Energy in Buildings and Communities Programme

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RESIDENTIAL VENTILATION AND HEALTH

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INTERNATIONAL ENERGY AGENCY

Energy in Buildings and Communities Programme

AIR INFILTRATION AND VENTILATION CENTRE

THE AIVC BOARD HAS LED THE REVIEW PROCESS OF THIS TECHNICAL NOTE

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TECHNOTE:

RESIDENTIAL VENTILATION AND HEALTH

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PREFACE

THE INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. A basic aim of the IEA is to foster international co-operation among the 29 IEA participating countries and to increase energy security through energy research, development and demonstration in the fields of technologies for energy efficiency and renewable energy sources.

THE IEA ENERGY IN BUILDINGS AND COMMUNITIES PROGRAMME

The IEA co-ordinates international energy research and development (R&D) activities through a comprehensive portfolio of Technology Collaboration Programmes. The mission of the IEA Energy in Buildings and Communities (IEA-EBC) Programme is to develop and facilitate the integration of technologies and processes for energy efficiency and conservation into healthy, low emission, and sustainable buildings and communities, through innovation and research. (Until March 2013, the IEA-EBC Programme was known as the IEA Energy in Buildings and Community Systems Programme, ECBCS.)

The R&D strategies of the IEA-EBC Programme are derived from research drivers, national programmes within IEA countries, and the IEA Future Buildings Forum Think Tank Workshops. These R&D strategies aim to exploit technological opportunities to save energy in the buildings sector, and to remove technical obstacles to market penetration of new energy efficient technologies. The R&D strategies apply to residential, commercial, office buildings and community systems, and will impact the building industry in five areas of focus for R&D activities:

- Integrated planning and building design
- Building energy systems
- Building envelope
- Community scale methods
- Real building energy use

THE EXECUTIVE COMMITTEE

Overall control of the IEA-EBC Programme is maintained by an Executive Committee, which not only monitors existing projects, but also identifies new strategic areas in which collaborative efforts may be beneficial. As the Programme is based on a contract with the IEA, the projects are legally established as Annexes to the IEA-EBC Implementing Agreement. At the present time, the following projects have been initiated by the IEA-EBC Executive Committee, with completed projects identified by (*):

Annex 1: Load Energy Determination of Buildings (*)
Annex 2: Ekistics and Advanced Community Energy Systems (*)
Annex 3: Energy Conservation in Residential Buildings (*)
Annex 4: Glasgow Commercial Building Monitoring (*)
Annex 5: Air Infiltration and Ventilation Centre
Annex 6: Energy Systems and Design of Communities (*)
Annex 7: Local Government Energy Planning (*)
Annex 8: Inhabitants Behaviour with Regard to Ventilation (*)

Annex 9:	Minimum Ventilation Rates (*)
Annex 10:	Building HVAC System Simulation (*)
Annex 11:	Energy Auditing (*)
Annex 12:	Windows and Fenestration (*)
Annex 13:	Energy Management in Hospitals (*)
Annex 14:	Condensation and Energy (*)
Annex 15:	Energy Efficiency in Schools (*)
Annex 16:	BEMS 1- User Interfaces and System Integration (*)
Annex 17:	BEMS 2- Evaluation and Emulation Techniques (*)
Annex 18:	Demand Controlled Ventilation Systems (*)
Annex 19:	Low Slope Roof Systems (*)
Annex 20:	Air Flow Patterns within Buildings (*)
Annex 21:	Thermal Modelling (*)
Annex 22:	Energy Efficient Communities (*)
Annex 23:	Multi Zone Air Flow Modelling (COMIS) (*)
Annex 24:	Heat, Air and Moisture Transfer in Envelopes (*)
Annex 25:	Real time HVAC Simulation (*)
Annex 26:	Energy Efficient Ventilation of Large Enclosures (*)
Annex 27:	Evaluation and Demonstration of Domestic Ventilation Systems (*)
Annex 28:	Low Energy Cooling Systems (*)
Annex 29:	Daylight in Buildings (*)
Annex 30:	Bringing Simulation to Application (*)
Annex 31:	Energy-Related Environmental Impact of Buildings (*)
Annex 32:	Integral Building Envelope Performance Assessment (*)
Annex 33:	Advanced Local Energy Planning (*)
Annex 34:	Computer-Aided Evaluation of HVAC System Performance (*)
Annex 35:	Design of Energy Efficient Hybrid Ventilation (HYBVENT) (*)
Annex 36:	Retrofitting of Educational Buildings (*)
Annex 37:	Low Exergy Systems for Heating and Cooling of Buildings (LowEx) (*)
Annex 38:	Solar Sustainable Housing (*)
Annex 39:	High Performance Insulation Systems (*)
Annex 40:	Building Commissioning to Improve Energy Performance (*)
Annex 41:	Whole Building Heat, Air and Moisture Response (MOIST-ENG) (*)
Annex 42:	The Simulation of Building-Integrated Fuel Cell and Other Cogeneration Systems (FC+COGEN-SIM) (*)
Annex 43:	Testing and Validation of Building Energy Simulation Tools (*)
Annex 44:	Integrating Environmentally Responsive Elements in Buildings (*)
Annex 45:	Energy Efficient Electric Lighting for Buildings (*)
Annex 46:	Holistic Assessment Tool-kit on Energy Efficient Retrofit Measures for Government Buildings (EnERGo) (*)
Annex 47:	Cost-Effective Commissioning for Existing and Low Energy Buildings (*)
Annex 48:	Heat Pumping and Reversible Air Conditioning (*)
Annex 49:	Low Exergy Systems for High Performance Buildings and Communities (*)
Annex 50:	Prefabricated Systems for Low Energy Renovation of Residential Buildings (*)
Annex 51:	Energy Efficient Communities (*)
Annex 52:	Towards Net Zero Energy Solar Buildings (*)
Annex 53:	Total Energy Use in Buildings: Analysis & Evaluation Methods (*)
Annex 54:	Integration of Micro-Generation & Related Energy Technologies in Buildings (*)

Annex 55:	Reliability of Energy Efficient Building Retrofitting - Probability Assessment of Performance & Cost (RAP-RETRO) (*)
Annex 56:	Cost Effective Energy & CO_2 Emissions Optimization in Building Renovation
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Annex 69:	Strategy and Practice of Adaptive Thermal Comfort in Low Energy Buildings
Annex 70:	Energy Epidemiology: Analysis of Real Building Energy Use at Scale

Working Group - Energy Efficiency in Educational Buildings (*)
Working Group - Indicators of Energy Efficiency in Cold Climate Buildings (*)
Working Group - Annex 36 Extension: The Energy Concept Adviser (*)

CONTENTS

1 EXECUTIVE SUMMARY

Exposures in homes constitute the major part of exposures to airborne pollutants experienced through the human lifetime. They can constitute from 60 to 95% of our total lifetime exposures, of which 30% occurs when we sleep. The airborne pollutants constituting these exposures have sources outdoors and indoors. Pollutants having sources outdoors penetrate building envelope through cracks, gaps, slots and leakages, as well as through open windows and ventilation systems. Indoor pollutant sources include humans and their activities related with hygiene, house cleaning, food preparation, laundry, etc.; building construction materials, furnishing, and decoration materials; mould, bacteria, and fungi; tobacco smoking and combustion processes; as well as pets and pests. Studies have measured over 250 fifty pollutants in the indoor air in homes. Volatile organic compounds (VOCs) have the highest airborne concentrations in homes due to higher volatility however other pollutants impact occupant health as well. Indoor concentrations vary from home to home as well as over time in a given home.

Exposure controls should be designed to minimize health hazards and avoid unwanted odours. To do this, we must identify the pollutants driving the health risks and identify the best control strategies for those pollutants. High concentrations are not necessarily indicative of a health hazard. Pollutant concentration data alone cannot be used to identify pollutants driving health hazards. Toxicity varies widely from pollutant to pollutant and extensive research has been undertaken to link exposures levels of specific pollutants to specific adverse health outcomes. Toxicology and epidemiology have traditionally been used to link concentrations/exposures to health outcomes. However, in-silico[1] and in-vitro based assessments of toxicity are gaining prominence.

Several studies have attempted to prioritize pollutants for mitigation in the indoor environment based on the prevalence of disease in the community, occupant exposure estimates, and the research derived links between exposures and health outcomes. The key pollutants identified as driving chronic health impacts include: $PM_{2.5}$ (particulate matter with a diameter less than 2.5 microns), mould/moisture, radon, environmental tobacco smoke (ETS), formaldehyde and acrolein. To reduce the exposure of contaminants different control strategies can be applied. The most effective are (1) source control and reduction of pollutant sources and (2) enclosure and encapsulation of sources. Ventilation plays a key role in reducing exposures that cannot be controlled by these measures. Effective local ventilation, such as cooker/range hoods, are critical for removing pollutants from periodic high emission sources such as cooking. Other contaminants can be removed by making use of mixing ventilation or displacement ventilation. The correct amount of ventilation is still an area of debate.

