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FINAL PROJECT REPORT

COMMERCIAL BUILDING VENTILATION EFFECTS ON INDOOR AIR QUALITY, HUMAN HEALTH AND PERFORMANCE, AND BUILDING ENERGY USE AND IMPLICATIONS FOR FUTURE VENTILATION STANDARDS

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PREFACE

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ABSTRACT

Ventilation of buildings using outdoor air is necessary to maintain acceptable indoor air quality and health conditions for occupants; however, the outdoor air must often be heated or cooled and dehumidified before it is used. Ventilation rate standards specify minimum rates of ventilation; however, scientific data for selecting minimum ventilation rates has been sparse. The main objective of this project was to advance knowledge about how ventilation rates in California's commercial buildings affect indoor air quality, occupant health and performance, and energy consumption. Several related research tasks were performed, including: a survey of ventilation rates and air quality in retail buildings; a longitudinal study of ventilation rates and absence in offices; a controlled laboratory study of ventilation rates and human performance; analysis of how ventilation affects chronic health risks; and modeling of how ventilation rates affect energy use and indoor pollutant concentrations. Findings included widespread high ventilation rates in offices and stores and widespread exceeding of formaldehyde reference levels, with particle filters with fiberglass filter media identified as a substantial source of formaldehyde. Moderate changes in chronic health risks and changes in human performance along with changes in ventilation rates were found, but acute health symptoms and absence rates in office workers were not affected by ventilation rates at the very high ventilation rates encountered. Ventilation rates were found to moderately affect energy use in offices and schools and to more substantially affect energy use in medium-size stores. Recommendations to formulate new ventilation standards that take advantage of scientific data were developed. This research will help policymakers and building designers and operators strike a balance between the benefits and costs of higher ventilation rates.

Keywords: commercial buildings, energy, health, indoor air quality, performance, standards, ventilation

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TABLE OF CONTENTS

Acknowledgements ..... **i**

PREFACE ..... **ii**

ABSTRACT ..... **iii**

TABLE OF CONTENTS ..... **iv**

LIST OF FIGURES ..... **vii**

LIST OF TABLES ..... **viii**

EXECUTIVE SUMMARY **1**

Introduction 1

Project Purpose 1

Project Results 2

Project Benefits 6

CHAPTER 1: Background **7**

CHAPTER 2: Overall Methods **10**

CHAPTER 3: Results **13**

3.1 Assessment of Indoor Air Quality Procedure 13

3.1.1 Objectives 13

3.1.2 Methods 13

3.1.3 Results 14

3.1.4 Discussion 16

3.1.5 Conclusions 16

3.1.6 Significance 17

3.2 Retail Cross Sectional Study 17

3.2.1 Objectives 17

3.2.2 Methods 17

3.2.3 Results 18

3.2.4 Discussion 19

3.2.5 Conclusions 20

3.2.6 Significance 20
3.3 Chronic Risk Evaluation 20
3.3.1 Objectives 20
3.3.2 Methods 21
3.3.3 Results 21
3.3.4 Discussion 23
3.3.5 Conclusions 24
3.3.6 Significance 24
3.4 Effects of Ventilation Rates Per Person and Per Floor Area on Human Outcomes 24
3.4.1 Objectives 24
3.4.2 Methods 24
3.4.3 Results 25
3.4.4 Discussion 29
3.4.5 Conclusions 30
3.4.5 Significance 30
3.5 Effects of Ventilation Rates on Acute Outcomes in California Office Workers 30
3.5.1 Objectives 30
3.5.2 Methods 30
3.5.3 Results 31
3.5.4 Discussion 34
3.5.6 Conclusions 35
3.5.6 Significance 35
3.6 Effects of Ventilation Rates on Building Energy Use and Indoor Air Quality 36
3.6.1 Objectives 36
3.6.2 Methods 36
3.6.3 Results 37
3.6.4 Discussion 43
3.6.5 Conclusions 44

3.6.6 Significance 44
3.7 Framework for Producing Evidence-Based Standards for Minimum Ventilation Rates 44
3.7.1 Objectives 44
3.7.2 Methods 44
3.7.3 Results 45
3.7.4 Discussion 45
3.7.5 Conclusions 46
3.7.6 Significance 46
3.8 Contaminant Emissions from Particle Filters 46
3.8.1 Objectives 46
3.8.2 Methods 46
3.8.3 Results 46
3.8.4 Discussion 48
3.8.5 Conclusions 49
3.8.6 Significance 49
3.9 Project Outreach Activities 49
3.9.1 Objectives 49
3.9.2 Methods 49
3.9.3 Results 50
3.9.4 Discussion 51
3.9.5 Conclusions 51
3.9.6 Significance 51
CHAPTER 4: Overall Discussion 52
GLOSSARY 53
REFERENCES 55
APPENDIX A: Links to Project Documents A-1
APPENDIX B: Remaining Priority Research Needs B-1

LIST OF FIGURES

Figure 1: Ventilation Rates Measured in 13 Retail Stores 14

Figure 2: Indoor Contaminant Concentrations Measured in Big-Box Store at Different VRs 15

Figure 3: Indoor Contaminant Concentrations Measured From 21 Retail Store Visits 19

Figure 4: Percent Removal of VOCs and SVOCs with Different Log(Koa), Ranging From <8 to >12, by Ventilation 22

Figure 5: Comparison of Average CO_2 Concentration Across the Different Conditions for the First Hour and the Subsequent 3 Hours of Each Test 26

Figure 6: Average Percentile Ranks (± 1 Standard Deviation) for High and Low VR per Person 28

Figure 7: Average Percentile Ranks (± 1 Standard Deviation) Presented High and Low VR per Unit Floor Area 29

Figure 8: Measured Minimum Ventilation Rates Compared to the Title 24 Requirement 32

Figure 9: Statewide HVAC Energy Use versus MVR for Offices with Economizers 38

Figure 10: Statewide HVAC Energy Use versus MVR for Offices without Economizers 39

Figure 11: Statewide HVAC Energy Use Intensity in the Primary School versus MVR Expressed as a Percentage of the Title 24 Required VR 39

Figure 12: Statewide HVAC Energy Use Intensity in the Secondary School versus MVR Expressed as a Percentage of the Title 24 Required VR 40

Figure 13: Statewide HVAC Energy Use Intensity in the Retail Building versus MVR Expressed as a Percentage of the Title 24 Required VR 41

Figure 14: Office HVAC Energy Use Intensity by Climate Zone and MVR for Buildings with Economizers 42

Figure 15: Office HVAC Energy Use Intensity by Climate Zone and MVR for Buildings without Economizers 42

Figure 16: Annual Average Normalized Contaminant Concentration as a Function of MVR 43

Figure 17: Formaldehyde Emission Rate (EF) as a Function of Relative Humidity in Low (ν = 0.013 m/s) and High (ν = 0.5 m/s) Face Velocity Experiments 47

Figure 18: Indoor Formaldehyde [CH2O] Levels Measured in Zone 1 (Z1) and Zone 2 (Z2) of a Modular Office Over Several Weeks at 50 Percent RH and 80 Percent RH Indoors, and With Filters P1 (Polyester) or F4 (Fiberglass) Installed in the HVAC Units 48

LIST OF TABLES

Table 1: Ventilation Rates Measured in Retail Stores from 21 Sampling Visits 18

Table 2: List of Priority VOCs 23

Table 3: Total Health Burden on U.S. Building Occupants Expressed in Dalys per Year (95 Percent Confidence Interval in Parenthesis) at Current Ventilation Rate (VR) and Two Alternatives: (1) Doubled VR, and 2 More Effective Particle Removal Using MERV 13 Air Filters 23

Table 4: Ventilation Rates for Each Condition 26

Table 5: Results of Pair-Wise ANOVA for the Per Person Ventilation Scenarios 27

Table 6: Results of Pair-Wise ANOVA for the Floor Area Ventilation Scenarios 27

Table 7: Prior Three-Month* Median of Daily Ventilation Rates (VRs)**, Daily Mean CO_2, and Daily Maximum CO_2, by Study Space 34

Table 8: Key Features of Simulated Buildings 37

EXECUTIVE SUMMARY

Introduction

Ventilation using outdoor air must be provided to buildings to control indoor air concentrations of indoor-generated air contaminants. Research completed prior to this project has shown that lower outdoor air ventilation rates (VRs) are associated with decreases in satisfaction with indoor air quality and increases in building-related acute health symptoms, often called sick building syndrome symptoms, in office workers. Reductions in some aspects of office- and school-work performance have also been demonstrated at lower VRs. Limited research has found that student and worker absence rates from schools and offices are higher when VRs are low. However, gaps in the knowledge about how VRs in commercial buildings affect people still existed. Virtually no research on the health implications of VRs had been performed for retail buildings. No estimates were available on how VRs affect the risks of chronic health effects. Studies of how VRs affect absence rates and respiratory infections were extremely limited. No data were available to indicate the relative importance of controlling occupant-generated contaminants or contaminants emitted by the building and its furnishings.

The ventilation air provided to buildings must often be heated or cooled and dehumidified, increasing building energy consumption. Also, higher VRs can increase indoor air concentrations of some contaminants found in outdoor air. Thus, it is necessary to strike a balance between the benefits and costs of higher VRs.

Many medium and large commercial buildings require cooling even when the outdoor air temperature is moderately lower than the indoor air temperature because the heat loss that occurs through the building envelope is not sufficient to remove all indoor-generated heat. Thus, the heating, ventilating, and air conditioning (HVAC) systems in commercial buildings often employ outdoor air economizers that increase VRs above a minimum ventilation rate (MVR) when the increased ventilation can reduce the need for mechanical cooling by compressor-based or similar energy-intensive space-cooling systems. In buildings with economizers, the MVR provided when the economizer is not activated affects building energy use the most. In buildings without economizers, the mechanical VRs remain approximately constant over time.

MVRs are specified in various standards, including in California's Title 24 Building Energy Efficiency Standards. However, current standards are substantially based on decades-old research that considered only how VRs affect satisfaction with indoor air quality. Development of scientifically-based MVR standards has been hindered by gaps in knowledge about both how MVRs influence health and performance of people in commercial buildings and how MVRs affect building energy use. In addition, procedures had not been developed to explicitly use the results of research in the development of MVR standards.

Project Purpose

The main purpose of this project was to advance knowledge about how ventilation rates in California's commercial buildings affect indoor air quality, occupant health and performance, and energy consumption and to provide recommendations that can be used to develop MVR

standards that take advantage of the advances in knowledge. The research was motivated specifically by the goal of improving MVR standards in California's Title 24 standards.

Project Results

This project included the following studies and their respective results:

Assessment of the Indoor Air Quality Procedure

The MVR standard for commercial buildings produced by the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) includes an alternative performance-based option for determining MVRs called the Indoor Air Quality Procedure (IAQP). The IAQP allows any MVR to be used as long as calculations or data indicate that concentrations of critical contaminants will be maintained below limits and perceived air quality is maintained above a certain level. Users of the IAQP may be able to save energy by reducing MVRs. The California Energy Commission sought an evaluation of the IAQP to inform their decision about adopting the IAQP in California's Title 24 standards. Accordingly, this study performed calculations to determine IAQP MVRs in 13 retail buildings, evaluated the potential benefits and limitations of the IAQP, and developed associated recommendations. The calculated IAQP MVRs were, in most cases, far higher than the MVRs specified in Title 24. In most buildings, IAQP MVRs were driven by the requirements to maintain indoor formaldehyde concentrations below the California Environmental Protection Agency's stringent reference level. When the National Institute for Occupational Safety and Health's less stringent reference level for formaldehyde was used in the calculation, most IAQP MVRs remained above the MVRs in Title 24. The research team recommended not adopting the existing IAQP in Title 24 because of its complexity and because it provides insufficiently detailed specifications to ensure proper implementation.

The research team suggested these three alternatives to the existing IAQP for potential development and adoption:

- The Alternative MVR Procedure, which would allow moderate reductions in MVRs if particle filter efficiency met certain above-average standards and if a specified indoor contaminant source control procedure was implemented.
- The Equivalent Indoor Air Quality Procedure (EIAQP), which would allow moderate reductions in MVRs when specified types of gas phase air cleaning were employed to prevent increases in indoor concentrations of contaminants.
- An ASHRAE-like IAQP, but with critical contaminants, reference levels, and procedures precisely defined, which would allow greater ease of implementation.

Effects of VRs on Acute Outcomes in California Office Workers

This longitudinal study monitored carbon dioxide concentration, temperature, and humidity over a full year in 16 spaces within office buildings in California. VRs were estimated during each work day from the carbon dioxide data gathered. The average measured VRs were very high relative to the MVR requirements for offices in Title 24. Additionally, in 15 out of 16 spaces, the measured MVRs also exceeded requirements, often by a large margin. There were

no consistent, statistically significant associations of VRs with rates of absence due to illness, rates of respiratory illness, perceived air quality, or other illness symptoms. There has been only one prior sizable study of VRs in relation to worker absence rates in offices. In that study, plus two studies in schools, it was found that lower VRs are associated with increased absences. There were no other studies of office environments identified that have investigated whether VRs affect respiratory illnesses or not. However, many previous studies have found that lower VRs in office buildings were associated with increased levels of sick building symptoms and less satisfaction with air quality by the office workers. The very high VRs in the current study may explain the lack of statistically significant associations of VRs with human outcomes.

Retail Cross Sectional Study

This study measured VRs and indoor and outdoor contaminant concentrations in retail buildings in California. The study included 19 total stores, including grocery, apparel, furniture, and hardware stores, from different California climate zones, with two stores evaluated twice. The resulting data were used to calculate indoor contaminant emission rates needed to assess the IAQP and to analyze how VRs affect risks of chronic health effects. In most stores, the measured VRs exceeded the MVR requirements specified in Title 24. Concentrations of most contaminants were below the most stringent associated limits. However, indoor formaldehyde concentrations usually exceeded the reference level recommended by the California Environmental Protection Agency. Also, in grocery stores, levels of particles, acetaldehyde, and acrolein often exceeded stringent reference levels, probably because of the emissions from cooking. Analyses of data indicated that increasing VRs sufficiently to reduce indoor formaldehyde concentrations to the California Environmental Protection Agency's reference level would often be impractical, emphasizing the importance of formaldehyde source control and suggesting the necessity of developing air cleaning systems that reduce formaldehyde levels. Analyses also indicated that for better control of indoor particle concentrations, improvements of particle filtration systems will generally be more effective than increases in VRs.

Effects of VRs per Person and per Floor Area on Human Outcomes

Current MVR standards for commercial buildings prescribe MVRs that are calculated based on a combination of a MVR per person and a MVR per unit floor area; however, virtually no data were available on which to assign MVRs to these two components. In this task, adult subjects spent time in a unique chamber facility simulating an office. One set of subjects experienced high and low VRs per person, while the other experienced high and low VRs per unit floor area. All other factors remained constant. Sick building symptoms and perceived air quality were assessed via web-based surveys, and a validated computer-based tool was used to determine decision-making performance. Statistical models were used to evaluate how both VRs per person and VRs per unit floor area affected the survey outcomes and decision making. The changes in VRs had no statistically significant effects on acceptability of air quality or acceptability of odor and almost no effects on sick building symptoms. The lack of an effect of VRs on the acceptability of air quality and odor, which was assessed after subjects' sensations of odors had decayed, was expected. However, the lack of an effect on symptoms was inconsistent with most prior data; that said, larger numbers of subjects are usually necessary to detect effects

on symptoms. There were statistically significant moderate size reductions in seven of eight metrics of decision-making performance with both a lower VR per person and a lower VR per floor area. A change of 1 liter per second (L/s) per person had a moderately larger impact on decision-making performance than a change in 1 L/s per square meter of floor area. Current MVR standards require several L/s per person of ventilation but only about 1 L/s per square meter of floor area. Thus, the study results indicate that realistic changes in the VR per person of a few L/s per person will have a much larger effect on decision making than realistic changes in VR per floor area on the order of a fraction of 1 L/s per square meter. While the results of this task indicate that both VR per person and VR per unit floor area are important, the findings suggest greater emphasis on maintaining a MVR per person.

Chronic Risk Evaluation

This study compiled and analyzed existing data to identify a set of key contaminants present in commercial buildings at concentrations of potential concern and then, via mass balance modeling, determined the subset of these contaminants with indoor concentrations substantially affected by VRs. Subsequently, the risks of chronic health effects as a function of VR were assessed using standard risk assessment methods that rely on published data relating pollutant exposures with chronic health risks. The projected chronic health risks were moderate in magnitude and substantially smaller than the risks associated with exposure to contaminants in homes where people spend more time. The largest estimated cancer risk was from exposure to formaldehyde. Increases in VRs did not significantly reduce total chronic risks because the leading chronic health risks are from exposure to particles, which are controlled more effectively by filtration than by ventilation. Based on these analyses, together with other research, it was suggested that the setting of MVRs in standards should be driven primarily by the need to limit acute health outcomes, not by the need to limit risks of chronic health effects.

Framework for Producing Evidence-Based Standards for MVRs

This task first reviewed and critiqued current MVR standards and the process used to develop these standards. Then, a new procedure that makes fuller use of existing scientific data on the benefits and costs of higher MVRs was described. The analysis found that current prescriptive MVR standards for commercial buildings do not take advantage of the existing scientific data relating MVRs with human outcomes or building energy use. This task yielded a procedure for selecting MVRs that makes better use of existing scientific data on the benefits and costs of higher MVRs and, via example calculations for offices, showed that it is feasible to apply the procedure. Applying the recommended procedure is expected to result in MVR standards with both a stronger scientific basis for protecting occupants and a more explicit balancing of benefits and costs than the current standard-setting process offers.

