Technologies (1995) used three tracer gas methods to measure VRs for 49 non-residential buildings, selected as a sample of convenience, in four climate zones in California, including retail, office, and school buildings. The climate zones included north coast, south coast, north interior, and south interior. The retail and office categories were each divided into small (less than 40,000 sq ft) and large buildings. Rates measured were the sum of mechanical ventilation and infiltration when the systems were at minimum damper settings, averaged across the building zones. Table 5 summarizes the building total air change rates measured, reported by Lagus Applied Technologies (1995) as air changes per hour (ACH) and converted here to cfm/person or cfm/sq ft. We converted air change values to cfm/person using formula [1] and to cfm/sq ft using formula [2]:

$$Q/\text{person (cfm/person)} = (ACH * H) / (D*60) \quad [1]$$

$$Q/\text{square foot (cfm/sq ft)} = (ACH * H) / 60 \quad [2]$$

where
ACH = air change rate in air changes per hour

D = typical maximum occupant density figures from ASHRAE Standard 60.1 1989
H = ceiling height
Q = the outside air ventilation rate

Table 5. Building total ventilation rates in non-residential buildings in California (Lagus Applied Technologies 1995)

Building Use	**N**	**Ventilation Rates**			
		Median	**25^{th} %**	**75^{th} %**	**Mean**
		cubic feet per area (cfm/sq ft)			
Retail					
Small	8	0.502	0.385	0.778	0.678
Large	5	0.368	0.192	0.500	0.360
		cubic feet per occupant (cfm/person)			
Office					
Small (<40,000 sq ft)	16	27.8	19.2	42.2	33.0
Large	6	27.2	26.0	50.5	35.8
School classrooms	14	11.2	8.2	14.1	12.2

Table 6 compares the ventilation guidelines used by Lagus (1995), from ASHRAE 62-1989 (ASHRAE 1989), with the most recent equivalent ASHRAE standards in ASHRAE 62.1-2010 (ASHRAE 2010). The recent standards specify both a ventilation rate per person, and one per square foot of occupied area, which are added to give a total ventilation rate requirement, labeled as ASHRAE 62.1 2010. While these two numbers cannot be combined without reference to a specific occupant density, the "combined" ventilation rate column in Table 6 uses typical occupant densities for each type of building use to calculate an overall ventilation rate. The value *ranges* given in the "combined" column of Table 6 reflect varying ventilation rate requirements for different *subcategories* of use within some general building uses.

Lagus (1995) noted that in the offices tested the median ventilation rates were 36% higher than the 20 cfm specified in the ASHRAE 62-1989 requirements. Using more recent guidelines (ASHRAE 62.1 2010), measured ventilation rates exceed the combined minimum ventilation rates by 61%. Schools, in contrast, experienced ventilation rates that were consistently lower than the ASHRAE 62-1989 requirements: 21% of schools had ventilation rates less than half the required 15 cfm /person. Retail ventilation rates shown in Table 5 were found on average to be 50% higher than the 0.3 cfm/sq ft prescribed in ASHRAE 62-1989. Retail ventilation rate standards have changed significantly since 1989, with a shift towards specifying ventilation rates by type of retail. Ventilation requirements for retail sales floors, for instance, if assuming an occupant density of 15 people per square foot, are given as 0.24 cfm/sq ft in ASHRAE 62.1 2010.

Table 6. ASHRAE ventilation rate requirements (ASHRAE 1989, ASHRAE 2010)

	ASHRAE 62-1989	ASHRAE 62.1-2010		ASHRAE 62.1-2010 combined*
Office	20 cfm/person	5 cfm/person	0.06 cfm/sq ft	17 cfm/person
Retail	0.3 cfm/sq ft	7.5 cfm/person	0.06 -0.12 cfm/sq ft	9-26 cfm/person
Classrooms	15 cfm/person	10 cfm/person	0.12 cfm/sq ft	13-15 cfm/person

* assumed occupant densities (cfm/person) are: Office, 5; Retail, 8-40; Classrooms, 25-35.

Another relevant study for California is the Building Assessment Survey and Evaluation Study, in which the U.S. Environmental Protection Agency in 1994-1998 collected data from a representative set of (mostly larger) office buildings across the U.S. (Persily and Gorfain 2008). The study employed three different, widely used methods to estimate VRs, and found that estimates from the different methods varied substantially in ways that could not be explained. This suggests large uncertainty in how to accurately measure ventilation rates in large surveys, and highlights the lack of a standard for comparison.

Among these U.S. office buildings, the median VR based on the three methods were 30 L/s-person, 31 L/sec-person, and 18 L/s-person, based on duct traverses at the air handler intakes, CO_2 ratios, and peak indoor CO_2 concentrations, respectively. These relatively high values reflected, according to the authors, the common use (in 70% of buildings) of economizers that provided “free cooling” by increasing outdoor airflow during mild weather. Because many study measurements occurred during mild weather, the average outdoor air fraction was nearly 40%, compared with the typical 10-20% outdoor air during minimum intake conditions. Among buildings with outdoor air fractions below 20%, however, which were presumed to be operating at minimum intake conditions, 41% of buildings failed to meet the per-person VR requirement of ASHRAE 62-2001 (Persily et al. 2005). (It was not known what proportion of buildings not measured during minimum intake conditions would have also failed to meet this requirement.) So despite the high median and mean VRs, this suggests that a large proportion of U.S. office buildings, especially at times of very cold or hot weather, provide less outdoor air than specified in current standards.

Among 15 California office buildings included in the BASE study, all air-conditioned, we estimated overall mean and median VRs (see Table 7) from data in Persily and Gorfain (2008). These values were estimated using the four to six mean or median VR values provided for each building by Persily and Gorfain; each original measurement was taken during two-three consecutive weekdays during the study week, in either winter or summer, for one morning or one afternoon. Estimated mean and median VRs in California were, by all three measurement methods, substantially higher (medians from 33-133% higher) than those in the US generally. This is likely to be due at least in part to the mild weather conditions in California allowing more use of economizers.

Other data are available from European buildings. The European Audit Project assessed VRs in 56 office buildings in 9 European countries in winter, 1993-1994, using a variety of methods across study centers to measure outdoor air ventilation that included air from ventilation systems, infiltration through the building envelope, and air from adjacent rooms. The average outdoor VR was 25 L/s-person (52.5 cfm/person) (Bluyssen et al. 1996). While difficult to compare directly to U.S. VRs from the BASE Study, these European VRs are still substantially higher than the ASHRAE minimum levels.

Table 7. Outdoor air ventilation rates in U.S. and California office buildings, as estimated with three methods in the U.S. EPA BASE Study, 1994-1998 (Persily and Gorfain 2008)

	OUTDOOR AIRFLOW in L/s-person (cfm/person)		
	Volumetric	CO_2 Ratio	Peak CO_2
U.S. (100 buildings)			
Mean	49 (105)	44 (94)	20 (43)
Median	30 (63)	31 (65)	18 (37)
California (15 buildings)*	77 (161)	60 (127)	28 (59)
Mean	70 (146)	55 (116)	24 (50)
Median			

* California summary numbers calculated from data in Persily and Gorfain (2008)

Few sources provide an estimate of the energy impact the provision of outside air ventilation has on the total whole building energy use. The most careful estimates identified were from a set of simulations performed by the National Renewable Energy Laboratory (NREL) and reported in two publications (Benne et al. 2009; Griffith et al. 2008). These papers provide values of Energy Use Intensity (EUI) predicted with building energy models created using the EnergyPlus 2.1 program. The EUI is the annual energy use per unit floor area. Both papers include results of modeling a large set of hypothetical buildings representative of the existing U.S. commercial building stock based on a national database of commercial building characteristics – the Commercial Buildings Energy Consumption Survey (CBECS; see http://www.eia.doe.gov/emeu/cbecs/). Griffith et al. (2008) provide the predicted EUI values while Benne et al (2009) predict how EUI changes when the minimum mechanical outdoor air ventilation is eliminated (i.e., the observed minimum in the data base of buildings, not the required minimum). For the simulations, Benne et al. (2009) used published measured values of minimum mechanical ventilation rate, which varied with building type and which exceeded the minimum ventilation rates specified in ventilation standards such as Title 24. Based on these simulations, for the full commercial building stock, eliminating the minimum mechanical ventilation decreased the whole building energy use by 6.6%; the natural gas EUI decreased by 21.4%, with a 0.0% change to the electricity EUI. Considering just the national retail sector, the total EUI decreased by 8.6% on average, with the gas EUI decreasing by 27.8%.

