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Developing evidence-based prescriptive ventilation rate standards for commercial buildings in California: a proposed framework

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February20,2014

The research reported here was supported by the California Energy Commission Public Interest Energy Research Program, Energy-Related Environmental Research Program, award number 500-09-049, via Contract DE-AC02-05CH11231 between the University of California and the U.S. Department of Energy. The authors thank Rengie Chan for the helpful review of the draft manuscript.

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List of Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-conditioning Engineers
BRS	building-related symptoms CEC
	California Energy Commission
EPA	Environmental Protection Agency
HVAC	heating, ventilating, and air-conditioning
IAQ	indoor air quality
IAQP	Indoor Air Quality Procedure

LBNL	Lawrence Berkeley National Laboratory
MVR	minimum ventilation rate
OEEHA	Office of Environmental Health Hazard Assessment
SBS	sick building syndrome
SVOC	semi-volatile organic compound
VOC	volatile organic compound
VR	ventilation rate
VRP	Ventilation Rate Procedure
WHO	World Health Organization

Abstract

Background - The goal of this project, with a focus on commercial buildings in California, was to develop a new framework for evidence-based minimum ventilation rate (MVR) standards that protect occupants in buildings while also considering energy use and cost. This was motivated by research findings suggesting that current prescriptive MVRs in commercial buildings do not provide occupants with fully safe and satisfactory indoor environments.

Methods - The project began with a broad review in several areas – the diverse strategies now used for standards or guidelines for MVRs or for environmental contaminant exposures, current knowledge about adverse human effects associated with VRs, and current knowledge about contaminants in commercial buildings, including their their presence, their adverse human effects, and their relationships with VRs. Based on a synthesis of the reviewed information, new principles and approaches are proposed for setting evidence-based VRs standards for commercial buildings, considering a range of human effects including health, performance, and acceptability of air.

Results – A review and evaluation is first presented of current approaches to setting prescriptive building ventilation standards and setting acceptable limits for human contaminant exposures in outdoor air and occupational settings. Recent research on approaches to setting acceptable levels of environmental exposures in evidence-based MVR standards is also described. From a synthesis and critique of these materials, a set of principles for setting MVRs is presented, along with an example approach based on these principles. The approach combines two sequential strategies. In a first step, an acceptable threshold is set for each adverse outcome that has a demonstrated relationship to VRs, as an increase from a (low) outcome level at a high reference ventilation rate (RVR, the VR needed to attain the best achievable levels of the adverse outcome); MVRs required to meet each specific outcome threshold are estimated; and the highest of these MVRs, which would then meet all outcome thresholds, is selected as the target MVR. In a second step, implemented only if the target MVR from step 1 is judged impractically high, costs and benefits are estimated and this information is used in a risk management process. Four human outcomes with substantial quantitative evidence of relationships to VRs are identified for initial consideration in setting MVR standards. These are: building-related symptoms (sometimes called sick building syndrome symptoms), poor perceived indoor air quality, and diminished work performance, all with data relating them directly to VRs; and cancer and non-cancer chronic outcomes, related indirectly to VRs through specific VR-influenced indoor contaminants. In an application of step 1 for offices using a set of example outcome thresholds, a target MVR of 9 L/s (19 cfm) per person was needed. Because this target MVR was close to MVRs in current standards, use of a cost/benefit process seemed unnecessary. Selection of more stringent thresholds for one or more human outcomes, however, could raise the target MVR to 14 L/s (30 cfm) per person or higher, triggering the step 2 risk management process. Consideration of outdoor air pollutant effects would add further complexity to the framework. For balancing the objective and subjective factors involved in setting MVRs in a cost-benefit process, it is suggested that a diverse group of stakeholders make the determination after assembling as much quantitative data as possible.

Discussion - Minimum VR standards can consider evidence associating VRs with human outcomes both directly (e.g., building-related symptoms), even when specific causal indoor contaminants are unidentified; and indirectly through VR-influenced indoor concentrations of specific indoor contaminants. Prior VR standards have considered limited evidence of the first type, but not that of the second type, and little evidence of both types has been available. The principles and approaches suggested here, although more complex than current approaches, would provide more explicit protection for occupants of commercial buildings from adverse effects of indoor contaminants, while also considering VR-related costs. Ideally, in the future, this process would include separate reference VRs for occupant-proportional and building-proportional MVRs, but sufficient data are not yet available. The suggested new framework for VR standards also highlights the need for substantial new data on the direct and indirect relationships of VRs with adverse human outcomes.

Epigram:

. . . when you make a thing, it is so complicated making it that it is bound to be ugly, but those that do it after you they don't have to worry about making it and they can make it pretty and so everybody can like it when the others make it.

-- Gertrude Stein (1874 - 1946)

Background

Current ventilation standards: approaches and limitations

Standards for minimum ventilation rates (MVRs) in commercial buildings are intended to provide indoor air quality (IAQ) "that is acceptable to occupants and that minimizes adverse health effects," according to the American Society for Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) (2010). "Ventilation rate" (VR) here refers to the flow rate of outdoor air into buildings by mechanical or natural means. Consensus standards from ASHRAE provide the basis for most legal MVR codes in the U.S. The State of California sets its own MVR standards independently. Current MVR standards for commercial buildings in California are prescriptive, and set MVRs by specific type of building use, in a way similar to the prescriptive option (the Ventilation Rate Procedure or VRP) in the ASHRAE VR standard (ASHRAE 2010), with some key differences described later in this document.

Currently prescribed MVR levels were historically based on amounts of ventilation required to control odors from building occupants, and have more recently considered odors from materials and furnishings, as well as building-related symptoms. In recent decades, MVR standards have also implicitly reflected a balance between occupant satisfaction and the increased energy costs of higher VRs. This balance has been based on the historic data on control of odors, anecdotal reports, and professional judgment, but scientific evidence linking health effects and VRs has received limited consideration. It has become clear more recently, however, that airborne contaminants from multiple sources in and outside buildings also need consideration in ventilation standards, because these contaminants can have both odors and health effects.

Substantial evidence (primarily from offices) now documents that indoor commercial settings, with their current contents, recommended ventilation rates, and resulting levels of indoor contaminants, do not consistently provide adequately healthy or acceptable environments (Mendell and Apte 2013). Links between lower VRs and adverse human health and other outcomes are now clear (Li et al. 2007; Seppänen et al. 1999). It is also clear that ventilation increases building energy use. Based on analyses of Benne et al. (2009), 6.5% of all energy used in U.S. commercial buildings is for heating and cooling of mechanically-supplied ventilation air, with air entering through infiltration contributing further to building energy demands (Emmerich et al. 2007). Given the increased available data from research, it is now possible and appropriate to develop evidence-based MVR standards that explicitly balance the goal of providing safe and acceptable indoor environments with the energy costs of increased ventilation. This paper describes a revised approach to MVR standards, involving the identification of relevant scientific data on occupant impacts of VRs, and the input of these data into a decision-making process to set feasible MVR standards by balancing the benefits of higher VRs against the costs.

Aims of this paper

The key purpose of this document is to define a process for setting scientifically defensible, evidence-based MVR standards for commercial buildings in California that make the best use of existing data on human impacts of VRs and, to the extent feasible with respect to energy use and costs, keep VR-related adverse occupant outcomes at acceptable levels. In defining and applying

this process, and identifying the available relevant data, an additional goal is to highlight what additional data and analytic approaches are needed to improve this process. While this approach was developed for California, it is applicable to other locations.

This paper does not consider "performance-based" standards such as the ASHRAE Indoor Air Quality Procedure (IAQP) (ASHRAE 2010). Portions of this paper's technical approach, however, are similar to some aspects of the IAQP, and the approaches developed here may be relevant for performance-based standards. The IAQP, without prescribing MVRs, allows building designers to set performance goals for contaminant levels and occupant satisfaction for each building, and then to specify a building and ventilation system design that meets those goals. Performance-based VR standards may allow lower or require higher VRs than a prescriptive VR standard for the same type of building use.

Methods

The materials used in this paper were gathered from a review of materials in the peer reviewed literature, in conference proceedings, or on the Internet. First, approaches used to develop current prescriptive building ventilation standards are summarized, compared, and evaluated. Then current approaches for quantifying and setting contaminant exposure limits related to maximum acceptable levels of adverse human effects, both in outdoor air and in occupational settings, are then summarized and considered for relevance to setting MVR standards. The analyses, principles, and approach described here assume that MVRs should protect building occupants from all adverse effects from inadequate VRs, including effects on health, performance, and odor or perceived indoor air quality among visitors.

Based on the reviewed materials, general principles are proposed for developing improved MVR standards that, to the extent feasible with respect to energy use and costs, protect occupants against excessive adverse outcomes of VR-associated exposures in commercial buildings. Based on methods adapted from existing approaches and principles developed in this review, a framework is proposed for making decisions on feasible MVRs in commercial buildings in California. Specific outcomes are identified for which sufficient data are available for current consideration in setting MVR standards. Available data associating each outcome with VRs are summarized, whether directly, or indirectly through VR-influenced contaminants. The approach also considers potential effects of increased VRs on indoor exposures to outdoor-sourced contaminants. Overall approaches are suggested for combining data on relationships of multiple specific outcomes and VRs, and for considering these data in conjunction with data on VR-related energy costs, in order to inform the setting of feasible, health-protective MVR standards.

Results: review of work by others

<u>Current U.S. and California approaches to prescriptive ventilation rate standards</u>

Description of U.S. and California ventilation standards for commercial buildings
Currently prescribed MVR levels are rooted historically in laboratory studies that documented the outdoor air flow per person needed to dilute odorous bioeffluents from building occupants

and produce subjectively acceptable air quality for a substantial majority (e.g., 80%) of visitors. Pettenkofer in 1858 recommended 1,000 ppm of CO_2 as the hygienic limit for this purpose, corresponding to approximately 10 L/s per person, and Yaglou in 1936 recommended 7-8 L/s per person of outdoor air to control bioeffluent odors for visitors (as cited by Dimitroulopoulou and Bartzis (2013)). The MVRs required in ASHRAE VR standards for office buildings have varied over the years, decreasing from 14 L/s (30 cfm) per person in the early 1900s to 7 L/s (15 cfm) per person during the years 1946-1973; decreasing further in 1981, after the peaking energy costs of the 1970s, down to 2.5 L/s (5 cfm) per person; then increasing in 1989, in response to the widespread episodes of acute building-related health symptoms called "sick building syndrome" (SBS), to 9.5 L/s (20 cfm) per person; and most recently, decreasing in 2010 to 8 L/s (17 cfm) per person at default occupancy levels (ASHRAE 1989, 2010). In California, current VR standards for commercial buildings, set in the Title 24 Energy Regulations (California Energy Commission 2008), are prescriptive and similar to the prescriptive option (the Ventilation Rate Procedure, or VRP) in the VR standard from ASHRAE (ASHRAE 2010), with key differences. Both these standards specify two MVRs, one per person and one per unit of occupied floor area, in order to reflect the need to control indoor pollutants emitted from both occupant and non-occupant indoor sources. In the ASHRAE standard, both specific MVRs differ by occupancy type, and *the two MVRs are added* to give a total required MVR per occupancy type. For each occupancy type, the standard provides a typical occupant density and from this calculates an overall default MVR, although the user is directed to use actual design occupant densities. Title 24, in contrast, specifies a fixed MVR per person and, for each of various occupancy types, a specific MVR per floor area, with the required total MVR being *the greater of the two*. Title 24 also provides default occupant densities used to calculate overall default MVRs.

For instance, for mechanically ventilated office spaces, ASHRAE 62.1-2010 requires 2.5 L/s (5 cfm) per person plus 0.3 L/s per square meter (0.06 cfm/ft^2) or, at the ASHRAE default occupant density of 5 persons/1000 ft^2, a total of 8.5 L/s (17 cfm) per person (possibly increased to allow for reduced ventilation system efficiency) (ASHRAE 2010). Title 24 requires the larger of 7 L/s (15 cfm) per person for the expected number of occupants and 0.75 L/s per square meter (0.15 cfm/ft^2) of conditioned floor area or, at the Title 24 default occupant density of 10 persons per 93 m^2 (1000 ft^2), an overall rate of 7 L/s (15 cfm) per person, without consideration of ventilation system efficiency (California Energy Commission 2008, pp. 73-76). These MVRs at the corresponding default densities, 8.5 and 7 L/s per person, are similar. However, Title 24 at the ASHRAE default density would require 14 L/s (30 cfm) per person, almost double the ASHRAE requirement. Thus, depending on the occupant density used in the calculation, Title 24 can require significantly more or less ventilation than Standard 62.1.