Effects of VRs on Building Energy Use and Indoor Air Quality

The EnergyPlus building energy simulation model was used to estimate how HVAC energy use varied as the MVR was changed in small, medium, and large office buildings in each California Climate zone. A new IAQ calculation feature of the EnergyPlus model was also used to predict how the MVRs affected indoor air contaminant concentrations for contaminants deriving primarily from sources within the building. Similar modeling was performed for a primary

school, a secondary school, and a medium-size retail building in each California climate zone. For the full stock of offices in California, complying with current Title 24 MVRs increased HVAC energy use by 6 percent, compared to providing no minimum mechanical ventilation. For California offices with economizers, increasing MVRs 50 percent and 100 percent relative to the Title 24 prescribed MVR increased HVAC energy use by 7.6 percent and 21.6 percent, respectively. In office buildings without economizers, increasing VRs up to 150 percent of the current Title 24 minimum saved HVAC energy in many climate zones because cooling energy savings exceeded heating energy increases. In the modeled school buildings, which had no economizers, VRs made little impact on HVAC energy use, gas heating energy increased modestly with increased VR, and air conditioning energy decreased modestly with increased VR. In the retail building stock, the gas heating energy and total HVAC energy increased markedly with VR, similar to the effects of MVR projected for small offices. Total retail building energy use was moderately affected by VR; for example, increasing the VR from the Title 24 requirement by 150 percent was projected to raise total retail building energy consumption by approximately 7 percent. For buildings with economizers, MVRs had a small effect on the predicted annual average workplace contaminant exposure rates in most climate zones since the economizers were activated and controlled VRs most of the time. However, peak indoor concentrations of indoor-generated contaminants were substantially affected by MVRs. In the school buildings, which had no economizers, VRs substantially affected time-average indoor contaminant concentrations, with more moderate changes in contaminant concentrations with MVRs predicted for the retail buildings. For example, reducing the VR from the Title 24 requirement by 50 percent increased projected time-average school-day contaminant concentrations by 75 percent and increased average work-day contaminant concentrations in the retail building by 25 percent. In summary, MVRs had a significant but moderate influence on building energy use, with larger effects in buildings with economizers. MVRs had a small influence on time-average indoor contaminant concentrations in buildings with economizers. However, MVRs substantially affected peak indoor contaminant concentrations in buildings with economizers and time-average indoor concentrations in buildings without economizers.

Contaminant Emissions from Particle Filters

In bench-scale laboratory experiments, rates of formaldehyde emission were measured from four filters with fiberglass filter media and three filters with polyester filter media. The experiments were performed with different air velocities and air humidity values. Additionally, the highest emitting filter was installed in the HVAC system of a small unoccupied office, and indoor air formaldehyde concentrations were measured. The test was then repeated using a filter with negligible formaldehyde emission rate as a comparison. One filter containing fiberglass media was found to be a large source of formaldehyde, and other fiberglass filters were also a significant source of formaldehyde. The emission rates of formaldehyde increased with humidity, suggesting that the emissions are a consequence of a chemical reaction of formaldehyde-containing binders used in the fabrication of the filter media with water molecules. This new finding, which is the subject of further research, indicates that avoidance of certain types of fiberglass filters will improve indoor air quality without the need for increased VRs.

Project Benefits

This project has advanced the knowledge about how VRs in commercial buildings affect people's health and performance, as well as building energy consumption. The research team devised a procedure for utilizing this new knowledge along with the results of other research in the development of MVR standards. The research team also developed recommendations pertaining to the incorporation of an indoor air quality procedure in the MVR standards in California's Title 24 standards. The project's findings and recommendations will enable development of future MVR standards for commercial buildings throughout California's different climate zones that strike a balance between the benefits and costs of higher VRs on both building occupants and the environment.

CHAPTER 1: Background

Ventilation using outdoor air must be provided to buildings in order to control indoor concentrations of indoor-generated air contaminants that may adversely affect indoor air quality. Research completed prior to this project, although limited, has shown that lower outdoor air ventilation rates (VRs) are associated with decreases in satisfaction with indoor air quality, increases in acute building-related health symptoms often called sick building syndrome symptoms, and reductions in aspects of office work and school work performance (Seppänen, Fisk et al. 1999, Seppänen and Fisk 2004, Fisk, Mirer et al. 2009, Sundell, Levin et al. 2011). More limited prior research suggested that lower VRs are associated with increases in absence rates and possibly with lower rates of infectious respiratory disease (Milton, Glencross et al. 2000, Shendell, Prill et al. 2004, Li, Leung et al. 2007, Mendell, Eliseeva et al. 2013). These findings indicate the benefits of providing higher VRs to commercial buildings, even though it is known that higher ventilation rates can increase indoor concentrations of some types of outdoor air pollutants.

Ventilation rates also affect building energy consumption. When it is cold outdoors, incoming ventilation air must be heated and, in some cases, humidified. When it is hot outdoors, incoming ventilation air must be cooled and usually also dehumidified. Many medium- and large-size commercial buildings require cooling even when the outdoor air temperature is moderately less than the indoor temperature because the heat loss that occurs as air moves through the building envelope is not sufficient to remove all indoor-generated heat. Thus, the heating, ventilating, and air conditioning (HVAC) systems in commercial buildings often employ outdoor air economizers that increase VRs above a minimum ventilation rate (MVR) when the increased ventilation can reduce the need for mechanical cooling using compressor-based or similar energy-intensive systems. In buildings with economizers, it is the MVR that most affects building energy use and the MVR is specified in ventilation standards. There has been surprisingly little assessment of the effects of MVRs on commercial building energy consumption. These energy impacts are not easily measured because there is rarely a distinct HVAC system dedicated to the conditioning of incoming outdoor air. The energy impacts of maintaining different MVRs can be modeled. Benne, Griffith et al. (2009) modeled the U.S. stock of commercial buildings and estimated that mechanically supplied minimum ventilation (the ventilation provided by HVAC systems) increased total building energy consumption by 6.5 percent, compared to providing no minimum mechanical ventilation. Although they did not quantify how building energy use is affected by infiltration (uncontrolled outdoor air entry through the building envelope), their results suggest that infiltration slightly increases the total building energy use.

Given the benefits and costs involved, building designers and operators need guidance on selection of MVRs for commercial buildings. California's Title 24 Building Energy Efficiency Standards (California Energy Commission 2013) specify MVRs that are larger than the VR per person and the VR per unit floor area, reflecting the need for ventilation to control pollutants

emitted by people and their personal products and the simultaneous need to control pollutants emitted by the building, furnishings, equipment, and products used in buildings. Title 24 specifies MVRs that vary somewhat among commercial building types. The major U.S. national standard for MVRs in commercial buildings is Standard 62.1, which was developed by a committee of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE 2013). This standard specifies MVRs that are the sum of a MVR per occupant and a MVR per unit floor area. Again, the specified MVRs vary somewhat by commercial building type. The ASHRAE and Title 24 standards require similar MVRs at their specified default occupancy density levels, but can require very different MVRs at other levels of occupant density.

The ASHRAE ventilation standard (ASHRAE 2013) also provides an alternative performance-based option for determining MVRs called the Indoor Air Quality Procedure (IAQP). The IAQP allows any MVR to be used as long as calculations or data indicate that concentrations of critical contaminants will be maintained below limits and perceived air quality is maintained. The user of the IAQP has complete flexibility in selecting the critical contaminants and their concentration limits as long as the limits are defined by a cognizant authority. The user also selects the minimum requirement for perceived air quality and the method for assessing perceived air quality. The IAQP is not commonly used, in part because it is often considered impractical. However, it does provide an opportunity to employ alternatives to ventilation, such as pollutant source control and air cleaning, for maintenance of adequate indoor air quality. In some cases the IAQP pathway, with reduced MVRs, may enable energy savings (Bridges, Carlson et al. 2013). In California, there has been an interest in applying the IAQP, particularly in retail buildings; however, Title 24 does not have an IAQP pathway.

Current prescribed MVRs in the Title 24 standards and in the prescriptive part of the ASHRAE standard are rooted historically in laboratory studies documenting the outdoor air flow per person needed to dilute odorous gaseous bioeffluents emitted from building's occupants, such as alcohols, keytones, and aldehydes, sufficiently enough to produce subjectively acceptable air quality for 80 percent of visitors (ASHRAE 2010). More recently prescribed MVRs have also considered odors from materials and furnishings, as well as building-related symptoms in occupants. This balance has been based on historic data on odor control, anecdotal reports, and professional judgment; however, scientific evidence linking health effects and VRs has received limited consideration. Also, current standards have not explicitly balanced the energy costs and benefits of higher MVRs. For example, the ASHRAE standard specifies the same MVR for buildings in the severe Minneapolis and mild San Diego climates, in which ventilation imposes dramatically different energy costs.

There have been many gaps in current knowledge about the relationship of MVRs to human outcomes such as health, performance, and absence. When this research project was initiated, most of the available data came from studies of offices, with acute health symptoms, work performance, and perceived air quality as the study outcomes. Limited data were available from studies in schools. No identified studies had assessed how VRs affect human outcomes in retail buildings. Prior to this project, there had been no analyses of how VRs affected chronic health risks in commercial buildings; even the effects of VRs on energy use had been studied

sparingly. Accordingly, this multi-faceted project had four main goals: (1) to advance knowledge about the effects of VRs in California's commercial buildings on human outcomes and energy consumption, (2) to provide guidance for associated improvements in future versions of California's Title 24 standards, (3) to assess the potential benefits and drawbacks of adding an IAQP option to the Title 24 standards, and(4) to evaluate pollutant emissions from the particle filters used in commercial building HVAC systems. The study of pollutant emissions from particle filters was motivated by limited prior research indicating that these pollutant emissions could degrade indoor air quality and make it necessary to provide more ventilation or even negate the benefits of more ventilation (Clausen 2004).

CHAPTER 2: Overall Methods

This section provides an overview of the project tasks and indicates how and why they were selected and how they fit together. Overall study methods are also described. The next section of this report provides more detailed information on the methods employed in each task.

The project's scope of work identified project goals and general areas of work to be performed; however, at the start of the project it was necessary to more precisely define research tasks. Shortly after project inception, a two-day in-person workshop attended by 25 external stakeholders was held to obtain input for prioritization of project tasks. The stakeholders included researchers, utility representatives, HVAC and building energy professionals, and representatives of the building owner and manager community. In addition to the 25 external stakeholders, members of the research team and three members of the Energy Commission staff participated. Workshop attendees were informed of the project objectives and scope and were presented with options for tasks and asked to indicate and discuss their priorities. Final decisions were made in conjunction with the contract manager.

The selection of tasks was guided by the following principles. The work performed should:

- Be consistent with the project goals and scope of work.
- Address key gaps in current knowledge.
- Assess how ventilation rates (VRs) affect both human outcomes and commercial building energy use.
- Include an assessment of the Indoor Air Quality Procedure (IAQP) (specified in the scope of work).
- Include an assessment of pollutant emissions from particle filters (specified in the scope of work).
- Lead to information of value for revisions of the minimum ventilation rate (MVR) requirements specified in future versions of California's Title 24 Building Energy Efficiency Standards.

The previous section described some of the gaps present in the knowledge about how VRs in commercial buildings affect people, including the lack of prior assessments of how VRs affect chronic health risks, the shortage of existing data applicable to MVR requirements in retail buildings, the need for information on how MVRs affect absence rates, and the limited understanding of how MVRs affect building energy use, particularly in California. It was also recognized that no prior research had assessed the independent needs for MVRs per person and per floor area; thus, the associated specifications in current MVR standards were poorly supported. Consequently, the program of research was designed to address each of these gaps, to include an assessment of the IAQP use in California, to include a task on pollutant emissions

from filters, and to include development of specific recommendations applicable to Title 24. After the initial selection of tasks, proposed research methods were summarized in writing and provided to a Technical Advisory Group (TAG) for comment. In some cases, methods were changed after receiving comments. Members of the TAG and the Contract Manger also provided review comments on draft reports or papers resulting from the tasks. In some cases reviews were also obtained from other experts. The interactions with the TAG improved project plans and work products and also constituted a form of outreach.

The project work tasks are described briefly below:

- *Assessment of the IAQP*: This task determined IAQP MVRs for retail buildings in California and compared IAQP MVRs to the MVRs specified in Title 24. Data from a subset of the 19 buildings in the retail cross sectional study, and from one big-box store, were used in mass balance models to predict the IAQP MVRs that maintained concentrations of critical contaminants below limits specified by California Environment Protection Agency and other authorities. Experiments in the big-box store validated the modeling and also incorporated an assessment of satisfaction with air quality as the VR was varied. Based on the findings of this assessment of the IAQP, recommendations were developed regarding adoption of an IAQP in Title 24.
- *Retail Cross Sectional Study*: This cross sectional study measured VRs and indoor and outdoor contaminant concentrations in retail buildings in California. The study included 19 total stores from different California climate zones, with two stores evaluated twice. Included were grocery, apparel, and furniture and hardware stores. The resulting data were used to calculate indoor contaminant emission rates needed for the assessment of the IAQP and also for analyses of chronic health risks.
- *Chronic Risk Evaluation*: This task compiled and analyzed existing data to identify a set of key contaminants present in commercial buildings at concentrations of potential concern and then, via mass balance modeling, determined the subset of these contaminants with indoor concentrations substantially affected by VRs. Subsequently, the risks of chronic health effects as a function of VR were assessed using standard risk assessment methods that rely on published data relating pollutant exposures with chronic health risks.
- *Effects of VRs per Person and per Unit Floor Area on Human Outcomes*: In this study, adult subjects experienced high and low VRs per person. Another set of adult subjects experienced high and low VRs per unit floor area in a unique chamber facility simulating an office. All other factors were maintained constant. Sick building syndrome symptoms and perceived air quality were assessed via web based surveys and a validated computer based tool was used to determine decision making performance. Statistical models evaluated how VRs per person and per unit floor area affected the survey outcomes and decision making.
- *Effects of VRs on Acute Outcomes in California Office Workers*: This longitudinal study monitored carbon dioxide concentration, temperature, and humidity over a full year in 16 spaces within office buildings in California. Every three months, web based surveys

collected data from occupants on respiratory illnesses, absence due to respiratory illness, perceived air quality, and sick building symptoms. The carbon dioxide data were used in mass balance models to estimate VRs and statistical models assessed the relationships of VRs with the survey outcomes.

- *Effects of VRs on Building Energy Use and Indoor Air Quality*: The EnergyPlus building energy simulation model was used to estimate how HVAC energy use varied as the MVR was changed in small, medium, and large office buildings, a primary school, a secondary school, and a medium-size retail building, in all California climate zones. A new indoor air quality (IAQ) calculation feature of the model was validated by comparison to analytical models and used to predict how the MVRs affected the concentrations of an indoor-generated air contaminant. Model output data were also analyzed to evaluate the potential energy savings and IAQ effects of varying MVRs on a monthly basis in offices, with higher MVRs provided in periods of mild weather and lower MVRs provided during severe weather when the energy costs of ventilation are increased.

- *Framework for Producing Evidence-Based Standards for MVRs*: This task first reviewed and critiqued current MVR standards and the process used to develop those standards. Then, a new procedure was developed and articulated that makes use of existing scientific data on the benefits and costs of higher MVRs. An example application of the procedure to select MVRs for offices was provided. The framework developed used results from Tasks 1 to 6 described above, as well as results of the research team's prior related research and research by others.

- *Contaminant Emissions from Particle Filters*: In bench-scale laboratory experiments, rates of formaldehyde emission were measured from four filters with fiberglass media and three filters with polyester media. The experiments were performed with different air velocities and air humidity values. Additionally, in a small unoccupied office, indoor air formaldehyde concentrations were measured when the HVAC system contained the filter with the highest formaldehyde emission rates in the bench scale studies. Results were compared with results from when the HVAC system was operated with a filter with negligible formaldehyde emission rates.

- *Outreach*: Activities undertaken to communicate project results included frequent interaction with a Technical Advisory Group (TAG) of stakeholders, presentation of results to staff at the Energy Commission responsible for Title 24 standards, presentation of findings at technical meetings, and publication of reports and journal papers. The recommendations developed as part of Task 1 on the potential adoption of an IAQP in Title 24 and the development of the framework for producing evidence-based standards for MVRs in Task 7, were also forms of outreach.

CHAPTER 3: Results

3.1 Assessment of Indoor Air Quality Procedure

3.1.1 Objectives

This study has three main objectives: (1) assessing, in a set of California retail stores, the adequacy of the ventilation rates (VRs) currently prescribed by California's Title 24 Building Energy Efficiency Standards (California Energy Commission 2013) in providing the indoor air quality (IAQ) level specified by the indoor air quality procedure (IAQP) process; (2) determining the VRs needed to satisfy the objective component of the IAQP; and (3) evaluating whether several VRs implemented experimentally in a big-box store, including the current VR as measured before the intervention, the Title 24-prescribed VR, and a calculated IAQP-based VR, would achieve adequate IAQ, assessed both objectively and subjectively. The data from this study can inform discussions about the possibility of adding an IAQP-like option to Title 24.