The most populated areas of California are almost entirely in climate zone 3C, with part of the

Los Angeles area in zone 3B. In these two climate zones, the models estimated that eliminating the minimum levels of mechanical ventilation in the full commercial building stock decreased natural gas use by 10.5% and 12.5%, but increased electricity use by 3.2 and 1.0%. The total predicted net decreases in energy use (gas and electricity) were only 0.2 and 1.4%. If these predictions are accurate, even substantial reductions in the minimum outside air ventilation rate in commercial buildings in California, if implemented throughout the year, would not produce substantial reductions in overall energy use. Reductions in minimum mechanical ventilation rates during the heating season would, however, significantly decrease gas energy consumption.

The electrical energy *savings* from providing mechanical ventilation in the moderate 3C and 3B climates is presumed to be a consequence of the free cooling provided by the outdoor air ventilation in buildings without economizer systems, and of imperfect control of existing economizers. Economizer systems provide outdoor air when doing so reduces cooling energy consumption. When the mechanical ventilation is eliminated and no economizer system is present, more mechanical cooling is required. If all buildings had economizers with optimal controls, energy savings from mechanical ventilation *above that provided by economizers* would be eliminated.

B. IAQ acceptability and health among building occupants in current commercial buildings

Since ASHRAE has defined acceptable air quality as air considered acceptable by at least 80% of occupants, it may often be assumed that the VRP specifications in ASHRAE 62.1, (Ventilation for Acceptable Indoor Air Quality) will produce buildings that meet that criterion (just as it is may often be assumed that these buildings meet other implicit criteria, such as for health). It has been often noted, however, that little information is available to document that VRs specified in the VRP achieve “acceptable indoor air quality,” for either perceived air quality or health. The IAQP, in contrast, without the historical assumptions of adequacy behind it, comes with requirements to document successful achievement of both acceptability and health targets, whether it leads to lower or higher VRs than those specified in the VRP.

Little information is available on occupant satisfaction with the indoor environment in commercial buildings in the U.S. One of the largest available databases with information on this question has been created by the Center for the Built Environment (CBE) at the University of California, Berkeley. The CBE has published a summary of findings from a web-based survey of indoor environmental quality in office buildings, including responses from 34,169 occupants in 215 buildings in North America and Finland, received by October 1, 2005 (Huizenga et al. 2006). Of the surveyed buildings, 90% are in the U.S., the others in Canada and Finland; about 80% are owned or leased by either federal, state, or local government entities. The sample, made up of buildings whose owners/employers volunteered to participate, is not systematically constructed and may not well represent the general population of buildings. Private-sector buildings are certainly under-represented. The majority of the responses were in summer. The average response rate in buildings was 46% (so findings may or may not extrapolate well to the full target population, depending on whether those who responded were similar to the overall population). The survey asks respondents how satisfied they are with the air quality in their workspace, with responses collected on a 7-point scale ranging from Very Satisfied (+3) to Very Dissatisfied (-3), with a central neutral point at 0. While the overall average vote was slightly positive (0.17), *only in 26%* of the buildings were at least 80% of responding occupants satisfied (votes of 0 or higher); that is, in almost three quarters (74%) of the buildings, fewer than 80% of occupants were satisfied with their indoor air quality (see Table 8). The average building-level satisfaction rate was only 69%, with about half the buildings having lower proportions of satisfied occupants. The proportion of buildings in which smoking was allowed is not known.

Table 8. Proportions of responding occupants satisfied with indoor air quality in office buildings in North America and Finland (Huizenga et al 2006 (Figure 8))

Proportion (%) of occupants satisfied with indoor air quality	Proportion (%) of buildings surveyed with at least the indicated proportion of occupants satisfied
100%	2%
At least 90%	11%
At least 80%*	**26%**
At least 70%	51%
At least 60%	71%
At least 50%	90%
At least 40%	98%
At least 30%	99%
At least 20%	100%

* per ASHRAE, acceptable indoor air quality requires that at least 80% of occupants rate the indoor air as acceptable

Two other interesting findings reported by Huizenga et al (2006): A very strong relationship was seen between satisfaction with air quality and self-assessed productivity impacts – the higher the satisfaction with air quality, the more the air quality was reported to enhance the occupant's ability to get their job done. The slope of the estimated regression line for this relationship, was 0.8. The validity of self-assessments of productivity, however, is unknown. Also, while the overall mean air quality satisfaction rating was 0.17 (on a scale from -3 to +3), occupants with operable windows had significantly greater mean satisfaction ratings than those without operable windows: 0.48 vs. 0.14 ($p<0.01$).

The European Audit Study collected data on satisfaction with IAQ in office buildings among occupants and also using trained panels of visitors, along with measuring VRs as mentioned above (Bluyssen et al. 1996). The response rate of occupants to the survey averaged 79%, allowing confidence that responses represented occupants of the study buildings generally. Overall, 27% of occupants in the European buildings found the IAQ not acceptable at the time of the survey (comparable to the 31% dissatisfied in U.S. buildings), and 32% found it unacceptable during the previous month. In addition, 50% of visitors found the IAQ unacceptable. This was despite the high average measured VRs of 25 L/s-person, far above existing standards. The authors also examined IAQ within only those buildings with adequate ventilation. Among the 44 buildings (79% of the 56 buildings studied) that provided at least the minimum VR specified in ASHRAE 62, only 17 buildings (36% of this subset) also met the ASHRAE aim that 80% of occupants find the air acceptable. The authors concluded that meeting existing ventilation standards [i.e., the ASHRAE VRP] is no guarantee of adequate acceptability of indoor air quality. Perceived air quality by the sensory panels was on average only slightly (but significantly) better in buildings with higher ventilation rates. The article did not report on the proportion of occupants finding air quality acceptable at specific high VRs. It should be noted that some buildings in this study allowed smoking, but no separate findings were provided for buildings with and without indoor smoking.

Other findings of interest in the European Audit Study: a) perceived air quality by the trained sensory panel had no statistically significant correlation with occupants' acceptability rating, or their number of building-related symptoms; b) the mean perceived air quality by the sensory panels had no correlation with the mean TVOC concentration; c) the most important identified pollutant sources (for impact on perceived air quality) were materials, furnishings, and activities in the buildings, and, notably, the ventilation systems, whereas occupants were less important pollutant sources; d) in half the buildings, the ventilation system was identified as the most important pollution source for impaired air quality, and in these buildings, filters and air circulation from other rooms were often specifically identified as the problem source; e) buildings with natural ventilation had the lowest total energy use; f) there was no apparent relationship between VR and total building energy use, suggesting that energy was used primarily for other purposes; and g) higher total energy consumption in buildings was, for unknown reasons, significantly correlated with a *higher* number of building-related symptoms, indicating that high energy consumption did not guarantee a healthier environment, and that low energy buildings could have high indoor air quality (Bluyssen et al. 1996).

The main aim of the European Audit Study, conducted in 1993-1994, was to "develop assessment procedures and guidance on ventilation and source control, to help assure good indoor air quality and optimize energy use in office buildings (Bluyssen et al. 1996, p. 221)." (This provides an example of European countries preceding the U.S. in taking indoor air quality seriously, in the same way that California has also generally preceded the rest of the U.S., such as in this project.) Bluyssen et al. (1996) concluded that the large European Audit Study indicated that in the study buildings, "sources of pollution . . . comprised mostly building materials and components in the ventilation systems. Since the source of pollutants was mainly the building rather than the occupants . . . it is essential to acknowledge the building, including the ventilation system, as a pollution source. To improve indoor air quality without consuming more energy, source control should be applied. Source control should be the first priority instead of dilution of pollutants by ventilation or by cleaning the air. Source control must be applied to the materials, the systems and activities (e.g., smoking). By reducing pollution sources, e.g., by selection of low-polluting floor covering, indoor air quality may be maintained or even improved at lower ventilation rates. Manufacturers of building materials and furnishings should be encouraged to provide information on their products so that engineers and architects more easily can select low-polluting materials. Designers of systems, manufacturers of components and maintenance professionals must be aware of the importance of systems as a potential source of pollution (Bluyssen et al. 1996, p. 237)."

The surprisingly low levels of indoor air acceptability found in U.S. office buildings by Huizenga et al. (2006) were mostly in a population of U.S. government office buildings, but VRs were not measured. These buildings may be similar to the large office buildings represented in the BASE study, which were found to have surprisingly high VRs (except for many with low levels when the systems were at minimum outdoor air flow levels). It is not possible from the published data to assess the level of IAQ acceptability in U.S. buildings with adequate ventilation.