[1] *toxicity assessments performed on computer or via computer simulation*

The following top five research needs were identified in a pair of workshops held by the Air Infiltration and Ventilation Centre (AIVC) and its partners in 2012: (1) Impact of user behaviour on the control of indoor environmental quality; (2) Development, implementation and harmonization of new, advanced methods for monitoring indoor air quality and its effects on health and comfort in buildings; (3) Development of ways to increase the accountability of building contractors, designers, producers, constructors and installers; (4) Tools and methods for ensuring a robust and performance-based design, operation and maintenance of building systems while maintaining good indoor air quality; and (5) Quantification of health and comfort outcomes in terms of public health and economic criteria. Workshop participants recommend that these research needs be addressed quickly so that indoor air quality (IAQ) and health in highly energy efficient buildings are not compromised. It is also of utmost importance to benchmark systematically differences in exposure to pollution sources and their associated health risks in buildings having different occupancy and purpose, from traditional through energy-retrofitted buildings to highly energy-efficient buildings to create reference points for further development. The tighter building envelopes of energy-efficient buildings will reduce adventitious ventilation and increase the need for designed ventilation systems to provide good IAQ. New materials in homes may also introduce new pollutants of concern.

These topics can be used for a number of purposes: they can guide research directions and the priorities of public, private, national and international agencies supporting research, they can be used to develop innovative solutions and they can indicate policy needs. Policies should be aligned, integrated, and harmonized with regulations and standards for highly energy efficient buildings and indoor environmental quality, and consistent requirements should be developed for any of their crosscutting and overlapping criteria.

2 INTRODUCTION

Ventilation has historically played a key role in designing healthy indoor spaces. Several nations have ventilation standards for commercial and residential buildings to provide acceptable or good indoor air quality. A lack of sufficient information on indoor sources and health impacts of indoor pollutants has resulted in ventilation standards relying heavily on engineering judgement.

Ventilation a solution for all IAQ problems?

Ventilation is not the only factor that determines people's exposure to pollutants indoors. Contaminant emission rates, absorption and desorption processes on building materials and furnishings and transport within buildings have comparable impacts to ventilation. Insight is needed into the indoor and outdoor sources of pollutants and pollutant behaviour indoors.

Part 1 IAQ and health
Part 2 Control strategies

There have been many exposures identified in the indoor environment but there is still uncertainty regarding which exposures drive the risks. Because exposure controls should be designed to minimize health hazards, this Technote identifies the pollutants driving the health risks and the best control strategies for those pollutants based on available literature. The relationship between ventilation and health has been the subject of many publications, resulting in a fragmented body of work; this Technote aims to give an overview of the literature available for specialists to acquire knowledge about the topic. This Technote consists of two parts. In Part I the relationship between indoor air quality and health is described. It starts with an overview of pollutants in homes that have been measured. It prioritizes pollutants for mitigation in the indoor environment and identifies potential health outcomes. In Part II control strategies to reduce health effects from these and other pollutants are described, including different strategies to reduce exposure and the role of ventilation. The final chapter describes the research needs.

Focus on residential buildings

The focus of this Technote is residential buildings in developed countries, and it does not address the needs and health concerns of developing or undeveloped countries. Cooking on open fires in poorly ventilated enclosures or outdoors is therefore out of scope. Tobacco smoke is considered as an avoidable contaminant in homes and therefore is not handled in detail in this Technote. The increased health risk associated with simultaneous exposure to environmental tobacco smoke, second hand smoke and radon is not considered either. In the case of radon associated with emissions by building materials and soil, other specific measures to reduce exposure have to be taken, such as the depressurization of subfloors. These specific measures and systems are mostly systems, which are separated from the general ventilation systems. Therefore this will also not be discussed in this Technote.

The content of this Technote includes:

Chapter 1 is the Executive summary of this Technote and describes the relationship between indoor air quality and health, control strategies and the research agenda.
Chapter 2 provides a basic introduction in the Technote and describes the role of ventilation in the exposure to pollutants indoors.
Chapter 3 summarizes published data on indoor pollutants concentrations.
Chapter 4 prioritizes pollutants for mitigation in indoor environment based on the prevalence of disease in the community, occupant exposure estimates, and the research-derived links between exposure and health outcomes.
Chapter 5 identifies potential health effects based on what is currently known about the toxicity of indoor pollutants predominantly based on epidemiological and toxicological findings.
Chapter 6 looks at control strategies to reduce health effects due to pollution indoors. Strategies are identified to reduce exposure, including ventilation to effectively remove and dilute hazardous pollutants.
Chapter 7 provides recommendations for residential buildings research needs, solutions for achieving good IAQ, policy needs and other general comments.

Overview of pollutants, sources and exposure

Appendices provide an overview of pollutants in the residential environment including concentrations of chemical pollutants, radon in homes and the presence of dampness and mould in homes. An overview is provided of studies associating acute exposure with health outcomes.

Throughout the text reference is made to the literature consulted in the development of this Technote. These citations are listed in the reference section. AIVC publications are available at Airbase, the database on www.aivc.org.

PART I: INDOOR AIR QUALITY AND HEALTH

3

OVERVIEW OF POLLUTANTS IN HOMES THAT HAVE BEEN MEASURED

Hundreds of chemicals and pollutants have been measured in the indoor residential environment. The goal of this section is to summarize existing data on what pollutants are present in homes and their concentrations.

3.1 DATA ON CONCENTRATIONS OF POLLUTANTS IN HOMES

Sleeping and exposure

Exposures in homes constitute the major part of exposures to airborne pollutants experienced through the human lifetime. They can constitute from 60 to 95% of our total lifetime exposures, of which 30% occurs when we sleep. Exposures can be modified by controlling sources of pollutants, their local removal or trapping at the point of release, general ventilation with unpolluted air, and filtration and air cleaning. Short-term and long-term exposures to airborne pollutants indoors can create risks for acute health problems such as irritation or aggravation of asthma and allergy symptoms, for chronic diseases such cardiovascular and respiratory problems, and can elevate risk for premature death. There are numerous non-airborne pollutants in the indoor environment, such as phthalates in settled dust and endocrine disrupters in sunscreen, however since these are not impacted by ventilation standards, they will not be covered in this Technote.

Indoor / outdoor

Exposures in homes have different origins. The airborne pollutants constituting these exposures have sources outdoors and indoors. Pollutants having sources outdoors penetrate building envelope through cracks, gaps, slots and leaks, as well as through open windows and ventilation systems. Exposures to these pollutants also occurs outdoors but have much shorter durations than the exposures indoors due to human activity patterns (Klepeis et al. 2001). There are numerous indoor pollutant sources as well. Indoor pollutant sources can emit constantly, episodically, and periodically. Sources include home furnishings and products, human activities, and indoor combustion. Exposures to these pollutant sources only occur indoors.

Outdoor pollutant sources

The main sources of pollutants having outdoor origin include combustion of fuels, traffic, atmospheric transformations, and vegetation activities of plants. The examples of pollutants that are emitted because of these processes include particulate matter, including pollens; nitrogen oxides; organic compounds such as toluene, benzene, xylenes and polycyclic aromatic hydrocarbons; and ozone and its products. A specific example of a pollutant having outdoor origin is radon, a natural radioactive gas emitted from some soils that penetrates building structure through cracks in the envelope and other openings. The risk of exposure to radon is location-dependent condition to the geological structure of the site where the building is constructed. Radon mitigation will not be discussed in the body of the present TechNote. Methods for radon mitigation, independent of ventilation standards, have been thoroughly investigated elsewhere (ASTM 2007, WHO 2009).

The main sources of pollutants having indoor origin include humans (e.g. bioeffluents) and their activities related with hygiene (e.g. aerosol product use), house cleaning (e.g. uses of chlorinated and other cleaning products), food preparation (e.g. cooking particle emissions), etc.; building construction materials including furnishings and decoration materials (e.g. formaldehyde emissions from furnishings); tobacco smoking and combustion processes occurring indoors, as well as pets (e.g. allergens). Mishandling of installations such as improperly maintained ventilation or heating systems can also become important sources of pollutants having origin indoors.

Figure 1: House cleaning can be a main source pollutants

Indoor pollutant sources

The pollutants measured in homes are summarized in the following to identify those that have been ubiquitous, and those having the highest measured mean and peak concentrations. Two indicators describing the pollution level are used to address both chronic and acute exposures. In most of the cases the measured data is weighted by number of measurements which in many cases is in number of homes. The selection is based on the data reported by Logue et al. (2011a) who reviewed 79 reports and compiled database including summary statistics for each pollutant reported in these reports. The data of Logue was compared with the few reports published later (Klepeis et al. 2001; Langer et al. 2010; Beko et al. 2013; Langer and Beko 2013; Derbez et al. 2014; Langer and Beko 2015).