3.1.2 Methods

Two types of data were collected to evaluate the application of the IAQP in California retail buildings: observational data from stores functioning as usual and data from an intervention study in one big-box store. VRs and indoor and outdoor concentrations of contaminants of concern (CoC) were measured in 13 stores, including three grocery, five furniture/hardware, four apparel, and one big-box store. Mass balance models were employed to calculate indoor contaminant emission rates for CoCs in each store. Mass balance models were then used, with these emission rates and typical outdoor air contaminant concentrations, to calculate, for each store, the IAQP VR that would maintain indoor CoC concentrations below selected reference concentration limits (RCLs). If ventilation was not able to maintain concentrations of a CoC below the concentration limit, for example, because of high outdoor air concentrations, that CoC was neglected in the calculation of IAQP VRs. These IAQP VRs were compared with observed VRs and to the Title 24-prescribed VRs.

In addition, a VR intervention study was performed in the sole big-box store among the group of stores assessed to determine how objectively assessed indoor contaminant levels (from measured air concentrations) and subjectively assessed IAQ (from subject surveys) varied with VR. The general merchandise big-box store is located in northern California and has a sales floor area of 10,000 m^2. The three VRs in the intervention study were an approximation of the store's current VR (0.24 h^{-1}), the Title 24-prescribed VR (0.69 h^{-1}), and the calculated IAQP-based VR (1.51 h^{-1}). The VRs were controlled by varying the damper settings of the variable air volume rooftop units. The store's mechanical VRs were fixed at these rates for one-week study periods each allowing for small variations due to infiltration. During each study period, IAQ was assessed objectively by measuring indoor contaminant concentrations and subjectively by surveys regarding perceived air quality and acute health symptoms.

For both the observational and intervention studies, particle counts and concentrations of inorganic contaminants such as ozone and carbon monoxide were measured continuously using

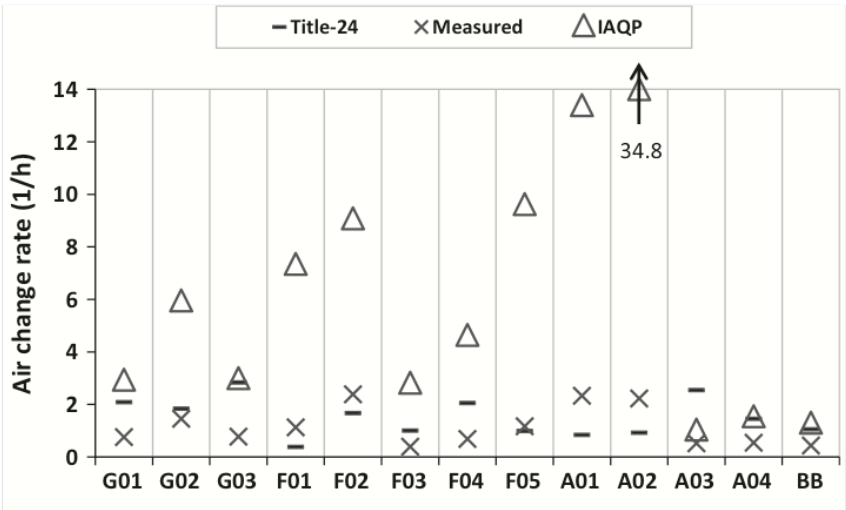
real-time instruments. Time-integrated concentrations of volatile organic compounds (VOCs), aldehydes, and particle mass were also measured. Contaminant concentrations were measured at one to four indoor locations. Outdoor concentrations were measured using a set of identical instruments placed either on the building rooftop or at ground level outside the store. The outdoor air VR was measured using the sulfur hexafluoride (SF_6) decay method in which SF_6 was added to the indoor air, mixed to obtain an approximately uniform indoor-air concentration, and then the rate of decrease in indoor concentration was measured.

Once the VR had been held constant for three to four days to achieve approximately steady-state indoor contaminant concentrations, subjectively perceived IAQ was assessed in the big-box store using three independent groups of untrained human subjects. Subjects took surveys both immediately upon entering the building and at 12-minute intervals at five additional marked locations within the store. Survey questions include questions on olfactory responses, subjective symptoms, and IAQ acceptability. In addition, age, demographic, health factors, and shopping habits were also recorded. A human subjects' protocol for this study was developed, reviewed, and approved by Lawrence Berkeley National Laboratory's Committee for the Protection of Human Subjects.

3.1.3 Results

The IAQP-based VR (shown in Figure 1) was the largest of the VRs needed to maintain indoor concentrations of formaldehyde, acetaldehyde, acrolein, octanal, and hexanal below each contaminant's individual health or olfactory guideline. These CoCs were selected because measured indoor concentrations exceeded RCLs in some of the stores. The IAQP-based VRs exceeded Title 24-prescribed VRs in all stores except store A03.

Figure 1: Ventilation Rates Measured in 13 Retail Stores

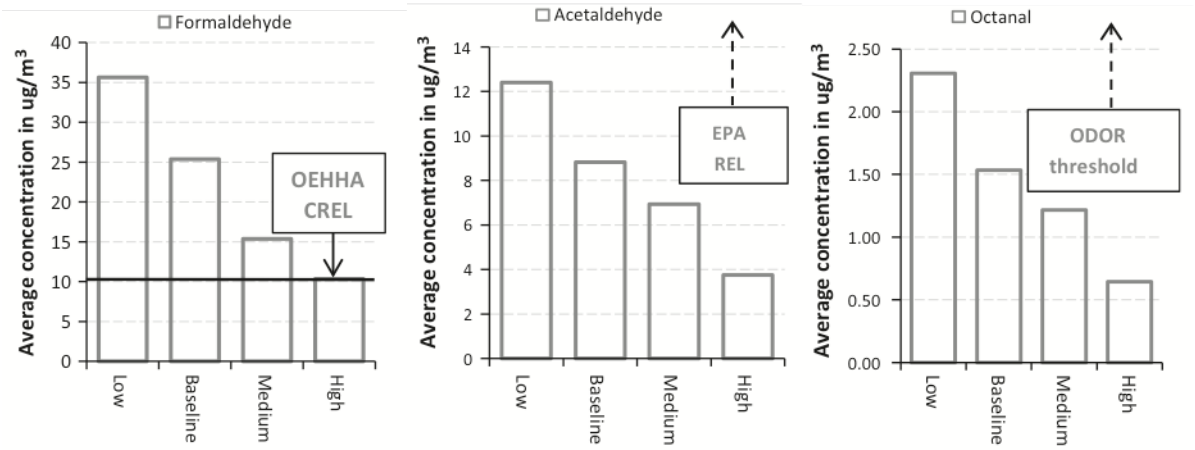


Measured VRs in comparison with VRs prescribed by Title 24, and IAQP-based VRs. G = grocery stores, F = furniture/hardware stores, A = apparel stores, and BB = big-box store.

The IAQP calculation for the big-box retail store identified formaldehyde as the principal driver of the IAQP VR; all other measured contaminants were below reference levels at the surveyed baseline VR. For the furniture and apparel stores, formaldehyde was also the dominant driver for IAQP-based VRs. But in grocery stores, acetaldehyde and octanal defined the IAQP-based VRs. High concentrations of acrolein were also observed both indoors and outdoors, above RCL, in grocery stores. But, within the context of the IAQP, where outdoor concentrations exceeded RCL's, ventilation could not be used to define the IAQP-based minimum VR for acrolein.

The results of steady-state indoor concentrations of CoCs measured in the big-box store at the three intervention VRs were consistent with predictions using simple mass balance models. At the IAQP-based VR of 1.51 h^{-1}, mean formaldehyde concentration measured in the big-box store equaled the reference concentration level (RCL) (chronic reference exposure level [CREL] from California Office of Environmental Health Hazard Assessment [OEHHA], see Figure 2). Indoor concentrations of other CoCs were all below RCLs. This shows that the application of IAQP-based VR successfully achieved its objective of controlling indoor concentrations of all CoCs to at or below RCLs.

Figure 2: Indoor Contaminant Concentrations Measured in Big-Box Store at Different VRs



VRs: low = 0.24 h-1 (current store VR), baseline = 0.43 h-1 (store VR measured during baseline characterization prior to intervention), medium = 0.69 h-1 (Title 24 prescribed VR), and high = 1.51 h-1 (IAQP-based VR). REL (Reference Exposure Level)

In all cases, the targeted minimum IAQ acceptability rating of 80 percent was exceeded; that is, more than 80 percent of both males and females rated the IAQ as acceptable. The average binary responses for unadapted subjects(subjects who had just entered the store), based on the results of the surveys completed immediately after entering the store, were 90 percent, 95.5 percent, and 98.9 percent acceptability at 0.24 h^{-1} (current VR), 0.69 h^{-1} (Title 24 prescribed VR), and 1.51 h^{-1} (IAQP-based VR), respectively, suggesting increasing acceptability of air quality correlated with increasing VRs, but the improvements were not statistically significant. With adapted subjects(subjects who had been in the store for at least 12 minutes), based on surveys

implemented after subjects had been in the store for 12 or more minutes, there was no evident trend of acceptability with VR using either the binary or continuous scales of IAQ satisfaction. No significant correlation was found between the subjects' responses with either temperature or relative humidity for either adapted or unadapted subjects.

The results of this task, and the methods employed, are described in greater detail in Dutton, Chan et al. (2013), Fisk , Dutton et al. (2013), and Dutton and Fisk (2014).

3.1.4 Discussion

IAQP-based VRs exceeded 3 h^{-1} in about two-thirds of the 13 stores and exceeded 5 h^{-1} in about half of the studied stores. In these cases, using ventilation alone to manage indoor contaminants would likely be prohibitively expensive because of both the resulting increase in ongoing energy use and the possible increase in ventilation system size required to provide these higher VRs. Under these circumstances, alternative strategies to lower indoor concentrations of CoCs are needed, such using source control to do so or applying air cleaning systems for VOCs.

Subjective responses to perceived indoor air quality are affected by both odor and irritation (Cometto-Mu and Cain 1995). Irritation caused by exposure to airborne contaminants has been shown to increase with increased time of exposure (Shusterman, Matovinovic et al. 2006). Comparing mean responses from unadapted (0.49) and adapted responses (0.45) showed that perceived air quality decreased marginally as subjects remained within the store for more than a few minutes and also as subjects moved deeper into the store. Therefore, one explanation for the results is that the subjects' odor perception fatigued over time while exposure-related irritation increased, with the overall effect being a marginal decrease in perceived IAQ. An alternative interpretation is that local variations in odor counter a general adaption to the store environment. Either way, this result has potentially broader implications for ventilation standards that rely on perceived IAQ and use adapted subjects.

3.1.5 Conclusions

When the American Society of Heating, Refrigerating, and Air Conditioning Engineers's (ASHRAE) IAQP was applied in 13 stores, the minimum VRs needed in 11 stores to maintain concentrations of CoCs below stringent limits were higher, often substantially, than the minimum VRs specified in Title 24. Thus, application of the IAQP would only enable reduced VRs and associated energy savings when contaminant source control or gas-phase air cleaning of indoor contaminants was implemented.

When IAQP was applied, formaldehyde control drove the IAQP VR in ten of 13 stores, based on California's stringent RCL of 9 $\mu g/m^3$. Even when using the higher formaldehyde RCL, 19.6 $\mu g/m^3$ from the National Institute for Occupational Safety and Health, formaldehyde remained the driver for the IAQP VR in many buildings. In grocery stores, however, the IAQP VRs were dictated by the VRs needed to maintain acetaldehyde or octanal below reference levels.

The intervention study in the big-box store found that, for the CoCs that were closest to reference levels (formaldehyde, acetaldehyde, and octanal), increased ventilation was effective at lowering steady-state indoor concentrations. At the IAQP-based VR, indoor concentrations of

all CoCs were maintained below concentration limits. At all VRs in the big-box store, subjective satisfaction with air quality exceeded the 80 percent target.

3.1.6 Significance

In California, there is ongoing consideration of the merit of incorporating an IAQP-like procedure into the state's Title 24 building efficiency standards (California Energy Commission 2013). The key change in approach when using the IAQP rather than the prescribed minimum VRs is to consider outdoor air ventilation as just one of several possible tools for achieving adequate IAQ. Considering a wider range of tools would be an important step toward reducing energy use in buildings while maintaining or improving IAQ. In theory, this is a win–win strategy. In practice, however, this study shows that applying the IAQP with stringent concentration limits can increase energy use unless effective alternatives to increase ventilation are also considered. In buildings with already weak indoor contaminant sources, application of the IAQP to lower VRs has immediate potential to save energy without requiring additional control methods.

Currently, users of the ASHRAE IAQP have complete flexibility to select critical contaminants and RCLs even though many users will not have the expertise necessary to select the contaminants most relevant to occupants' health. It is therefore recommended that future versions of an IAQP, including any version developed for inclusion in Title 24, include lists of critical contaminants to be considered and appropriate contaminant limits to be applied. Development of additional forms of VR standards that combine elements of current VR and IAQ procedures in practical ways might allow improvements over both and also allow for energy to be saved without degrading IAQ.

3.2 Retail Cross Sectional Study

3.2.1 Objectives

The purpose of this field study was to estimate the whole-building source strengths of CoCs in California retail stores. The data are needed to determine the VRs necessary to maintain indoor concentrations of CoCs below applicable health guidelines and to estimate the influence of VRs on risk of chronic health effects.

3.2.2 Methods

Three types of retail stores are included in this study: grocery, furniture/hardware, and apparel stores. California's Title 24 standards (California Energy Commission 2013) specify the same minimum ventilation rate (MVR) for these store types, but differences in indoor contaminant source strengths by store type would imply different requirements for ventilation. Nineteen stores were recruited from the various parts of California, including 10 from the North/Central Coast (San Francisco Bay Area), 4 from the Central Valley (3 near Sacramento, and 1 in Fresno) and 5 from the South Coast (Los Angeles area). Two stores were sampled twice, resulting in 21 store visits. Field sampling started in September 2011 and ended in March 2013. Stores volunteered to participate in this study so they formed a convenience sample.

A key focus was indoor VOCs because there are numerous indoor sources, such as building materials, occupants, and merchandise. Also, the indoor air concentrations of many VOCs are highly affected by VRs (Parthasarathy, Fisk et al. 2013). Other indoor air contaminants measured included carbon dioxide (CO_2), carbon monoxide (CO), ozone (O_3), and particulate matter (PM). Store VR was measured using a SF_6 tracer gas decay method, described in Section 3.1.2. In addition, acrolein samples were collected by pumping air through pentafluorophenyl hydrazine-coated cartridges that were prepared based on the derivatization method by (Ho and Yu 2004). The cartridges were then analyzed in the laboratory to determine acrolein concentrations (Chan et al. 2015b).

The experimental setup in each store was largely the same. Indoor samples of air contaminants were collected from a central location on the sales floor. In larger stores, this was supplemented by two to three additional locations on the sales floor where additional VOC samples were collected. Outdoor air samples were collected near the main point of entry of outdoor air —near a rooftop air intake in mechanically ventilated stores or near the store front door in naturally ventilated stores. Contaminant source strengths were calculated using simple mass balance equations.

3.2.3 Results

VR per floor area, calculated using the age-of-air approach, met the Title 24 requirement of one L/s-m^2 in almost all of the stores (Table 1). The only store with VR substantially lower than Title 24 requirement was F3 (store A4 and F6 had estimated VRs near 1 L/s-m^2, considering measurement uncertainty). Store F3 had a low VR on the day of sampling because the store front door was closed, there was no other intentional opening that would allow outdoor air to enter the stores, and the mechanical ventilation system was not operated.

Table 1: Ventilation Rates Measured in Retail Stores from 21 Sampling Visits

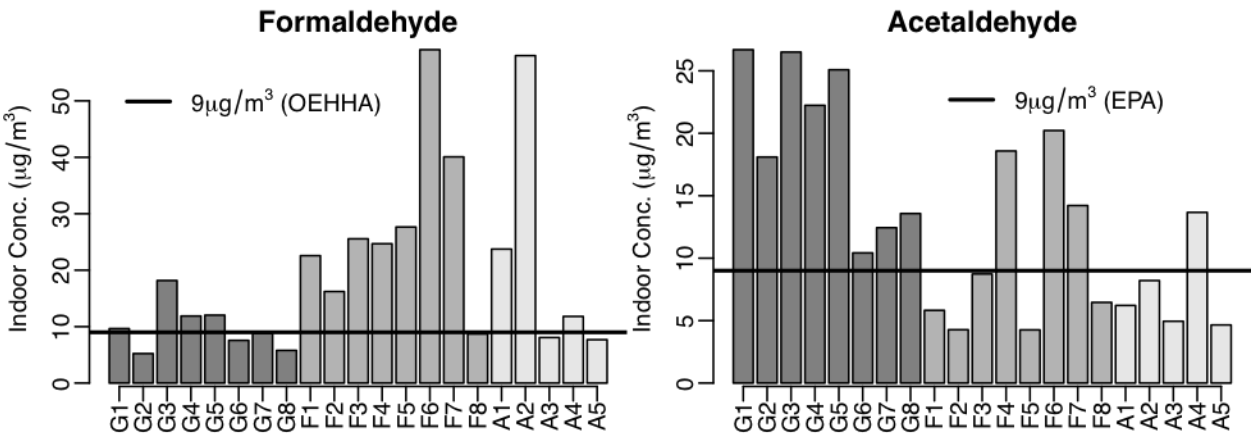
Grocery Stores	Measured VR (L/s-m^2)	Furniture/ Hardware	Measured VR (L/s-m^2)	Apparel Stores	Measured VR (L/s-m^2)
G1	1.6	F1*	1.3	A1**	2.0
G2	2.8	F2*	4.0	A2**	2.1
G3	2.2	F3**	0.4	A3	1.3
G4	1.5	F4	1.4	A4	0.8
G5	1.3	F5**	1.2	A5	4.1
G6	2.7	F6	0.9		
G7	2.2	F7	1.3		
G8	3.2	F8	1.2		

Stores were mechanically ventilated unless denoted: *natural ventilation or **mixed mode (stores used natural ventilation on the day of sampling).