Regarding VRs in commercial buildings and health of occupants, a number of recent reviews have assessed this relationships and provided evidence on whether currently recommended ventilation rates adequately protect the health of occupants. Seppanen et al. (1999) found from a review of all available studies at the time that, while VRs reduced below 10 L/s-person were associated with significant worsening of health outcomes (and of perceived air quality) among occupants, increases in VRs above 10 L/s-person in many studies, up to approximately 20 L/s-person, were associated with further decreases in symptoms among occupants (and decreases in dissatisfaction with perceived air quality). This suggests, but does not prove, that the lower VRs led to increased indoor exposures that increased occupants' symptoms. A more recent controlled experimental study found that VRs of 30 L/s-person, compared to 10 L/s-person, caused significantly decreased symptoms of difficulty thinking, dry mouth and throat, increased satisfaction with perceived air quality and odor and freshness or air, and improved performance of multiple office tasks (Wargocki et al 2000). A recent meta-analysis of VRs and symptoms in commercial buildings confirmed that, based on a quantitative summary of eight available studies, symptoms in occupants increased at VRs below 10 L/s-person, but that as VRs increased from 10 up to 25 L/s-person, symptom prevalence decreased another 29% -- see Figure 1 (Fisk et al. 2009). While this analysis is based on a relatively small number of studies, each using somewhat different symptom-based outcomes, it is the best available summary of the relationship between VRs and occupant symptoms in current commercial buildings.

There is also general agreement among the reports summarized above in suggesting that VRs of 10 L/s-person in current buildings, relative to lower VRs, decreases the occurrence of symptoms and dissatisfaction with air quality, but that even higher VRs – up to 20-30 L/s-person, would further improve health and environmental acceptability. In addition, findings from a number of recent papers on relationships between VRs in buildings and transmission of respiratory infectious diseases among occupants, as reviewed by Li (2009), suggest consideration of this important aspect of health in VR guidelines. Li concludes, based on the available research, that

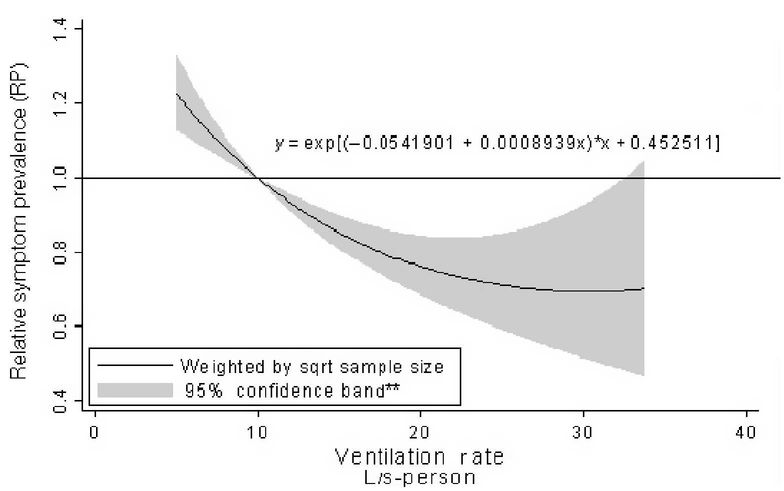

Figure 1. Estimated relative SBS symptom prevalence vs. ventilation rate (copy of Figure 2 from Fisk et al. (2009).

low ventilation rates in buildings are associated with increased infection rates or disease outbreaks through airborne transmission of some infectious diseases, including tuberculosis, SARS, influenza, pneumococcal disease, and febrile acute respiratory illnesses (Li 2009). Li also concludes, based on available evidence, that airflow direction influences airborne transmission of some diseases, including tuberculosis, measles, smallpox, chickenpox, and SARS. Li notes that insufficient data are available to quantify these relationships of ventilation with disease, in order to specify ventilation rates sufficient to prevent the spread of airborne infection, and above which little further benefit results despite additional use of energy. Li points out that further careful epidemiologic research is needed, as simply demonstrating presence of a viable airborne pathogen does not demonstrate airborne transmission of disease, the relative importance of airborne transmission among other routes, or the potential role of building ventilation in reducing transmission.

C. Effect of ventilation rates on indoor concentrations of volatile organic compounds and other contaminants

It is important, when considering requirements for an effective IAQP, to focus on the set of indoor air contaminants for which increased general ventilation could effectively reduce indoor concentrations. Other contaminants, although of genuine concern, should not influence required VRs, but should be controlled using alternate strategies.

Of the categories of indoor air contaminants, only a minority are influenced by ventilation rate. VOCs, many with adverse effects on occupants, are emitted by building materials, contents, and occupants, and can be reduced by ventilation as well as by source control and various air cleaning strategies. Indoor exposures to semi-volatile organic compounds (SVOCs) are not strongly influenced by ventilation. For inorganic gases such as carbon monoxide, oxides of nitrogen, and radon, the lack of significant indoor sources in commercial buildings means that increased ventilation may tend to increase indoor concentrations. CO_2, emitted by occupants, is strongly affected by ventilation, and is not yet controllable by available air-cleaning technology; however, CO_2 at levels encountered in commercial buildings is currently considered not a harmful contaminant, but simply an indicator of the building's performance in diluting occupant-produced bioeffluents. (This would change if CO_2 even at moderate levels were documented to have direct adverse effects on health or performance, as suggested by recent reports (e.g., Kajtar, Herczeg et al. 2006).) For particles from either indoor or outdoor sources, whether inorganic or organic/biological (e.g., fungal spores or pollens), increased ventilation is not an effective way to further reduce indoor concentrations, for two reasons: (1) the repeated recirculation of air through conventional particle filters, as is usual in commercial buildings, removes particles fairly well, so that indoor particle concentrations tend not to be sensitive to VRs; and (2) increasing outdoor air ventilation would increase intake of ambient particles, including ambient fungal spores and pollens, which are generally at higher concentrations outdoors. Even for bioaerosols from indoor sources, such as microbial growth in buildings or infectious agents from occupants, increased ventilation would not be as effective a control strategy as slightly increased effectiveness of particle filtration. Thus, consideration of indoor air contaminants for which acceptable levels can be maintained through adequate ventilation should focus currently on VOCs (and, pending future research findings, possibly CO_2), as long as particle filtration efficiency is adequate to control indoor generated biological bioaerosols and other particles.

It is often assumed that the influence of VRs in buildings on the indoor concentrations of VOCs emitted by the buildings, their contents, and their occupants can be readily estimated with mass balance models. Limited research is available on these relationships in real buildings, rather than in chambers or from mathematical models. Hodgson et al. (2003) studied a call center office building, manipulating VRs over a 13-week period while measuring VOCs and CO_2 concentrations on 7 days. Only several of the eight VOCs measured showed the often assumed clear inverse relationships between their indoor minus outdoor concentrations and VRs. However, given the known effects of outdoor air pollutants, linkage of emission rates to indoor air concentrations, and depositional losses of pollutants, one should not expect simple inverse relationships between ventilation rates and indoor pollutant concentrations. Net indoor concentrations of low volatility compounds, for instance, showed little change with ventilation, presumably due to sorption and re-emission. The authors concluded that, because the efficacy of ventilation for controlling indoor VOCs can be quite variable, effectively limiting VOC concentrations in office buildings requires source control in addition to adequate ventilation. They mention, as potentially effective source control measures: exhaust ventilation for localized pollutants, use of low-emitting materials for surfaces and furnishings, use of low-emitting cleaning products, and limited use of products with chemicals highly reactive with ozone.

Formaldehyde concentrations in Target stores were not consistently reduced at higher VRs within the range of 0.05-0.10 cfm/ft^2 (Grimsrud et al. 2009). Available findings in residences were not fully consistent. In a residential survey in California, VRs had substantial and significant inverse correlations with indoor formaldehyde concentrations, stronger than the other home characteristics and environmental conditions studied (Offerman 2009). However, in another residential study, formaldehyde concentrations did not change in predicted ways with ventilation rate, which the authors attributed to a potentially positive relationship between formaldehyde *emission* rates and ventilation rates (Hun, 2009).

VII. Discussion

This review provides information to aid the CEC in deciding whether to adopt the current ASHRAE 62.1-2007 (with its approved revisions for 2010) into Title 24, thus allowing use of the IAQP for setting minimum required VRs in big box stores and other commercial buildings in California. We will consider these subsidiary questions:

- Is the current (2010) IAQP language sufficient, and are enough information and expertise available, to implement this strategy successfully in California, so that commercial buildings such as big box stores could save energy while providing still reliably acceptable and healthy indoor environments?
- If the current IAQP language is not suitable, or the available information and expertise are not sufficient, are there either revisions or new data that could produce a suitable IAQP?