For typical retail sales space, the ASHRAE requirements are 3.8 L/s (7.5 cfm) per person plus 0.6 L/s per square meter (0.12 cfm/ft^2), and at the default occupancy of 15 persons per 100 m^2 (1000 ft^2) a total of 7.6 L/s (16 cfm) per person is required (ASHRAE 2010). The Title 24 requirement for retail spaces is the larger of 7 L/s (15 cfm) per person for the expected number of occupants and 1 L/s per square meter (0.20 cfm/ft^2) of conditioned area, which for the same retail occupant density would be 7 L/s (15 cfm) per person, again similar to the ASHRAE requirement (California Energy Commission 2008).

Evaluation of current U.S. and California VR standards
It has been necessary historically to develop VR standards that are practical for building designers to use. Large gaps in available knowledge hindered development of evidence-based standards that protect occupants from effects other than odors and unacceptable perceived air quality. Considering the research knowledge now available, however, the scientific underpinning of all current approaches for setting MVR standards is weak. Much recent research has demonstrated that multiple pollutant sources in and outside buildings, including the building envelope, the HVAC system, the building contents, and building maintenance activities all release, in addition to odors, chemical or microbiologic contaminants that may adversely affect occupants. The occupants, in addition to emitting odors, can also emit infectious disease agents. Control of all these contaminants has not been explicitly addressed in VR standards, leaving occupants with uncertain protection, although ASHRAE standards attempt to provide occupants with both acceptable indoor air quality (i.e., for >80%) and healthy indoor environments, although not guaranteeing them (ASHRAE 2010). The inclusion in recent decades of separate components in the MVR calculation, per occupant and per unit floor area, is an appropriate strategy since both people and buildings emit potentially uncorrelated contaminants. Yet, the changes in ASHRAE MVR standards have been based only on evidence regarding control of odor and irritation, and to some extent recently, of SBS symptoms, rather than of a broader range of adverse human effects (ASHRAE 2011). Lowering of MVRs (e.g., in 1981) was done without an explicit analysis of the health-based evidence, but from a decision to base the minimum required rates on perception of odors by adapted occupants rather than unadapted visitors (ASHRAE 2011). The increase in 1989, after the previous drastic decrease, may have been in response to anecdotal reports of building-related symptom episodes (i.e., SBS), rather than based on scientific analysis.

Despite increasing available information about a range of health consequences of inadequate ventilation, this information has not, by and large, been utilized explicitly in recent updates to ventilation standards. The current standards still tend to specify MVRs traceable to laboratory studies on VRs and dissatisfaction from human bioeffluent odors, plus newer studies on odors related to buildings, with some additional consideration of the relation of overall VRs to SBS symptoms. However, evidence is accumulating that current practices do not consistently provide adequately acceptable environments. Most current office buildings, according to large surveys conducted in both the U.S. and Europe, do not provide a substantial majority of occupants with indoor air quality they consider acceptable (Bluyssen et al. 1996; Huizenga et al. 2006; Mendell and Apte 2013). In the U.S., only 26% of buildings surveyed provided the ASHRAE-suggested minimum 80% of occupants with satisfactory perceived air quality (Huizenga et al. 2006). In Europe, 50% of visitors found the IAQ unacceptable; and even within buildings documented to provide at least the ASHRAE-specified MVR, only 36% of buildings met the requirement for IAQ to satisfy 80% of occupants (Bluyssen et al. 1996).

Many studies have documented that increasing VRs in office buildings above the levels specified in current standards reduce acute building-related symptoms in the occupants, with VRs up to 20 or 25 L/s per person (40-50 cfm/person) substantially reducing occupant symptoms (Fisk et al. 2009; Seppänen et al. 1999). This suggests that higher VRs reduce levels of indoor pollutants that cause, through unidentified mechanisms, a variety of building-related symptoms in occupants. Insufficient evidence is available on the exact relationship between current MVRs in

standards and occupants' risk of respiratory infections transmitted in indoor air, but the available evidence suggests that increasing required MVRs would reduce indoor transmission of infectious respiratory disease (Li et al. 2007).

An analysis of the cancer and other chronic health risks of indoor volatile organic compounds (VOCs) indicates relatively moderate risks at the current MVR standards (Parthasaranthy et al. 2013). Formaldehyde is the primary driver of cancer risk in offices (Parthasaranthy et al. 2013). Workplace lifetime cancer risk estimates for offices, using California OEHHA cancer potency factors (Office of Environmental Health Hazard Assessment 2009) with the method of Parthasaranthy et al. (2013), are 1.9×10^{-5} and 1.6×10^{-5}, for the Title 24 and ASHRAE 62.1-2010 MVRs at default occupancies, respectively. These are just above the risk level of approximately one in 10^{-6} that is considered sufficient to justify regulation or corrective measures (Travis et al. 1987). At present, no data are available on the combined risks of chemicals with common modes of action, such as multiple aldehydes. Non-cancer chronic risks are estimated to be substantially lower than cancer risks (Parthasaranthy et al. 2013). While available data on these other chronic health risks do not suggest inadequate protection from current MVR standards, these other risks merit explicit consideration in future evidence-based MVRs, as new data on chronic health risks become available, and especially if lowering of current MVR standards is contemplated.

The MVR standards of ASHRAE and Title 24 differ in the way they treat the occupant-related and space-related components of indoor contaminants. The ASHRAE standard sets the required total MVR as the *sum* of the separate MVRs for the occupant-related and space-related emissions. This would be most appropriate if the two types of indoor sources, the occupants and everything else in the space, emitted pollutants with *similar* biologic mechanisms of action for effects on the occupants, so that the amount of ventilation actually needed is for the summed pollutants, as if the two types of sources emitted the same contaminant. (For instance, if odorous emissions from occupants and spaces were the primary emissions of concern, summing their corresponding MVRs would be appropriate (ASHRAE 2011).) However, if the two types of pollutants had no common mode of effect, this additive approach could lead to excess ventilation; e.g., the ventilation needed to control just indoor levels of human bioeffluents would simultaneously be effective in controlling other types of pollutants from other sources. The Title 24 approach to a MVR standard, in contrast, sets the required MVR as the *larger* of the separate MVRs for occupant-related and space-related emissions. This would be most appropriate if the two types of indoor sources emitted pollutants with *different* mechanisms of action for effects on the occupants, so that if a larger amount of ventilation were needed to remove one type of pollutant in a space, this would more than adequately remove the other type of pollutants. This seems more appropriate for controlling health-related, rather than odor-related, emissions. In practice, the two standards set similar total MVRs at their respective default occupant densities; however, the ASHRAE standard allows much lower MVRs per person when the occupant density is high: at very high occupant densities, the total ASHRAE MVR requirement approaches the per-person requirement of 2.5 L/s (5 cfm) per person, while the Title 24 standard requires 7 L/s (15 cfm) per person.

Neither of these two general approaches, nor their associated required MVRs, has been based on actual data about indoor pollutant emissions or associated chronic health risks. When the

ASHRAE standard was changed to incorporate rates per person and per floor area, the parameters selected yielded, at the default occupant density, approximately the same required MVRs as in previous versions of the standard, suggesting that engineering judgment tended to favor VRs that had been considered adequate. The Title 24 approach, taking the larger of the two component-specific MVRs, seems more generally appropriate, as occupant-emitted and building- emitted contaminants other than odors seem likely to be controlled by the same ventilation air (assuming that the different sets of emissions operate through different biologic mechanisms and receptors); however, each component-specific MVR should be evidence-based with respect to controlling odors as well as non-odor-related outcomes.

The development of the existing standards has apparently attempted, by requiring what seems to be minimum acceptable VRs for odors and SBS, to achieve a balance between provision of good IAQ and the increased energy use and costs of higher VRs (although ASHRAE 62.1-2010 does not explicitly consider energy). However, the standards have not employed objective methods for establishing even this balance. Also, such prescriptive standards, which do not allow reduced MVRs even with documentation of indoor contaminant concentrations lowered through other strategies, do not facilitate energy savings.

Current European approaches to prescriptive ventilation rate standards

Description of current European ventilation standards for commercial buildings
Commercial VR standards for the European Community have been set in EN 13779:2007 and EN 15251:2007 directly, which provide default values for member countries without national standards (Dimitroulopoulou and Bartzis 2012; Riviere et al. 2012, pp. 34-35). Like ASHRAE 62.1-2010, the European standard specifies both a MVR per person to control emissions of odors and other bioeffluents from occupants (but to a level acceptable for unadapted visitors), and a MVR per floor area to control emissions from the building, furnishings, and heating, ventilating, and air-conditioning (HVAC) system. Both rates are added together to obtain the total MVR required. (Note that the specific national building regulations within Europe include a wide diversity of ventilation requirements, most in the range 6-11 L/s (about 13-23 cfm) per person, except for two at 14 L/s (about 29 cfm) per person (Dimitroulopoulou and Bartzis 2012). Another reference shows European national office MVR standards ranging from 5.6 to 25 L/s per person (Brelih and Seppänen 2011).

The European Community VR standards are substantially more complex than those of ASHRAE or California (Dimitroulopoulou and Bartzis 2013). First, they define three levels of *outdoor air pollution* – low, high, and very high, with high and very high levels requiring air cleaning to allow acceptable indoor air quality, before the need for ventilation is considered. Then, three categories of *indoor pollutant emissions* are defined for buildings – very low polluting, low polluting, and non low polluting – determined by whether the majority of building materials meet national or international criteria for very low polluting or low polluting materials. In addition, a category is defined for buildings with indoor smoking. These categories affect the outdoor air flows required for the space-specific component of the MVR. Finally, categories of desired IAQ are defined – III, II, and I – essentially good, better, and best, with sequentially increasing required airflows for both the area-specific and the person-specific MVR components. (A fourth category of IAQ, considered acceptable only for limited parts of the year, is not often

included in charts of required MVRs.) MVRs for each of a variety of commercial building occupancy categories are specified as per-person and per-area, with nine levels based on combinations of the above indoor pollutant emission levels and desired IAQ levels. Using default assumptions for density of occupancy simplifies the combination of the per-person and per-area numbers, producing up to nine default MVRs per building occupancy category (Dimitroulopoulou and Bartzis 2013; Riviere et al. 2012). (The ASHRAE standard 62.1-2010 and the California Title 24 standard, in contrast, when using default values for density of occupancy, each produce one default MVR per occupancy type, except that the ASHRAE standard MVR may be increased for specific spaces with lower ventilation system efficiency.)

Evaluation of current European ventilation standards

Overall, the current default European standard includes similarities to the current ASHRAE 62.1 and California Title 24 standards, as well as desirable additional or more extensive features. The use of per-person and per-area components of a MVR standard, as in the ASHRAE and Title 24 standards, is an appropriate structure for dealing with different types of indoor contaminant sources. Requiring air cleaning for high levels of outdoor air pollutants seems appropriate (as ASHRAE 62.1 does also to a limited extent), given current knowledge about effects of outdoor pollutants and their entry indoors through ventilation systems. Practical and effective air cleaning technologies, however, may not be available for all outdoor air pollutants. It also is reasonable to consider the levels of indoor contaminant emissions in buildings, based on prior testing of the materials present, in the formulation of MVR standards. This would allow flexibility and efficiency in setting MVRs and also motivate increased availability of lower-emission materials. The emissions data and administrative structure that have been established in Europe for categorizing all indoor material emissions, however, do not seem adequate for present use in California, so that a sustained effort would be necessary to move toward making such provisions feasible. The complex type of MVR standard required for this will not be considered for California in this paper. The definition of three categories of desired IAQ, with multiple MVRs specified depending on the choice of the building owner or tenant, is also a potentially desirable strategy, although again with feasibility issues, including how these levels would be set in the context of cost/benefit balancing and energy efficiency. Also, the resulting nine levels of MVR specified for each building use even with simplifying assumptions about occupant density, while a logical result of the European approach, seems more complex than may be currently practical here.