Even though there was adequate ventilation according to Title 24 requirements, concentrations of formaldehyde and acetaldehyde exceeded the most stringent chronic health guidelines in many of the sampled stores (Figure 3). Formaldehyde concentrations measured in furniture/hardware stores tended to be higher than in the other two store types. Merchandise containing composite wood products is likely a key indoor source of formaldehyde in

furniture/hardware stores. Acetaldehyde concentrations in grocery stores were higher than in other store types, likely because they are a result of cooking-related emissions.

Figure 3: Indoor Contaminant Concentrations Measured From 21 Retail Store Visits



G = grocery stores, F = furniture/hardware stores, A = apparel stores. G1, G2, and F1 were measured on two consecutive days: (1) and (2).

Contaminant source strength calculations show that furniture/hardware stores had higher emissions of alkanes and halogenated compounds, whereas grocery stores had higher emissions of aldehydes and terpenoids. VOCs with high source strengths (exceeding 100 μg/h-m^2) in at least some of the retail stores sampled include formaldehyde, acetaldehyde, hexanal, d5-siloxane, d-limonene, acetone, m/p-xylene, and 2-butoxyethanol.

The California annual ambient air quality standard for particles less than 2.5 μm in aerodynamic diameter (PM2.5) is 12 μg/m^3. For particles less than 10 μm in aerodynamic diameter (PM10), the annual standard is 20 μg/m^3. The average particle concentrations measured in grocery stores (mean PM2.5 = 14.7 μg/m^3, mean PM10 = 21.2 μg/m^3) exceeded the ambient standards, but in the other retail stores concentrations of particles did not exceed ambient standards (mean PM2.5 = 8.1 μg/m^3, mean PM10 = 17.9 μg/m^3). Higher PM concentrations were measured in grocery stores likely because of cooking-related activities, which occurred throughout the day to prepare ready-to-eat food. In addition, almost all measured indoor acrolein concentrations exceeded the chronic health guidelines. In particular, the mean indoor acrolein concentrations of 10 μg/m^3 measured in grocery stores exceeded not only the chronic reference exposure level (0.35 μg/m^3, OEHHA), but also the eight-hour (0.7 μg/m^3) and acute reference exposure level (2.5 μg/m^3).

Study results are provided in greater detail by Chan, Cohen et al. (2014).

3.2.4 Discussion

The emission rate estimates of formaldehyde and acetaldehyde determined in this study agree well with estimates from two other field studies: (1) small and medium commercial buildings in

California (Wu et al., 2011), and (2) retail stores in Texas and Pennsylvania (Siegel, Srebric et al. 2012). These two studies also found acetaldehyde and PM source strengths to be substantially higher in grocery stores than in other retail store types. On the other hand, formaldehyde emission rates tend to be lower in grocery stores.

This study data suggest that some retail stores successfully used source control as an effective strategy to lower formaldehyde concentration indoors. Very low levels of formaldehyde emissions were measured in two recently renovated apparel stores A3 and A4. These two stores belong to the same retail chain that used low emitting materials in their recent renovations. Low formaldehyde emission rates (30 $\mu g/h\text{-}m^2$) were also estimated from a furniture store (F3) and a hardware store (F8). At this low level, the indoor formaldehyde concentration would meet the most stringent chronic health guideline of 9 $\mu g/m^3$ at the current Title 24 VR.

This study included several stores that relied on natural ventilation for the majority of the time. Five of the six stores that relied on natural ventilation for most of the time also had sufficient ventilation per Title 24. For them, the main concern is outdoor particles entering into the stores. If natural ventilation were to be used, retail stores would benefit from having the option to use mechanical ventilation when the outdoor air quality is poor.

3.2.5 Conclusions

Contaminant source strengths clearly differ by store types. The analysis from this study indicates that even if stores were to ventilate air at twice the MVR specified in Title 24, formaldehyde concentrations in retail stores would still exceed the California health-based guideline. Formaldehyde source control, as demonstrated in some of the retail stores in this study, may be a more viable strategy than increased VRs to meet the health-based concentration guidelines for formaldehyde.

Analysis of source strengths suggests cooking as a major source of indoor contaminants in grocery stores. There are options other than increasing the store VR that may be more suited to address this problem. For example, better capturing by exhaust hoods of the cooking fumes containing acrolein, acetaldehyde, and particles can improve indoor air quality. Using higher efficiency filters, such as minimum efficiency reporting values (MERV) 13 instead of MERV 8, will also lower indoor particle levels.

3.2.6 Significance

This research has shown that strategies other than increasing VRs are needed to lower indoor concentrations of formaldehyde, acetaldehyde, acrolein, and PM in grocery and other retail store types.

3.3 Chronic Risk Evaluation

3.3.1 Objectives

A wide range of air pollutants including volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), criteria air pollutants, biological contaminants, and radon are present in commercial buildings. There is a need to identify key contaminants of interest for the setting of minimum VR standards. The objectives of this task were to evaluate the effect of

ventilation on indoor pollutant concentrations, identify contaminants that are effectively controlled by ventilation, and quantify the effects of ventilation rates on chronic health risks.

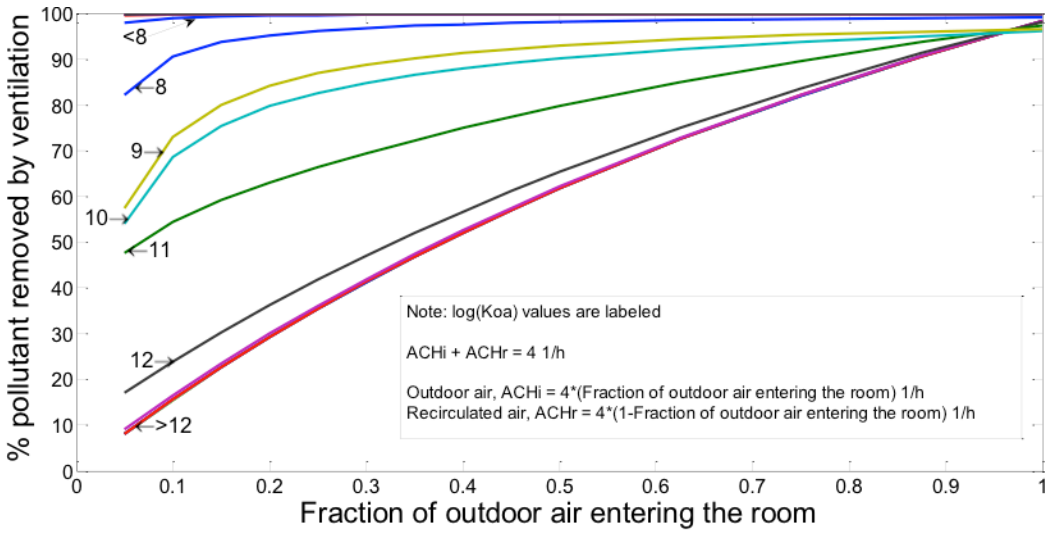
3.3.2 Methods

To identify contaminants of concern, literature on indoor air contaminant concentrations in commercial buildings was reviewed. The reported indoor contaminant concentrations were compared to health guidelines, odor thresholds, and thresholds for sensory (irritation) effects. A fugacity-based mass-balance model that accounts for contaminant sorption on indoor surfaces and airborne particles was used to simulate the impact of VR on indoor concentrations of VOCs and SVOCs. The transfer of VOCs and SVOCs among the major indoor media—air, dust, and surfaces (such as carpets, vinyl floors, walls, and ceilings)—were modeled as a function of the octanal-air partitioning coefficients (K_{oa}). The effectiveness of contaminant removal by ventilation was calculated relative to the removal by particle filtration and particle deposition on indoor surfaces. For contaminants with indoor sources and for which increases in VR are effective at reducing exposures, chronic health risks were evaluated as a function of VR. Analyses were performed for offices, schools, grocery stores, and other retail stores. In particular, the chronic health risks from exposure to VOCs and PM2.5 were modeled at existing VRs, with VRs increased or decreased by a factor two, and at the same time if higher efficiency air filters were used. The health burden on the exposed population was calculated using disability adjusted life years (DALYs) to account for both cancer and non-cancer effects. DALYs per year from exposure to VOCs and PM2.5 were calculated for adult workers and shoppers in the types of commercial buildings considered.

3.3.3 Results

For VOCs and SVOCs that are emitted from indoor sources, Figure 4 shows the predicted percent removal by ventilation as a function of the fraction of outdoor air in the supply airstream for compounds with different log(K_{oa}) values depicted by lines with different colors. VOCs with low log(K_{oa}) values are expected to be removed mainly by ventilation because they are predominantly in the gas phase. However, SVOCs with high log(K_{oa}) tend to be attached to particles, so the percent removal by ventilation is lower because some particles are removed by filtration and deposition on surfaces. The difference among compounds with different log(K_{oa}) values is the greatest when minimum outdoor air is supplied. This is because at minimum outdoor air, recirculated air would be at its maximum rate, and the rate of removal of indoor-generated particles by filtration is highest.

Figure 4: Percent Removal of VOCs and SVOCs with Different Log(Koa), Ranging From <8 to >12, by Ventilation



A list of 23 priority VOCs (Table 2) were identified that have low log(K_{oa}) ranging between 2.1 and 6.4, and with indoor concentrations that sometimes exceed the toxicity thresholds (non-cancer, reproductive, cancer) and/or perception of air quality (odor and pungency) thresholds. The majority of the listed VOCs have predominantly indoor sources. The few exceptions are benzene, toluene, ethylbenzene, and mp-xylene, which also have outdoor sources such as vehicle emissions.

The chronic health risks predicted for adult workers and shoppers in offices, schools, grocery, and other retail stores were low relative to the risks from exposure in homes primarily because of the greater amount of time spent in homes. Chronic health risks were driven primarily by exposures to PM2.5 that contributed to mortality, chronic bronchitis, and nonfatal stroke. The leading cancer risk factor was exposure to formaldehyde. Calculated lifetime cancer risks of workplace exposures were higher in retail stores (60 to 100 per million) than in offices and grocery stores (40 to 60 per million) due to higher indoor concentrations of VOCs. At current VRs, predicted lifetime cancer risks from exposure to VOCs were low in schools (10 per million) relative to the other buildings.

DALYs associated with VOCs exposure were largely from a few compounds. Formaldehyde accounted for 90 percent of the health burden from cancer effects, and acetaldehyde, toluene, mp-xylene, and naphthalene accounted for 90 percent of the non-cancer effects. Table 3 shows the total DALYs per year from exposure to PM2.5 and VOCs at current VR, and under two scenarios: (1) doubling of VR, and (2) upgrade to MERV 13 air filters. The calculations suggest that, in the U.S. population, the total health burden caused by exposures in offices is higher than the health burden in retail buildings due to larger number of people exposed. Doubling the current VRs has a negligible effect on DALYs. Halving the current VRs (results not shown) significantly increases the DALYs associated with VOCs.

Because PM2.5 is the key cause of DALY losses per year, the use of higher efficiency air filters (MERV 13) was predicted to reduce DALYs by a larger extent than doubling of VRs. The largest health burden reduction that could occur from using higher efficiency air filters was predicted for grocery stores where substantial indoor sources of PM2.5 exist (likely from cooking).

Table 2: List of Priority VOCs

Pentanal	Naphthalene	Acetaldehyde
Trichloroethene (Trichloroethylene)	Dichloromethane (methylene chloride)	Carbon tetrachloride
Tetrachloroethene	Formaldehyde	Chloroform
Butylacetate	Propylene Glycol	Propanal
Hexanal	Hexanoic acid	a-pinene
Tetrachloroethane	Benzene	Toluene
d-Limonene	1,4-Dichlorobenzene	Ethylbenzene
Octanal	mp-xylene	

Table 3: Total Health Burden on U.S. Building Occupants Expressed in Dalys per Year (95 Percent Confidence Interval in Parenthesis) at Current Ventilation Rate (VR) and Two Alternatives: (1) Doubled VR, and 2 More Effective Particle Removal Using MERV 13 Air Filters

	Current VR	(1) VR 2x	(2) MERV 13 Air Filters
Offices	19,000 (6,600, 81,000)	19,000 (6,300, 78,000)	12,000 (3,900, 50,000)
Schools	1,100 (370, 4,700)	1,100 (360, 4,500)	740 (250, 3,100)
Retail Stores	11,000 (4,800, 37,000)	10,000 (4,400, 32,000)	7,300 (3,000, 26,000)
Grocery Stores	14,000 (5,700, 52,000)	12,000 (4,900, 44,000)	10,000 (4,100, 38,000)

The results of this analysis are presented in greater detail in Chan, Parthasarathy et al. (2015).

3.3.4 Discussion

In addition to VOCs, SVOCs, and particles, there are other indoor air contaminants that are present in commercial buildings. But, exposures to inorganic gases, such as ozone, nitrogen dioxide, and carbon monoxide, are not the determining factors for setting minimum VRs in standards because outdoor air is the primary source of these pollutants. In general, radon is likely of secondary importance in California because radon levels tend to be low.

There are limitations in the modeling of SVOCs because there are SVOC removal processes that are not considered. For example, periodic cleaning removes SVOCs. Thus, estimates of the percent removal of SVOCs by ventilation shown in Figure 4 are likely upper bound results.

There are large uncertainties in the estimates of chronic health risks due to the inherent uncertainties in toxicological studies and dose-response parameters. The calculations did not

consider the health burdens among children, even though they are an important subpopulation, especially for schools. More work is needed to evaluate the effects of VR on children's health. For example, if asthma development or cases of asthma exacerbation were affected by VRs, than the DALYs associated with classroom VRs would be much higher than the estimates presented here.

3.3.5 Conclusions

Ventilation is the most effective at controlling indoor exposures to VOCs emitted from indoor sources. In particular, for VOCs with $\log(K_{oa}) < 9$, increased ventilation can significantly reduce exposures. Among the VOCs of potential health concerns in commercial buildings, exposure to formaldehyde with $\log(K_{oa}) = 5.2$, is the leading cancer risk factor. For PM2.5, the use of high efficiency air filters will have relatively larger benefits with respect to chronic health burdens than increases in ventilation rates since filtration is more effective than ventilation at controlling indoor concentrations.

3.3.6 Significance

Calculations of chronic health risks suggest that for the types of commercial buildings considered (offices, schools, grocery, and other retail stores), the effect of VRs is relatively small in contrast to the large impact ventilation has on acute health risks like sick building syndrome symptoms (Fisk, Mirer et al. 2009), perceived indoor air quality (Wargocki, Wyon et al. 2000), and work performance (Seppänen, Fisk et al. 2006, Fisk, Black et al. 2011). Therefore, setting of minimum VR standard should be based more on a consideration of other health outcomes than on chronic health risks.

3.4 Effects of Ventilation Rates Per Person and Per Floor Area on Human Outcomes

3.4.1 Objectives

The objectives of this task were to assess the independent effect of VR per person and VR per unit floor area on perceived air quality, sick building symptoms, and decision making performance.

3.4.2 Methods

One set of 16 adult subjects experienced high and low VRs per person while they worked in an office-like experimental chamber with very low rates of contaminant emissions from sources other than people. Using a unique two-chamber system, another set of 16 adult subjects experienced high and low VRs per unit floor area while the VR per person was maintained at a high level. All other test conditions were maintained constant. Study sessions were four hours long. In each session, subjects reported their satisfaction with indoor air quality and intensity of various acute sick building syndrome symptoms, such as eye and nose irritation and headache, via a web based survey. Also, in each session, the decision making performance of subjects was evaluated using a validated computer based test called the strategic management simulation. Temperature, humidity, VR, and concentrations of volatile organic compounds were measured during each study session. The study design controlled for day of week, morning versus afternoon, and order of exposure to high or low VR. Statistical models were employed to

evaluate the within-subject changes in perceived air quality, symptom, and decision making performance.

3.4.3 Results

Table 4 lists the ventilation rates provided in conditions 1 and 2with high and low VRs per occupant and in conditions 3 and 4 with high and low VRs per unit floor area. The corresponding requirements in both Title 24 (California Energy Commission 2008) and the ASHRAE standards (ASHRAE 2013) are also listed. The VR per person in condition 1 (8.5 L s^{-1} per person) exceeded the requirement of the Title 24 and ASHRAE standards, while the VR per person in condition 2 (2.6 L s^{-1} per person) approximately equaled the minimum allowable VR per person (2.5 L s^{-1} per person) in the ASHRAE Standard for a building with a very high occupant density. The VRs per unit floor area in condition 4 approximately equaled the minimum requirement per unit floor area of 0.75 L s^{-1} per square meter in the Title 24 standards. The VRs per unit floor area in condition 3 far exceeded the requirement of the standards.

The overall average temperature and relative humidity during the full study were 22.5 °C (± 0.12) and 40.4 percent (± 1.0 percent), respectively. The temperature and relative humidity were consistent across all conditions and within each condition.