In this section, we discuss the potential of the ASHRAE 62.1 IAQP, as is or revised, to improve the current, prescriptive ventilation rate standards. Given the previously listed benefits and limitations of the current IAQP, we discuss possible strategies for revision to achieve an adequate standard. Finally, we consider the suitability of adopting the IAQP into California Title 24, in its current form or in some revised form.

A. Problems with the current prescriptive VR standards

The findings reviewed in this paper suggest that a revised approach to a ventilation standard for commercial buildings is desirable, and will become increasingly necessary, Two primary problems, a present and a future one, are evident with the current prescriptive "ventilation rate procedure" standards used for commercial buildings in California and many other places:

- Current commercial buildings, designed and operated per VRP specifications, are not now providing occupants with the quality of indoor air implicitly promised by the standards. Commercial buildings in both the U.S. and Europe, given current building features, contents, occupants, and ventilation rates, do not provide air considered acceptable by a sufficient proportion of occupants. Furthermore, ventilation rates above current minimum guideline levels significantly reduce health symptoms in occupants, and these benefits do not begin to taper off until substantially higher levels than the current recommended minimum, implying that current recommended ventilation levels allow levels of indoor pollutants that increase symptoms in occupants. Dramatically increasing ventilation levels as a solution, however, seems too costly and energy-intensive, still might not adequately reduce indoor pollutants of concern, and in some locations would substantially increase existing problems with intake of highly polluted or humid outside air.
- California buildings must, by State law, achieve zero net energy status by 2030. Ventilation, heating, and cooling systems consume a large proportion of the energy used in buildings. Thus, reducing ventilation rates and the associated costs of heating and cooling the outdoor supply air seems clearly necessary. Yet available evidence suggests that this would not be achievable by simply lowering prescriptive ventilation standards, because this would lead to indoor air even less acceptable and less healthy than the current situation.

B. Potential promise of the IAQP

Any feasible solution to these problems is likely to require methods of pollutant reduction in addition to outdoor air ventilation, so that VRs lower than those prescribed today can produce adequate IAQ. This will also require a more explicit approach to ensuring safe and acceptable indoor environments. The current IAQP (2010 language), requiring designs that control COCs to specified health- and acceptability-related limits using strategies that may include source control, air cleaning, and outdoor air ventilation, allows movement in this direction, whereas the VRP does not. With the IAQP, outdoor air ventilation would be *just one of multiple tools* for achieving adequate IAQ.

The current IAQP, relative to the current VRP, offers potential benefits of two types (listed in Table 1). One type of benefit is that the IAQP allows lower VRs while providing at least equivalent IAQ and thus allows a) savings on energy and operational costs; b) possible savings on construction costs; and c) reduced problems when taking in very polluted or humid outdoor air. These benefits *require lower VRs* than with the current VRP. The other type of benefit is that the IAQP allows *improved IAQ, health, and satisfaction* in buildings through setting of explicit health-based and acceptability-based concentration limits, which can be achieved through a combination of strategies beyond ventilation. This second type of benefit is available even now using the current VRP, but offers little incentive for most building owners and managers using the VRP to undertake the extra effort and cost, because it does not allow accompanying reduction of VRs below prescribed levels. Ventilation rate standards that are linked to achieving specified levels of indoor pollutants and acceptability, rather than prescribed without explicit consideration of air quality, could better document healthful indoor environments, and also reward designers and owners who control indoor pollutants by allowing lower energy costs from reduced outdoor air ventilation.

One additional aspect of the IAQP: the consideration of substance-specific concentration limits in the design of general indoor environments would make ventilation standards for commercial buildings more parallel to health standards for occupational settings and outdoor air, in which maximum allowable concentrations are set for specific recognized harmful exposures, based on a goal of health protection. This would eliminate a blind spot in the current protection of the general public in commercial buildings and also of indoor, non-industrial workers. Note that health-protective concentration limits in general indoor environments in commercial buildings may well differ from those in industrial work environments: the presence in commercial buildings of many, mostly uncharacterized, potentially changing exposures to a diverse population, some with increased susceptibilities, differs from the smaller numbers of well-studied exposures to healthy workers in industrial settings. But the IAQP in theory allows selection of concentration limits deemed appropriate for any specific environments and populations.

C. Limitations of the current IAQP

There seems to be little disagreement in principal, in the material reviewed here, on the *desirability* of an IAQP-like approach to VR standards. Nevertheless, the current IAQP seems to many to be too limited by insufficient specifications and inadequate available data for current use. The various critiques simply say, not this version, or not with the currently available data, or not with the currently available level of expertise among designers. These concerns have resulted in a general reluctance to use the IAQP even in U.S. locations where it is allowed.

Major limitations of the current IAQP (listed in Table 2) can be grouped in four categories:

- *may not adequately protect IAQ and occupants initially;*
- *may not adequately protect IAQ and occupants in the future;*
- *too imprecise, can calculate too wide a range of required VRs;*
- *poor fit with skills, knowledge, experience, and needs of engineers/designers.*

These multiple, substantial limitations make the IAQP in its current form seem inappropriate for application in California. Of course, the VRP has some of the same limitations (including that providing the VRP-prescribed VRs does not guarantee indoor air contaminants below any threshold levels or target concentrations, does not guarantee healthy indoor air quality), and also other limitations (such as providing no evaluations of this effectiveness, for health or acceptability).

D. Possible strategies for improving the current IAQP

The current IAQP provides an excellent framework for a new approach to VR standards, that allows savings on energy and costs, but it has substantial limitations related to inadequate protection of occupants, imprecision, and difficulty in use. In response to criticisms made of the current IAQP, strategies are proposed in Table 9 to improve the IAQP so that it will provide healthy and acceptable indoor air at acceptable levels of energy use and cost. The suggestions are organized under seven goals, but not by priority. Items requiring research are marked with [R].

A table summarizing sources of pollutants of concern for consideration with an IAQ Procedure that allows lowered ventilation rates is provided in Appendix 4.

Meanwhile, an "alternate VRP" might serve as a useful transition to a fully developed IAQP, focused on a different goal than the IAQP: not achieving "fully adequate IAQ," but "saving energy, with IAQ at least as good as with the VRP." A fully effective IAQP, which would save energy while also assuring acceptable indoor air quality and acceptability, based on available evidence would provide more healthful and acceptable IAQ than the current VRP. The changes needed to allow such an effective IAQP, however, are many and complex, and it is not clear how long this would take, or if it is even achievable. Because of the urgent need to save energy, a compromise approach might be acceptable. An alternate VRP could allow reduction of ventilation rates below those prescribed by the current VRP, with accompanying energy savings, while ensuring that the specific indoor COCs that are effectively controlled by ventilation were no higher, and possibly lower, than levels achieved by the current VRP. This would involve identifying all such relevant COCs, measuring their levels with the current VRP, (possibly determining if any of these were above acceptable levels,) and then setting upper limits for indoor air in a building, through use of source reduction, air cleaning, and outdoor air ventilation. Relevant COCs for this would include VOCs and possibly CO_2. Particle filtration efficiency may need some increase to adequately control indoor generated biologic aerosols, whether from microbial growth or infectious agents. This approach would provide incentives for development and use of strategies for both source reduction and air cleaning to reduce VOCs at lower VRs, possibly resulting in lower COCs than with the current VRP. It might also serve as a practical step on the path to developing progressively more health-protective VR standards, with progressively lower limits for key COCs.

Table 9. Possible strategies for improving the current IAQP (not ordered by priority; items requiring research marked [R])

Reduce aspects of IAQP that deter engineers and owners • Revise IAQP so less arbitrary and challenging to use and results more consistent, to provide a clearer path to successful compliance, in order to reduce designers' fear of error and liability to a level that, given appropriate supplementary expertise, will be no greater than with VRP. • Explicitly define the supplementary, non-engineering expertise that is required to use the IAQP successfully. • Collect or facilitate development of standardized information for use with IAQP, such as on COC selection, concentration limits, and material emissions, to eliminate need for designer to recreate this info for each design. [R] • Provide incentives for designers/owners to use IAQP; necessary because the increased complexity and time required for IAQP currently discourages use; incentives are initially justified by the positive external social benefits that will result; eventually positive internal benefits may incentivize more directly. • Resolve the current problem that an IAQP-based design cannot be successfully completed until the confirmation of subjective acceptability by occupants of the completed building, thus requiring occupancy before the system design is "completed." • Work with designers/owners to learn what approaches in a revised IAQP would make adoption feasible. [R]