<u>Current approaches for setting acceptable environmental levels of contaminants, and their relevance to MVR standards</u>

Standards or guidelines from various agencies and organizations set limits on human exposures to specific environmental contaminants. These strategies contain elements relevant to VR standards, although not yet used by them: e.g., what human outcomes are considered; what evidence for adverse effects is considered; how this evidence is evaluated and analyzed; and finally, how the scientific conclusions and other inputs are considered together in setting specific prescribed limits. A number of approaches for setting limits on environmental levels of contaminants are described below.

Population exposures to ambient pollutants
The U.S. Environmental Protection Agency (EPA), by mandate of the Clean Air Act, sets legally acceptable levels for a specified set of ambient pollutants. The EPA issues air quality criteria that "reflect the latest scientific knowledge useful in indicating the kind and extent of all identifiable effects on public health or welfare, which may be expected from the presence of such pollutant in the ambient air" (National Research Council 1983). The EPA uses a combination of "risk assessment" and "risk management" processes. The risk assessment process, now widely adopted in the U.S. and elsewhere, includes four steps: hazard identification, dose-response assessment, exposure assessment, and risk characterization. The scientific and objective risk assessment process provides its findings as input to the more subjective risk management process, in which societal decisions are made based on weighing of costs/benefits. For example, the EPA generally considers a *de minimis* risk of up to $1x10^{-6}$ as an acceptable goal, but risk management considerations may result in exposure standards associated with higher or lower levels of risk. (For instance, the 4 pCi/L action level of radon in homes is associated with a 7/1,000 lifetime risk of lung cancer among nonsmokers, much higher than risk levels allowed for carcinogens in good and water (U.S. Environmental Protection Agency 2012). This level is set based on the levels considered achievable in most homes for a reasonable cost.) In setting policies, the EPA is mandated to establish primary standards that are "neither more nor less stringent than necessary . . . to protect public health with an adequate margin of safety;" that is, "not at a zero-risk level but rather at a level that avoids unacceptable risks to the public health, including the health of sensitive groups." Additional details of this process as used by the EPA, and an example of its application to an ambient standard for nitrogen dioxide (NO_2), are provided in Appendix 1.

Within the California Environmental Protection Agency (CalEPA), the Office of Environmental Health Hazard Assessment (OEHHA) has parallel goals in risk assessment as the U.S. EPA, but approaches them with some differences. This process is used for widespread ambient air pollutants such as particles and ozone as well as for pollutants emitted from sources such as industrial facilities. Four detailed OEHHA Technical Support Documents describe acute reference exposure levels (acute RELs), chronic RELs (CRELs), cancer potency factors, point estimates and distributions for exposure parameters, and the general exposure assessment methodology (Office of Environmental Health Hazard Assessment 2003). OEHHA defines a reference exposure level (REL) using the following language: "the concentration level at or below which no adverse health effects are anticipated for a specified exposure duration . . . RELs are based *on the most sensitive, relevant, adverse health effect* {emphasis added} reported in the medical and toxicological literature. RELs are designed to protect the most sensitive individuals in the population by the inclusion of margins of safety. Since margins of safety are incorporated to address data gaps and uncertainties, exceeding the REL does not automatically indicate an adverse health impact" (Office of Environmental Health Hazard Assessment 2003).

Occupational exposures
The American Conference of Government Industrial Hygienists (ACGIH) establishes Threshold Limit Values (TLVs), described as occupational exposure levels to which nearly all workers may be repeatedly exposed without adverse effect (American Conference of Governmental Industrial Hygienists 2013). Although these are widely referenced, TLVs apparently have a limited basis in

evidence, as shown in an extensive and revealing analysis by Roach and Rappaport (1990). This analysis showed that TLVs did not reflect levels protective of workers (in the supporting studies, 17% on average showed adverse effects at the TLV), but simply levels actually measured in workplaces and, the authors concluded, levels considered to be achievable, rather than thresholds for health protection. TLVs thus apparently reflect actual practice rather than health-related limits, or even potential limits of economic or technical feasibility. TLVs have no legal standing, but are widely considered in standards for many organizations world-wide.

The National Institute for Occupational Safety and Health (NIOSH), in the U.S. Centers for Disease Control and Prevention, "develops and periodically revises recommended exposure limits (RELs) for hazardous substances or conditions in the workplace. . . . To formulate these recommendations, NIOSH evaluates all known and available medical, biological, engineering, chemical, trade, and other information relevant to the hazard. These recommendations are then published . . . for use in promulgating legal standards {by OSHA}. . . Unless noted otherwise, RELs are time-weighted average (TWA) concentrations for up to a 10-hour workday during a 40-hour workweek" (National Institute for Occupational Safety and Health 2000). Note that NIOSH RELs are different than OEHHA RELS. NIOSH recommendations are advisory and have no legal standing; legal workplace standards are set by the U.S. Occupational Safety and Health Administration (OSHA). NIOSH RELS are to be based on the best available science, using human or animal health effects data, but not on economic factors. According to the CDC's website, the Occupational Safety and Health Act of 1970 charges NIOSH to ". . . describe exposure levels that are safe for various periods of employment, including but not limited to the exposure levels at which *no employee* {emphasis added} will suffer impaired health or functional capacities or diminished life expectancy as a result of his work experience (U.S. Department of Labor 1970)."

Federal OSHA sets, as occupational exposure standards for the U.S., Permissible Exposure Limits (PELs), which are not based strictly on science, but are subject to the rulemaking and political process and consider the interests of all parties involved. The OSHA PEL is a legal exposure limit, but not necessarily a safe limit below which harm cannot occur for most or all exposed people (ChemDAQ Inc. 2010). For instance, the OSHA PEL for formaldehyde, a human carcinogen, is 0.75 ppm as an 8-hour time-weighted average, compared to the science-based NIOSH REL at 0.016 ppm 8-hour time-weighted average (and the ACGIH TLV of 0.3 ppm). About 500 PELs have been established, most of which have not been updated since the late 1960s. Many chemicals have no PEL at all. A majority of the current PELs are based on ACGIH TLVs (with the limitations described above) established more than 40 years ago. In the late 1980s, when OSHA tried to update a large number of the PELS en masse by incorporating a set of TLVs, the 11th Circuit Court of Appeals barred OSHA from doing this, saying the agency instead must make the case for each PEL, including showing that the PEL would reduce a significant risk from the existing standard and was also economically and technologically feasible. It is, however, not feasible economically or politically for OSHA to keep PELS up-to-date based on current scientific knowledge (Morrison 2013).

A somewhat different approach to controlling contaminant exposures is that in the California 1350 Specification. This is not a contaminant exposure standard, but a voluntary standard for building material emissions developed for the State of California by the Indoor Air Quality

Section (IAQS) of the California Department of Public Health (Indoor Air Quality Section 2010). The intention is to control indoor contaminant concentrations by specifying maximum product emissions. While developed initially for a single model State office project, it has achieved more widespread inclusion in other specification programs (e.g., California Reference Specifications for all major State construction, the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) certification program, the Collaborative for High Performance Schools (CHIPS), the Carpet and Rug Institute (CRI) Green Label Plus Carpet Testing Program) because it provides manufacturers with a consistent protocol for testing their products (Lent 2009). The standard contains an emissions testing protocol, done for all VOCs included in the California OEHHA CREL list. Emissions per area of the material are determined by a standard protocol and used as input into a model. A predicted indoor air concentration for each chemical is modeled based on an estimated amount of material used, a standard volume of space, and a specified MVR rate for a hypothetical office or school building. To pass, the material must have no chemicals with estimated indoor air concentrations exceeding ½ of the CREL (or formaldehyde at greater than half of 23 ppb). This approach demonstrates the practicality of non-regulatory, market-based movement towards lower material emissions, which could lead to lower MVRs needed to maintain specified indoor concentration limits.

Relevance to MVR standards of current approaches for setting environmental exposure standards

The above strategies for setting contaminant exposure standards contain elements relevant to an MVR standard, for which the goal is simultaneous control of multiple contaminants by ventilation. The EPA, in setting legal exposure limits, considers all adverse effects of exposure for which there is evidence as part of an evidence-based risk assessment process, which then feeds into a risk/benefit approach, thus combining independent considerations of science with considerations of feasibility (technical, economic, and political). In a somewhat similar fashion, the NIOSH RELs, reflecting scientific evidence on harmful effects of exposures, feed into the OSHA process that considers science and feasibility to produce regulatory PELS. The ACGIH TLVs, apparently not fully evidence-based to be health-protective, but more practice-based, do not seem to have relevance for improved MVR standards.

The EPA risk assessment process includes multiple features appropriate for an evidence-based MVR standard: it considers all identified relevant adverse outcomes as input into the risk assessment; gathers information on dose-related adverse effects rather than just strict thresholds of acceptability; focuses on selected strategies (analogous to selected MVRs) for which to produce data as input for risk management decisions; and explicitly considers cumulative risks from multiple exposures. California OEHHA uses some of the same strategies, including use of margins of safety designed to protect the most sensitive individuals in the population.

While the California 1350 specifications are not a ventilation standard, these emission specifications could be referenced in a European-style MVR standard that allowed lower MVRs in buildings with verified low-emitting materials. (This kind of hybrid prescriptive MVR standard would provide some of the advantages of a performance-based standard, such as the ASHRAE Standard 62.1 Indoor Air Quality Standard, but perhaps with less complexity.)

While a consideration of risk estimation, by comparing indoor pollutant concentrations at different VRs to selected concentration limits such as published RELs, is necessary for setting minimum ventilation standards, it is not sufficient. The risk analyses, and RELs and PELs, focus on chronic and some acute adverse health effects such as sensory irritation**.** Existing data regarding indoor air indicate that ventilation rates also affect other occupant outcomes, including satisfaction with air quality, prevalence rates of sick building syndrome symptoms, work performance, and, very possibly, absence rates. These effects are not explicitly considered in the traditional risk assessments or in the setting of RELs and PELs.

LBNL research on scientifically-based MVR standards

With support from the California Energy Commission, researchers at Lawrence Berkeley National Laboratory (LBNL) are performing extensive research exploring relationships between VRs, indoor contaminant emission rates, indoor contaminant concentrations, exceedances of contaminant concentration guidelines, and associated chronic health risks (Apte et al. 2012; Chan et al. 2012; Dutton et al. 2013; Parthasaranthy et al. 2012b, 2013). Also, the direct relationships of VRs with several human outcomes are being studied. These outcomes include absence rates in classrooms (Mendell et al. 2013); absence rates, respiratory illness, and sick building symptoms in offices (ongoing research); and satisfaction with air quality in a retail store (Dutton et al. 2013). In addition, controlled exposure studies (ongoing) are investigating how VR per person and VR per unit floor area separately affect prevalence and severity of sick building syndrome symptoms, perceived air quality, and decision-making performance. With support from the U.S. EPA, LBNL and collaborators have also completed meta-analyses of the relationship of VR in offices with sick building symptoms and office work performance. This research, along with research by others, is substantially expanding the scientific base for MVR standards in commercial buildings. These findings are discussed in more detail in the following sections of this paper.

Results: proposed solutions

Proposed principles for setting MVRs in prescriptive standards for California commercial buildings

A set of proposed overall principles for setting MVR standards in California to protect occupants from adverse effects of indoor air contaminants in commercial buildings, while considering energy use and costs, is provided in Table 1. These are based on consideration of the material described above: current and proposed approaches to VR standards in the U.S. and Europe, current approaches to contaminant exposure limits in the U.S., and ongoing work at LBNL on setting scientifically-based VR standards.