3.2 DATA ON THE PREVALENCE OF MOULD/MOISTURE

Certain conditions indoors, e.g. excessive humidity levels which are impacted by ventilation, can also lead to mould development which may emit pollutants including organic compounds, particulate matter, allergens, fungi and moulds, and other biological pollutants, contagious species and pathogens.

The moisture content in the air (relative humidity) is an important agent modifying our exposures in homes. The moisture is not and should not be considered as a pollutant. However, too high or too low levels of humidity can modify exposures and/or can initiate processes that can lead to elevated exposures levels. This is why humidity should be considered in the context of exposures in homes and health. Humans and their activities indoors are usually main sources of moisture indoors unless there are any major construction flaws causing leaks or penetration of moisture from ambient air. Moisture can be also brought indoors by infiltrating air or through dedicated ventilation systems.

3.3 LIMITED INFORMATION ON AIRBORNE POLLUTANT CONCENTRATIONS

Several studies have measured indoor concentrations of airborne pollutants in residences. The most prevalently measured volatile organic compounds [grouped and ordered by number of studies in the descending order] were: [toluene], [benzene], [ethylbenzene, m,p-xylenes], [formaldehyde, styrene], [1,4-dichlorobenzene], [o-xylene], [alpha-pinene, chloroform, tetrachloroethene, trichloroethene], [d-limonene, acetaldehyde], [1,2,4-trimethylbenzene, methylene chloride], [1,3-butadiene, decane] and [acetone, Methyl tert-butyl ether]. Table 1 shows the selection of volatile organic compounds from Logue et al (2011), a study that aggregated data from 77 studies that measured airborne non-biological pollutants in homes in industrialized nations. Table 1 reports the weighted-mean concentration and 95th percentile concentration from available studies for each pollutant. These levels can be compared with the measured concentration of total volatile organic compounds (TVOCs) sometimes reported by the studies performing measurements in buildings. Recent reports from Swedish building stock show mean TVOC levels at 140 to 270 μg/m^3(Langer and Becko 2013). The potential sources of ubiquitous volatile organic compounds and the compounds with the highest concentration are presented in Table 4.

Table 1: VOCs measured in residential environments with the highest mean and 95th percentile concentration in μg/m³ (data from Logue et al., 2011)[1,2]

COMPOUND	MEAN CONCENTRATION	COMPOUND	95% PERCENTILE CONCENTRATION
Ethanol	860	Ethanol	3,000
Formaldehyde	69	1,4-Dichlorobenzene	270
Isobutane	52	Limonene	120
1,4-Dichlorobenzene	50	Toluene	95
Acetone	40	Alpha-Pinene	90
Alpha-Pinene	37	Acetone	46
Butanol	35	Undecane	45
Limonene	34	Acetaldehyde	40
Acetaldehyde	22	Decane	39
Butylacetate	21	MTBE	36
2-Propanol	18	Heptane	35
Ethylacetate	18	3-carene	31
Acetic acid	15	Freon 11	30
Decane	15		
Toluene	15		

[1] *A comprehensive review of Brown et al. (1994) of 47 studies also reported that ethanol had the highest weighted average concentration in dwellings at 50 μg/m³, and that 18 compounds had concentrations above 5 μg/m³ including benzene, n-decane, 1,4-dichlorobenzene, ethylacetate, ethylbenzene, nonanal, tetrachloroethylene, 1,2,4-trimethylbenzene, o-xylene, camphene, 1,2-dichloroethylene, dichloromethane, m,p,o-xylenes, 2-propanone, limonene, toluene, 1,1,1,-trichloroethane, ethanol*

[2] *occasional activities can cause elevated exposures to some pollutants, e.g. oven cleaning can elevate formaldehyde concentration to 129 to 417 μg/m³ and chloroform 157 μg/m³ during showering (Logue et al. 2011a)*

The most prevalent semi-volatile organic compounds (SVOCs) [grouped and ordered by number of studies in the descending order] were: naphthalene; pentabromodiphenylethers (PBDEs) including PBDE100, PBDE99, and PBDE47; BDE 28; BDE 66; benzo(a)pyrene, and indeno(1,2,3,cd)pyrene. There are also numerous other SVOCs measured including phthalate esters and polycyclic aromatic hydrocarbons. but because of the complicated analytical requirements they are not always measured and thus reported only occasionally. Table 2 shows the selection of semi-volatile organic compounds with the measurement weighted mean concentration from all available studies and with the highest top-of-range concentration together with the reported concentration level. It can be observed that the concentrations are at least one order of magnitude lower than in case of VOCs. The potential sources of common semi-volatile organic compounds and the compounds with the highest concentration are presented in Table 4.

Table 2: SVOCs measured in residential environments with the highest mean and top-of-range(highest measured) concentration in µg/m³ (data from Logue et al., 2011)[1,2]

COMPOUND	MEAN CONCENTRATION	COMPOUND	TOP-OF-RANGE CONCENTRATION
2-Ethylhexanol	3.7	Naphthalene	3.7
Naphthalene	1.2	2.3-Dimethylnaphtalene	0.23
Methylbenzoate	0.64	Phenantrhrene	0.19
Phenol	0.36	Biphenyl	0.17
Phenantrene	0.018	Fluorene	0.12
Dibezothiophene	0.0036	2-Methylnaphtalene	0.084
1-Methylanthracene	0.0035	1-Methylnaphtalene	0.075
Transchlorodane	0.0035	Acenaphthene	0.058
Chrysene	0.0021	Acenaphtylene	0.023
1-Methylphenanthrene	0.002	2,3-Dimethylnaphtalene	0.023

[1] *some studies report concentration of SVOCs as a mass fraction in dust samples collected in homes (µg/g dust) not the concentration in air as reported in the table above; reported ranges of concentrations were as follows for phthalates: DEP: 1.7-340, DnBP: 1.2-9930, DiNP- 639, DiBP:1.9-97, BBzP: 3.7-340, and DEHP: 210-1,310 µg/g, respectively) and for PAHs: pyrene:0.12-1.33, benz(a)anthracene: 0.01-0.57, and benzo(a)pyrene: 0.009-0.72 µg/g dust (data from (Langer et al. 2010)and (Bornehag et al. 2005))*

Table 3 shows the concentrations and 95th percentile for other pollutants including carbon monoxide (CO), nitrogen oxides (NO_x), and particular matter (PM) having size fraction lower than 2.5 µm ($PM_{2.5}$) and ultrafine particles (UFP) with the size lower that 0.1 µm, as well as sulphur hexafluoride (SO_2) and ozone (O_3). Potential sources of these pollutants are given in Table 4.

Table 3: Concentration of selected pollutants measured in residential environments in µg/m³ (data from Logue et al. (2011a) and Beko et al. (2013))[1,2,3]

COMPOUND	MEAN CONCENTRATION	95^{th} PERCENTILE CONCENTRATION
O_3	17.2	80.5
$PM_{2.5}$	15.9	86
UFP	29,100[4]	106,000[4]
SO_2	15	n/a
NO_2	13.1	144.2
CO	810	6,030

[1] *People emit CO_2 which since the 19^{th} Century was used as an indicator of indoor air quality and adequacy of ventilation; the emission rates of CO_2 for adults are from 10 L/h (sleeping) through 17-19 L/h (at normal activity of 1.2 met) to even 50 l/h at medium activity of 3 met; the emission rates for children are slightly lower but can be similar as that for adults because children especially at kindergarten and elementary school age have high activity and mobility. typical levels of CO_2 in residential buildings are usually below 3,000-4,000 ppm and rarely exceed 5,000 ppm even in very tight dwellings (Logue et al. 2011a; Zhang et al. 2014)*

[2] *activities in homes can occasionally elevate concentration of some pollutants, e.g. $PM_{2.5}$ up to 6,381 µg/m³ , NO_2 up to 2,422 µg/m³ or CO (in case of unvented fireplace) up to 114,000 µg/m³ (Logue et al. 2011a)*

[3] *PM_{10} measured in French dwellings was 31.3 µg/m³ (median) and 182 µg/m³ (95^{th} percentile) (Kirchner et al. 2009)[3] in counts per cm³; measurements taken only during occupied hours were slightly higher (Beko et al. 2013)*

Figure 2: Mould in a bathroom

Biological pollutants sources

There have been numerous biological pollutants measured in homes especially in studies of mould and moisture in homes associated with fungal proliferation and bacteria activity as well as release of allergens and mycotoxins. Examples include *Candida*, *Aspergillus*, *Pennicillum*, ergosterol, endotoxins, 1-3β–D glucans. Presence of pets or proliferation of house dust mites can also result in elevated levels of allergens. Typical indoor concentrations of fungi in homes in US, UK and Australia have been seen to range from 10^2 to 10^3 colony forming units (CFU) per m^3 and as high as 10^3 to 10^5 CFU/m^3 in particularly moisture damaged environments (McLaughlin 2013). The measured median levels of dog allergens (*Can f 1*) and cat allergens (*Fel d 1*) in French houses were below limit of quantification respectively 1.02 ng/m^3 and 0.18 ng/m^3 whereas 95% percentile concentration was 1.6 ng/m^3 and 2.7 ng/m^3 respectively (Kirchner et al. 2009). Mite allergens in mattress measured in 567 dwellings in France were 2.2 µg/g and 1.6 µg/g for *Der f 1* and *Der p 1* allergens respectively, while the corresponding 95% percentile levels were 83.6 µg/g and 32.6 µg/g (Kirchner et al. 2009).