Create standardized information on COCs, protective target concentrations, and effective control methods
• Synthesize model lists of COCs based on observed levels in commercial buildings and current estimated hazard to human health and acceptability, to ensure consideration of important compounds/mixtures and to facilitate use of IAQP by designers;
  o consider available exposure and human response data. [R]
  o distinguish priority levels among potential COCs, based on indoor concentrations and estimated human hazards. [R]
  o consider including compounds mentioned in the studies cited in this report, additional compounds or health effects not considered in cited studies (e.g., compounds that are very volatile, of low occurrence, not currently well-measured, or not included in the literature, and compounds with other effects such as carcinogenic, immunologic, allergic, neurologic, or reproductive), and sources in buildings shown to be problematic but with specific problem emissions not yet identified, such as ventilation systems and filters (see Appendix 4 for examples of approaches for identifying additional sources or emissions of concern). [R]
  o explicitly consider indoor exposures of emerging concern, such as aldehydes, phthalates, other plasticizers such as TXIB, flame retardants, glycol ethers, carbon dioxide, dampness/mold, and infectious airborne agents. [R]
  o recognize, in selection of COCs and target levels, the current inability to measure all indoor air contaminant exposures that may have adverse effects and, even for many exposures that can be measured, the lack of health-based exposure limits, including limits for potential chronic effects.

o consider creation of alternate lists per specific space uses, with included compounds determined in part by input from the relevant industry, such as hardware, clothing/fabric, building materials, furniture, electronics, etc. [R] o explicitly consider the HVAC system, including filters, as a source of indoor pollutants with odor or health consequences. o produce key missing data through emission testing, health effects testing, and creation of product emission databases. [R] • Suggest concentration limits for specific compounds and mixtures: o include consideration of the issue of mixtures of compounds with related mechanisms of human biologic response. o identify key missing data on exposures and human response, for compounds with either widespread high exposure levels or high index of suspicion for adverse health effects. [R] • Revise the IAQP to address issues for specific building uses, such as different COCs expected, or the greater importance of emissions from products in retail buildings, which may be relatively more important than contents in other building uses, may emit a broader variety of compounds, and may change more over time. • Assemble or create data on methods of control for classes of COC for which removal by ventilation is not easily predicted or is not effective; document the relationships between VRs and indoor concentrations of: o Compounds for which air concentrations cannot be easily estimated by mass balance models, such as formaldehyde. [R] o Compounds not effectively reduced by ventilation, such as SVOCs, inorganic particles, outdoor sourced inorganic gases and organic/biologic particles, which may require control entirely by strategies other than ventilation, and thus may not belong in a VR standard.
Revise IAQP to increase confidence that the building system would protect occupants over time • To ensure protection at initial occupancy, require post-construction but pre-occupancy commissioning (testing/measurements) of indoor concentrations, ventilation rate. • Require documentation of efficacy over time of approved IAQP design, re provided VRs, air cleaners, and indoor concentrations, to prevent loss of occupant protection due to poor maintenance, changed operation, or degradation of equipment; such requirements should be balanced against posing a substantial burden that will limit use of the IAQP. • Develop certification of air cleaning technologies, re efficacy, lifetime, and required maintenance, with respect to multiple types of COCs. • Include explicit provision for maintaining adequate IAQ during periods of increased indoor concentrations, such as after periods of no ventilation, or after constructions or renovations.
Increase acceptability of IAQP to the public health and occupational health communities • Develop and emphasize parallels to the traditional model of environmental health risk assessment and risk management routinely used for public health environmental policies, such as in occupational settings and with ambient pollutants. • In specifying procedures for protecting occupants, consider different building uses, and require that those in the building for longer periods be the occupants considered most at risk for health effects (e.g., store employees vs. customers), whereas for odor acceptability,

consider that visitors will be more sensitive.
Facilitate potential of the IAQP to lead to lower indoor emissions and lower VRs, by linking VR standards and product emission standards and testing such as in the California Green Building Standards • Consider linking VRs to Green Chemistry policies to provide some protection against wide use of novel compounds/products with adverse health effects • Consider defining a process to identify new products of potential concern that will be used in buildings, and any needed adjustments in buildings to control concentrations
Identify the sources and contaminants causing widespread low acceptability of IAQ in current commercial buildings [R]
Develop improved, practical methods for measuring VRs to allow confirmation that systems meet design intent [R]

VIII. Conclusions: Issues in adopting an IAQP into California Title 24, especially for use in Big Box stores

The purpose of this report is to provide the Nonresidential Building Standards Program of the CEC with information that will help it establish ventilation rate standards for big box stores and other commercial buildings that would balance reduced energy use with the maintenance (or improvement) of occupant comfort, health, productivity, and performance.

Although many might say the current VRP is working well, careful research has shown that it has failed to provide the acceptability of air and even the health protection that is assumed. The VRP has many of the same limitations as the current IAQP, including lack of guarantee that compliance guarantee that compliance provides adequate IAQ, either initially or later. Addition to the VRP of some features or strategies associated with the IAQP, such as reduced emissions and air cleaning, documented sub-limit concentrations of COCs, and verified acceptability of air to occupants, should improve health and acceptability of indoor air even at the VRP-prescribed VRs. However, owners have no current incentive to undertake this extra effort and cost, and are unlikely to take these steps unless newly required. This kind of requirement could be a state-level standard, or an optional guideline from a group such as ASHRAE or the U.S. Green Building Council. And the primary potential energy- and cost-reduction benefits of the IAQP are available only with reduced VRs, and thus cannot be attained with the current VRP.

The opinions we encountered on the use of the IAQP to set ventilation standards ranged from believing that the current IAQP was usable in roughly its current form with adjustments sufficiently minor so as not to make it burdensome, to, at the other extreme, believing that because we cannot yet confidently define healthy indoor air and harmful indoor exposures, we should not yet use an IAQP to reduce minimum VRs in buildings to save energy, but should use heat recovery strategies with current VR levels until we accumulate sufficient new knowledge.

In California, energy-related benefits from the IAQP due to lower outdoor air intake will be smaller than in other areas of the U.S. Reduced energy use from a reduced need to condition outdoor air is not always a large savings in California, due to moderate summer and winter climates in the most heavily populated zones. Ability to use economizer cooling for many hours of the year in California means that cooling load is low or zero. The IAQP will also offer limited benefits from allowing reduced intake of very humid outdoor air. However, the benefit from reduced intake of very polluted outdoor air would be substantial in many parts of California, such as the south coast and internal valleys.

It thus will be necessary to consider for California the more limited potential benefits of a revised IAQP than in other parts of the U.S., in combination with the extra costs of following its more complex requirements and the risks that it will fail to protect occupants without substantially increased knowledge about the nature of healthy and acceptable indoor air.

Amidst the complex weighing of the factors involved in changing such a key California standard, there is also the issue that the financial benefits from the IAQP of reduced initial construction costs (from downsizing of the HVAC system for lower required VRs) and long-term operational costs (from reduced energy use by the HVAC system) must be weighed against any increased initial and long-term costs of enhanced air cleaning technologies and reduced-emission materials, plus the costs of any initial and ongoing confirmation that the building is meeting design targets of IAQ over time.

Given the current limitations of the current ASHRAE 62.1 IAQP (2010), in combination with the lack of information and expertise needed to use it, it does not seem that implementation for big box stores and other commercial buildings in California now could save energy while providing reliably acceptable and healthy indoor environments. Still, an IAQP approach seems ultimately essential to achieving this goal.

Revisions and availability of new data could allow an improved and effective IAQP. However, most of these changes would add to the complexity of the standard, some of the changes would add to the burden of building owners, some would require changes in professional practices or in the market, and, while some might be implemented relatively quickly, some would require substantial research and time.

It may be that some combination of elements from the current 62.1 VRP and an IAQP with revisions and additional data may allow a modified VRP that provides a more suitable California ventilation standard than either the current VRP or IAQP alone. Such a hybrid that synthesized an overall strategy, incorporating the strengths and reducing the weaknesses of each, and allowing reduced VRs to save energy, might have promise. This could be improved over time to provide better IAQ as knowledge increases and available technological strategies improve.

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Appendix 1. Material on benefits and limitations of the current IAQP, from the literature review

1a. Three types of potential benefits from the IAQP have been mentioned:

- Allow lower VRs to save energy and money, while providing IAQ at least equivalent to VRP
    - Muller (2008) points out that, for designers wishing to save building energy while maintaining or improving IAQ, the VRP does not allow energy saving through reduced VRs, even if using air cleaning. (Energy savings with an economizer cycle or heat recovery systems are not mentioned.) To save energy, the presentation says, the IAQP must be used, and allows "a balance to be struck between IAQ and energy conservation."
    - Camfill Farr (2002) points out that the IAQP allows substituting air filtration for some outdoor ventilation air to improve air quality, which allows savings from reduced ventilation.