If the goal of a MVR standard was to prescribe MVRs that would keep the levels of all relevant adverse human effects below specified levels, regardless of energy use, cost, or other feasibility issues, then the MVRs could be based purely on levels of adverse human outcomes or pollutant exposures considered acceptable. In this case, the risk management function would be implicit, with all levels of cost and energy use assumed to be feasible. If, however, adverse effects of low

Table 1. Proposed principles for effective, feasible MVR standards in California intended to protect occupants from adverse effects of indoor airborne contaminants in commercial buildings

Standards should be evidence-based, and should consider: • all human outcomes for which data suggest relevant effects (including health, performance, and perceived air quality effects). • risks of human outcomes associated with specific VR-influenced contaminants and also human outcomes shown to be associated directly with VRs even if the specific VR-influenced contaminants involved are not known. • effects of multiple simultaneous indoor contaminant exposures – their single effects and, to the extent evidence allows, the coordinated effects of multiple VR-influenced contaminants. • outdoor pollutants whose concentrations may increase indoors at higher VRs, representing a disadvantage or "cost" of increased VRs. • only contaminants for which both the indoor air concentration and associated risk are important and substantially affected by the VR. • only contaminants for which no widely available other technology (e.g., air cleaning) can limit indoor exposures at a lower cost than ventilation; for such contaminants (e.g., particles), the standard should require use of such technology and not consider the contaminant in selecting MVRs.
Standards should specify: • MVRs by occupancy category, with assumed typical levels of contaminant sources for each . Strategies to account for the expected variation in typical levels need to be developed. • the proportion of the population the MVR is intended to protect, and any approaches used to achieve protection of sensitive subgroups.
The standard setting process, for transparency and flexibility, should separate risk assessment (assembling data on risks) and risk management (involving cost/benefit balancing). • After the risk assessment process has characterized relationships between MVRs and adverse outcomes, the risk management process selects acceptable levels of each adverse outcome, which considered together determine the required MVR. • If an MVR maintaining all adverse outcomes down to specific selected levels is not feasible (for technical, economic, or political reasons), cost-benefit analyses should be used to revise the MVR. • A standard using cost/benefit analyses needs to consider evidence not just on "thresholds of acceptability" for specific outcomes (which reflect prior risk management decisions), but also on exposure/response relationships. Selecting among health-based contaminant exposure limits available from different cognizant authorities involves implicit risk management decisions, which should be made explicit. • Setting MVR standards that are feasible, by balancing costs and benefits, may result in greater than desired levels of adverse outcomes. • Cost/benefit balancing in standard setting should, for efficiency, compare specific selected MVR solutions, not all possible solutions.

VRs and costs of higher VRs, particularly energy costs, were both to be considered, then the standard-setting process must include a risk management process that balances costs and benefits to determine feasible MVRs, using risk characterization data on VR/response relationships as input. For example, in social policy decisions, a balancing of risks and cost is necessary for carcinogens, for which no exposure is considered completely safe, and for which zero exposure is generally neither cost-feasible nor achievable. Also, available data indicate that acute health symptoms and work performance in buildings continue to improve with increasing VRs, although with decreasing rates of change, even at impractically high VR levels.

Consequently, in the subsequent discussion, it is assumed that a balancing between adverse effects and costs is likely to be necessary for setting MVRs in standards. With this assumption, absolute thresholds, indicating maximum pollutant levels or levels of health effects, would serve to set initial target MVR levels. If some initial target MVRs were not feasible, then relationships between changing VRs and human outcomes, and the associated costs of providing different amounts of MVRs, would need to be quantified for input into a risk management process that balances adverse human outcomes and costs. In that process, the relevant stakeholders would consider the available information on human effects and costs, and select MVRs. Economic analyses that estimate the monetized values of changes in human outcomes as well as the costs of energy and equipment associated with ventilation can inform the risk management process, but in the end the process will require judgments in the face of uncertainties.

In setting standards, the variability in sensitivity between individuals and the effects on subgroups with either unusual exposures or unusual susceptibilities are always issues of concern. Some sensitive individuals may find an indoor environment unacceptable at any VR. Collecting sufficient data to support such decisions directly for many specific contaminants and subgroups is challenging, because large or specifically focused studies of human response are necessary. Given the generally limited available data on such questions, these issues are often dealt with in the risk management process by inclusion of protection factors. An example would be, for a specified compound, dividing the maximum contaminant dose considered generally acceptable by a “protection factor” estimated to protect unusually sensitive individuals or groups; this factor for various compounds with limited data would be estimated from the detailed data that has been collected for a few compounds. The proposed approaches will assume the use of this strategy, used by the U.S. EPA in ambient air quality standards. The amount of protection factor considered feasible may be influenced by the balancing of costs and benefits.

Proposed approaches for setting MVRs in standards

Types of indoor pollutant exposures relevant to setting MVR standards

A pollutant exposure is considered relevant for the setting of MVR standards if it (1) occurs indoors at levels posing significant risk of adverse human effects, and (2) is significantly affected by the VR. Related to the first of these criteria, Parthasaranthy et al. (Parthasaranthy et al. 2012b), as an initial screen, reviewed available data to identify indoor contaminants with measured concentrations in commercial buildings approaching guideline concentrations for acute and chronic health effects or thresholds for odor or sensory irritation effects. The resulting pollutants of potential concern included VOCs, semi-volatile organic compounds (SVOCs), biologic and non-biologic particles, heavy metals, and numerous inorganic gases. Related to the

second of these criteria, Parthasaranthy et al. (2012b) determined the primary location of sources (indoors or from outdoor air) and modeled the impact of VRs on indoor concentrations of the pollutants. The key pollutants considered potentially relevant to MVR standards, because they were substantially influenced by VRs and not better controlled by filtration, local exhaust, or other strategies, were only the gaseous pollutants emitted from indoor sources, excluding low volatility SVOCs. Contaminants not considered relevant to control by VRs included outdoor-sourced pollutants, combustion products (including from tobacco), particles, and SVOCs. The reasons are described below.

Ventilation will not reduce indoor concentrations of outdoor-sourced pollutants. Most, but not all, commercial buildings have minimal indoor sources of ozone and combustion products, so outdoor air is usually the predominant source. Buildings with combustion-based cooking can have substantial indoor sources of combustion products. For the outdoor air pollutants that are removed by indoor surfaces, which include nitrogen dioxide and ozone, increased VRs will modestly increase indoor concentrations. For the outdoor air pollutants that are non-reactive, such as carbon monoxide, at steady state the VR will not affect the steady state indoor concentration. With time-varying outdoor carbon monoxide concentrations, VRs can have a modest impact on the indoor concentrations during periods of occupancy. For these pollutants, ventilation is ineffective in reducing indoor concentrations, and can be counterproductive. In an ideal health-based MVR standard, the risks from increased indoor exposures to outdoor air pollutants with higher VRs would need to be balanced with the coincident decreased chronic risks from indoor-generated pollutants, plus improvements in acute health symptoms, satisfaction with air quality, and work performance.

If there is a widely available and more effective approach for reducing an indoor exposure at an equal or lower cost than ventilation, then if one desires to reduce the exposure, that approach, and not ventilation, should be employed. In that case, the exposure should not be considered in setting MVRs. Obvious examples are the combustion products produced by combustion appliances such as furnaces, boilers, and water heaters. It has long been accepted that exposures to these combustion products should be controlled by locally venting the exhaust products to outdoors, rather than by letting these pollutants mix with the indoor air and then further diluting the pollutants with outdoor air ventilation. In the U.S., there is a general belief, reflected in regulations, that eliminating tobacco smoking in commercial buildings is necessary. Thus, MVRs in commercial buildings should not be set to control pollutants from indoor smoking.

There is also a strong case for not considering any particles in the setting of MVR standards. Modeling indicates that indoor concentrations of outdoor air particles, and also indoor-generated particles, will not be highly affected by VRs in commercial buildings that filter incoming outdoor air and recirculated indoor air with moderate or high efficiency filters (Parthasaranthy et al. 2012b). In buildings with low efficiency filters or no recirculation, indoor concentrations of particles from outdoors will rise significantly with increasing VRs, potentially a factor in selection of an upper limit for MVRs, while indoor concentrations of indoor-generated particles will decrease. However, improving filter efficiency is a practical, effective, and relatively low cost method of controlling indoor exposures to particles (Fisk et al. 2002) and multiple analyses have predicted substantial health benefits of improved particle filtration (Fisk 2013b). Total costs of particle filtration in commercial office buildings were estimated at $1 to $2 per person per

month (Fisk et al. 2002), and the additional cost of increasing filter efficiency to a moderate level above the minimum requirement would be less than this typical cost. Beko (2008) estimated even lower filtration operating costs. Even moderate efficiency filters will reduce indoor concentrations of particles less than 2.5 microns in diameter, the size range most clearly associated with adverse health effects, by 50% or more (Beko et al. 2008; Fisk et al. 2002; Parthasaranthy et al. 2012b). In contrast, a doubling of ventilation rates will increase indoor concentrations of particles from outdoor air but will decrease indoor concentrations of indoor-generated particles by less than 50% (Parthasaranthy et al. 2012b). When indoor air is recirculated through filters, the usual practice in commercial buildings in the U.S., practical increases in VRs reduce concentrations of indoor-generated particles only modestly, because these particles are also removed by filtration and deposition on surfaces. Thus, filtration, not ventilation, is the preferred option to control indoor particle concentrations.

Semi-volatile organic compounds (SVOCs) partition between indoor surfaces, the surfaces of airborne particles, and indoor air, but are present primarily on the two kinds of surfaces. Through modeling, Parthasaranthy et al. (2012a) has shown that inhalation exposures to SVOCs with a log K_{oa} larger than nine (K_{oa} is the octanol-air partition coefficient) are only marginally affected by VRs, mainly because the airborne portion of these SVOCs is largely present on airborne particles and thus more effectively removed by filtration, and to a lesser degree the transport of SVOCs between air and surfaces dampens any effect of a changing VR. In addition, exposures to these SVOCs via contact with surfaces and food further reduce the influence of VRs on exposures (Shin et al. 2013). Thus, these high-K_{oa} SVOCs are not of primary relevance for setting MVR standards. Examples of such compounds include brominated flame retardants, heavier phthalates like diethyl-hexyl phthalate, pesticides like permethrin, and dioxins (Parthasaranthy et al. 2012a).

Thus, the key types of pollutants in commercial buildings that are reasonable to control with ventilation, given current ventilation and filtration system practices, are the indoor-sourced gaseous pollutants with low octanal-air partitioning coefficients (K_{oa} <9; i.e., not SVOCs). The section below considers in more detail, with respect to specific occupant outcomes, the first criterion for contaminants that should be considered in setting MVR standards – that they occur at levels posing significant risks (individually or, to the extent known, in mixtures acting through the same biologic pathways).

Adverse human outcomes potentially relevant for setting MVR standards

A list of human outcomes potentially influenced by building VRs would include the following:

- Any human outcome shown to be affected by VRs in epidemiologic, experimental, or other data, even when the underlying pollutant exposures are unknown.
- Any human outcome known to be affected by a pollutant exposure, if VRs significantly affect that exposure, and if, in addition, indoor concentrations of the pollutant are sufficient to raise concerns.

In both cases, the strength of evidence for causality in the relationship to be required in order to consider the outcomes in VR standards needs to be decided. The U.S. EPA, for instance, requires sufficient evidence to infer a “likely causal relationship” between an exposure and a health effect (U.S. Environmental Protection Agency 2008).

Table 2 lists human outcomes potentially relevant to standards for building VRs. Three categories of outcome are included: health, satisfaction, and performance. As the current list is likely to be incomplete, revision over time may be necessary as new data are identified or produced. For each outcome, the table indicates whether sufficient quantitative data are available to make the outcomes currently relevant to VR standards, whether the available data relate the outcome directly to VRs, or indirectly through indoor contaminants influenced by VRs. Quantitative evidence is available on the associations of VRs directly to three types of adverse outcomes – building-related symptoms (BRS), unacceptable perceived indoor air quality, and diminished performance – and on the association of VRs indirectly, through VR-influenced indoor contaminants, with one type of adverse outcome – cancer risk. The following section will provide more details about the available evidence relating these outcomes directly or indirectly to VRs.

Table 2. Human outcomes potentially relevant to MVR standards (Y indicates sufficient data for initial consideration in VR standards, (L) indicates limited or suggestive evidence, '---' indicates little or no evidence; outcomes listed in **bold** are those to be considered initially for a VR standard)

Outcomes	**Sufficient evidence associating health outcomes quantitatively with VRs**	
Health outcomes	**Associated with VRs**	**Associated with indoor-sourced contaminants influenced by VRs**
Building-related symptoms (BRS) or sick building syndrome (SBS)	**Y**	(L)
Allergy/asthma – exacerbation or causation	(L)	(L)
Infectious disease with airborne transmission	(L)	---
Cancer and other chronic effects	---	**Y**
Satisfaction Outcomes		
Unacceptable perceived air quality / odors	**Y**	---
Performance Outcomes		
Diminished performance (workers or students)	**Y**	(L)
Absence	(L)	---

Note – exposures excluded from consideration include tobacco smoke, SVOCs, particles, indoor combustion emissions, outdoor-sourced contaminants, and radon (see text).