Table 4 shows the major sources associated with selected pollutants listed above. A distinction is made, if possible, whether the sources are located indoors or outdoors. It is clear that the pollutants in dwellings originate from many sources and it would be quite challenging to identify one or two sources being mainly responsible for elevated exposures.

Table 4: Major pollutants in dwellings with the associated sources of their origin; (O) indicates sources present outdoors and (I) sources present indoors

COMPOUND	SELECTED MAJOR SOURCES
1,4-Dichlorobenzene	Carpets (nylon, synthetic) (I), laminate floorings (I), household fumigant (mothballs, moulds) and deodorants and air fresheners (I)
2-Ethylhexanol	Solvent, products containing plastic (plasticizer) (I)
Acetaldehyde	Photochemical oxidation and combustion of other carbon/hydrocarbon compounds (I,O), motor vehicle exhausts from traffic (O), tobacco smoking (I), carpets (I), floorings incl. resilient non-rubber based and cork (I), gypsum products (boards) and plaster boards (I), wood based panels (I), paints and varnishes (I), thermal insulation products (I)
Acetone	Humans (I), carpets (I), paints and varnishes (I), external and internal wall ceiling finishes (acoustical ceiling panels) (I), adhesives (I), wood based panels (chipboard, fiberboard) (I), floorings (cork) (I), gypsum products (boards) and plaster boards (I), plastic laminates and assemblies (I), resilient floorings rubber based (I), thermal insulation products (I)
Acrolein	Combustion of organic matter (O,I), biocides (O), motor vehicle exhaust from traffic, also biodiesels (O), tobacco smoking (I), cooking (frying in oils) (I)
Alpha-Pinene	Plant oils (O), carpets (I), adhesives (I), floorings (I), wood based panels (I), paints and varnishes (I), adhesives (I), cleaning products and deodorizers (I)
Benzene	Motor vehicle exhausts (O), tobacco smoking (I), flooring and sealants with rubber, lubricants and dyes, detergents and pesticides (I)
CO	Unvented/improperly vented combustion in homes (I) outdoor combustion (O)
CO_2	Humans (I) unvented combustion (i.e. from cooking, unvented alcohol or natural gas fireplaces) or improperly vented combustion (i.e. backdrafting from draft-induced ventilated furnaces) in homes (I) outdoor combustion (i.e. traffic, power plants, and biomass burning) (O)

COMPOUND	SELECTED MAJOR SOURCES
Ethanol	Humans (I), ethanol fireplaces (I), air fresheners (I), deodorizers (I), cleaning products (I)
Ethylbenzene	Motor vehicle exhausts (O), pesticides, synthetic rubber products (I), paints and inks (I)
Formaldehyde	Photochemical oxidation and combustion of other carbon/hydrocarbon compounds (I,O), motor vehicle exhausts from traffic (O), tobacco smoking (I), cosmetics and disinfectants (I), carpets (I), resins and wood based panels (urea formaldehyde wood products) (I), paints and varnishes (I), gypsum products (boards) and plaster boards (I), internal and external wall finishes incl. acoustical ceiling panels (I), floorings (vinyls, PVC) (I), adhesives (I), thermal insulation products with fiberglass (I), corks (I)
Limonene	Common solvent and additive in cosmetic products, deodorizers and cleaning agents (I), adhesives (glues) and paints (I), 3D printers (I), carpets (I), wood based panels (I) resilient floorings rubber based (I)
Naphthalene	Household fumigant (mothballs) (I), concrete and plasterboard (wallboard or drywall) (plasticizer) (I)
NO_x	Unvented/improperly vented combustion in homes (I) outdoor combustion (O)
Ozone	Atmospheric reactions (O), transport from upper atmosphere (O), electronic equipment operating at high voltage (I), air cleaners and ozone generators (I), printers (I)
Phenol	Plastic materials and cosmetic products (I), adhesives (I), floorings incl. resilient non-rubber based (I), plaster boards with synthetic resins (I), acoustical ceiling panels (I), paints and varnishes (I), cork panels (I), gypsum boards (I), laminates (I)
Phthalates	Products containing plastic such as floorings (PVC), paints and adhesives (I), solvents in hygienic products, lotions and perfumes (I), pesticides (O,I), carbonless copy paper (I), flame retardants (I)
$PM_{2.5}/PM_{10}$	Unvented/improperly vented combustion in homes (I) outdoor combustion (O) secondary organic aerosol formation (I/O) aerosol product use (I) re-suspension of particles (I) physical processes (I/O)
Polycyclic aromatic hydrocarbons (PAHs)	Motor vehicle exhaust (O), combustion (O), emissions from heavier fractions of petroleum such as roofing, tars and asphalt (O), smoking (I), cooking (I) and gas fired appliances (I)
SO_2	Combustion of sulfur containing fuels (O)
Styrene	Rubber, plastic, insulation, fiberglass (I), carpets (backing) (I), floorings (I), gypsum products and plaster board (I)
Tetrachloroethene	Solvent for organic materials, “dry cleaning” (I)
Toluene	Motor vehicle exhausts from traffic (O), common solvent for paints, paint thinners, silicone sealants, rubber, printing ink, adhesives (glues), lacquers, leather tanners, and disinfectant (I), internal and external wall ceiling finishes and acoustical panels (I), carpets and rubber based resilient flooring (I), fiberboards (I), gypsum products and plaster boards (I), plastic laminates and assemblies (I)
Trichloroethene	Solvent for organic materials, “dry cleaning” (I), paints, inks, varnishes and adhesives (I), consumer products such as cleaning fluids for rugs, spot removers, and correction fluids (I), carpets (I), wood based panels (fiberboards) (I), resilient floorings non rubber based (I)
Ultra fine particles (UFP) with an aerodynamic diameter less than 100microns	Similar as for PMs and additionally atmospheric reactions creating secondary aerosols (O,I)

Figure 3: Paint can be a source of different pollutants

4

PRIORITIZING POLLUTANTS IN THE INDOOR ENVIRONMENT

It is widely accepted that ventilation is critical for providing good indoor air quality (IAQ) in homes. However, the definition of “good” IAQ, and the most effective, energy efficient methods for delivering it are still matters of research and debate.
In order to effectively improve indoor air we need to identify the air pollutants that drive the need for ventilation as part of a larger effort to develop a health-based ventilation standard. This section will provide an overview of common methods that have been used to prioritize pollutants in the indoor environment.

4.1 METHODS OF PRIORITIZING POLLUTANTS FOR MITIGATION IN THE INDOOR ENVIRONMENT AND QUANTIFYING THE IMPACT OF VENTILATION

Assessment and ranking

There are several available methods for assessing and ranking the impacts of toxicants in the indoor environment. This section address several methods found in the literature for identifying pollutants that drive risks and for assessing the cost and benefits of ventilation. These methods discussed here are:

- Hazard assessment: Standards and guidelines have been developed that represent a “safe” level of exposure or “safe” concentration threshold for the general public. Additional guidelines have been developed for occupational exposures. A hazard assessment approach compares pollutant concentrations to existing standards and guidelines to determine whether a pollutant is a potential hazard or not. This approach cannot rank pollutants, only identify which are potential hazards and which are not.
- Impact Assessment: Toxicological and epidemiological relationships exist that link exposures with frequency of health outcomes on a population scale. Impact assessment attempts to estimate the harm or health impacts associated with exposures and rank pollutants based on health damage.
- Cumulative Risk Assessment: This approach attributes disease rates and impacts witnessed in a population to specific causes. This approach can also be used for ranking pollutants or pollutant sources.
- Analysis of specific interventions: Measuring the impact of a specific outcome due to changes in home conditions. These studies tend to link ventilation or a specific intervention such as air cleaning to acute exposure impacts, but may not be able to determine benefits to long term health due to changes in the indoor environment. The studies are usually used to determine the effectiveness of a specific intervention or to rank a limited number of interventions.
- Cost benefit analysis (CRA): CRA and impact assessment allow for monetization of the benefits of reducing exposures. This allows for costs and benefits to be compared to determine if interventions are cost effective.