  Other benefits of this type mentioned by participants at the TAC meeting:
    - Allows lower VR for indoor spaces with low pollutant loads
    - Lower VRs with IAQP allow reduced initial construction costs for smaller and simpler HVAC equipment
    - Significant resulting reduction in energy use leads to lower peak electrical demand
    - Can help California achieve zero net energy in non-residential buildings by 2030

- To improve IAQ and health in buildings through setting of explicit health-based and acceptability-based limits for contaminant concentrations
    - Stanke (2007) notes that the IAQP is particularly useful for projects where "specific contaminant concentrations or specific levels of occupant perceived satisfaction are the design goal." These projects "might be expected to require more outdoor airflow than that prescribed by the VRP," and "the IAQP helps determine how much more."
    - Camfill Farr (2002), in a Technical Services Bulletin, points out that for buildings with unusual contaminant sources, including the recently constructed or renovated, the IAQP must be used. This bulletin also points out that reduced VRs allowed by the IAQP can solve problems with polluted outdoor air that, when introduced by ventilation, may increase indoor contaminant levels
    - Bayer (2009) points out that ventilation rates higher than current standards, even up to 45 cfm/person, have been shown to improve health, productivity, and learning of occupants; however, using these rates would require substantially increased energy and costs, and would increase indoor levels of outdoor air pollutants in some locations. Therefore, gas phase filtration could improve IAQ without raising VRs, or even while lowering them. [Note – the former would not require use of the IAQP, while the latter would.]

  Additional benefits of this type mentioned at the October TAC meeting include:
    - To improve IAQ and health in buildings through reduction or removal of indoor pollutants
    - To provide VR standards that actually protect health, which VRP may not (explicitly estimates VR necessary to protect occupants, whereas the VRP may not be adequately protective)
    - To identify and reduce some sources of indoor pollutants

  - To help educate about IAQ by stimulating consideration of which contaminants may be of concern
  - To encourage use of low-emitting building materials and cleaning/maintenance products
  - To encourage collection and availability of standardized data on low-emitting building materials and cleaning/maintenance products

- Reduces problems with intake of outdoor air

  Benefits of this type mentioned by the TAC include:
  - To reduce outdoor air (OA) intake where outdoor air pollutant levels are high, which reduces amount of dirty outdoor air needing cleaning, and improves indoor air quality
  - To reduce OA in areas with high outdoor relative humidity, which solves problem of either providing inadequate OA, bringing in too humid OA with resulting problems, or cost involved in extra humidity removal (not so important in CA)

1b. Three general types of limitations of the current IAQP have been mentioned:

- <u>May not adequately protect occupants or IAQ, in the present or the future</u>
  - Offerman (2008), in a presentation that assesses the available data on exposures to indoor contaminants for use in building design using the IAQP, lists key limitations in available knowledge. Insufficient information is available to determine the healthfulness of indoor air, due to a) the current inability to assess and measure all indoor air contaminant exposures; b) for those exposures that can be measured, a lack of sufficient health-based exposure criteria to determine acceptable levels for many; and c) even with available health-based exposure criteria, because they are only set for single contaminants, we lack the ability to assess effects of multiple contaminants that may have additive/synergistic or antagonistic effects. Thus, he says, air contaminant concentrations that are below established health-based criteria levels provide necessary but not sufficient evidence for lack of health effects from air in a building. Offerman provides an example, from his consulting practice, of building occupants with respiratory symptoms clearly related to indoor exposures (in a laser printer test lab) but not explainable by existing measured exposures and health guidelines. His hypothesis is that ultra-fine particles containing cyclic siloxanes, emitted by laser printing but without exposure guidelines, cause the respiratory irritation.
  - Offerman (2008) recommends against reducing minimum VRs in buildings to save energy, because of our limited current ability to define healthy air only for the few air contaminants that are measurable and also have health-based exposure limits, and our inability to document health-protective criteria for indoor air as a basis for evaluating specific lower levels of VR in buildings.
  - Shaw (1997) suggests more complex VR specifications for controlling contaminants in order to resolve a limitation of the IAQP -- it now allows a designer to have a newly constructed building occupied before initial material outgassing occurs, and then to conduct assessments of contaminant concentrations and IAQ acceptability at some indefinite time later after emissions have declined. This may cause adverse

exposures of two kinds – from indoor build-up after short periods of no ventilation, such as over weekends and vacations, and after renovations.

Additional limitations of this type mentioned at the October TAC meeting include:

- The current IAQP requires control of specific "contaminants of concern for purposes of the design" (ASHRAE 2006). An earlier version of the IAQP required "the control of all known contaminants to some specified acceptable levels within a space." The language has gone from very inclusive to much too nonspecific.
- Specification of contaminants and mixtures of concern, which health-based limits and which time period, taken from which cognizant authority, all left entirely to designer, who as mechanical engineer traditionally has been entirely untrained to make these judgments; no minimum list of required contaminants or limits, no standardization, and no oversight (see also limitations below related to lack of guidance for designer on COCs)
- An IAQP based on current limited health risk data may not fully protect health (or performance) of occupants; e.g., may not protect occupants' health because reduced VRs would increase airborne concentrations and adverse effects of a) current measured contaminants with unknown chronic effects, b) currently unknown/unmeasured contaminants with adverse effects, or c) contaminants from future contaminant sources that emerge after IAQP process and building design
- The IAQP has a big problem because some concentration limits from cognizant authorities may not sufficiently protect the health of general populations. For example, the OSHA formaldehyde limit, updated in 1992, sets an 8 hour TWA of 750 ppb for occupational exposures. This is therefore the *current* legal limit for workers in offices, stores, and schools. However, this is much higher than the current limits from California OEHHA, HUD and other authorities, yet a designer has perfect freedom to choose higher levels available.
- Designers using the IAQP will usually specify a VR adequate for the <u>worst single indoor contaminant</u>, which ignores potential combined effects of multiple chemicals each at low, sub-limit concentrations; this is a problem if multiple chemicals have effects on the same organ system are additive or more than additive, because their total concentration may exceed an acceptable levels but would not be considered
- The IAQP should explicitly consider the HVAC system as a source of pollutants, including filters, based on current scientific findings
- Specific examples of chemicals that might need consideration in the IAQP, based on recent scientific findings --formaldehyde, phthalates, TXIB, other plasticizers, glycol ethers, fire retardants; dampness/mold; infectious airborne agents from occupants
- If IAQP becomes widely used for setting ventilation rates, new chemical emissions from continually introduced new indoor materials (buildings, furnishings, surfaces, products) may increase unrecognized health risks at commonly used ventilation rates,
- Systems designed with the IAQP can rely on untested systems for air cleaning
- A reduced-capacity HVAC system per IAQP calculations may not be adequate for increased future ventilation needs due to new pollutant sources or activities
- California health-related agencies (CalOSHA, CDPH) and the health community worry that reducing VRs will reduce occupants' margin of safety without adequately reducing

sources of risk; VRP-prescribed VRs may not have a solid scientific basis, but have history and track record;
- Title 24 doesn't include continued maintenance over time; we have already seen poor compliance and maintenance with current VRP standards; lowering VRs even further with IAQP is a potential problem if low maintenance/compliance because less margin of error, especially for sensitive populations
- A one-time measurement to determine the indoor concentration of contaminants in a building for the future in inadequate; this really merits ongoing periodic monitoring or real-time sensors, or even do demand-controlled VRs.

- <u>Procedures too imprecise, can calculate wide range of VRs\</u>
    - Muller (2008) points out that the LEED criteria require use of the ASHRAE VRP or the applicable local code, whichever is stricter, which may require filtration of outdoor air pollutants, but does not allow use of the IAQP, as its specifications are too imprecise.
    - Too many unknowns, so calculated OA flow outcomes will vary broadly (maybe less problematic in repeat, similar buildings, eg, big box retail)
    - IAQP can be manipulated to give desired answer; needs more detailed guidance

- <u>Reluctance of engineers/designers to use IAQP</u>
    - Stanke (2007) says that while many ventilation system designers would like to use "credit" from increased air-cleaning or lower indoor emissions to specify lower VRs, they may be reluctant to make the non-engineering judgments required to used the IAQP to justify these lower VRs, because of the additional knowledge required and the perceived risks involved with these new kinds of judgments, including:
        - Issues with the requirement to select COCs – the standard doesn't stipulate whether to select based on experience, analysis of similar buildings, documented contaminants indoors or outdoors, or findings from others, nor does it include any comprehensive list of contaminants. The identification of an appropriately complete set of COCs requires non-engineering judgment and, while possible, may seem daunting to engineers, and would also pose risks of error.
        - Issues with identifying sources for each selected COC, or conversely selecting COCs based on knowledge about indoor or outdoor sources -- this requires new cooperation of the engineer with the architect, and new material-emissions knowledge.
        - Issues with determining source strengths for each COC for all identified indoor and outdoor sources -- these determinations may require literature searches or materials testing in areas involving non-engineering judgment.
        - Issues in specifying concentration limits and exposure times for COCs and the corresponding cognizant authorities – all these determinations require non-engineering judgments.
        - Issues of increased burden from detailed documentation, relative to the VRP.
    - Muller (2008) says that calculating expected indoor contaminant concentrations or required ventilation rates for the IAQP can be difficult and confusing. He says that the apparent complexity of applying the IAQP, and the increased requirements for

assuring compliance are the reasons the IAQP is not often applied, despite the significant cost and energy savings it makes possible.