Some exposures have been excluded from consideration, and are not considered in Table 2: tobacco smoke, SVOCs, particles, and indoor combustion emissions. Outdoor-sourced contaminants are not considered here as an indoor contaminant that can be reduced through

ventilation, but receive separate consideration as an adverse effect of increasing VRs. Radon is also not considered because concentrations in most commercial buildings in California are expected to be low; however, in some locations radon may need to be considered in the setting of MVRs, if ventilation is considered the most appropriate mitigation strategy.

Existing information on relationship of VRs to human outcomes

The adverse human outcomes with the best quantified relationships to VRs or to VR-influenced contaminants, and thus suitable for current consideration in setting VR standards, are (Table 2): acute building-related symptoms (BRS, also sometimes called sick building syndrome or SBS); unacceptable perceived indoor air quality, diminished performance; and cancer and other chronic health conditions. These outcomes are discussed below. (Additional details on these outcomes, provided in Appendix 2, Tables A2-1, A2-2, A2-3, and A2-4, include strategies to: a) quantify the outcomes; b) assess their relationships with VRs or with indoor contaminants influenced by VRs; and c) provide input to a risk management process for setting MVR standards that balance benefits and costs. Summaries of the current status of the measurement strategies and concentration data are also provided.)

Building-related symptoms (Table A2-1)
Many studies have shown a consistent association between lower VRs in office buildings and increased BRS (or SBS) (Seppänen et al. 1999). The review by Seppänen et al. (1999) found that significant increases in at least one symptom outcome were consistently observed when the lower of two VRs being compared was below 10 L/s (21 cfm) per person. There was no clear upper VR threshold for effects, with some but not all findings showing continued decrease in BRS with VRs increasing above 10 L/s (21 cfm) per person, possibly up to 25 L/s (52 cfm) per person (Seppänen et al. 1999; Sundell et al. 2011). Fisk (2012) also discussed benefits of increased VRs in offices in reducing SBS, using data from a meta-analysis on VRs and BRS by Fisk et al. (2009). A recent summary of the available evidence is provided by the IAQ Scientific Findings Resource Bank on the page on Impacts of Building Ventilation on Health and Performance, Ventilation Rates and Sick Building Syndrome Symptoms (Fisk 2013a). Based on the meta-analysis by Fisk et al. (2009), the Resource Bank estimated (with considerable uncertainty) the average proportion of occupants experiencing at least one BRS in offices with VRs ranging from 5 to 34 L/s (11 to 72 cfm) per person. The analysis indicates a decrease in proportion of occupants with symptoms as VRs increase from 5 to approximately 25 L/s (11 to approximately 53 cfm) per person, with no further significant decrease in symptoms as VRs increase above 25 L/s (53 cfm) per person. Thus, 25 L/s (53 cfm) per person can be used as a reference VR (i.e., a VR corresponding to the “best achievable” BRS level), because higher VRs have equivalent amounts of associated BRS. (It turns out that approximately 25 L/s (53 cfm) per person also works well as a reference for perceived air quality, work performance, and cancer risk. For each of these outcomes, there is minimal benefit of providing more than 25 L/s (53 cfm) per person of ventilation.) For BRS, examples of the estimated increases in prevalence at VRs lower than this reference level are as follows: 50% as VR decreases from 25 to 8 L/s (53 to 17 cfm) per person, and 72% as VR decreases from 25 to 5 L/s (53 to 10.6 cfm) per person. Such numbers, although approximate, can be used as an initial input for setting MVRs and for cost/benefit analyses comparing specific MVRs.

Perceived indoor air quality **(**Table A2-2)
Historically, controlled exposure studies have established relationships between VRs and proportion of *unadapted visitors* satisfied with indoor air quality related to bioeffluents from occupants (Fanger 1988). These findings determined an equation (1) for estimating the percent dissatisfied at different VRs:

$$\text{Percent dissatisfied (\%)} = 395 \exp(-1.83\ VR^{0.25}) \qquad (1)$$

where VR is the ventilation rate in L/s per -person, greater than 0.32.

The VR corresponding to at least 80% of *unadapted visitors* finding the indoor air quality acceptable was 7 L/s (15 cfm) person. For 90% acceptability, 16 L/s (34 cfm) per person was required (Fanger 1988). Note that more recently, the ASHRAE 62.1 standards have considered occupant-related components of MVRs needed to satisfy *adapted occupants*, a less stringent requirement.

Existing data also indicate that perceptions of odors indoors are sometimes affected by specific known contaminants that have concentrations that change with VRs, and for which olfactory threshold information may be available. It would be possible to estimate building emission factors for these odorous contaminants, their changes in concentrations at different VRs, and thus the VRs that keep each pollutant below its olfactory threshold. It is not clear, however, how the presence of specific pollutants at or above their olfactory thresholds impact overall satisfaction with indoor air quality. Some odors may be considered pleasant and others objectionable. It seems likely that VRs that maintain a desired level of overall satisfaction with IAQ also maintain odors at acceptable levels, since odors are believed to be a key factor determining satisfaction with IAQ. The available estimates on MVR rates that are needed to control occupant-generated bioeffluents for acceptable IAQ are suitable as initial inputs into MVR standards. The standard may include a formula with a separate component for diluting non-occupant-related odors.

Work performance **(**Table A2-3)
Many studies, including nine experimental studies, have evaluated the associations between lower VRs in office buildings or schools and performance (Mendell and Heath 2005; Seppänen et al. 1999). Fisk (2012) discusses benefits of increased VRs in offices for work performance using the results of a meta-analysis (Seppänen et al. 2006). Recent summaries of available evidence on associations between VRs and performance in offices and schools are provided by the IAQ Scientific Findings Resource Bank page on Impacts of Building Ventilation on Health and Performance (Fisk 2013a). In offices, performance (speed and accuracy) of typical office tasks improves, on average, with increased ventilation rate. “For initial ventilation rates between 6.5 and 14 L/s (14 and 30 cfm) per person, the average performance increases by approximately 1.0% per 5 L/s (11 cfm) per person increase in ventilation rate. At higher ventilation rates, the average performance increase is smaller, approximately 0.3% per 5 L/s (11 cfm) per person increase in ventilation rate. For ventilation rates less than 6.5 L/s (14 cfm) per person, performance increases with ventilation rate seem likely; however, sufficient data are not yet available to confirm this hypothesis.” An equation was generated based on the available

experimental data, relating relative performance to VRs within the approximate range 6.5 to 47 L/s (14-100 cfm) per person, allowing production of a table of estimated values, on the IAQ Scientific Findings Resource Bank page on Impacts of Building Ventilation on Health and Performance: Supporting Information (Fisk 2013a). For instance, relative to a VR of 24 L/s (51 cfm) per person, at 15 L/s (32 cfm) per person, estimated work performance is approximately 1.0% less and at 7.5 L/s (16 cfm) per person estimated performance is 2.2% less. For schools, data relating ventilation rate with school performance are more limited, but available data do indicate improved performance with increased VR up to approximately 10 L/s (20 cfm) per person.

Cancer and other chronic outcomes **(**Table A2-4)
For cancer and other chronic outcomes, obtaining evidence linking them directly to VRs is generally not possible due to the duration and size of studies necessary. Existing data can be used to relate cancer risks to exposures to specific volatile organic compounds (VOCs) present indoors. The indoor concentrations of many of these VOCs are substantially affected by VRs and the effect of VRs on indoor concentrations can be estimated with mass balance models. Parthasaranthy et al. (2012b) identified VOCs that are present in commercial buildings (e.g., (Bennett et al. 2011; U.S. Environmental Protection Agency 2013a)) at levels approaching established guidelines and standards and for which indoor air concentrations are affected by VRs. Parthasaranthy et al.(2013) subsequently estimated the increased cancer risks and non-cancer chronic health risks of these VOCs at different VRs using cancer potency information from California OEHHA and the U.S. EPA.

The estimated median current office VR is about 20 L/sec per person (Parthasaranthy et al. 2013). The individual *annual* risk of cancer due to exposures to VOCs in offices was estimated to be less than one (0.8) in a million at the current VRs found in office buildings and schools (Parthasaranthy et al. 2013). An individual's workplace *lifetime* increase in cancer risk from VOC exposures, for 35 years of work in an office building at current VRs, is about 2.8 in 100,000. Formaldehyde is the primary driver of this cancer risk (Parthasaranthy et al. 2013). Workplace lifetime cancer risk estimates for offices across a range of VRs, calculated using the method of Parthasaranthy et al.(2013) with California OEHHA cancer potency factors (Office of Environmental Health Hazard Assessment 2009), are shown in Figure 1. Inputs to these calculations included: an indoor formaldehyde emission rate of 28.4 $\mu g\ m^{-3}h^{-1}$ based on a mass balance calculation (Parthasaranthy et al. 2013) using data from the U.S. EPA's survey of 100 office buildings; a ceiling height of 3.7 m, 27.7 m^2 of floor area per person, an outdoor air formaldehyde concentration of 3 $\mu g\ m^{-3}$ (all from the EPA survey), a breathing volume of 15 m^3 per day, a body weight of 70 kg, and a cancer potency factor of 0.021 days per mg formaldehyde inhalation per kilogram of body weight (Office of Environmental Health Hazard Assessment 2009). At the reference VR of 25 L/sec per person, the estimated lifetime office workplace cancer risk is 0.7×10^{-5}. As examples, the VR at which the cancer risk is increased by 1×10^{-5} above the risk at the reference VR is 8 L/sec per person (with estimated risk of 1.7×10^{-5}), and for an increase of 1×10^{-6}, 20 L/sec per person.

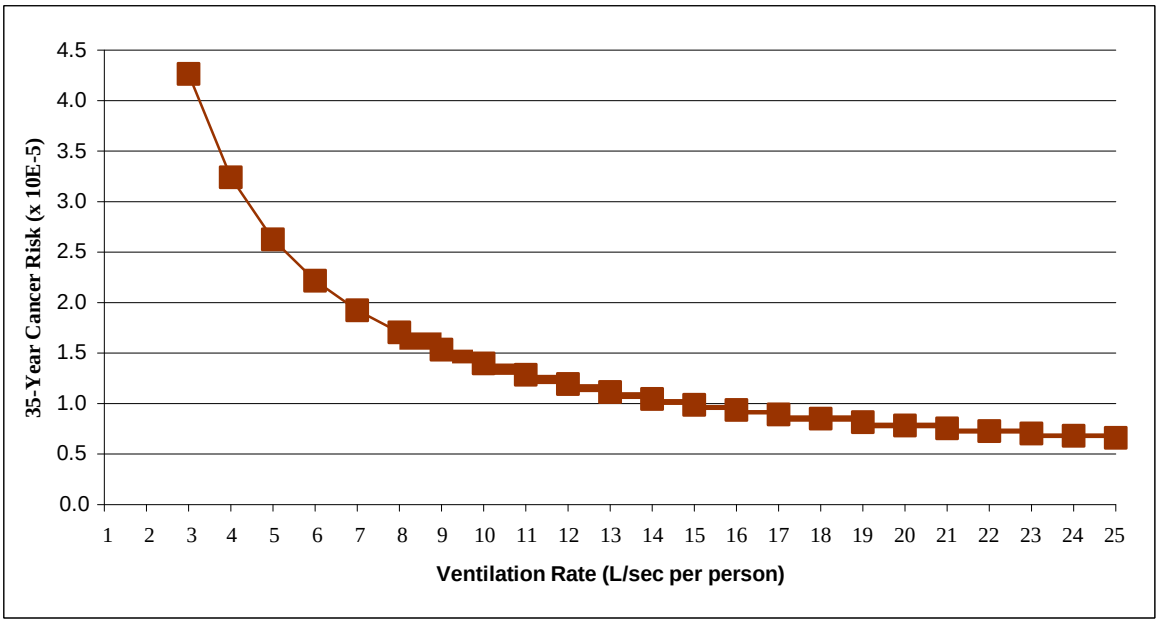

Figure 1. Estimated 35-year office lifetime cancer risk from exposure to formaldehyde, by ventilation rate

Although the cancer risks from working lifetime formaldehyde exposures in commercial buildings are at a level considered near the margin of regulatory significance, current indoor formaldehyde concentrations in commercial buildings (and also in homes) usually exceed the stringent 9 µg m^{-3} respiratory-related chronic REL of California's OEHHA. This is true even though existing VRs in U.S. offices have a median VR of 20 L/sec per person, far above the current California Title 24 office standard of 7 L/sec per person (Parthasaranthy et al. 2013). In a study of large retail stores (Dutton et al. 2013), indoor formaldehyde concentrations were substantially reduced by higher VRs; however, several-fold increases in VRs above the levels in current standards would be necessary to consistently maintain indoor formaldehyde levels below 9 µg m^{-3} without implementation of formaldehyde source control or air cleaning. Also, one can question whether standards should require MVRs that maintain indoor formaldehyde levels in commercial buildings below 9 µg m^{-3} unless such a requirement was also incorporated in ventilation standards for homes, which typically have higher indoor formaldehyde concentrations than commercial buildings. In addition, there is substantial uncertainty among cognizant authorities about acceptable exposure levels of formaldehyde. A recent rule in California limiting formaldehyde emissions from composite wood products (California Air Resources Board 2003) and likely soon to be implemented nationally by the U.S. EPA (2013b), is expected over time to reduce the amount of ventilation needed to maintain formaldehyde concentrations below the OEHHA REL, at least with respect to newly manufactured building materials and contents.