4.2 REVIEW OF EXISTING STANDARDS/GUIDELINES

Exiting standards for contaminant concentrations are thought to represent “safe” levels of exposure for vulnerable subpopulations or concentrations that result in minimal levels of harm. The U.S. Environmental Protection Agency (USEPA) sets National Ambient Air Quality Standards (NAAQS) for outdoor concentrations of six criteria pollutants specified in the 1970 Clean Air Act: carbon monoxide (CO), nitrogen dioxide (NO_2), ozone, particulate matter (PM), lead, and sulfur dioxide (www3.epa.gov/ttn/naaqs/criteria.html). Several of these standards have been tightened since their inception in the 1970s. Local municipalities have the ability to set stricter standards in the US, for example the California Environmental Protection Agency (CalEPA) has set standards that are more stringent than USEPA standards. Many governmental bodies outside of the U.S. promulgate standards for the same pollutants. The World Health Organization (WHO) tends to publish the most health-protective standards (2005), but unlike USEPA standards, these are recommendations or goals rather than legally mandated targets. The World Health Organization (WHO) is the only organization that has published non-occupation indoor air concentration guidelines (WHO 2010). They published guidelines for 9 pollutants: tetrachloroethylene, trichloroethylene, radon, polycyclic aromatic hydrocarbons, nitrogen dioxide, naphthalene, formaldehyde, carbon monoxide, and benzene.

Relevant organizations and reference sources

Several organizations publish guidelines for what safe exposure concentrations are select pollutants. Title III of the 1990 Clean Air Act Amendments established a new regulatory category for chemical air contaminants that are known or suspected to cause serious health effects; 189 chemicals were named to the initial list of hazardous air pollutants (HAPs, also called “air toxics”), of which 187 are still on the list. The USEPA is charged to maintain and update this list, which includes VOCs, SVOCs, metals, and polycyclic organic matter (POM). The CalEPA maintains a separate list of toxic air pollutants referred to as Toxic Air Contaminants (TACs). There is considerable overlap between the CalEPA TAC the USEPA HAP lists, but there are some key differences. For a subset of these pollutants the USEPA has listed chronic non-cancer reference concentrations (RfCs) and cancer unit risk estimates (UREs) through its Integrated Risk Information System (IRIS) and Health Effects Assessment Summary Tables (HEAST). Non-cancer RfCs report the exposure concentrations that are assumed to represent a safe level in that they are unlikely to cause health effects even for sensitive subgroups of the population. UREs estimate the incremental increase in cancer risk that accrues for each 1 µg m^3 increase in chronic exposure. The California Office of Environmental Health Hazard Assessment (OEHHA) publishes non-cancer Reference Exposure Levels (RELs) and its own cancer UREs. In addition to the California and USEPA values, the U.S. Occupational Safety and Health Administration (OSHA) sets reference concentrations for workplace exposures, and the Agency for Toxic Substances and Disease Registry (ATSDR) publishes RfCs for chronic exposure. Since OSHA regulations are intended to protect generally healthy adult workers, their allowable concentrations tend to be higher than those set for HAPs/TACs by the USEPA and CalEPA. Several other countries and organizations have established guidelines for pollutants. The Toxicological Excellence for Risk Assessment organization maintains a database, ITER, of relevant standards and guidelines for individual pollutants from several US entities including the EPA, local municipalities, and the CDC; the World Health Organization; Canada; and the Netherlands (www.tera.org/iter/index.html). It is important to remember that standards and regulations do not represent a uniform level of hazard because of policy motivations, judgment of policy makers, and the level of information available about each pollutant. The setting of a regulation or standard does not mitigate the uncertainty associated with the outcome of exposure, it just draws a line in that uncertainty based on the motivating factors of setting the regulation/standard.

Whereas exposure concentration limits are specified for acute effects and for chronic non-cancer endpoints, concentration-based standards are not uniformly available for cancer. The European Union and the CalEPA have estimated no-effect concentration levels based on an acceptable level of risk. The USEPA has not defined a generally acceptable cancer risk level for HAPs. However, a case-specific determination was made in the 1989 Benzene National Emission Standard for Hazardous Air Pollutants (NESHAP). This rule set an upper limit of acceptability of 1 in 104 lifetime cancer risk for highly exposed individuals and the goal of reducing lifetime risk to 1 in 106 for the general public.

In addition to the chemical pollutants that have available health-based concentration standards, there are several contaminants of emerging concern with comparably limited toxicity data. These include the following pollutants: SVOCs that are HAPs/TACs with no available health-based standards; SVOCs that are not HAPs/TACs including pesticides and brominated fire retardants; short-lived products of indoor secondary organic aerosol (SOA) chemistry; and ultra fine particles (UFPs). Since the toxicological and epidemiological data are as yet insufficient to set standards for these compounds, there are no safe levels established.   Moving forward standards may be developed based on additional data or novel method of assessing toxicity.

4.3 HAZARD ASSESSMENT OF INDOOR POLLUTANTS

A hazard assessment compares typical exposure concentrations to existing standards or guidelines to identify which compounds present a potential hazard. Logue et al (2011a) conducted a hazard analysis of indoor air pollutants in the residential environment. Summary results were compiled from published studies and used to calculate representative mid-range and upper-bound concentrations relevant to chronic exposures for over 300 pollutants and peak concentrations relevant to acute exposures for a few pollutants.

For over 100 pollutants, measured concentrations were compared to available chronic and acute health-hazard standards and guidelines from the U.S. Environmental Protection Agency (USEPA), California Office of Environmental Health Hazard Assessment (OEHHA), the U.S. Occupational Safety and Health Administration (OSHA), the Agency for Toxic Substances and Disease Registry (ATSDR), and the World Health Organization. Fifteen diverse pollutants were identified as potential chronic or acute health hazards for many homes.

A subset of pollutants were identified as priority chemical pollutants based on the prevalence of the pollutant in homes and the quality of available measurements in homes. Table 5 lists the identified priority hazards.

Table 5: Pollutants that potentially pose an adverse indoor health risks

PRIORITY POLLUTANTS FOR CHRONIC EXPOSURE	POTENTIAL ACUTE EXPOSURE CONCERNS
Acetaldehyde	Acrolein
Acrolein	Chloroform
Benzene	Carbon Monoxide
Butadiene, 1,3-	Formaldehyde
Dichlorobenzene,1,4-	NO_2
Formaldehyde	$PM_{2.5}$
Naphthalene	
NO_2	
$PM_{2.5}$	

A hazard assessment can narrow down a large list of chemicals to a much smaller group of pollutants of concern. But within the list of identified pollutants, this method is not sufficient to rank the importance of these pollutants for the following reasons. Standards and guidelines do not represent uniform levels of health impacts or harms. In the case of Logue et al, the pollutants identified as potential hazards originate from a diverse set of sources including cooking, dry cleaning, pesticides, combustion, and infiltration from outdoors. There is not a universal approach to address them all and no method for quantifying the benefits of reducing the concentrations to non-hazardous levels.

Figure 4: Cooking is a source of pollutants identified as potential hazards

4.4 CUMULATIVE RISK ASSESSMENT

Burden of Disease BoD

There has long been interest in identifying what drives population health impacts to identify which diseases/health issues are the most damaging to a population and prioritize those diseases for remediation. Burden of Disease (BoD) studies aggregate the rates of illnesses and associated harm in populations based on actual disease incidence rates and Cumulative Risks Assessments (CRA) attempt to use statistical comparisons of populations exposed to a certain hazard versus those not or available scientific data on disease causes to assign harm to specific causes. BoD studies use available statistics to determine the disease incidence rate as a function of age, sex, and geographical location. They then assigned a harm value for all outcomes using the same metric based on the severity of the outcome so that comparisons can be made between outcomes. BoD analyses go from illness to harm. CRA analysis take this a step further to go from harm to sources of harm on a population basis.

The metric DALY

The World Health Organization (WHO) conducts the most comprehensive worldwide BoD analyses. The WHO compiles disease incidence data for all communicable and non-communicable diseases and injuries to determine the total number of Disability Adjusted Life Years (DALYs), the common metric of harm, lost per year for 192 countries (WHO 2009). The Disability Adjusted Life Year (DALY) metric is a powerful tool for quantifying and inter-comparing the damages from health endpoints that can result from specific pollutant intake. DALYs quantify overall disease damage including both mortality and morbidity. DALYs are the equivalent years of life lost to illness or disease and include years of life lost (YLL) to premature death and equivalent life years lost to reduced health or disability (YLD).

$$DALY = YYL + YLD \tag{1}$$

Several authors have determined the DALYs lost per incidence of specific diseases using the preeminent work of Murray and Lopez (Murray and Lopez 1996a; Murray and Lopez 1996b; Lvovsky et al. 2000; Huijbregts et al. 2005; WHO 2009). Multiplying a disease incidence rate by a “damage factor” yields a rate of lost DALYs per disease incidence.

$$DALYs = \frac{Damage}{Disease\ incidence} * Disease\ Incidence \tag{2}$$

Damage rates multiplied by available disease incidence statistics, integrated over all diseases of interest, are often used to determine the total burden of disease in a community.