Averages and standard deviations of indoor CO_2 concentrations are plotted in Figure 5. Concentrations closely approached their steady state value after an hour (Maddalena et. al., 2013). Average concentrations for the final 3 hours were about 900 parts per million (ppm) in condition 1 and 1800 ppm in condition 2. Also as desired, CO_2 concentrations in conditions 3 and 4 were very similar.

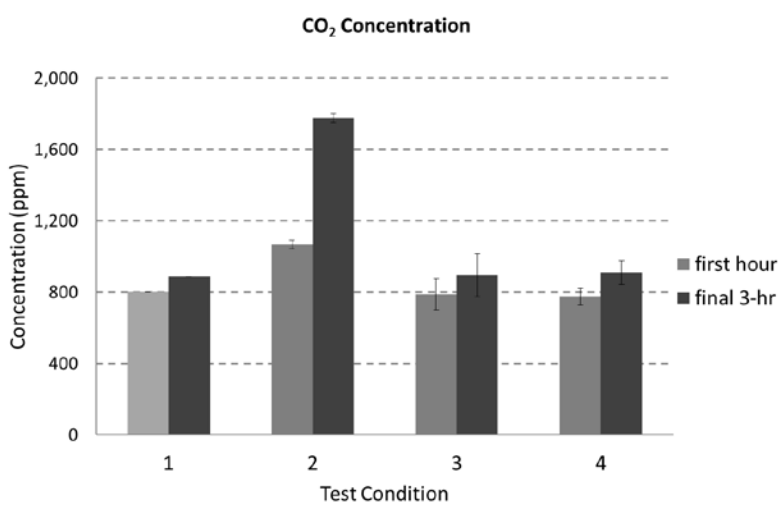
Table 4: Ventilation Rates for Each Condition

	Occupant-based VR (L s^{-1} per person)			Floor-area-based VR (L s^{-1} per m^2)		
Condition	Average (standard deviation)	Title 24 Requirement*	ASHRAE Standard 62.1 Requirement*	Average (standard deviation)	Title 24 Requirement*	ASHRAE Standard 62.1 Requirement*
1	8.47 (0.03)	7.1	4.1	5.62 (0.06)	1.35	0.78
2	2.57 (0.24)	7.1	4.1	+	1.35	0.78
3	8.39 (0.06)	7.1	4.1	5.48 (0.04)	1.35	0.78
4	8.41 (0.09)	7.1	4.1	0.77 (0.01)	1.35	0.78

*total rates for the occupant density during experiments; requirements vary with occupant density

+no flow from the source room to test room, thus, VR per floor area was approximately infinite

Figure 5: Comparison of Average CO_2 Concentration Across the Different Conditions for the First Hour and the Subsequent 3 Hours of Each Test



The changes in VRs had no statistically significant ($p < 0.05$) effects on acceptability of air quality or acceptability of odor. Symptom data from subjects with specific symptoms prior to arrival on their experimental day was excluded from the analysis. There were no statistically significant differences in symptom prevalence with VR on the dichotomized scales regardless of the analysis method. In analyses of symptom severity via the paired t-test and Wilcoxon signed-rank test, there were no statistically significant findings. In analysis of symptom severity with

linear regression models, eye symptoms were significantly decreased ($p = 0.047$) in condition 2 (low VR per occupant) relative to condition 1 (high VR per occupant), contrary to expectations.

There were statistically significant reductions in seven of eight metrics of decision making performance with a lower VR per person, and also in seven of eight metrics with a lower VR per floor area. The associated p values from the within-subject analyses are provided in Tables 5 and 6.

Table 5: Results of Pair-Wise ANOVA for the Per Person Ventilation Scenarios

Performance Metric	F-Ratio	Significance
Basic activity	5.46	P = 0.034
Applied activity	30.0	P < 0.001
Focused activity	15.64	P = 0.001
Task orientation	15.54	P = 0.001
Initiative	32.84	P < 0.001
Information management	1.16	P = 0.299
Breadth of approach	6.51	P = 0.024
Strategy	88.14	P < 0.001

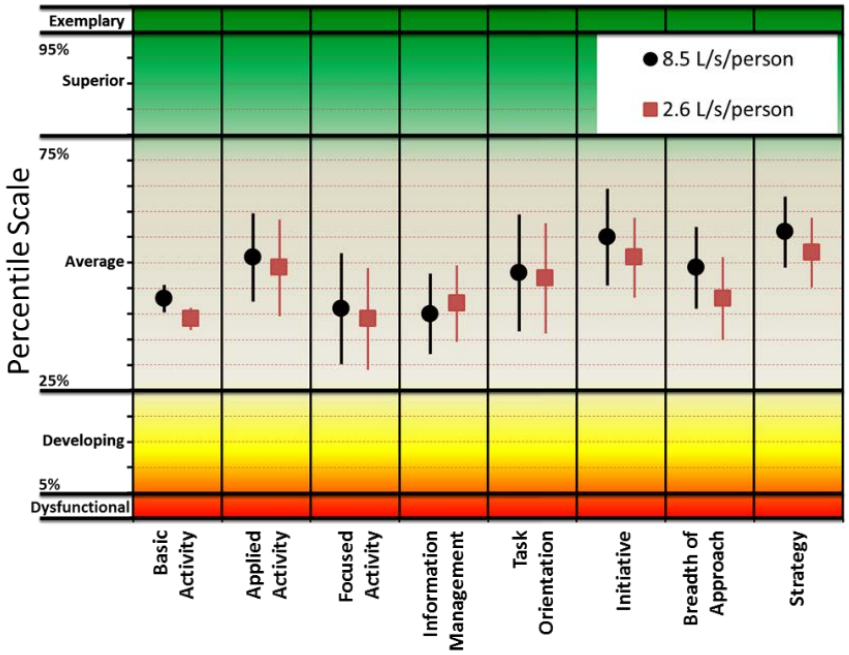
Table 6: Results of Pair-Wise ANOVA for the Floor Area Ventilation Scenarios

Performance Metric	F-Ratio	Significance
Basic activity	8.731	P = 0.010
Applied activity	37.80	P < 0.001
Focused activity	15.380	P = 0.001
Task orientation	14.423	P = 0.002
Initiative	80.00	P < 0.001
Information management	5.528	P = 0.033
Breadth of approach	43.808	P < 0.001
Strategy	168.896	P < 0.001

The decision making scores were normalized to rank percentiles using data from a reference population of more than 20,000 U.S. adults, ages 16 to 83, who previously completed the test of decision making. The resulting group-average percentile ranks are shown for each of the eight performance metrics for the per-person ventilation scenarios in Figure 6 and the per-floor area ventilation scenario in Figure 7. In general, percentile ranks are decreased a few percentile points at the lower VRs. Although the error bars (indicating standard deviations) for high and low VRs overlap substantially, the overlaps are a consequence of performance variability among individuals. The differences are highly statistically significant in the within-subject analysis of variance (ANOVA), as indicated by the low p-values in Table 5 for high and low VR per person and in Table 6 for high and low VR per floor area. The significant reductions in decision making performance occurred without the subjects being aware of degraded indoor air quality, as shown by the lack of effects for the perceived air quality and symptoms.

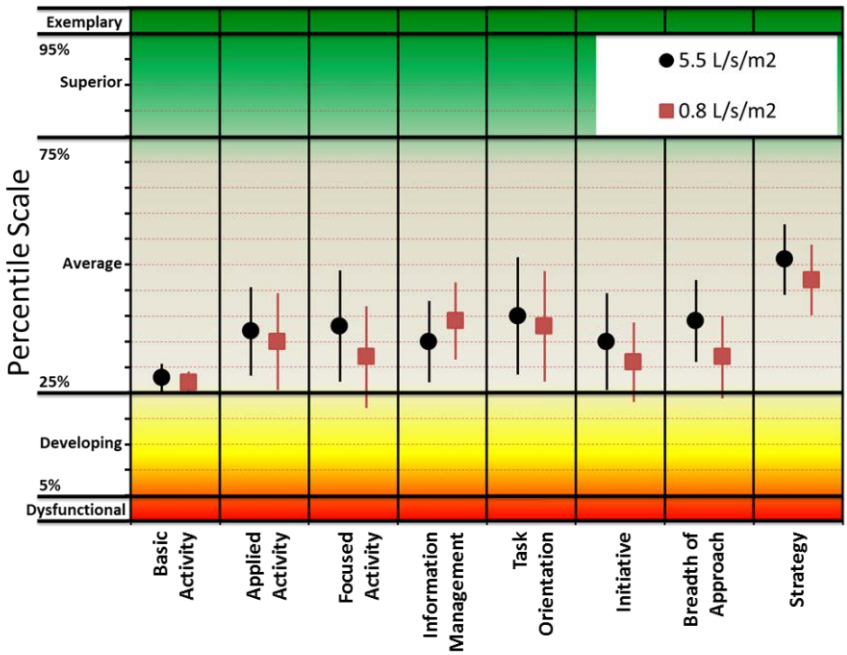
In this study, a change of 1 L/s per person had a moderately larger impact on decision making performance than a change in 1 L/s per square meter of floor area (Maddalena, Mendell et al. 2014), although the relative significance of these two VRs is likely to vary depending on the strength of pollutant emissions from the building and its contents. Current standards, as shown in Table 4, require several L/s per person of ventilation, but only about 1 L/s per square meter of floor area; thus, the study results indicate that realistic changes in VR per person of a few L/s per person in magnitude will have a much larger effect on decision making than realistic changes in VR per floor area of a fraction of a 1 L/s per square meter.

Figure 6: Average Percentile Ranks (± 1 Standard Deviation) for High and Low VR Per Person



The error bars indicate variability among subjects and the within-subject changes are statistically significant.

Figure 7: Average Percentile Ranks (± 1 Standard Deviation) Presented High and Low VR per Unit Floor Area



The error bars indicate variability among subjects and the within-subject changes are statistically significant.

3.4.4 Discussion

There were no significant effects of VRs on satisfaction with air quality and odor. This finding was not surprising because perceptions of the air depend highly on the sensation and perception of odor, which can diminish rapidly after a change in exposure to odorous compounds.

With one small exception, the changes in VRs also did not have statistically significant effects on symptoms. This finding is inconsistent with results of studies performed in actual offices. The available data from reported field studies were analyzed by Fisk, Mirer et al. (2009) and indicate an overall statistically significant decrease in symptoms with increased VR per person, with symptoms decreasing with increased VR until the VR reaches approximately 20 or 25 L/s per person. The shorter exposure period in the current study, and the small number of study subjects, are possible explanations.

The study detected statistically significant decreases in most metrics of decision making performance with decreasing either VR per person and also with decreasing VR per floor area. The decreases in nearly all metrics of decision making were a few points on the percentile scale of decision making performance derived from a reference population of thousands. The magnitude of decreases in decision making performance in this study was similar to the decreases in prior research when subjects had a blood alcohol content of 0.05 percent (Streufert,

Pogash et al. 1993). For reference, a blood alcohol level of 0.05 percent would be achieved in an 82 kg person after two to three drinks each containing 15 mL of alcohol. In the United States, a blood alcohol limit of 0.08 percent (0.04 percent in commercial drivers) is the legal limit for driving. Many other countries have set the blood alcohol limit at 0.05 percent for legal driving and some countries have lower limits.

The study results indicate that realistic changes in VR per person of a few L/s per person will have a much larger effect on decision making than realistic changes in VR per floor area of a fraction of a 1 L/s per square meter.

More information from this task is available in Maddalena, Mendell et al. (2013), Maddalena, Mendell et al. (2014), and Maddalena, Chan et al. (2014).

3.4.5 Conclusions

In a setting simulating an office, most aspects of decision making performance were diminished when VR per person was decreased and also with decreasing VR per floor area.

3.4.5 Significance

The study results provide support for maintaining minimum requirements for both VR per occupant and VR per floor area in MVR standards. The results also indicate that avoiding low VRs per occupant is more critical for decision making performance than avoiding low VRs per unit floor area. Study results also show that human performance can be degraded by low VRs and even when perceptions of air quality and health symptoms are unaffected.

3.5 Effects of Ventilation Rates on Acute Outcomes in California Office Workers

3.5.1 Objectives

The objective of this task was to assess the associations of VRs, estimated from indoor CO_2 concentrations, with the amount of respiratory infections, illness-related absences, building-related health symptoms, and satisfaction with air quality in occupants of offices in California.

3.5.2 Methods

Buildings in California were solicited for participation by emails, flyers, and phone calls to the employers. Eligible office buildings were from the public or private sector in three distinct climatic regions of California: the Bay Area, the Central Valley, and the South Coast. In each participating building, one or more study spaces with at least 30 occupants was selected. Each study space was either a subset of the building and its workers or the full building, within which relatively uniform VRs were anticipated based on the space layout and HVAC system design.

In each study space, indoor CO_2, temperature, and relative humidity were measured at ten-minute intervals, usually for a full year. Concentrations of CO_2 were measured at two or three indoor locations. Information on selected characteristics of the buildings and ventilation systems was collected. Data collected from the two to four sensors within each study space were first averaged at each time point to provide overall real-time estimates for the study space. As

the primary VR metric for analysis (VR Method 1), real-time spatially averaged CO_2 data from 8 a.m. to 5:30 p.m. on workdays were used to estimate daily workday VRs (as outdoor airflow rates in L/s per person) using the equilibrium CO_2 method; that is, from observed peak moving 60-minute-averaged CO_2 concentrations, per ASTM D6245-12 (ASTM 2012). An alternative method (VR Method 2) was also used for estimating VRs, based on the build-up of indoor CO_2; this required no assumption about equilibrium but assumed stable VRs and occupancy during selected periods. This method considers build-up of CO_2 during selected two-hour periods in each study space with relatively stable occupancy numbers and also in the afternoon after workers returned from lunch.

Data on occupants and their outcomes were obtained from occupant surveys every three months during the study, starting three months after initial sensor installation in the building, using a web-based survey tool. In the initial survey for each participant, data were obtained on personal/demographic variables that can influence risk of respiratory illness (age, gender, smoking status, asthma status), home variables (young children at home), and work factors (job type, office space sharing, hours per week worked in building). In the initial survey and in each recurring survey, data were obtained on the number of episodes of infectious respiratory illnesses and the number of days of absence caused by respiratory illnesses in the prior three months. These surveys also included questions on perceived air quality and on severity of four symptoms on the day of the survey. The four symptoms were dry, itching, or irritated eyes; headaches; unusual tiredness or fatigue; and congested nose. Respondents were asked to rate each symptom at the time of survey completion on a severity scale from 0–10 (none to very severe) and also, if they reported the symptom at a level of 1 or higher, whether they had the symptom before arriving at work that day. Respondents were asked to rate the indoor air quality in two questions, on acceptability of air quality and acceptability of odor, with the response scale for each ranging from 1 to 7 (clearly acceptable to clearly unacceptable).

Data collected were analyzed to assess the relationships between estimated VRs in L/s per person or CO_2 concentrations, either daily or averaged over the prior three-month periods, and occupant outcomes assessed in the survey at the end of each quarter. Appropriate statistical models were selected for analysis of each type of human outcome, all using bootstrap procedures for variance of estimates to account for clustering on individuals and study spaces. For respiratory illness episodes and illness absence days, zero inflated negative binomial, zero inflated Poisson, negative binomial, or Poisson models were the statistical models used to estimate the incident rate ratios. For symptom outcomes, which have highly skewed distributions with many zero values, zero-inflated negative binomial models were used. For perceived air quality and odors, generalized estimating equation linear and logistic regression models were used to estimate the regression coefficients and odds ratios (ORs), respectively. All adjusted models included covariates for potential confounding as appropriate. Additional methodological details are provided in Mendell, Eliseeva et al. (2014).

3.5.3 Results

Data from 16 study spaces in nine buildings were included in the analyses. All study spaces had air conditioning and were reported to have economizers. Response rates to the occupant survey

were lower than expected, despite financial incentives for responding. The 1,297 valid surveys received represented an overall 27 percent response on the four surveys, varying from 16 to 41 percent across study spaces. Respondents included slightly more males (53 percent), included a broad range of ages from under 30 (17 percent) to over 50 (29 percent), and were highly educated (98 percent with at least a college degree, 45 percent with a graduate degree). Most (81 percent) had no children up to age 3 years at home. Most (78 percent) reported never smoking. Half (50 percent) reported some history of allergy or asthma, including 25 percent for hay fever and 16 percent for asthma, and 11 percent reported current asthma. Most participants (75 percent) worked in open office spaces, with 70 percent sharing their workspace with at least 7 others; only 18 percent had private offices.

For the number of respiratory infection episodes in the prior three months, the overall mean was 0.92, with a range across study spaces from 0.67 to 1.32. The 95th percentile value overall was 3, ranging in specific study spaces from 2 to 4. For the number of respiratory illness-related work absences in the prior three months, the overall mean was 0.78, with a range across study spaces from 0.10 to 1.38. The 95th percentile value overall was 4, ranging in specific study spaces from 1 to 6. The overall proportions of surveys reporting any of eye, headache, fatigue, or nose symptoms at work (considering all eligible surveys from all study spaces together) were 65 percent, 35 percent, 61 percent, and 51 percent respectively, with respective mean severity scores among those reporting any of each symptom of 4.4, 3.8, 4.4, and 4.0 out of 10. For the eye, headache, fatigue, and nose symptoms, the minimum proportions reported in any study space were 40 percent, 15 percent, 44 percent, and 30 percent, and the maximum proportions reported were 82 percent, 57 percent, 74 percent, and 68 percent, respectively. The proportion of surveys rating the indoor air quality as unacceptable (on a dichotomous scale) was 10.2 percent overall, ranging across study spaces from 2.5 to 30 percent. Averaged over the 4 surveys in each space, only two of 16 spaces failed to provide acceptable air quality for at least the minimum 80 percent proportion of occupants.