- A 1997 article by Trane analyzes the 1993 version of the IAQP, concluding that the IAQP "fails to provide a well-defined, enforceable path to compliance with the standard. Until it is revised, this procedure is not likely to be widely used by building designers." (Trane 1993, P. 7) While several of the cited problems are no longer in the standard, several still remain. For instance, The Trane article says that the 1993 IAQP standard set required concentration limits for 10 contaminants (Trane 1997), but says that this does "not include all known contaminants that may be of concern, and these concentration limits may not . . . ensure acceptable indoor air quality with respect to other contaminants (Section 6.2.1)." Since then, the language in the standard has changed. Now, in 62.1-2007, informative Appendix B provides selected standards and guidelines from various cognizant authorities, but emphasizes that the table is presented only as background information. It says that specialized expertise should be used to select from these values for calculating required VRs for the IAQP, but also says, "Meeting one, some, or all of the listed values does not ensure that acceptable IAQ . . . will be achieved," and "At present, there is no quantitative definition of acceptable IAQ that can necessarily be met by measuring one or more contaminants." (ASHRAE 2007, p. 23) Thus, the Trane comment about the prior language is still relevant: "…this observation unravels the IAQP as the performance-based path to acceptable indoor air quality. It implies that, even if the known and specifiable contaminants listed are controlled to the established concentration levels, indoor air quality still may not be satisfactory. . . . The building designer has no clear, indisputable definition of acceptable indoor air quality. . . Consequently, many designers choose to use the VRP in which the requirements are clearer and compliance to those requirements is more easily demonstrated."
- The Trane article also points out a problem with the IAQP requirement for subjective evaluation of acceptability of the indoor air: "From the designer's viewpoint, this requirement weakens the IAQP considerably. . . The building designer is required to design a system that adequately controls contaminants to a level that will be judged acceptable in subjective evaluation by impartial observers. So, a positive subjective evaluation is a system design requirement. But it can only occur after system installation and building occupancy. It is unclear how a building can be occupied before the system design is completed. (Trane 1993, p. 4) Furthermore, ". . . a designer cannot comply with the standard without a successful subjective evaluation of the completed system" (Trane 1993, p.5).
- Bayer (2009) says that limited use of the IAQP is due to, for example, lack of understanding of how to select and design for indoor and outdoor COCs, lack of data demonstrating use and effectiveness, and cost-effectiveness of the IAQP, and concerns about determining filter lifetimes.
- Tshudy (1998) demonstrates step-by-step application of the IAQP (as defined in ASHRAE 62.1-1989) to four hypothetical but typical building situations. The goals of the article were: to demonstrate the key decisions required, demonstrate potential problems, uncertainties, misinterpretations, and needed clarifications; suggest additional research and information needed to follow the procedure. One major problem in application is the many judgment-based decisions required, each requiring

greater knowledge and understanding than is possessed by most design engineers: e.g., identifying contaminants of concern; identifying specific sources, including their amounts and emission rates; establishing outdoor concentrations; determining relevant exposure times; selecting acceptable indoor concentrations of contaminants for specific human responses, which includes selecting a relevant cognizant authority; selecting a time point for prediction of indoor concentrations; selecting a sufficiently accurate method for calculating VRs, and selecting a method for defining occupant acceptability. Another critical problem is the limited availability and quality of the data needed on emissions. The resulting large variability in calculated VRs (by a factor of up to 26) resulting from the many judgments, assumptions, and estimates required in the process allow, says Tshudy, limited confidence in the successful application of the procedure. The results would not be acceptable from either an engineering or a legal point of view. Tshudy lists specific clarifications, types of additional information, and additional research needed to make the IAQP procedure practical and commercially useful. These include improved and expanded materials emission data from standardized protocols, estimated emissions over time from well-characterized products, increased information on human responses to key indoor pollutants, expanded availability of authoritative guidelines on acceptable human exposures to indoor contaminants, development of more sophisticated procedures for VR calculations that reflect the variety and time-dependence of indoor sources, and improved methods for evaluating acceptability of indoor air quality.

Additional limitations of this type mentioned at the TAC meeting include:

- Engineers are not trained in the IAQP and don't know how to use it
- Fear of liability with the IAQP -- use of the VRP, although not science-based, takes much of liability risk off engineer; although VRP says that it may not provide adequate VR (a caveat included to protect ASHRAE), most designers using the VRP never consider whether any atypical sources are present
- If an engineer initially tries the IAQP, finds higher VR than with VRP, and then applies the VRP instead, any resulting liability may be a disincentive to even trying the IAQP
- The IAQP is too expensive to use in one-off buildings; engineers don't have time to fully engineer the system, because hard to get owners to pay for cutting edge design
- Too much time required to use complex IAQP procedure, to no practical to use; in fact, conscientious engineers may price themselves out of the market
- Engineering fee is usually % of costs, and IAQP is likely to being construction costs down, making it even more unattractive for engineers to use.
- The IAQP is most practical for use by owners creating multiple buildings of similar design, can fine-tune results over time in sequential buildings at acceptable cost

Additional types of limitations mentioned at the TAC meeting include:

- <u>Technical limitations to lowering VRs using the IAQP</u>
  - Required exhausts and pressure relationships in a building may set a practical minimum VR supply below which even no reduced pollutant load will allow further reduction; this needs to be made clearer
- <u>Cost disadvantages of IAQP</u>

- Air cleaning/filtration increases costs for installation, maintenance, labor, which reduces cost advantages of IAQP

Appendix 2. Benefits and limitations of the current IAQP mentioned during an exercise at the TAC meeting on October 26, 2009.

Benefits of the IAQP

<u>Improve IAQ/health through pollutant reduction/removal</u>

- Cleaner indoor air, regardless of impact on OA flow rates
- Encourage use of low-emitting building materials and cleaning/maintenance products
- Control of indoor airborne contaminants are limited below acceptable levels
- Clean up dirty outdoor air; lower VRs reduce amount of dirty air needed to be cleaned when outdoor air is polluted
- Lead to VR standards that actually protect health, which VRP may or may not
- ID & reduce some sources of pollutants
- IAQP helps educate folks about IAQ by having them consider what/which contaminants may be of concern

<u>Lower ventilation rate standards to save energy/money</u>

- The State is moving towards zero net energy by 2030 for non-residential buildings. Lower IAQ ventilation rates will help us get there
- When appropriately applied, significant energy reduction including peak electrical demand reduction
- Reduce energy consumption during peak demand periods
- Allow less vent rate for space with low pollutant load
- Save energy – can work well for predictable contaminant sources
- Current T24 IAQP wastes energy due to over-ventilation
- LEED-increased ventilation wastes energy. Why increase 62.1 rates by 30% if 62.1 provides needed VR?