Several studies have tried to apportion the identified risks to specific causes using CRA. McKenna et al. (2005) aggregated United States' mortality and morbidity data to determine the top 20 causes of DALY losses for men and women in 1996. Ezzati and Lopez (2004) estimated the total DALYs lost from smoking and tobacco use in industrialized nations by determining the impact of disease beyond what would be expected in non-smoking homes. CRA type analysis have also been conducted at the national level to apportion diseases to sources. Two examples include the analyses of the impacts of Radon (EPA 2003) and SHS (Cal EPA 2005) on those exposed.

Cumulative risk assessment CRA

CRA analysis of indoor air have predominately focused on the impacts of household solid fuel use in low-income countries with the exception of the 2 CRA bases analyses conducted in Europe as part of the EnVIE Study (de Oliveira et al. 2004) (Jantunen et al. 2011a) and 1 CRA conducted on the impacts of inadequate housing by the World Health Organization (WHO 2011). The EnVIE study aggregated the impacts of diseases that are impacted by exposures, identified the dominant pollutant exposure causing the disease, and apportioned the disease to indoor air impacts based on the relative indoor/outdoor exposure contributions. Their approach identified, on a population level, the burden associated with specific indoor pollutant sources for EU countries. Their results allowed for the ranking of sources and pollutant exposures based on health impacts. Their results indicate that combustion products, bioaerosols and VOCs dominate the health impacts due to indoor air in the EU on a population basis. These studies allowed for solid population level policy suggestions for improving population health. The WHO identified the burden of inadequate housing in the EU (WHO 2011). They identified 13 main drivers of the health burden associated with inadequate housing. The identified drivers that are impacted by ventilation include mould, dampness, second hand smoke, carbon monoxide, and formaldehyde.

4.5 IMPACT ASSESSMENT EXPOSURE

Impact assessment analyses differ from BoD and CRA analyses in that they go from exposure to illness to harm. The method for going from illness to harm is the same as those for BoD analyses (the metrics of harm may vary), however instead of taking the disease rate from available health statistics, impact assessment estimates the rates of disease based on the known levels of exposure using available health based data linking exposures to health outcomes. Existing impact assessments have relied on epidemiology and toxicology based studies, however as in-silico and in-vitro based assessments progress, there is the possibility to include these types of studies in health based assessments in the future. The US EPA has conducted several large scale impact assessment studies as part of the cost benefit analyses of the US clean air act that limited the allowable outdoor concentrations of 6 criteria pollutants (EPA 1999). A large number of studies have followed in this tradition to assess life cycle impacts and costs and benefits associate with changes in outdoor concentrations (Gilmore et al. 2006; Gilmore et al. 2010; Amin 2014; Song 2014; Wei et al. 2014). Fewer studies have applied this methodology to indoor air. One possible reason is that outdoor analyses focus on criteria pollutants that have a large body of available literature for health impacts associated with exposure and a methodology outlined by previous EPA work. In the indoor environment, there are significant concerns about VOCs which have less available data for health impacts. Additionally, there are few studies that have linked changes in indoor concentrations with changes in population health outcomes. Predominantly studies, such as those included in Appendix 2, compare outdoor changes in concentration with changes in health outcomes. Changes in outdoor concentrations are not directly linked to changes in exposure which occur predominately indoors.

A given outdoor change in concentration may result in a much lower change in exposure in a protective environment. The resulted concentration-response functions develop relationships between outdoor concentration changes and indoor exposures which may underestimate the burden of changes in indoor concentration which are more closely linked to changes in exposure. Despite these issues, researchers have applied impact assessment methodologies for assessing the health impacts of chronic and acute exposure in homes. An example of one such analysis is included below.

4.5.1 IMPACT ASSESSMENT OF CHRONIC RESIDENTIAL EXPOSURES

Logue et al. synthesized disease incidence and health damage models to develop a methodology for quantifying indoor air quality and then applied the methodology to calculate the population average health damage due to chronic inhalation of non-biological air pollutants in U.S. residences (Logue et al. 2011b). They compared estimates of current air pollutant intake in U.S. homes (using measurement based estimates of population-averaged, residential chronic exposure concentrations) to the theoretical case of a home with no pollutants. Aggregated concentrations-response functions from the literature were used to estimate the increase in disease rates expected due to residential exposures. Disease incident rates due to second hand smoke (SHS) and radon were taken from cumulative risk assessment data in the literature. Disease rates were multiplied by the expected DALYs lost per incidence of disease.

Figure 5 shows the damage in DALYs per year per 100,000 people from exposure to the 15 pollutants with the highest central estimate of damage. The whiskers indicate the aggregate uncertainty (95th percentile confidence interval) in the disease incidence and disease damage factors. Figure 5 shows the clear result of the analysis: on a population average, the most harmful pollutants in residential indoor air are $PM_{2.5}$, SHS, formaldehyde, acrolein, radon and ozone. The hazards of SHS and radon are more widely recognized and focused in a smaller fraction of homes. By contrast, $PM_{2.5}$, acrolein, and formaldehyde are present at substantial levels in most homes yet there may be less widespread recognition of these hazards.

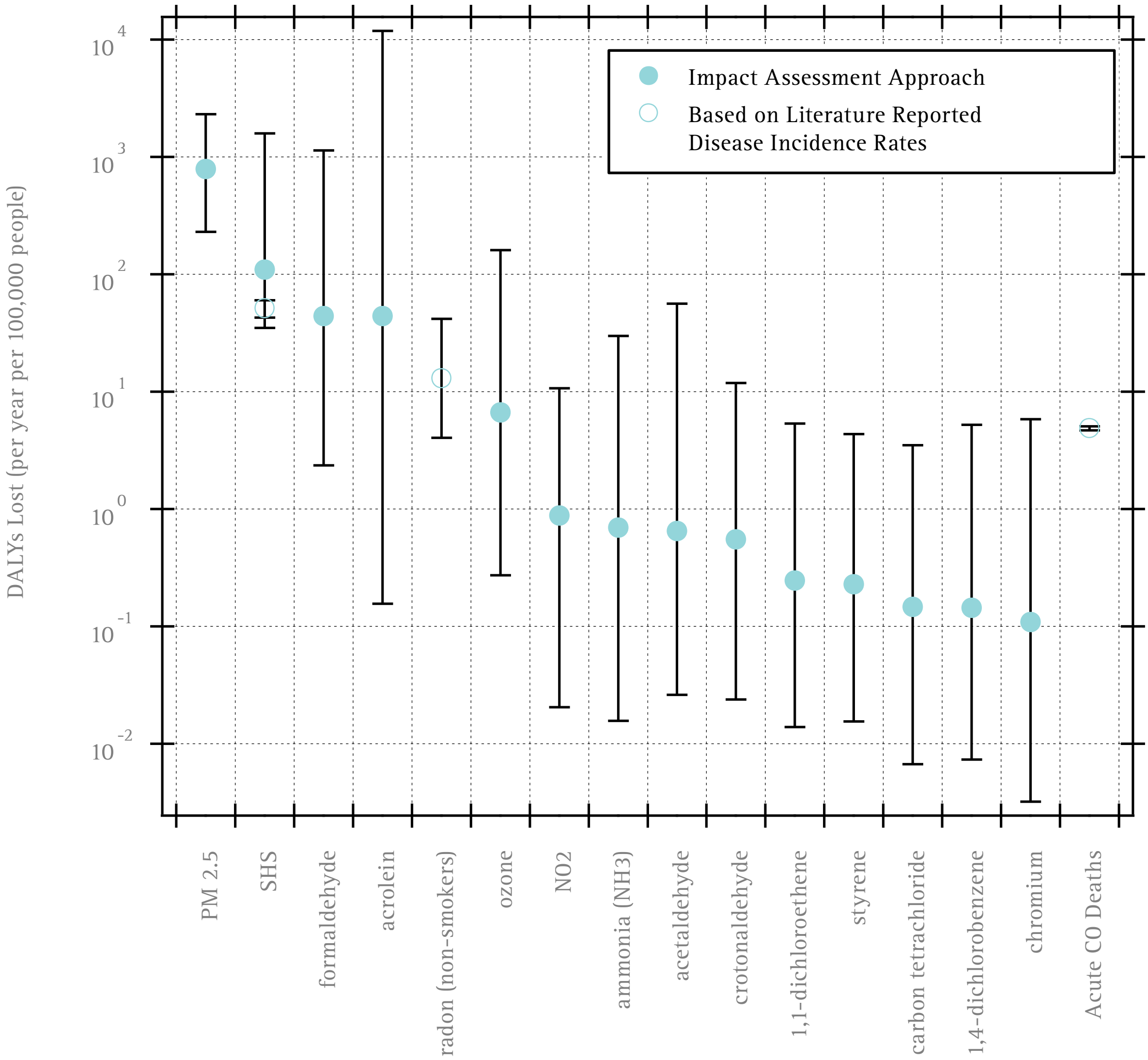

Figure 5: Estimated population averaged annual cost, in DALYs, of chronic air pollutant inhalation in U.S. residences; results for the 15 pollutants with highest mean damage estimates.