Insufficient quantitative evidence for current consideration in MVRs

Other human outcomes, such as absence, asthma and allergies, and respiratory infections, have data that are suggestive but insufficient for consideration in MVR standards. These outcomes should be re-evaluated as more data become available.

There are data indicating that chemical reactions occurring in indoor air, often the result of reactive pollutants such as ozone from outdoor air, can produce chemicals such as aldehydes known to be irritants, and the reaction rates and concentrations of these irritants are affected by VRs (Weschler and Shields 2000). However, it is not clear that indoor air concentrations of reaction products are high enough to be of consequence.

Additional data are available on relationships of VRs to indoor concentrations of outdoor-sourced contaminants and relationships of the outdoor-sourced contaminants to a variety of outcomes, including allergy/asthma, cancer, cardiovascular effects, illness absence, and death. The largest source of risk is outdoor air particles, and the prior text has suggested that filtration, not ventilation, is the appropriate strategy for controlling indoor exposures to these particles. Ozone is generally considered the second largest source of health risks of this kind, and buildings "shelter" occupants from ozone because ozone is removed by reaction with indoor surfaces. Increased VRs will increase indoor concentrations of ozone; however, the magnitude of increase is modest because of the high rates of ozone removal by deposition on surfaces. Still, increased risks from outdoor air ozone, and potentially from other gaseous outdoor air pollutants, should be considered as a cost of specifying increased MVRs in cost benefit analyses. ASHRAE 62.1-2010 requires air cleaning of incoming air in buildings when outdoor air does not meet the National Ambient Air Quality Standards (ASHRAE 2010). A provision such as this, or a more stringent one such as in the European ventilation standard, may be appropriate to include in an evidence-based MVR standard.

Summary of evidence on outcomes

Research has provided evidence that BRS, perceived air quality, and aspects of work performance are affected by VRs, even though the underlying pollutant exposures are not well understood. Increased cancer rates from formaldehyde are the only chronic health effect influenced by VRs sufficiently to consider along with these other three outcomes in setting MVRs.

Proposed process for determining MVRs in standards

The proposed process for determining MVR standards begins with selection of reference VRs for evaluating specific costs and benefits. The reference VR for each outcome, selected based on current knowledge, is one of two kinds: for outcomes that *worsen* with decreasing VRs, the reference VR is the lowest VR that provides the best outcome level achievable, with the outcome not significantly improved further by higher VRs; for outcomes that *improve* with decreasing VR, the reference VR is simply the VR that provides the best outcome level achievable. . For outcomes that worsen with decreased VR (BRS, perceived air quality, work performance, and cancer risks from indoor-generated contaminants), 25 L/s (53 cfm) per person is selected as the reference VR. For outcomes or other costs that improve with decreased VR (energy costs and health risks from indoor exposures to outdoor air contaminants), 0 L/s (0 cfm) is selected as the reference VR. (Ideally, this process would include separate reference VRs for occupant-proportional and building-proportional MVRs, but sufficient data are not yet available.)

The process then includes two components:

- First, specify acceptable thresholds for the relevant adverse human outcomes (e.g., BRS should not increase more than x% relative to the reference VR) and estimate the *overall MVR* (called the target MVR) needed to meet thresholds for all outcomes considered.
- Then, if the overall target MVR is considered too high to be feasible, estimate the magnitudes of adverse outcomes and associated costs at a variety of MVRs and use the resulting information in a risk management process to identify a suitable MVR.

A sequence of recommended steps is outlined in more detail in Table 3. Steps 1-6 develop MVRs intended to control all relevant adverse outcomes below thresholds. Steps 7-10 apply a cost/benefit balance when the MVR identified in steps 1-6 is considered by decision makers to be infeasibly high.

Table 3. Steps in a proposed process for determining MVR standards

<u>Developing MVRs intended to control all relevant adverse outcomes to target level</u>

1) Identify the set of relevant human outcomes affected by VRs, per Table 2.
2) Select a set of occupancy categories or building classes.
3) Synthesize available information relating each outcome to VR, separately for each occupancy category as feasible. Develop estimates of the quantitative relationships of VRs with each human outcome, as feasible. At present, use 25 L/s (53 cfm) per person as the reference VR (VR corresponding to the best achievable outcome level) for outcomes that worsen with decreasing VR and use 0 L/s (0 cfm) per person as the reference VR for outcomes that improve with decreasing VR. (This process includes only reference VRs per person, but given sufficient data, separate reference VRs per area should also be determined.) Include associations of the outcome (a) directly with VRs and (b) indirectly with VR through VR-influenced indoor contaminants, as available. The latter includes identifying the types of indoor contaminants that affect occupant outcomes, are influenced by VRs, and are appropriate to control with ventilation, and then characterizing relationships of the specific relevant contaminants and VRs in typical buildings of each occupancy category. Focus on the set of outcomes having relationships with VRs, or VR-influenced contaminants, of sufficient magnitude and responsiveness to merit consideration in MVR standards. (Use a metric of VR/person now in order to use available data, although eventually a metric for VR/area would be more appropriate for contaminants emitted by building materials and by many products used in buildings.)
4) Set initial threshold levels for each adverse outcome based on the maximum amounts considered acceptable (a risk management process, which could be performed by a specific cognizant authority or a committee of stakeholders), and estimate the set of corresponding initial MVRs to control each outcome to its initial threshold.
5) Determine an overall target MVR that will control all relevant outcomes. In combining outcome-specific MVRs, assume in the absence of evidence to the contrary that the different outcomes are caused by exposures with independent mechanisms of action, so that the highest single MVR needed to control any specific outcome, when selected as the target MVR, will control all other outcomes. (Occupant-based and building-based MVRs for odor/perceived air quality outcomes, for instance, should be added; the present process, however, does not include building-based components.) For outcomes with

indirect relationships with VRs through specific contaminants, consider, to the extent possible with available data, possible cumulative effects from multiple contaminants operating through the same biologic mechanisms.

6) If the overall target MVR is considered feasible (this determination may change with time, based on the prior existing MVRs, costs of energy, technical feasibility, politics, etc.), determine whether at this VR the increased risk from *outdoor pollutants indoors* is below the specified target threshold. If yes for both, the target MVR is the final MVR. If yes on feasibility and no on outdoor air risks being within limits, specify the level of air cleaning required, and then the target MVR is the final MVR. If no on both, a cost-benefit process is necessary.

<u>Applying a cost-benefit balance when the MVR identified in steps 1-6 is considered by decision makers to be infeasibly high</u>

7) If the overall target MVR required to control all outcomes to the desired levels for a specific building occupancy category is deemed by decision makers to be too high to be feasible, apply a cost-benefit analysis to compare total costs and estimated benefits at selected levels of VR. This analysis could include, for instance, the MVR in current standards, the MVR that controls all outcomes, and an MVR that controls all outcomes except the single outcome requiring the highest MVR. (This focus on several selected alternative solutions follows the EPA's current environmental health risk assessment approach.)
8) As feasible, estimate the increase in adverse human outcomes and their monetary values at each MVR considered, relative to baseline reference VRs (RVRs). The costs should represent the broad societal costs, not just the costs experienced by the employer. The RVR for human outcomes that worsen with decreased VR can be a high VR, above which further increases do not yield significant benefits. This RVR in offices might be 25 L/s (53 cfm) per person because there is little evidence of benefits from exceeding this VR. The suggested RVR for human outcomes that improve with decreased VR, i.e., the health effects of outdoor air pollutants indoors, is 0 L/s per person.
9) Quantify the energy, and when possible the equipment, operation, and maintenance costs, of providing different amounts of ventilation in each class of building, relative to a RVR of zero, for a range of climate zones. (This may include design load calculations and equipment sizing (capital costs), and annual energy simulations for the building (operating costs) at different VRs. These costs might also include more comprehensive costs including environmental impacts of energy use.
10) Assemble a team of stakeholders representing employers, building designers and operators, public health experts, and the general public; provide them with the relevant information listed above; and challenge them to develop recommended MVRs that balance the benefits and costs of ventilation. Provide a technical support team that can explain existing findings to stakeholders and provide additional analyses for questions that arise. Over time, as new compounds are introduced into buildings and new data on health effects become available, update the data gathering and risk management process.

An example of the application of this proposed process for determining MVRs for an office setting is provided in Table 4. In this example, the human outcomes are perceived indoor air

Table 4. Example of proposed process for determining evidence-based MVRs for an office, including consideration of outdoor pollutant effects, and feasibility*

Steps	A	B	C	D	E	F	G
		Outcomes that worsen with decreasing VR				Outcomes that improve with decreasing VR	
1	Select human outcomes with demonstrated associations with VR	Visitor Dissatis-faction with IAQ	BRS	Work Perfor-mance	Increase in Cancer Risk from Formaldehyde	Increase in Mortality Risk from Outdoor Air Pollutants	Energy and Equipment Costs of Ventilation
2	Reference VRs (RVRs)	25 L/s per person				0 L/s per person	
3	Specify thresholds (examples provided) for maximum acceptable increases in outcomes, relative to RVR	10% absolute increase (to 16.6%)	50% relative increase	-2% relative decrease	1/100,000 absolute increase	1/100,000 absolute increase	---
4	Calculate Target MVRs (TMVRs) needed to meet targets in Columns B--E Step 3	9 L/s per person	8 L/s per person	8.5 L/s per person	8 L/s per person	---	---
5	Select highest TMVRs (HTMVR) from Columns B-E	**9 L/s per person**				---	---
6	Calculate increased risk (X) from outdoor air contaminants at HTMVR relative to the Column F RVR	---	---	---	---	X	---
7	If X exceeds Column F Step 3 target, specify air cleaning for outdoor air and go to Step 8, or go to Step 9	---	---	---	---	---	---
8	If HTMVR is judged feasible, Final MVR = HTMVR; otherwise go to Step 9	---	---	---	---	---	---
9	If HTMVR is judged not feasible or X exceeds target outdoor air pollutant risk, select various Lower Target Minimum VRs (LTMVRs)	---	---	---	---	---	---
10	Estimate increases in human outcomes and associated monetary costs at HTMVR and the various LTMVRs relative to RVR (column B--E)	$M1, $M2, $M3, ….	$N1, $N2, $N3, …	$O1, $O2, $O3, …	$P1, $P2, $P3, …	---	---
11	Estimate increases in human outcomes from outdoor air pollutants and associated monetary costs at HTMVR and various LTMVRs relative to the Column F RVR	---	---	---	---	$Q1, $Q2, $Q3, …	---
12	Estimate increases in energy and equipment cost (E) at HTMVR and various LTMVR relative to the Column G RVR	---	---	---	---	---	$E1, $E2, $E3, …
13	Use data from steps 9-12 in Risk Management Process plus subjective values to select Final MVR	---	---	---	---	---	---

* This table considers only VRs per person; with adequate data, VRs per area should also be included; Note: '---' indicates Not Applicable;

quality, BRS, work performance, and the cancer risk from formaldehyde, with VR-related risks estimated assuming 25% time in an office for 35 years. (Currently available evidence is generally only in terms of VR per person, so this example uses VR per person for all outcomes, with a default density of occupancy. Ultimately, with availability of sufficient data, MVRs should combine appropriate components of VR per person and VR per area.) Threshold (maximum acceptable) levels of outcome changes were defined relative to outcomes at a high baseline VR of 25 L/s (53 cfm) per person, because there is little evidence of benefits from providing more than this amount of ventilation. The example threshold levels selected here for human outcomes were: a 10% absolute increase in those dissatisfied with indoor air quality, a 50% relative increase in proportion of occupants with one or more BRS, a 2% relative decrease in work performance, and an absolute increase in formaldehyde cancer risks of 1×10^{-5}.