<u>Lower VR to make vent system design easier/better</u>

- Optimizes package design and operation for OA
- Reduce OA so as to allow easier application of packaged equipment
- Drive use of more effective technologies

Limitations of the IAQP

<u>May not adequately protect occupants/IAQ, in present or future</u>

- May not protect against chronic health effects
- Problematic if there are unpredictable contaminant sources
- Allows CO_2 levels to rise, particularly in buildings with high occupancy
- If not properly done it could affect IAQ negatively (health + productivity)
- Inappropriate use of any ventilation procedure can lead to poor IAQ
- Reduced VRs increase airborne concentrations of unknown/unmeasured compounds
- Can mandate reliance on untested systems –
- HVAC capacity may not handle future needs for ventilation, etc., e.g., new pollutant sources/ activities
- Potential failure to address COC that emerge subsequent to IAQP/building design

Only guidance for minimum; higher than minimal levels should be encouraged

<u>Too imprecise, can calculate wide range of VRs</u>

Too many unknowns, so OA flow outcomes will vary broadly in general design of buildings (maybe less problematic in repeat, similar buildings, eg, big box retail)

IAQP can be manipulated to give desired answer; needs more guidance

Appendix 3. Additional comments from the TAC meeting on October 26, 2009

Opinions on current IAQP

- Unknown contaminants
- New contaminants
- The problem of how to allow for future design changes (although also a problem for VRP)
- Design of V system parallels the bldg design issues -- bldg designers only now are starting to think about specific pollutants (e.g., LEED); VR designers with the IAQP are now thinking about specific emissions
- Fear of liability to designer is one of biggest problems; even though VRP is not necessarily science-based, it takes much of the risk off the engineer
- Important issue of combined effects of chemicals even if each is below its health threshold;
    - Current VRP uses additive approach to be conservative- requires addition of VR for occupant emissions to VR for bldg/content emissions to calculate total VR; this would not be necessary if their effects are fully independent;
    - however, most will not use the IAQP additively, but will end up calculating a VR that ventilates for the worst indoor contaminant; if classes of contaminants have additive effects, their total concentration is what matters, yet this would not be considered, and their total may end up exceeding an acceptable level.
- Engineers depend on the code, focus on Chap 6, don't lean on Appendix A so much; this leads to higher VRs, not so good for client's budget;
    - much time is associated with the more complex procedures, so it too difficult to apply, conscientious engineers may price themselves out of the market
- Is engineer liable for clear omissions? Small omissions?
- If engineer initially tries the IAQP, finds high VR, then applies VRP for lower VR, is there liability? Is this a disincentive to explore IAQP?
- If a special source, standard engineering practice says must consider, so even though not explicitly providing for changes . . .
- VRP says may not provide adequate VR – actually a caveat to cover ASHRAE – but most engineers never consider with VRP whether typical or atypical sources
- VRP is a blind process, but IAQP opens up process
- MA – maybe "adding IAQP" is not the right question, but instead need to resolve differences between VRP and IAQP → an acceptable overall strategy

CEC

standards must move towards zero energy buildings by 2030,
but sister agencies don't agree (Cal OSHA, CDPH)
reducing margins of safety but unclear how reducing sources of risk
current numbers not on solid scientific basis, but have a track record and history
Title 24 doesn't include continued maintenance over time
Mazi – maybe an onboard diagnostic tool, but how about formaldehyde?
CalOSHA – what concerns? what sources?
The health community is unconvinced – big obstacle here.

MM - this may be the time, to get the Cal health community on board, to reconfigure VR standards to the environmental health risk assessment model; IA may be about to jump the fence to join the occupational environment paradigm

MA – What can/might we do for specific examples of big box stores?
Mazi – ok if just show <u>no harm</u>

Target – now ventilation is 24 hours, some advantages
Scott W – Target is lowering VRs, and keeping IAQ within acceptable limits, but has not used air cleaning or changed/reduced sources!

suggests setting up a board in CA to start
People apply in CA, IAQP okay if meet certain specs

Tom P -- what are relative benefits in CA relative to possible health costs?
NREL – LA - $250K ??

- Engineers not trained in IAQP, don't know how to do it
- How then do engineers get charge with inappropriate VR design?
- Engineers don't have time to fully engineer the system; hard to get owners to pay engineers for more cutting edge design
- Engineering fee usually % of costs, and IAQP is likely to bring construction costs down!!!

<u>IAQP – cost/benefit</u>

- Filtration may increase energy costs
- Ambiguous benefit – reducing need for high VR in areas of high outdoor humidity (not important in CA)
- For toxic schools with OA pollutants from the ground, only gas phase filtration allows bringing in outdoor air.
- [be clearer on benefits of IAQP → lower VRs +
- Berkeley has 3 schools in the top 100 US schools for contaminated outdoor air (USA toxic schools, using EPA model
- Health benefits of reduced energy usage (large scale, pooled benefits)
- Problem that LEED won't accept IAQP – so much judgment, so little information, outcomes calculated are too variable
- Problem in 1-off buildings
- But those repeatedly buildings of similar design can resolve much of this problem, can get more consistent, corrected results [perhaps they can be useful early adopters to help state fine-tune approach for all users?]
- If sensors were developed, could do demand-controlled V to achieve adequate dilution; really need real-time info, not picking a 1-time measurement
- Specific example chemicals of concern – nonanyl (with phenol)– very persistent pesticide

- Both VRP and IAQP face issues of changing environments vs. original design, but IAQP gets the scrutiny
- The required exhausts and required pressures may set a practical minimum VR supply
- Dennis Stanke – VR guidelines have been established by “a little bit of science and a lot of ‘it sounds pretty good to me.’”
- Research on both
  - How much VR needed to handle the emissions
  - What are the emission sources and can they be reduced
- Other strategies to reduce needed VR, save energy, such as alternate ventilation strategies such as underfloor ventilation; big box may be well suited because of high ceilings
  - Walmart is using displacement V, has published some [**find??]
- Energy recovery in big box stores? (SM – didn’t work so well for Target?)
- Maybe CEC require IAQP just at peak period if a compromise needed.

<u>Current objections</u>

- Have seen poor compliance and maintenance with current VRP standards
- Providing even lower VRs with IAQP is a potential problem if poor maintenance, especially for sensitive subpopulations

Choosing COCs

- Agnes – NHANES data on biomonitoring; which, e.g., phthalates, are at higher levels in the popn?

<u>Occupant satisfaction</u>

- Some POE done for occ satisfaction; is 89% sufficient for public buildings, given the major impact on productivity? Issue of sensitive people
- How to assess satisfaction – what is evidence on occs vs trained vs. untrained panels?

<u>Modeling IAQP – Big Box Retail</u>

Model - What do changing VRs do, with different parameters and changing sources
Similar task as designers w/IAQP – what COCs, what sources?
Tom Philips - Eckland, VRs, Austin – VOCs in retail.

Scott W – NREL – energy modeling, different VR design approaches, savings potential.
Charlene Bayer – writing a full paper on VOC levels, she’ll send.

Appendix 4. Pollutant sources of concern for consideration with an IAQ Procedure that allows ventilation rates lower than per current VR Procedure

Source	Pollutant	Source reduction strategies feasible?	Pollutant removal strategies feasible?	Notes
Indoor sources				
Building materials and surfaces	VOCs, SVOCs	Use low-emitting materials; provide continuous ventilation	OA, gas filtration	Large numbers of compounds from existing materials, with new compounds added continually
Building HVAC system – poor design and maintenance	Odors, particles, microbial agents and materials	Use proper design strategies; use rigorous maintenance strategies	OA, particle filtration, gas filtration	An unusually contaminated HVAC system can contribute pollutants to the indoor environment (e.g., unchanged particle filters, mold overgrowth on damp duct insulation downstream of cooling coils, mold and slime in poorly draining drain pans).
Building HVAC system – intrinsic	Odors, microbial agents and materials (e.g., filters)	Develop and use new design and maintenance strategies;	OA, particle filtration, gas filtration	Research has demonstrated contaminant sources of concern even in properly designed and maintained conventional HVAC systems; for instance, odors and chemical reactions from used particle filters, and microbial growth and emissions from intentionally wet surfaces on cooling coils and drainage pans. Lower than currently recommended ventilation rates, set to maintain acceptable indoor concentrations of a variety of indoor sourced pollutants from low-emitting materials, may be less adequate in diluting the classes of HVAC-produced contaminants, whether chemical or biological.
Building contents, furnishings, and equipment	VOCs, SVOCs	Use low-emitting materials; use local exhaust ventilation	OA, air-cleaning	Large numbers of compounds from existing materials, with new compounds added continually

Source	**Pollutant**	**Source reduction strategies feasible?**	**Pollutant removal strategies feasible?**	**Notes**
Building maintenance and cleaning	Terpenes, irritants, asthmagens	Use low-emitting materials	OA, air-cleaning	
Building occupants	bioeffluents, carbon dioxide, personal care products, skin cells, bacteria, infectious biologic agents	none	OA; air cleaning – gases; air cleaning – particles	
Outdoor sources				
Building-related	re-entrained building exhaust air (e.g., bathroom exhausts); debris in outdoor air intake;	Proper design and maintenance	air cleaning – particles and gases	
Regional or local ambient pollutants	Gases and particles from regional or local sources such as roadways, nearby construction or demolition	Reduced OA	air cleaning – particles and gases	For reactive gases of outdoor origin (i.e., O_3), ventilation to achieve a residence time shorter than the reaction rate for generation of reaction products (i.e., for O_3, secondary organic aerosol, short lived reactive carbonyl compounds) may be better than lower ventilation rates that allow these reactions to go to completion indoors.

Abbreviations: OA, outdoor air