IAQ damage same magnitude as traffic and heart disease damage

This approach allowed for a clear ranking of pollutants for prioritization of removal as well as the ability to quantify and monetize the impacts of exposures in homes. Logue et al was also able to estimate that the current indoor air quality related heath damage to the U.S. population from all sources, excluding SHS and radon, is in the range of 4-11 mili-DALY/p/yr (mili-DALYs per person per year). This indicates that the damage attributable to indoor air is, comparatively, somewhere between the health effects of road traffic accidents (4 mili-DALY/p/yr) and all-cause heart disease (11 mili-DALY/p/yr) in the U.S. This study used the DALY metric of harm, however the metric of harm may be a currency (e.g. dollars or Euros) or lives lost or any other metric that is comparable between endpoints.

4.6 COST BENEFIT ANALYSES OF VENTILATION

Cumulative Risk Assessment and Impact assessments allow for the monetization of the impacts changes in the indoor environment. Extensive literature exists linking health outcomes to costs or damage metrics such as DALYS that have a direct cost equivalent. Cumulative risk assessment and impact assessment provide the missing piece of being able to link sources or exposures to disease outcomes. Being able to monetize the benefits of improvements in indoor air quality allows for the justification of costs of interventions. A well know examples of this for outdoor air is the assessments of the cost benefit analyses of the Clean Air Act (EPA 1999). For indoor air there have been several studies that have looked at specific interventions.

The World Health Organization has conducted global scale analysis of assessments of the costs and benefits of household energy use and health interventions (Hutton et al. 2006). Several studies have looked at interventions in the building stock of specific countries. Turner et al. (2013b) quantified the total costs and benefits of over ventilating and under ventilating compared to the US residential ventilation standard. Turner et al found that over-ventilation, assuming no outdoor sources, yielded health benefits exceeding associated energy costs. Logue et al. assessed the costs and benefits of range hood use in new California homes (Logue et al. 2014b). Once the exposure of concern is identified, cost-benefit analysis is an effective tool for identifying which interventions are the most cost effective.

4.7 THE IMPACT OF SPECIFIC SOURCES ON INDOOR CONCENTRATIONS

Specific pollutant sources in the indoor environment are associated with substantial changes in indoor concentrations of pollutants. Identifying important sources of pollutants can help to assess what mitigation tools are most appropriate to reducing concentrations. This sections will address two sources of indoor pollutants: natural gas appliances and infiltration of outdoor pollutants to illustrate the impact of indoor sources on concentrations. However, these two cases are by no means an exhaustive list of sources that impact indoor concentrations.

4.7.1 IMPACTS OF NATURAL GAS APPLIANCES ON INDOOR CONCENTRATIONS OF NO_2 AND CO

Unvented natural gas combustion emits air pollutants that can affect indoor concentrations and increase health risks. While most home heating systems are designed to safely vent pollutants to the outdoors, natural gas cooking and the use of unvented fireplaces can release pollutants into the occupied space (Dutton et al. 2001, Logue et al. 2014). Natural gas cooking is common in the United States

Natural gas is a common cooking fuel in the US and can be found in unvented fireplaces. Unvented indoor combustion of natural gas is a significant source of nitrogen dioxide (NO_2), carbon monoxide (CO) and other pollutants. In residences natural gas is used for cooking and can be used in unvented fireplaces. At elevated ambient concentrations, NO_2 has been associated with exacerbation of asthma (Hajat et al. 1999) and an increase in daily deaths (Touloumi et al. 1997). At higher concentrations, NO_2 has been found to increase the sensitivity to allergens in asthmatic patients (Tunnicliffe et al. 1994). Increased indoor NO_2 concentrations from gas cooking have been associated with adverse health effects such as wheezing and decreased respiratory function (Jarvis et al. 1998).

Carbon Monoxide CO a killer

Many studies have examined natural gas appliance-related concentrations of NO_2 (Spengler et al. 1994; Yang et al. 2004) and CO (Akland et al. 1985; Fortmann et al. 2001) in homes. The older studies sampled in homes with appliances that were different from contemporary appliances and therefore may have had different emission factors . A recent study measured concentrations in California homes (Mullen et al. 2012). During November 2011 through March 2012, pollutant levels were measured over 6-day periods in 155 homes, mostly in Northern California (Mullen et al. 2012). Among 117 homes that reported cooking with a gas appliance at least once during sampling, the time-integrated measurements had a fitted NO_2 geometric mean (GM) (geometric standard deviation (GSD)) of 22.6 $\mu g/m^3$ (4.1) in the bedroom and 28.2 $\mu g/m^3$ (4.3) in the kitchen. Time-integrated outdoor NO_2 levels in the measurement study had a GM (GSD) of 26.5 $\mu g/m^3$ (3.4). Valid time-resolved CO data were available for 116 of the homes in the measurement study. The GM (GSD) of the highest 1-hour CO was 3500 $\mu g/m^3$ (4800). Highest 1-h CO levels in the simulation homes had a GM (GSD) of 4800±183 $\mu g/m^3$ (3000±130). Highest 1-h CO due only to the gas burner emissions had a GM (GSD) of 3000±160 $\mu g/m^3$ (4800±260). The only US study of peak NO_2 concentrations that we identified in the literature (Fortmann et al. 2001) reported peak NO_2 concentrations during cooking that ranged from 75 to 280 $\mu g/m^3$ based on a single unvented stove. Logue et al (2014a) modeled NO_2 and CO exposures in homes with gas stoves in southern California. They estimated that in homes using natural gas cooking burners without coincident use of venting range hoods, 62% and 9% of occupants are routinely exposed to NO_2 and CO levels that exceed acute US health based standards and guidelines. Unvented natural gas cooking burner use increased the sample median of the highest simulated 1-hr indoor concentrations by 190 $\mu g/m^3$ and 3400 mg/m^3 for NO_2 and CO, respectively compared to not cooking.

Studies of unvented natural gas fireplaces in the U.S. have indicated significant accumulation of pollutants in home that use the devices for prolonged periods. Monitoring in 2 homes in Colorado indicated a 670 $\mu g/m^3$ concentration of NO_2 and CO concentrations greater than 144 mg/m^3 during prolonged use (Dutton et al. 2001). Unvented natural gas fire places are common in the U.S. but may not be common in other countries. Unvented ethanol fireplaces are becoming common in many countries and also present similar indoor air quality concerns (Schripp 2014). Equipment failures, such as backdrafting (i.e. when naturally vented combustion appliances spill into the home), is also a concern (Nagda et al. 1996). The identification of natural gas combustion appliances as major sources of concern for NO_2 and CO exposure allows for control technologies designed to cost effectively minimize the impacts of these pollutants such as task ventilation for cooking and sealed or well vented combustion for heating and cooling.

4.7.2 IMPACTS OF OUTDOOR POLLUTANTS ON INDOOR CONCENTRATIONS

Indoor/outdoor

Outdoor air is a major source of indoor pollutants. Building leakage, natural or mechanical ventilation air inlets and window and door opening allows for outdoor air to enter the home along with pollutants originating outdoors. The impact of outdoor concentrations of PM_{10} (particle mass with an aerodynamic diameter less than 10 microns), $PM_{2.5}$ (particle mass with an aerodynamic diameter less than 2.5 microns), and ultrafine particles (UFP <100 micrometers) have been explored in the literature.

Several studies have measured the ratio of the indoor concentration of $PM_{2.5}$ to the outdoor concentration in residences in the United States. This ratio is sometimes referred to as the infiltration ratio (Finf) in the literature. Due to large anthropogenic sources of sulfate in ambient air, outdoor $PM_{2.5}$ contains a significant fraction of ammonium sulfate. As indoor sources of sulfur are rare, and with the assumption that indoor loss mechanisms for the sulfur component of $PM_{2.5}$ are similar to those for infiltrated $PM_{2.5}$ as a whole, the ratio of measured indoor to outdoor sulfur content of $PM_{2.5}$ has been used to estimate Finf (Sarnat et al. 2002; Allen et al. 2003; Wallace and Williams 2005; Allen et al. 2012; Habre et al. 2014). The Relationship of Indoor, Outdoor, and Personal Air (RIOPA) Study (Weisel et al. 2005), the Detroit Exposure and Aerosol Research Study (DEARS) (Williams et al. 2009), the Multi-Ethnic Study of Atherosclerosis and Air Pollution (MA) (Allen et al. 2012), and Habre et al (2014) used this approach to estimate infiltration factors for multiple homes in distinct US cities. Allen et al (2003) used high time resolved data to extract indoor events to determine the ratio of indoor to outdoor $PM_{2.5}$.