In most spaces, as shown in Figure 8, MVRs substantially exceeded Title 24 requirements.

Figure 8: Measured Minimum Ventilation Rates Compared to the Title 24 Requirement

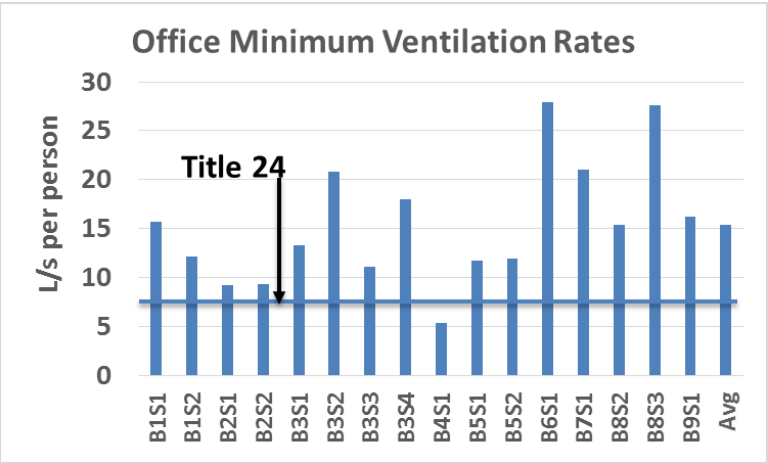


Table 7 summarizes, by study space and specific survey periods (S1—S4), median values during the prior three months of three VR-related variables: daily VRs (Method 1), daily mean CO_2, and daily maximum CO_2. Three-month median VRs in study spaces ranged from 6.9 to 65.8 L/s per person, medians of daily mean CO_2 from 425-957 ppm, and medians of daily maximum CO_2 from 494-1230 ppm. The VRs were high relative to the current MVR standards for office space: 8.5 L/s (17 cfm) per person from ASHRAE 62.1, at the default density of occupancy, and 7 L/s (15 cfm) per person from California Title 24. Other than one median quarterly VR of 6.9 L/s per person in space 4, all other quarterly medians exceeded 13 L/s per person, or almost double the Title 24 requirement.

VR and CO_2 metrics had no statistically significant relationships with occupant outcomes, except for a small significantly positive association of the alternative VR metric with respiratory illness-related absence, contrary to hypotheses. Some non-significant tendencies, such as for the CO_2 metrics and acceptability of odors measured on a continuous scale, were in the direction hypothesized from prior knowledge. In contrast, however, some non-significant tendencies, such as for the CO_2 metrics and the illness absence-related outcomes, were in directions opposite those hypothesized from limited prior findings.

Table 7: Prior Three-Month* Median of Daily Ventilation Rates (VRs), Daily Mean CO_2, and Daily Maximum CO_2, by Study Space**

Study Space	Three-Month Median of Daily VRs: (L/s -person)				Three-Month Median of Daily Mean CO2: (ppm)				Three-Month Median of Daily Maximum CO2: (ppm)			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Bay Area												
1a	21	19	20	21	571	605	607	58	669	703	702	679
1b	19	17	17	18	573	603	603	579	723	731	749	729
2a	21	18	14	20	569	615	660	587	661	713	803	678
2b	21.5	18.4	13.8	22.0	570	602	657	566	660	699	803	660
3a	18	25	22	20	550	534	513	533	713	628	664	672
3b	39	36	31	39	470	482	481	463	538	547	578	541
3c	14	24	20	15	587	532	526	534	873	652	704	843
3d	30	35	32	29	480	496	475	483	588	571	566	602
6	66	42	33	39	432	471	492	477	500	547	580	567
Central Valley												
4	19	13	7	14	602	663	957	656	720	825	1230	822
9	21	26	20	NA	563	529	577	NA	733	699	703	NA
South Coast												
5a	15	18	16	16	646	605	647	653	759	732	777	764
5b	18	20	17	21	555	572	580	569	711	682	752	673
7	23	28	27	27	574	530	538	541	659	594	618	629
8b	28	23	58	53	512	507	446	441	726	835	568	584
8c	31	42	59	65	525	471	448	425	581	528	501	494

*prior three-month period ending on the first day of each survey period (S1 – S4) in each space

**VR Method 1

3.5.4 Discussion

The objective of this study was to quantify the relationships of VRs in California office buildings with occupant outcomes that were hypothesized, based on prior research, to be increased by lower VRs: respiratory illnesses and respiratory illness-related absences, building-related symptoms, and dissatisfaction with indoor air quality and odors. No statistically significant relationships were found, except for a small significantly positive association of the alternative VR metric and respiratory illness-related absence, contrary to hypotheses. Given that over 35 associations were estimated, one or two statistically significant association would have been expected simply by chance without reflecting true underlying relationships.

The overall weakness of these signals suggest that actual relationships, within the range of VRs included in this study, were either absent or so weak that greater statistical power would be necessary to detect them. VRs were high over time in almost all study spaces. For the three-month median VRs in each study space, used in illness absence analyses, only one (6.9 L/s per person) was below 13; others ranged from 13.1-65.8 L/s per person. Most VR data in illness

absence analyses (between the tenth and ninetieth percentiles) were between 16 and 42 L/s per person, which is over two to over nine times the Title 24 requirement. For the daily VR values, the tenth-to-ninetieth percentile range was 13 to 45 L/s per person. Thus, this study was unable to assess relationships with VRs considered substandard, and could only compare high with very high VRs, a range in which indoor contaminant levels are highly diluted and little variation in contaminant concentration would result. The findings might in fact be interpreted as preliminary evidence for an upper bound of the range of VRs within which increased VRs may substantially reduce illness absence (about 16 L/s per person), or improve symptoms or perceived air quality (about 13 L/s per person). Establishing such bounds more firmly would require larger studies.

Milton, Glencross et al. (2000) reported lower rates of illness absence in offices with 24 versus 12 L/s per person, a contrast within the higher VR range of the current study. In studies of classrooms, Mendell, Eliseeva et al. found in 2013 that lower VRs within the range of approximately 2-20 L/s per person were associated with significantly increased illness absence in primary school students, with most observed VRs below 7 L/s per person. A large number of office studies generally have shown worsening of building-related symptoms and perceived air quality at lower VRs below about 20 or 25 L/s per person (Seppänen, Fisk et al. 1999, Wargocki, Sundell et al. 2002, Sundell, Levin et al. 2011). This study did not find such relationships, but daily VRs in this study were mostly above 13 L/s per person.

3.5.6 Conclusions

In this study, there were no consistent statistically significant associations of VRs with reported respiratory illnesses, illness-caused absence, building-related symptoms, or satisfaction with air quality. The lack of associations may be a consequence of the high VRs, generally far above the Title 24 requirement. The three-month median VRs in the study spaces, with one exception, ranged from 13.1 to 65.8 L/s per person, which is from almost twice to over nine times the Title 24 requirement of 7 L/s (15 cubic feet per minute [cfm]) per person. Thus, this study could compare only high with very high VRs, a range in which little variation in indoor contaminant concentration and occupant effects would result.

3.5.6 Significance

This study provided data on actual minimum VRs in California office buildings (during non-use of economizers), suggesting that, to the extent the studied buildings are representative, these VRs are usually substantially higher than required in the Title 24 standards. The study data also suggest that increasing VRs above approximately 16 L/s per person does not significantly reduce respiratory illness or associated absence, reduce building-related symptoms, or improve satisfaction with indoor air quality. Thus, the study results suggest the minimum VRs specified in standards for offices should not exceed 16 L/s per person, based on the outcomes considered.

3.6 Effects of Ventilation Rates on Building Energy Use and Indoor Air Quality

3.6.1 Objectives

The objective of this task was to estimate the effects of MVRs on energy use and indoor air quality in commercial buildings in California.

3.6.2 Methods

The EnergyPlus building energy simulation model (version 7.2) was used to estimate building energy use with different MVRs in offices (small, medium, and large), a primary school, a secondary school, and a medium-size retail building. The modeling assumed MVRs that are 0 percent, 50 percent, 70 percent, 100 percent, 130 percent, 150 percent, and 200 percent of the MVR's specified in Title 24 standards. Hourly simulations for a full year were performed for each building type in each of California's 16 climate zones. The models varied only the mechanically-supplied rate of ventilation. Air infiltration occurred at a rate unaffected by the mechanical ventilation rates. The "Zone Air Contaminant Balance" model of EnergyPlus was used to calculate hourly indoor air concentrations of a contaminant emitted indoors at a constant rate. Using weighting factors to account for the distribution of buildings among climate zones in California, statewide estimates were developed for both energy and indoor contaminant concentrations.

Table 8 provides the key building features that are most relevant to this analysis. In each case the building models started with U.S. Department of Energy reference models (Griffith, Long et al. 2008). The office models were versions of the Department of Energy reference models that had been modified to produce California reference building models consistent with Title 24 standards (Brunswick, Dutton et al. 2012), models for schools and the retail building were not modified.

Table 8: Key Features of Simulated Buildings

Building Type	Number of Floors	Floor Area (m^2)	HVAC Type(s)	Economizer
Small office	1	372	Packaged terminal air conditioner with direct expansion cooling coil and gas heating coil	Modeled with and without
Medium office	3	4982	Three multi-zone variable air volume packaged HVAC units, with three gas boilers for heat plus electric reheat coils	Modeled with and without
Large office	12	42757	Two water-cooled chillers, gas boilers, and a variable air volume HVAC system	Modeled with and without
Primary School	1	6871	Variable Air Volume and Constant Air Volume except Packaged Single Zone Air Conditioner in gymnasium, kitchen and café	No
Secondary School	2	19592	Variable Air Volume and Constant Air Volume except Packaged Single Zone Air Conditioner in gymnasium, kitchen and café	No
Medium size retail building	1	2294	Packaged Single Zone Air Conditioner, gas furnace	Yes for main retail area

Economizer controls, described in the background section, modify the effects of MVRs on building energy use and indoor contaminant concentrations. In many California climates and building types, economizers increase VRs above the MVR much of the time. When economizers are present, the MVR setting only affects the VR when weather is hot and mechanical cooling is required, or when it is cool and heating is necessary. For an intermediate range of outdoor air temperatures, such as 46.4 to 71.6 °F (8 to 22°C), that varies with building features, the economizer increases the VR above the MVR. As of 2003 to 2004, approximately 55 percent of the office floor area in California had an economizer (California Energy Commission 2014). Consequently, offices were modeled with and without economizers, and the weighting factors used to produce statewide estimates reflected data on economizer use as a function of building size. Available data indicated that only 20 percent of the floor area in schools in California is served by a HVAC system with an economizer (California Energy Commission 2014); thus, the models employed for the schools assumed no economizers. The retail building model employed was the Department of Energy Reference model that included some HVAC systems with economizers and some HVAC system without economizers.

In the office buildings and retail buildings, the simulations assumed changes in VRs throughout the entire building. The modeling of schools assumed no changes in VRs in the gymnasium, kitchen, and café areas, but changes in VRs in all other parts of the schools. More details are provided by Dutton and Fisk (2014) and Dutton and Fisk (2015).

3.6.3 Results

Statewide for offices, provision of MVRs at the rate specified in Title 24 was estimated to increase HVAC energy consumption by 6 percent relative to providing no mechanical

ventilation. Having economizers installed lowered HVAC energy use intensity by 20 percent. For California offices with economizers, 50 percent and 100 percent increases in Title 24 prescribed MVRs led to modeled increases in HVAC energy use by 7.6 percent and 21.6 percent, respectively. In office buildings without economizers in many climate zones, increasing VRs up to 150 percent of the current Title 24 minimum reduced HVAC energy. The energy savings occurred with increased VRs because reductions in cooling energy use during mild weather more than offset increases in cooling and heating energy use during periods with more hot or cold outdoor air temperatures. The projected trend in statewide HVAC energy use with MVR is shown in Figures 9 and 10 for offices with and without economizers, respectively.

Figure 9: Statewide HVAC Energy Use versus MVR for Offices with Economizers

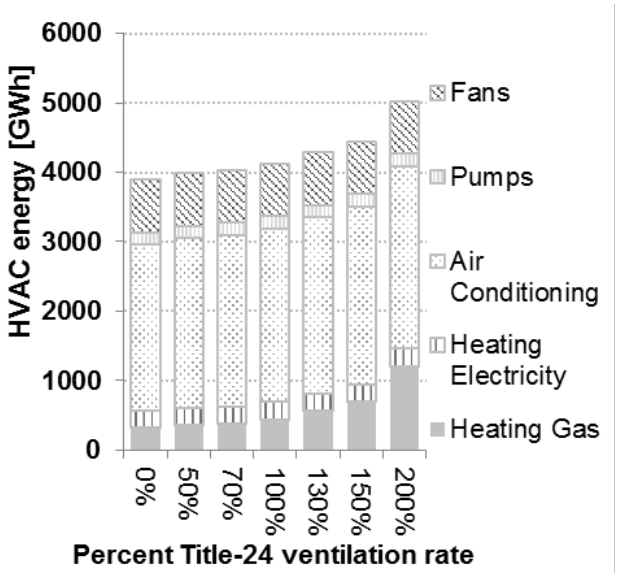
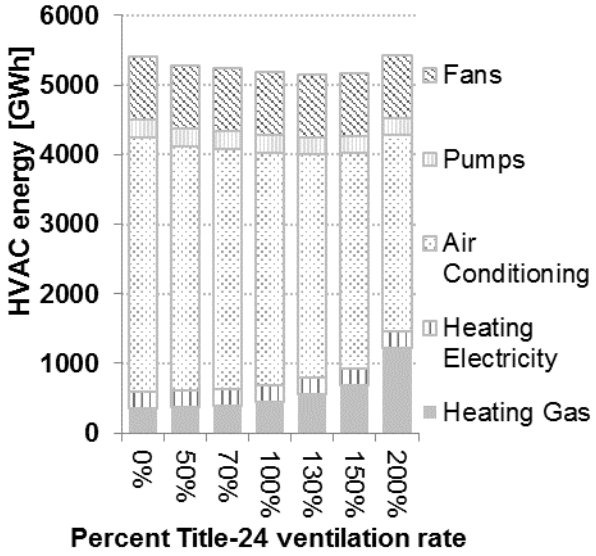


Figure 10: Statewide HVAC Energy Use versus MVR for Offices without Economizers



Statewide for both the primary and secondary school buildings, MVRs affected HVAC energy use by only a few percent. With increased MVRs, gas heating energy increased moderately and electricity energy use by the air conditioning system decreased moderately. These results are shown in Figures 11 and 12.

Figure 11: Statewide HVAC Energy Use Intensity in the Primary School versus MVR Expressed as a Percentage of the Title 24 Required VR

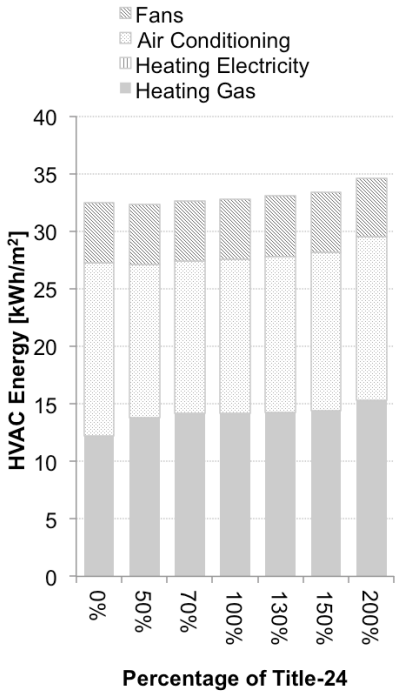
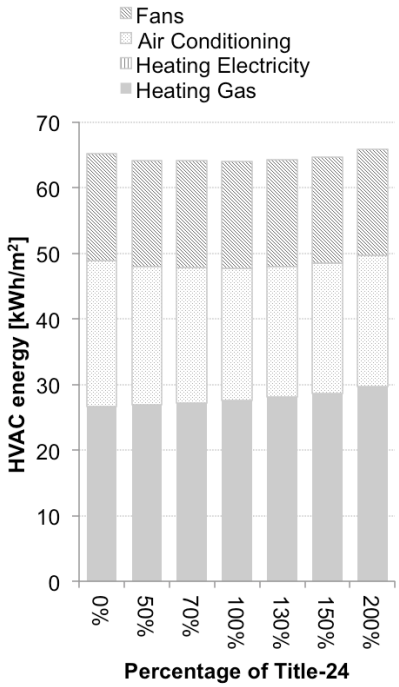
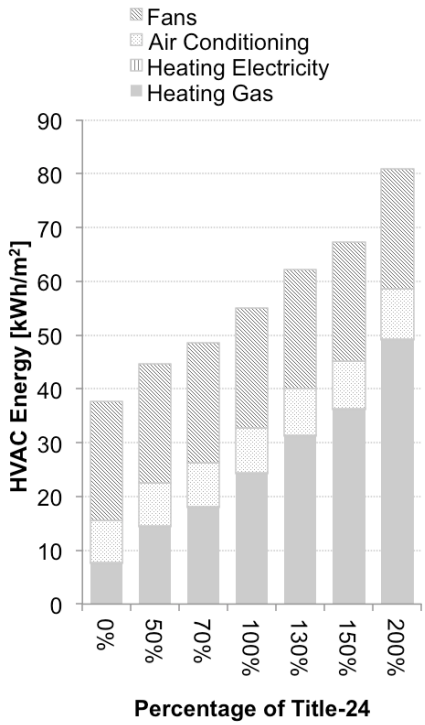


Figure 12: Statewide HVAC Energy Use Intensity in the Secondary School versus MVR Expressed as a Percentage of the Title 24 Required VR



Modeling indicated that statewide gas heating energy and total HVAC energy increased markedly with MVR in the retail building; a similar but less dramatic trend was projected for small office buildings. Building size, thermal characteristics of building envelopes, schedules of operation, and rates of internal heat generation influence the need for space heating and how much the MVRs affect the need for heat. The results for the retail building are shown in Figure 13.