For a table of predicted values of percent of dissatisfied visitors, based on equation (1) from Fanger (1988), see Table 5. Satisfaction with air quality was calculated with equation 1. The equations in Fisk et al. (2012) and Fisk (2013a), provided in Appendix 3, were used to estimate the effects of VRs on BRS and work performance. The cancer risk of formaldehyde was calculated using the method of Parthasaranthy et al. (2013), but with specific different inputs as described above. The estimated difference between workplace lifetime cancer risks from formaldehyde exposures at 25 and 8 L/sec per person (0.7×10^{-5} and 1.7×10^{-5}) was 1.0×10^{-5}. Significantly lower cancer risks would be estimated for the higher values of default occupant density in the current ASHRAE 62.1-2010 and California Title 24 Standards. Also, lower risks would occur in offices that have outdoor air economizer controls that increase the VR above the MVR to save energy when weather conditions are mild. The risks of outdoor air pollutants have not been calculated as they would depend on location and level of filtration specified.

Table 5. Predicted proportions of visitors dissatisfied with perceived air quality, by VR, using equation (1) from Fanger (1988)

	VR (L/s/person)	VR (cfm/person)	Predicted % dissatisfied	Absolute % increase vs. baseline
	1	2.1	63.4	56.8
	5	10.5	25.6	19.0
	6	12.6	22.5	15.9
	7	14.7	20.1	13.5
	8	16.8	18.2	11.6
Example Target level	**9**	**18.9**	**16.6**	**10.0**
	10	21.0	15.3	8.7
	15	31.5	10.8	4.2
	20	42.0	8.2	1.6
Baseline	25	52.5	6.6	0.0

The resulting outcome-specific MVRs are 9.0, 8.0, 8.5, and 8 L/s (19, 17, 18, and 17 cfm) per person, for satisfaction with air quality, BRS, work performance, and cancer risk, respectively,

leading to an overall target MVR of 9 L/s (19 cfm) per person. This VR, the equal to the maximum of the four outcome-specific MVRs, is projected to keep increases in all adverse outcomes below the selected threshold levels.

If, on the other hand, a smaller threshold value of 1% reduced work performance is chosen, then the calculation yields a target MVR just under 14 L/s (30 cfm) per person. Reducing the threshold for increase in BRS to 25% also yields a target MVR of approximately 14 L/s (30 cfm) per person. And a threshold of 1×10^{-6} for increased lifetime cancer risk from formaldehyde would set a target MVR of 20 L/sec (42 cfm) per person. Target MVRs of 14-20 L/s (30-42 cfm) per person would likely trigger the need for a cost/benefit balancing process to determine if such a high MVR is justifiable, or if some increased adverse effects can be accepted in exchange for the energy and cost savings of MVRs below 14 or 20 L/s per person.

Discussion

Synthesis

The goal of this paper was to propose a framework for setting MVR standards for commercial buildings in California that explicitly aims to protect occupants from VR-related adverse effects, to the extent feasible when considering energy and other costs. This task was motivated by research findings suggesting that current prescriptive MVRs in commercial buildings do not provide occupants with fully safe and satisfactory indoor environments, by the absence of a scientific underpinning for current MVR standards, and by potential decreases in building MVRs to reduce energy use in buildings. The process began with a review of three topics: strategies used to develop current MVR standards; strategies to develop health-based standards or guidelines for air pollutants; and current knowledge about relationships, direct or indirect, between VRs in commercial buildings and human outcomes. Using this information, general principles and procedures for selecting the MVRs in standards were proposed. The procedures include:
a) selecting a high reference value of VR above which further increases in VR appear to yield insignificant benefits; b) selecting thresholds for maximum acceptable increased adverse outcomes, relative to outcome levels at the high reference VR; c) estimating the specific MVRs that will control each adverse outcomes within its threshold; and d) selecting the maximum of the outcome-specific MVRs as the overall target MVR. The occurrence of increased outdoor-pollutant related outcomes at the overall target MVR is considered here with limited detail. The procedures include cost/benefit analyses as a second step, if the target MVR needed to meet all initial outcome thresholds leads to unacceptable energy use or is too high from a practical or political perspective.

Sufficient current evidence was identified to consider acute building-related symptoms (BRS), perceived indoor air quality, work performance, and cancer and non-cancer chronic effects in the selection of MVRs. Example calculations with these outcomes yielded a MVR of 9 L/s (19 cfm) per person for offices using an example set of outcome thresholds. This target MVR is close to the current MVRs prescribed in the ASHRAE and Title 24 standards. However, other reasonable threshold levels of these outcomes would produce substantially different target MVRs; for example, 14 or 20 L/s (30 or 42 cfm) per person. These higher values of MVR would be

sufficiently above current requirements to trigger cost-benefit analysis. Societal decisions about what target levels of each outcome to choose may be unfamiliar and difficult, but will be a necessary part of creating evidence-based ventilation standards intended to protect building occupants.

Strengths and limitations

The framework proposed here is intended to incorporate into MVR standards the strengths and accepted utility of many approaches now used for setting environmental limits to protect the population. The principles and approaches suggested here, if implemented, are likely to improve the protection for occupants of commercial buildings from adverse effects of indoor contaminants. The example presented, although more complex than current approaches to MVR standards, shows that application of the proposed approach is feasible.

This proposed framework and this paper have a number of limitations. Application of the proposed approach to selection of MVRs will be constrained by limitations in existing data relating VRs to human outcomes, as discussed subsequently. The framework proposed here suggests use of safety factors to protect sensitive subgroups, but does not describe how to select those safety factors. The methods for estimating the monetary value of adverse human outcomes and for estimating the energy costs of ventilation are not described, although these issues are discussed elsewhere (Fisk et al. 2012).

Limited data

Current data relating VRs to human outcomes rely almost exclusively on VRs per person. It would be much preferable to have data on how both VR per person and VR per unit floor area are related to many of the human outcomes, as a VR standard containing two evidence-based components, to control per-person and per-unit area emissions, would be more appropriate than one assuming all emissions are proportional to number of occupants. Data on potential coordinated effects among groups of contaminants with related modes of biologic action are also very limited. Lack of data, if such coordination of effects occurs, will lead to inadequate human protection by specific MVRs. Also, most of the data for estimating costs of outcomes are for office spaces, with available data for commercial spaces other than offices more sparse. There is less data of all kinds for non-office commercial spaces such as retail and schools.

The proposed framework requires more data than current approaches, and the available data are limited. For instance, there are few suitable available field studies on both VRs and BRS, or on VRS and diminished work performance, and each of these relationships is summarized in only one available quantitative meta-analysis. The metrics used to assess these outcomes are not standardized, making synthesis of findings across studies difficult. Limited findings strongly suggest relationships of VRs with absence and respiratory infections; however, current data are insufficient to allow incorporation of these outcomes in the proposed process for selecting MVRs.

Unresolved questions

For some human outcomes, such as SBS, there is still no agreement on how to measure them or how to define a background or reference level, despite an extended body of research over

decades. Researchers have measured: frequency of past symptoms (in the past week or month or two years), severity of current symptoms (at the moment, or during that day); symptoms with definitions that differ across researchers and studies, such as sore eyes, irritated eyes, itching or irritated eyes, tired eyes, etc.; symptoms experienced only in the building or experienced anywhere; and symptoms analyzed either individually, in various groupings based on biological reasoning or statistical correlation, or as total number of all symptoms. The quantitative meta-analysis used in the example in this paper simply considered significant increases within each study, based on however the symptoms were measured.

The approach described here assumes that MVRs should protect building occupants from all adverse effects of inadequate VRs, including on health, performance, and odor or perceived indoor air quality among visitors. It could be argued, however, that required MVRs should protect only health. Perhaps the level of perceived air quality in a building, and whether evaluated for occupants or more stringently for unadapted visitors, should be considered a matter for building owners and/or occupants to determine on their own, using nonbinding guidelines formulated for that purpose. Impaired occupant performance might be assumed to result from adverse physiologic/neurologic effects of indoor contaminants, and thus an appropriate outcome for a health standard. On the other hand, since even subtle variations within the acceptable range of indoor temperatures apparently cause variation in occupant performance, then perhaps performance should not be considered in a MVR standard, but left to building owners/tenants to negotiate based on available guidelines. Alternately, perhaps work performance should not be considered in selecting an MVR, but if the initial MVR is too high to be feasible and cost/benefit analyses are undertaken, then improved work performance from higher MVRs should be included as a benefit to weigh against increased energy costs.

The approach described here still requires substantial judgment in setting MVRs. Partly this is due to the limited available data. For instance, typical levels of many contaminants within buildings of each occupancy type have not been determined, but how should standards deal with the variation across different buildings in such levels? However, even with more data, many decisions, such as how much of a specific adverse human outcome is acceptable, or how to quantify the costs or benefits of difficult-to-quantify outcomes, will remain subjective. This may seem similar to the current process of MVRs based on engineering judgment. However, the proposed process provides a method for laying out all costs and benefits for more explicit consideration than current MVR standard approaches, in the same type of framework now used for complex societal decisions about contaminant limits for outdoor air, food, or drinking water.

While it is hard to disagree that outdoor air brought into a building should not degrade the indoor air and increase adverse health effects, it is not clear that including a requirement to clean all highly polluted outdoor air brought into buildings is currently practical, both because of the cost and because this is not yet technically feasible for some pollutants. This raises the question of whether currently feasible and affordable air cleaning technologies should be required for outdoor air, and what the applicable criteria should be. The current ASHRAE 62.1-2010 requires cleaning of outdoor air when the ambient levels exceed those specified in the National Ambient Air Quality Standards, although more stringent requirements might be advisable for protecting indoor air. It seems inefficient to require all buildings to install and maintain air cleaners for ambient air pollutants that are more effectively and efficiently controlled at their sources;

however, such a new cost might adjust the cost/benefit balance considered in societal decisions about control of ambient pollutant sources.

Another important unresolved question, raised in recent publications (Kajtar et al. 2006; Satish et al. 2012) is whether carbon dioxide (CO_2) itself may be an indoor pollutant, rather than just an indicator of ventilation adequacy for removing other pollutants. Significant decrements in decision-making performance were seen at CO_2 levels as low as 1000 ppm in a recent study (Satish et al. 2012). If this is confirmed, CO_2 concentrations may place a downward limit on MVRs separate from other human bioeffluents.

Prescriptive standards vs. performance-based standards

If current commercial buildings at current MVRs do not provide healthy and comfortable environments for occupants, a traditional approach to reduce indoor air contaminants to acceptable levels would be to increase MVRs to levels estimated to control adverse outcomes. However, increasing MVRs is only one of multiple available strategies for reducing indoor air contaminant levels, and has several disadvantages: increasing general ventilation is less efficient than reducing/eliminating indoor sources, it will increase indoor levels of outdoor pollutants, and it usually requires increased energy. Therefore, it is advisable, in determining how to define MVRs needed to protect occupant health, performance, and satisfaction, to consider a larger question: what available strategies can most effectively and efficiently reduce indoor contaminants and adverse human effects to acceptable levels? This larger question, however, cannot be fully considered with the current prescriptive MVR standard, but only with alternate approaches such as performance-based VR standards. Performance-based standards allow consideration of additional strategies such as air cleaning and source control to improve IAQ for each specific building, potentially reducing the required VRs. The increased complexity and data requirements involved, however, are substantial impediments to widespread use of performance-based ventilation standards (ASHRAE 2010; Fisk et al. 2013; Mendell and Apte 2013). While the approach outlined in the present document admittedly requires types of data and involves challenges of similar complexity as a performance-based standard, the collection of data and this complexity would be handled by those establishing the standard, rather than by those designing each specific building as in the ASHRAE 62.1-2010 IAQP.