Figure 13: Statewide HVAC Energy Use Intensity in the Retail Building versus MVR Expressed as a Percentage of the Title 24 Required VR



The influence of MVRs on energy use by climate zone is shown in Figure 14 for office buildings with economizers and in Figure 15 for office buildings without economizers. Similar trends with climate zone were projected for schools and the medium-size retail building (Dutton and Fisk 2015).

Figure 14: Office HVAC Energy Use Intensity by Climate Zone and MVR for Buildings with Economizers

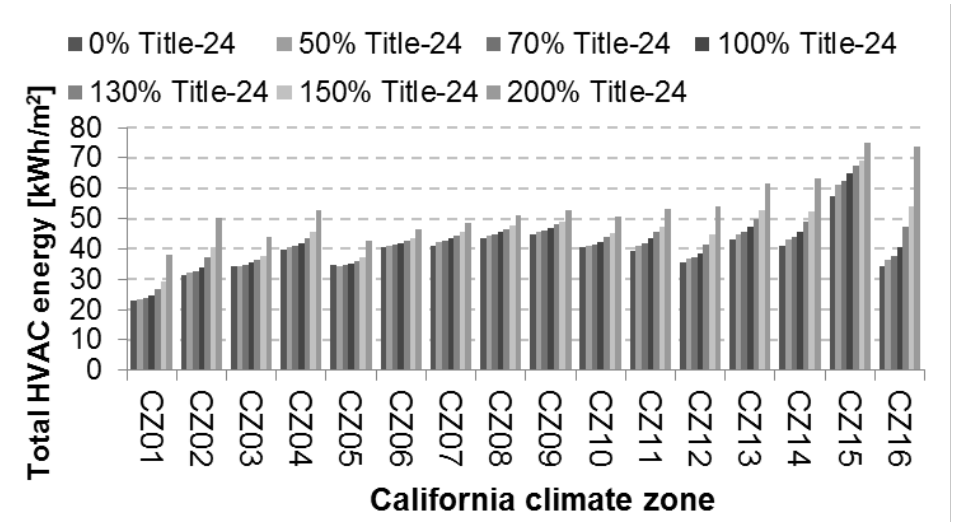
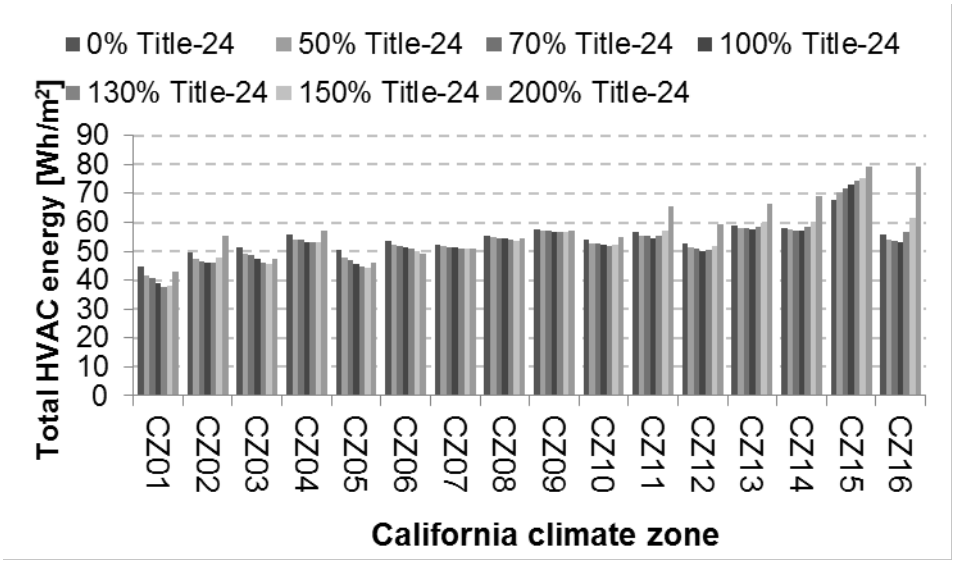


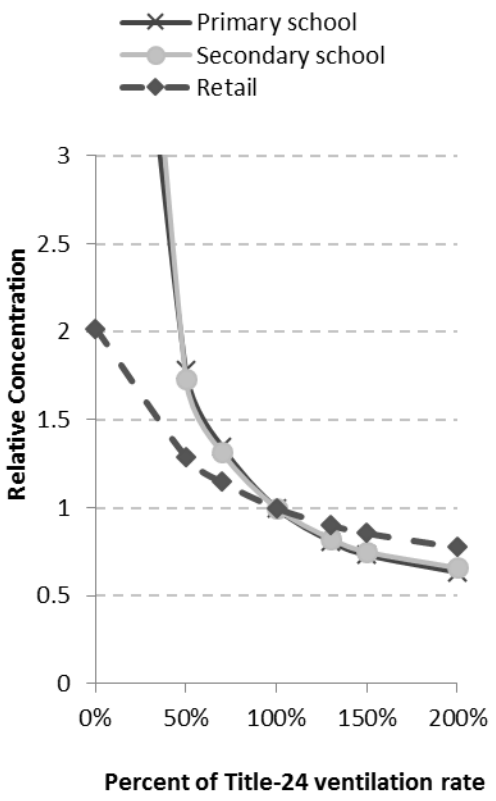
Figure 15: Office HVAC Energy Use Intensity by Climate Zone and MVR for Buildings without Economizers



Having economizers installed in offices reduced the work-time average indoor contaminant exposure by 38 percent. For California offices with economizers, 50 percent and 100 percent increases in Title 24 prescribed MVRs led to modeled decreases in the annual average workplace contaminant concentration by 8.6 percent and 14.4 percent, respectively. During times with economizer deactivation, indoor contaminant concentrations were much more highly affected by MVRs. In the large- and medium-size offices without economizers, doubling the current Title 24 MVR decreased the average indoor contaminant concentration during occupied periods by approximately 40 percent. In the schools that had no economizers,

statewide school-day annual-average indoor contaminant concentrations were highly affected by VRs. In the retail building, with partial economizers, statewide workday annual average indoor contaminant concentrations were moderately affected by MVRs. The trends in contaminant concentrations with MVRs for schools and retail buildings are shown in Figure 16.

Figure 16: Annual Average Normalized Contaminant Concentration as a Function of MVR



3.6.4 Discussion

Based on this modeling, the effects of MVRs on HVAC energy use and indoor contaminant concentrations will vary substantially with building type, building, size, and climate zone and are also highly affected by the presence or absence of an economizer system. In most cases, 100 percent increases or decreases in MVRs from the Title 24 requirement change HVAC energy use by less than 20 percent, and often by less than 10 percent. HVAC energy use is more highly affected by MVRs in small offices, the medium-size retail buildings, and in the more severe California climates, which contain a small fraction of the building stock. In many cases, increases in MVRs in buildings without economizers by up to 150 percent of the Title 24 required MVR saves energy because decreases in air conditioning energy during mild weather periods exceed the increases in heating energy during cold weather. Annual average indoor concentrations of indoor-generated contaminants will, in general, be much lower in buildings with economizers. In these buildings, MVRs have only a small effect on annual average indoor

contaminant concentrations. However, peak indoor contaminant concentrations in buildings with economizers are still substantially affected by MVRs. The contaminant concentrations in buildings without economizers can be highly affected by MVRs. For example, providing a VR in schools that is 50 percent of the Title 24 requirement, which is common practice (Mendell, Eliseeva et al. 2013), was projected to increase the school day annual average indoor contaminant concentration by 75 percent relative to providing ventilation at the rate specified in Title 24. In most instances, HVAC energy use increases more than linearly with increased MVR while the opposite trend applies for contaminants. Thus, decreasing MVRs below the current Title 24 requirements will save little energy but will substantially increases indoor contaminant concentrations in most of the modeled building types and climate zone.

3.6.5 Conclusions

The effects of MVRs on HVAC energy use and indoor contaminant concentrations will vary substantially with building type, building size, and climate zone and are also highly affected by the presence or absence of an economizer system. Economizers are attractive because they save energy, increase VRs during much of the year in most California climates, and substantially reduce annual average indoor concentrations of indoor-generated contaminants. Decreasing MVRs below the current Title 24 requirements will save little energy but substantially increase indoor contaminant concentrations in most of the modeled building types and climate zones.

3.6.6 Significance

The results of this modeling provide data that can be used for the selection of MVRs in future building standards. In addition, building designers, owners, and operators can use the results of this modeling to determine how their building design and operational decisions that influence VRs will affect building energy consumption and indoor air quality.

3.7 Framework for Producing Evidence-Based Standards for Minimum Ventilation Rates

3.7.1 Objectives

The objective of this task was to develop and describe a procedure for selecting MVRs in commercial building standards that take advantage of currently available scientific information and strike a balance between the benefits and costs of higher MVRs.

3.7.2 Methods

The structures and scientific foundations for various current MVR standards and current knowledge about the effects of VRs on human outcomes were reviewed. The approaches used to set limits for environmental conditions, such as outdoor air contaminant concentrations, that pose both risks and mitigation costs were also reviewed. A multi-step procedure was then developed that drew upon the process for selecting contaminant concentration limits while reflecting the state of knowledge about the effects of VRs on people and building energy consumption. Finally, as an example, the procedure was applied for offices.

3.7.3 Results

The procedure starts with a recommendation that MVR standards should specify use of pollutant source control and air filtration practices when they are widely available and proven to be more effective in controlling indoor contaminant levels and more cost-effective than ventilation in limiting an exposure of concern. In particular, particle filtration, not ventilation, was recommended for control of indoor particle levels. Two sequential steps follow:

In the first step, an acceptable threshold is set for each adverse human outcome that has a demonstrated relationship to VR. The threshold represents the maximum increase in the adverse human outcome, such as health symptoms, as the VR is reduced from a high value, above which further increases in VR have no demonstrable benefit. The adverse outcomes considered given current data, are building-related symptoms (sometimes called sick building syndrome symptoms), poor perceived indoor air quality, diminished work performance, and cancer and non-cancer chronic outcomes. Then, using existing data, the MVRs required to meet each specific outcome threshold are estimated; the highest of these MVRs, which would then meet all outcome thresholds, is selected as the target MVR. In a final step, implemented only if the target MVR is judged impractically high, costs and benefits are estimated quantitatively and this information is used in a risk management process to select a final MVR. For balancing the objective and subjective factors involved in setting MVRs, it was suggested that a diverse group of stakeholders make the determination, or at least advise the standards making entity. A technical support team should be available to assemble as much quantitative data as possible and to perform the necessary calculations and explain the findings. The recommended procedure is described in greater detail in Mendell and Fisk's 2014 document.

In an application of the procedure for offices, using a set of example outcome thresholds including a 50 percent increase in building-related health symptoms, 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 can raise the target MVR. For example if the threshold for the increase in building-related symptoms is 25 percent, the target MVR increases to 14 L/s (30 cfm) per person, which would likely trigger the risk management process.

3.7.4 Discussion

Minimum VR standards can consider evidence associating VRs with human outcomes both directly (as with 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 such as energy costs. Ideally, in the future, this process would yield separate reference MVRs per person and per unit floor area, but sufficient data are only available to produce a MVR per person.

3.7.5 Conclusions

Current prescriptive MVR standards for commercial buildings do not take advantage of the existing scientific data relating VRs with human outcomes or building energy use. 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.

Additional data relating VRs in commercial buildings to human outcomes will be necessary to make best use of the proposed framework.

3.7.6 Significance

Applying the recommended procedure is expected to result in MVR standards with a stronger scientific basis for protecting occupants, and with a more explicit balancing of benefits and costs, than the current standard-setting process.

3.8 Contaminant Emissions from Particle Filters

3.8.1 Objectives

The objectives of this task were to evaluate formaldehyde emission rates from particle filters and to estimate their impacts on indoor formaldehyde concentrations. Formaldehyde is an important indoor air pollutant that is a respiratory irritant and that has been designated a human carcinogen by the World Health Organization (World Health Organization International Agency for Research on Cancer 2006).

3.8.2 Methods

Bench scale experiments measured formaldehyde emission rates from sections (coupons) of filter media cut from four fiberglass and three polyester filters. To measure formaldehyde emission rates, air was passed through the coupons installed in filter cartridges and upstream and downstream formaldehyde concentrations and air flow rates were measured. The formaldehyde emission rate was calculated as the product of the air flow rate and the difference between the downstream and upstream formaldehyde concentration, divided by the area of filter media. Experiments took place at different air flow rates, yielding face velocities of 0.013, 0.05, and 0.5 m/s, and with various values of air relative humidity. The higher face velocity, 0.5 m/s, is typical of the air velocities in practice when filters are pleated.

In limited full-scale experiments, indoor formaldehyde concentrations were measured in the two identical rooms of a small unoccupied modular office. During some weeks, the HVAC systems serving the rooms contained the filter with the highest formaldehyde emission rates in bench-scale studies. During other weeks, the HVAC systems were operated with a filter that had negligible formaldehyde emission rates in bench scale studies.

3.8.3 Results

The emission rates of formaldehyde from the polyester filters were negligible or close to negligible. Figure 17 shows the formaldehyde emission rates plotted versus relative humidity from the four fiberglass filters (F1 — F4) all from the same manufacturer, with the error bars

providing estimates of uncertainties. Filters F1 and F4 were similar, except F1 has a coating of a tackifier to help retain particles. The emission rates were based on measurements taken after 24 to 48 hours when the face velocity was 0.013 m/s and after 48 hours when the face velocity was 0.5 m/s. Emission rates varied among filters and increased markedly with both RH and face velocity. Formaldehyde emission rates of F1 and F4 with a face velocity of 0.5 m/s were approximately 10-fold higher than emission rates at 0.05 m/s. As relative humidity increased from 20 percent to 80 percent, there was approximately a 15-fold increase in the formaldehyde emission rate. Emission rates of formaldehyde from F2 and F3 were only measured at the lower face-velocity condition.

Experiments using filter coupons from F1 and F4 and a face velocity of 0.5 m/s for up to 350 hours, indicate a moderate decline in emission rate (for example, a 25 percent decrease in formaldehyde emission rate during the first 24 to 50 hours). After that, a slow decline or stable formaldehyde emission rate was measured.