The increasing need to use energy sparingly, however, places increasingly stringent limits on how much we should look to ventilation alone to solve problems of indoor contaminant exposures. Thus, traditional prescriptive standards may need to incorporate elements that incentivize reduced indoor contaminant emissions or air cleaning by allowing reduced VR-related energy use, as in the current European VR standards.

Conclusions and recommendations

Current prescriptive MVR standards for commercial buildings do not take advantage of the existing scientific data relating VRs with human outcomes. The principles and procedures used to develop standards and guidelines for outdoor air pollutants can, to some extent, be incorporated into standard setting for MVRs in commercial buildings. This paper provides a

related framework for selecting MVRs and, via example calculations, shows that it is feasible to apply the framework.

An example calculation indicates that, relative to much higher VRs, there are substantial adverse effects associated with a MVR of 9 L/s (19 cfm) per person, although this is slightly higher than the MVRs currently specified for offices at default densities in the ASHRAE 62.1 and California Title 24 standards: 8.5 and 7 L/s (17 and 15 cfm) per person, respectively. These estimated adverse effects include a 10% absolute increase in visitors dissatisfied with air quality, a 50% relative increase in building related symptoms, a 2% relative reduction in office work performance, and a 1 per 100,000 absolute increase in cancer risk due to formaldehyde.

Additional data relating VRs in commercial buildings to human outcomes will be necessary to make best use of the proposed framework. Despite these substantial limitations, applying such a framework will result in MVR standards with a stronger scientific basis for protecting occupants than the current standard-setting process.

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Appendices

Appendix 1. The environmental health risk assessment and risk management process used by the U.S. EPA: a description and an example

Environmental health risk assessment at the U.S. EPA
The "risk assessment" process for environmental contaminant exposures includes four steps: hazard identification (evidence of potential harm from an exposure), dose-response assessment (using evidence from epidemiology, controlled exposures, or toxicology studies), exposure assessment (determining existing population exposures), and risk characterization (integrating the prior three steps to describe the probability of population harm at the described exposures). The more scientific and objective risk assessment process provides its findings as input to the more subjective "risk management" process, in which societal decisions are made based on weighing of costs/benefits and feasibility (technical, economic, and political).

After assessment of current exposure levels, the next step in the process is health risk characterization, to estimate potential health risks associated with several contaminant levels: current exposures, those associated with the current standards, or those in potential alternate standards, while considering uncertainty. The resulting evidence-based evaluations of the adequacy of the existing standard and potential alternative standards are provided as inputs for the EPA's risk management activity, in which policies are set. In setting policies, the EPA is mandated to establish primary standards that are "neither more nor less stringent than necessary . . . to protect public health with an adequate margin of safety;" that is, "not at a zero-risk level but rather at a level that avoids unacceptable risks to the public health, including the health of sensitive groups." The overall process of risk assessment and risk management, a complicated technical and political process, sometimes takes 10-20 years for single chemicals [Committee on Improving Risk Analysis Approaches Used by the U.S. E.P.A., 2009 #2187].

In 2009, an NRC report (Abt et al. 2009) on improving the risk assessment process made multiple recommendations, including: a) that the risk assessment process should follow after a preliminary identification of the potential options for managing risk from the identified hazard, and then be tailored in approach and complexity to assist in choosing among those specific risk management options (this change was reflected in the risk assessment for NO_2 that is described in the text); b) improvements in analyses of uncertainty and variable susceptibility; c) a unified approach to dose-response assessment in order to produce risk estimates for both cancer and non-cancer endpoints, based on estimating dose-related probabilities of harm that consider background levels of exposure and disease and vulnerable subgroups in the population, rather than strict threshold levels of acceptability; and d) more explicit consideration of cumulative risk assessment of multiple chemical and nonchemical stressors.

An Example of Risk Assessment at the U.S. EPA
An example of the current EPA risk assessment process that precedes risk management is the Final Risk and Exposure Assessment Report for the Primary National Ambient Air Quality Standard for Nitrogen Dioxide (NO_2), a criteria pollutant (U.S. Environmental Protection Agency 2008). The review of the evidence, separately for short-and long-term exposures, found evidence sufficient to infer a likely causal relationship between short-term exposures and

respiratory health effects, but not cardiovascular health effects or overall mortality, and not between long-term exposures and any studied outcomes. The EPA concluded: “The only endpoint for which the evidence is judged to be sufficient to infer either a causal or a likely causal relationship is respiratory morbidity following short-term NO_2 exposure. Therefore, for purposes of characterizing health risks associated with NO_2, we have focused on respiratory morbidity endpoints that have been associated with short-term NO_2 exposures.”

Appendix 2. Additional details on human outcomes with sufficient data on quantitative relationships to VRs to consider in MVR standards

Table A2-1. Building-related symptoms (BRS), sometimes called sick building syndrome (SBS) symptoms:* data available for VR standards and data needed

Reason selected	Much studied, common health effect in buildings, linked consistently in many studies to lower ventilation rates, but not yet to specific ventilation-related contaminants
Methods used to assess outcome, and related limitations	Assessed by self-administered questionnaire; problems in interpreting evidence include lack of agreement on which specific symptoms and by which definition to assess (e.g., single-symptom vs. multiple symptom questions, stringency, current severity vs. past frequency, period of recall), subjectivity of responses, and documented variation due to many non-environmental factors; no specific set of symptoms or symptom definition has shown stronger environmental links and thus achieved use as a standard assessment
Suggested strategy to assess associations of outcome with VRs or with VR-influenced exposures (overall or in susceptible groups**)**	Epidemiologic studies (both cross-sectional surveys and intervention studies) using occupant questionnaires plus measured VRs and/or contaminants; compare different symptom measurement approaches and choose standard; estimate relationships, overall and in potential susceptible groups (e.g., gender, age, allergy/asthma status)
Strategy to balance outcome with VR costs	Estimate exposure/response relationships; use metric of relative increase above reference level; if possible, adjust in analysis models for non-environmental factors with strong effects on BRS reporting; monetize the impacts of absolute increases in SBS, or choose maximum acceptable increase in proportion of occupants with BRS
Current status of methods and data	Much available data on BRS, including symptom frequency and severity, relative frequency of each symptom to other symptoms, and relative increase of specific symptoms with lower VRs, including quantitative meta-analyses; however, data includes many different types of symptom definition; no widely accepted common definition of what symptoms to consider, how to define or measure each or BRS overall, how to combine specific symptom data into overall BRS measure, whether all symptoms of equal importance, how to identify both baseline and maximum acceptable levels for BRS; whether to use additive or relative increase above reference level, how to adjust for strong effect on BRS of multiple non-environmental factors differing over place and time? **Much available field data; one available set of estimates on VR versus BRS relationships usable in a cost-benefit analysis; desirable to have additional data and estimates**

* e.g., symptoms commonly include eye, nose, throat, skin, breathing, headache, fatigue, tiredness, concentration difficulty

Table A2-2. Poor perceived air quality: data available for MVR standards and data needed

Reason selected	The original adverse outcome used to set MVRs, based on human bioeffluents; now known that non-human based indoor contaminants also contribute odors and sensory irritants, so required MVRs may require a component proportional to building area, in addition to a component proportional to occupant number (which may also need to reflect non-occupant-generated but occupant-proportional emissions as from computers or other equipment)
Methods to assess outcome	Questionnaires about acceptability of air quality; may be somewhat impractical for large scale use
Strategy to assess associations of outcome with VR or VR-influenced exposures	Field studies, cross sectional and intervention, with questionnaires plus measured VRs and contaminants; can assess acceptability for adapted or unadapted occupants; chamber studies can assess relationships focused on occupant-emitted bioeffluents; relationships could use, for outcome, metrics of the traditional absolute proportion of dissatisfied at a VR, or relative increase in proportion dissatisfied at lower vs. higher VRs, or ratio of proportion dissatisfied at lower vs. higher VRs
Strategy to balance outcome with VR costs	For cost/benefit, need to define relationship of VR to acceptability as an input into risk management process; could use traditional absolute proportion of dissatisfied, relative increase in proportion dissatisfied at lower VRs, or ratio of proportion dissatisfied at lower VRs, as absolute minimum for acceptability; requires decision as to whether to consider adapted occupants or unadapted visitors; develop monetization if feasible
Current status of methods and data	Data suggest current office buildings even at current VR standard usually do not provide PAQ acceptable to at least 80% of occupants (but not clear if studies included buildings allowing smoking); **methods are available to produce additional data for input into risk management for VRs**

Table A2-3. Diminished performance (on job or at school): data available for MVR standards and data needed

Reason selected	Available research data suggest diminished worker performance and student test performance at reduced VRs, with adverse economic effects, and suggesting adverse physiologic effects
Methods to assess outcome	Field studies, cross-sectional and intervention, with outcomes such as speed and accuracy of work tasks, neuropsychologic testing of cognitive function, or test scores in students
Strategy to assess associations of outcome with VR or VR-influenced exposures	Field studies, cross-sectional and intervention, plus controlled studies, assessing performance and VRs plus contaminants
Strategy to balance outcome with VR costs	Use relationship of VR to proportional or absolute increase in performance above reference level as input to risk management; quantify diminished performance as a health effect; could also monetize
Current status of methods and data	Limited data available on relationships using limited set of performance assessments; **one available set of estimates on VR versus performance relationships usable in a cost-benefit analysis; desirable to have additional data and estimates**

Table A2-4. Cancer and other chronic outcomes: data available for MVR standards and data needed

Reason selected	Multiple known carcinogens, with quantifiable decrease with increased VRs, are emitted into indoor air
Methods to assess outcome	Modeling of contaminant exposures and health risks
Strategy to assess associations of outcome with VR or VR-influenced exposures	Conduct field studies and modeling to assess how indoor concentrations are affected by VRs. Model risks at different VRs using existing data relating exposures with risks.
Strategy to balance outcome with VR costs	Use relationship of VR to excess cancer risk above background as input to risk management
Current status of methods and data	Methodology available, data available for substantial list of compounds of potential concern in some types of commercial buildings; **Sufficient data for current input into risk management process, although more data is desirable; data suggests that cancer risks from VOCs in current commercial buildings are generally too low relative to specific acute outcomes to drive VR standards, with the possible exception of formaldehyde and cancer risk.**

Appendix 3. Equations used to estimate effects of VRs on BRS and work performance

Estimated effects of VRs on BRS

Equation (1) was used to estimate the relationship of VRs in offices with prevalence rates of SBS symptoms (Fisk et al. 2012):

$$RSP = \exp(0.00089\, x^2 - 0.0542\, x + 0.453) \qquad (1)$$

where RSP is the relative SBS symptom prevalence, equal to the expected SBS symptom prevalence with a VR of x (in L/s per person) divided by the expected SBS symptom prevalence if the building had a VR of 10 L/s per person. This equation, based on a statistical analysis of published data from eight studies and 43 data points, indicates the average relationship for a range of SBS symptom types across a range of VRs from 5 to 35 L/s per person. [

Estimated effects of VRs on work performance

Values of relative performance (RP) were estimated with the following equations [Fisk, 2012 #2205]:

Equation (2) was used to estimate the relationship of VRs in offices with office work performance:

$$RMPVR=\exp((-76.38\, x^{-1} - 0.78\, x\, Ln(x) + 3.87\, x - y_0)/1000) \qquad (2)$$

where RWPVR is the relative work performance as affected by VR,
x is the VR in L/sec per person and
y_0 is calculated as follows:

$$y_0 = -76.38\, X_R^{-1} - 0{:}78\, X_R\, Ln(X_R) + 3.87\, X_R \qquad (3)$$

where XR is a reference (initial) value of VR in L/sec per person.

Equation (2) applies for VRs of 6.5 – 47 L/sec per person. This equation is based on statistical analysis of research data from nine studies and 26 data points. It is important to note that the studies analyzed by Seppänen et al. (2006) to derive equations (2) and (3) involved only call center work and work tasks for which speed and accuracy could be readily quantified. While the predicted performance increases with ventilation rate increases are statistically significant over much of the range shown, there remains a high uncertainty about the magnitude of performance increases one should expect in actual practice. It is possible that the effects of ventilation rate on work performance may vary substantially with type of work, with outdoor air quality, and with indoor pollutant emission rates or other building features that affect indoor environmental quality. In most of the studies analyzed by Seppänen et al. the occupant density was high.