Figure 17: Formaldehyde Emission Rate (EF) as a Function of Relative Humidity in Low (*v* = 0.013 m/s) and High (*v* = 0.5 m/s) Face Velocity Experiments

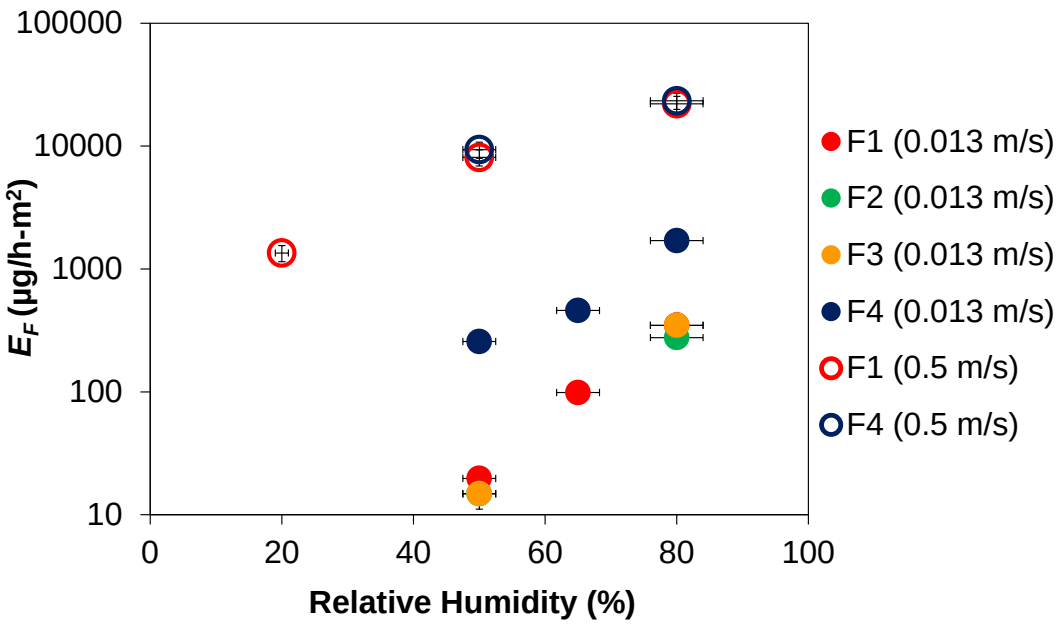
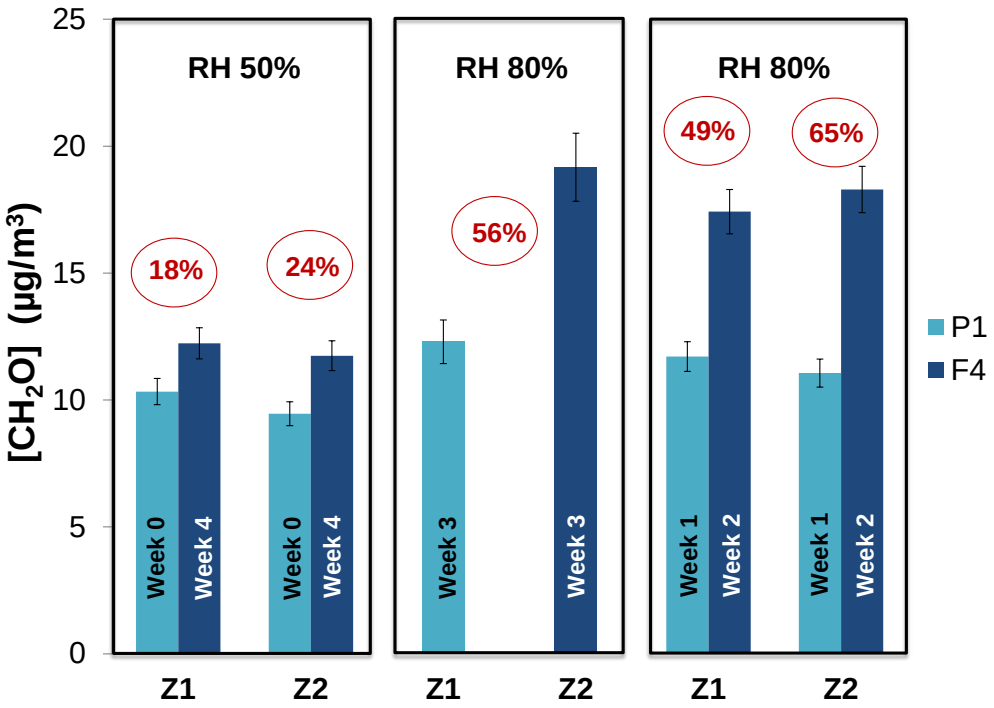


Figure 18 shows the measured indoor formaldehyde concentrations in the full scale experiments. With a relative humidity of 50 percent, indoor concentrations are 18 percent to 24 percent higher when fiberglass filter F4 is installed relative to with polyester filter P1 installed. At 80 percent RH, indoor formaldehyde concentrations are 49 percent to 65 percent higher with fiberglass filter F4 installed. More detailed results from this task are provided in Sidheswaran, Chen et al. (2013).

Figure 18: Indoor Formaldehyde [CH2O] Levels Measured in Zone 1 (Z1) and Zone 2 (Z2) of a Modular Office Over Several Weeks at 50 Percent RH and 80 Percent RH Indoors, and With Filters P1 (Polyester) or F4 (Fiberglass) Installed in the HVAC Units



The percent increases in indoor concentrations when filter F4 was used relative to P1 are reported in red circles.

3.8.4 Discussion

This is the first study to demonstrate substantial rates of emission of formaldehyde from fiberglass filters, with a large increase in emission rates with both air velocity and relative humidity. The increase in emission rates with relative humidity and information obtained in conversations with individuals in the filter industry suggest that the emissions are a consequence of hydrolysis of formaldehyde-containing binders, but further research would be necessary to confirm this hypothesis. The increase in emission rate with air velocity might be explained by enhancement in the mass transfer process or the availability of more water at the higher air velocities. The full scale-studies clearly demonstrate that real-word increases in indoor formaldehyde concentrations can be significant. The very low formaldehyde emission rates from polyester filters indicate an easy mitigation—the avoidance of fiberglass filters with high formaldehyde emission rates. However, uncertainties remain after completing this small study. There are many different fiberglass filters, and this study included only a small sample of four filters. Data collected over a longer period of time are needed to assess the trends in formaldehyde emission rates. Finally, the filters in this study were not used for a sufficient period to accumulate a heavy deposit of particles. Emission rates should be quantified after extensive accumulation of particles of various types. One of our prior studies suggests increased

formaldehyde emissions as particles accumulate (Destaillats, Chen et al. 2011), possibly because the accumulated particles adsorb water that can facilitate hydrolysis.

3.8.5 Conclusions

Some types of fiberglass filters can emit formaldehyde at a rate sufficient to significantly increase indoor formaldehyde concentrations. The rates of formaldehyde emission increased markedly with both air velocity and relative humidity.

3.8.6 Significance

The task has identified fiberglass filters with high formaldehyde emission rates as an important, easily avoidable source of indoor formaldehyde. However, further research is needed to determine if the problem of high formaldehyde emission from fiberglass filters is widespread or limited to a small number of filter types and to better characterize the effects of operating conditions and deployment time on formaldehyde emission rates. A follow-on study is being supported by the California Air Resources Board.

3.9 Project Outreach Activities

3.9.1 Objectives

The objectives of this task were to communicate research findings and associated recommendations about future MVR standards to stakeholders.

3.9.2 Methods

The following methods were employed to accomplish the project outreach objectives:

- A technical advisory group (TAG) of influential stakeholders was engaged throughout the project. Many members of the TAG participated in the initial two-day workshop. TAG members reviewed project reports and became familiar with the project's findings.
- Project results were communicated to stakeholders via technical presentations at meetings and via webinar presentations.
- Project results were communicated in reports, conference papers, and journal papers. Documents were made available via the project website. Appendix A provides both a list of reports and papers produced by this project and links to the documents.
- A document (Fisk, Dutton et al. 2013) was prepared providing recommendations to the Energy Commission pertaining to incorporation of an indoor air quality procedure in Title 24.
- Mendell and Fisk's 2014 document was prepared providing a procedure that can be used by the Energy Commission and others for selecting MVRs in commercial building standards that take advantage of currently-available scientific information and strike a balance between the benefits and costs of higher MVRs.
- Energy Commission staff responsible for Title 24 standards received an in-person briefing on the project's findings and recommendations.

3.9.3 Results

The TAG, consisting of influential stakeholders, was engaged throughout the project. Members of the TAG helped shape plans and reviewed work products. Through this engagement they became familiar with project findings.

Project results were presented at the following meetings and webinars. Some of the presentations also incorporated results of other research:

- Healthy Buildings 2012 Conference
- Indoor Air 2014 Conference
- U.S. General Services Agency Workshop on Indoor Environmental Quality, Health, and Productivity
- Indoor Air Quality Association 2013 Conference
- Federal Interagency Committee on Indoor Air Quality
- Environmental Law Institute Webinar
- Maine Indoor Air Quality Council Conference
- Environmental Protection Agency Workshop on Applying Green Buildings Research Today
- ASHRAE Annual Winter Conference 2014
- International Society of Exposure Science Annual Meeting 2012
- U.S. Green Building Council, Northern California Chapter, Building Health Initiative Member Meeting

Two documents were prepared as part of this project that emphasize recommendations for future MVR standards for commercial buildings. The first of these documents (Fisk , Dutton et al. 2013) provides a review and critique of the IAQP in the ASHRAE MVR standard (ASHRAE 2013) and then provides recommendations relative to adoption of this IAQP, or alternatives, in Title 24. Identified shortcomings of the IAQP include the absence of detailed specifications of critical contaminants, contaminant reference levels, and required levels of satisfaction with air quality. Also, implementation procedures are described only in very general terms. Given the lack of details, the user will often have insufficient expertise to apply the IAQP. The lack of details also opens the door for misuse of the IAQP to obtain almost any desired MVR. In a workshop, many prospective users characterized the IAQP as too complex and impractical. On the other hand, the IAQP procedure is attractive because it provides an incentive for use of pollutant source control measures and air cleaning systems that have the potential to improve indoor air quality and enable energy savings. The document recommends that the IAQP not be adopted in its current form in Title 24 and provides some options for consideration. One option, called the Alternative MVR Procedure, allows reduced MVRs if specified contaminant source control measures are implemented and particle filters meet a specified efficiency standard. A

second alternative, called the Equivalent IAQ Procedure, allows MVRs to be moderately reduced if air cleaning systems are employed, and if the user can demonstrate that the systems prevent indoor concentration increases in a specified set of critical contaminants. The third alternative is an improved ASHRAE-like IAQP, with critical contaminants, reference levels, and procedures specified. The document recommends further development and adoption of the Alternative MVR procedure.

The second document with recommendations for future MVR standards (Mendell and Fisk 2014) is described in section 3.7. This document provides a procedure for selecting MVRs in commercial building standards that take advantage of currently-available scientific information and strike a balance between the benefits and costs of higher MVRs.

In an additional project outreach activity, project staff met with staff members of the Energy Commission who are responsible for the applicable portions of the Title 24 standards. The project's key findings and recommendations were communicated.

3.9.4 Discussion

The mixture of outreach activities in this project was able to reach different categories of stakeholders. Technical papers targeted researchers and individuals working on MVR standards. Conference papers and presentations targeted a broader set of stakeholders, including many involved with building design and operation. Briefings targeted specific staff at the Energy Commission responsible for MVR standards in Title 24.

3.9.5 Conclusions

A variety of mechanisms were employed to implement project outreach including engagement of a TAG, presentations and papers, a briefing of Energy Commission Staff, and development of specific recommendations for future MVR standards.

3.9.6 Significance

As a consequence of the knowledge gained in this project and the various outreach activities undertaken, the Energy Commission and other organizations are better positioned to specify MVR requirements in standards that have a strong scientific underpinning and that balance concerns about the effects of MVRs on both human outcomes and building energy use.

CHAPTER 4:
Overall Discussion

This multifaceted research project has:

- Significantly advanced current knowledge about the effects of VRs in commercial buildings on people's health and performance.
- Developed estimates of the effects of VRs on the energy use in commercial buildings in California's climates.
- Recommended that an Indoor Air Quality Procedure contained in the ASHRAE commercial ventilation standard not be incorporated in Title 24, and suggested alternative to that procedure.
- Proposed a new approach for developing future MVR standards that use available scientific data to strike a balance between the benefits and costs of higher VRs.
- Identified high rates of formaldehyde emission from some types of filters used in ventilation systems.

As a consequence of this project, those responsible for MVR standards in commercial buildings have a stronger scientific basis, as well as more procedure options, for selecting MVRs. Also, building operators can use the project's results to inform their decisions about the VRs provided in their buildings.

Although this project and other research projects provide sufficient scientific data to enable improved MVR standards, our knowledge about the effects of VRs on health, performance, and energy use remain incomplete. Appendix B elaborates upon the following remaining high priority research needs addressing the effects of VRs on people:

- Effects on cognitive performance of longer-term high exposures to elevated CO_2 levels.
- Effects of VRs on acute health outcomes in schools and daycare centers.
- Effects of VRs on acute respiratory infections and absence rate.
- MVR requirements per person and per unit floor area.
- Health and performance benefits of outdoor air economizer controls.
- Development of performance-based MVR procedures.

In addition to the priorities identified above, the widespread problem of insufficient ventilation in California's classrooms needs much attention. Based on existing data, about half of classrooms fail to meet MVR standards, and many fail by a wide margin. The causes of these low VRs should be identified and reliable practical technical solutions should be developed.

GLOSSARY

Term	Definition
ANOVA	Analysis of variance
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
CoC	Contaminant of concern
CO_2	Carbon dioxide
CREL	Chronic reference exposure level
DALY	Disability adjusted life year
HVAC	Heating, ventilating, and air conditioning
HZEB	Healthy zero energy buildings
IAQ	Indoor air quality
IAQP	Indoor air quality procedure
k_{OA}	Octanal-air partitioning coefficient
MERV	Minimum efficiency reporting value
MVR	Minimum ventilation rate
OEHHA	Office of Environmental Health Hazard Assessment
PM	Particulate matter
PM2.5	Particulate matter with aerodynamic diameter less than 2.5 micrometer
PM10	Particulate matter with aerodynamic diameter less than 10 micrometer
RCL	Reference concentration level
RH	Relative humidity
RVR	Reference ventilation rate
SF_6	Sulfur hexafluoride
SVOC	Semi-volatile organic compound

Term	Definition
TAG	Technical advisory group
VOC	Volatile organic compound
VR	Ventilation rate

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APPENDIX A:
Links to Project Documents

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APPENDIX B:
Remaining Priority Research Needs

The subsequent text suggests six high priority areas of research related to human outcomes affected by ventilation rates (VRs). Research addressing these priorities would provide information to further improve building standards and operational practices. Basic research on health, such as studies of how key indoor air contaminants affect health, is not included, even though the results would inform the development of MVR standards. Research on how VRs affect health in sensitive subsets of the population is also not included, likely because the required research investment is considered prohibitively large.

Effects on Cognitive Performance of Longer Term Exposures to Elevated Carbon Dioxide Levels

It has long been thought that carbon dioxide, at the levels present in buildings, has no direct effects on peoples' health or performance. In Healthy Zero Energy Buildings (HZEB) task 2.4c (see section 3.4), realistic changes in VR per occupant, which led to increases in indoor levels of carbon dioxide and other bio effluents, reduced decision making performance. Two studies have found that adding carbon dioxide to the indoor air, with all other factors maintained constant, reduced decision making performance. This new evidence that higher levels of carbon dioxide within the range of concentrations encountered in buildings degrade cognitive performance suggests that MVR standards need to account for the effects of VRs on carbon dioxide levels.

The effects of carbon dioxide on people could constrain our ability to reduce MVRs to save energy and even put upward pressure on MVRs and associated energy use. This is because carbon dioxide is emitted by people, and, at present, removal of carbon dioxide by air cleaning systems is not broadly practical. However, all of the prior studies involved short periods of exposure to higher carbon dioxide levels lasting a few hours. Further research is needed to determine whether or not people adapt to regular periodic, or continuous, exposures to higher levels of carbon dioxide in a manner that prevents adverse effects on cognitive performance. Also, further research is needed to determine if adverse effects occur at concentrations below 1000 ppm, which is typical of most offices and retail buildings and is the lowest level studied to date.

Effects of VRs on Acute Health Outcomes in Schools and Daycare Facilities

Several studies, including large numbers of measurements in California, have found that VRs in classrooms are often far lower than the MVRs specified for classrooms. In the chronic risk evaluation in HZEB Task 2.5a (see section 3.3),VRs in schools were found to be lower than VRs in other commercial buildings. Research has also shown that low classroom VRs are associated with increased rates of student absence and reductions in student performance. However, there has been virtually no research on the relationship between classroom VRs and the occurrence of acute health symptoms among students and teachers. Further research is needed to fill this gap. In addition, research to identify both the causes of widespread insufficient ventilation in

classrooms and which practical energy efficient corrective measures should be used is a high priority.

Many young children spend time in daycare facilities; however, data on VRs and indoor air quality in daycare facilities are extremely limited. Homes are sometimes adapted for use as daycare facilities, and it seems likely that little attention has been placed on providing adequate VRs in such cases. Further research is needed to determine typical VRs in daycare facilities and how daycare VRs affect health outcomes, such as cases of respiratory infections, among children.

Effects of VRs on Acute Respiratory Infections and Absence

Common respiratory infections, such as influenza and the common cold, are a major cause of morbidity, especially among elderly populations, and of absence from work and school, thus imposing large economic costs. Given the importance of absence and respiratory infection, further research on how VRs affect these outcomes is a high priority. Two of two studies have found that absence rates among students increase when VRs are lowered. One of two studies of significant size, one being HZEB Task 2.4a (see section 3.5), have found that absence rates among office workers increase when VRs are lowered. Future studies should emphasize research in buildings without outdoor air economizers, which have lower VRs than buildings with economizers.

MVR Requirements per Person and per Unit Floor Area

Current MVR standards for commercial buildings prescribe MVRs that are a combination of a MVR per person and a MVR per unit floor area. The two-part requirement seems reasonable because both people and the building and its content are sources of contaminants. However, HZEB Task 2.4c (see section 3.4) is the only identified study able to investigate the independent effects of VRs per person and VR per unit floor area on health and performance. Thus, the data available to apportion MVR requirements between these two components remains weak, and further research is warranted. There are substantial challenges to perform research on this topic in real buildings, so other approaches such as chamber experiments should to be considered.

Health and Performance Benefits of Outdoor Air Economizer Controls

Economizer systems substantially increase time average VRs in buildings. Modeling for HZEB Task 2.6 (see section 3.6) indicates that, on average, economizers, when present, increase VRs almost 80 percent of the time in offices in California. Based on current knowledge, we can project that economizers substantially improve satisfaction with air quality and work performance, decrease sick building symptoms, and may reduce absence rates. On the other hand, indoor levels of some outdoor air pollutants, such as ozone, are expected to increase in buildings with economizers. At present, decisions about whether to invest in economizers are based almost entirely on investment, maintenance, and energy costs. Research to directly assess the effects of economizers on satisfaction with air quality, work performance, sick building symptoms, and absence rates is suggested as a priority. Such research is relatively straightforward, with recruitment of buildings being the largest challenge.

Development of Performance-Based MVR Procedures

The evaluation of the IAQP in HZEB Task 2.3 (see section 3.1) resulted in a suggestion that an Alternative MVR procedure be developed for adoption in Title 24. The procedure, properly defined, could simultaneously save energy and improve indoor air quality. The work performed in HZEB Task 2.3 only provided a general approach for the new procedure. A future effort is recommended to further develop an Alternative MVR that is practical to implement and that yields health and energy benefits.