Figure 6 shows data from these five studies. The RIOPA study apportioned indoor $PM_{2.5}$ to indoor and outdoor sources for the 300 homes in three US cities and found that, on average 56% of indoor $PM_{2.5}$ was apportioned to outdoor sources (Meng et al. 2005).

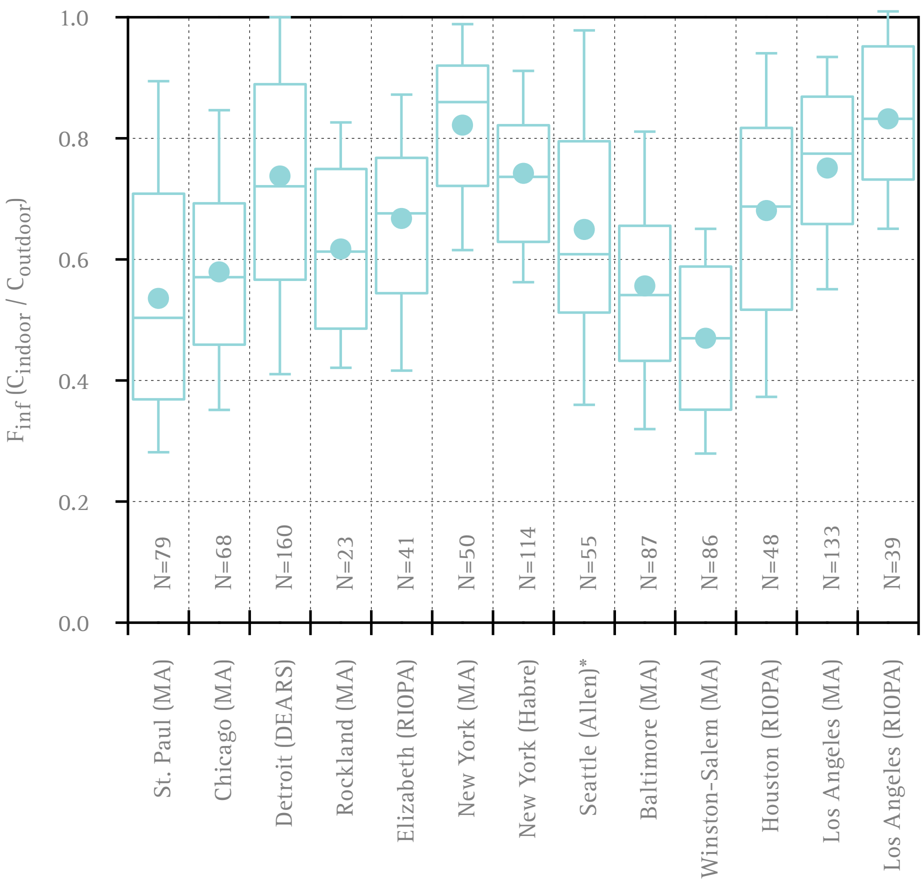

Figure 6: Comparison of measured infiltration factor (Finf) for $PM_{2.5}$. Data is from the Relationship of Indoor, Outdoor, and Personal Air (RIOPA) study, Detroit Exposure and Aerosol Research Study (DEARS) study, and Mesa Air (MA) study. Additional data was taken from two smaller studies Habre et al (2014) and Allen et al. (2003) Boxes span from 25th to 75th percentiles; the line inside the box is the median and the circle is the mean. Whiskers extend to the 10th and 90th percentiles.

Fine Particles

Modeling efforts have also been made to estimate $PM_{2.5}$ infiltration into homes (El Orch et al. 2014). Studies have also looked at PM_{10} infiltration into homes (Chen et al. 2012) and UFP infiltration (Stephens and Siegel 2012).

The impact of outdoor air on indoor concentrations of ozone (Walker and Sherman 2013), NO_2 (Baxter et al. 2007b) and CO have been also been studied in the indoor environment. Ozone and nitrogen dioxide are of concern when concentrations are elevated outdoors due to chemistry, outdoor sources, and meteorology. Carbon monoxide (CO) is a pollutant of major concern in the indoor environment due to indoor sources. Less focus is put on CO as a pollutant that infiltrates into the home from outdoors. Outdoor CO is typically of concern due to the use of high CO emitting combustion devices, such as generators or idling cars, located within or in close proximity to a home (Emmerich et al. 2014). Outdoor concentrations of VOCs tend to be lower than indoor concentrations for pollutants identified as potential health concerns (Logue et al. 2009). Individual point sources such as dry cleaners or bus depots may elevate VOC concentrations locally.

The identification and characterization of outdoor sources of pollution is critical for developing ventilation strategies that remove indoor pollutants, and at the same time do not bring in adverse amounts of outdoor pollutants.

4.8 OVERVIEW OF PRIORITY POLLUTANTS

The findings of the ENVIE Study as well as the Logue et al. point to six priority pollutants in the indoor environment for chronic exposures that are impacted by ventilation. Environmental tobacco smoke (ETS) and radon are predominantly impacted by home characteristics and occupant behavior and should not be considered in establishing ventilation standards. The remaining 4 pollutants that drive chronic health risks as shown in Table 6. The World Health Organization (WHO) and the ENVIE study both identified mould /moisture as significant chronic health burden in the indoor environment (WHO 2011, de Oliveira 2004). Since ventilation impacts moisture conditions in homes, mould/moisture has been included in Table 6 as a priority pollutant to consider when setting ventilation standards.

Chronic and acute effects

Less information is available allowing for the prioritization of acute exposures. Studies that have assessed acute exposures have predominately looked at a single source for a short period of time. Table 6 includes list of priority acute hazards, but they cannot be ranked with current information. Pollutant control strategies should focus on reducing exposures to these priority pollutants.

With the exception of known multi-pollutant exposures that have adverse health impacts (e.g. ETS), existing toxicology and epidemiology based prioritization tools only focus on individual pollutants. The World Health Organization (WHO 2013) identified the need to develop tools that address the impacts of pollutant mixtures. These tools may increase the pollutants that should be considered when developing a health based ventilation standard.

Table 6: Priority pollutants in the indoor residential environment for consideration in making ventilation standards

PRIORITY POLLUTANTS FOR CHRONIC EXPOSURE (RANKED BY POPULATION IMPACT)	POTENTIAL ACUTE EXPOSURE CONCERNS
Particulate matter	Acrolein
Mould/ moisture	Chloroform
Formaldehyde	Carbon Monoxide
Acrolein	Formaldehyde
	NO_2
	$PM_{2.5}$

5
IDENTIFICATION OF POTENTIAL HEALTH OUTCOMES

Long term diseases

The major cause for concern with indoor pollutants is that those exposures will result in adverse health effects for occupants. The health impacts of exposures have typically been viewed based on the duration of exposure. Chronic exposures indicated exposures over a lifetime and are often associated with cancer or other long term diseases such as chronic obstructive pulmonary disease (COPD) or heart disease. Acute exposures are those that take place over a limited time frame, typically on the order of hours or days, and are typically thought to trigger specific adverse health events such as a stroke or asthma attack.

There are far more pollutants in the indoor environment than those for which we have health impacts data. Two major ways that health impacts associated with exposure have been assessed are via epidemiology and toxicologically based studies. Epidemiology based studies have looked at changes in concentrations, predominately due to natural variations in pollutant concentrations or retrospectively at an incident or accident that lead to a high exposure, and develops statistical relationships between changes in concentrations and changes in health outcomes on a population bases. Toxicological studies expose animals to high levels of pollutants, identify the health outcomes from those pollutant exposures, and use conversion factors to estimate the impact on humans. Most standards or guidelines for allowable concentrations have been derived from either toxicological or epidemiological assessments of health impacts. In addition to these more traditional methods of assessing health impacts, in recent years scientists have been using computational tools (often referred to as in-silico assessments) and in-vitro studies to assess potential toxicity. One major example of computational tools used for toxicity assessment are quantitative structure-activity relationship (QSAR) models. QSAR models can predict the potential toxicity of a compound based on the physiochemical and/or structural properties of the compound based on previous studies of similar compounds (Benigni et al. 2003; Morales Helguera et al. 2008; Matt et al. 2011; Rusyn et al. 2012). QSAR approach is recognized by the European Union Registrations, Evaluation, Authorization, and Restriction of Chemicals (REACH) program as method of screening chemicals that are manufactured or shipped into Europe by industry for health and environmental impacts. In-vitro studies assess the impacts of exposures on a cell or cell components instead. Several in-vitro assays (Bradley et al. 1981; Dey et al. 2012;(Rogakou et al. 1998; Redon et al. 2011) have been developed to assess mutagen city and genotoxic potential of compounds.

This section will present a review of what is currently known about the toxicity of indoor pollutants predominately based on epidemiological and toxicological findings. The relative importance of in-vitro and in-silico assessments of toxicity and potential harm will likely continue to gain more prominence but is not included in this Technote because significant additional research is needed to use these tools to assess indoor air quality. This section focuses on subsets of pollutants based on volatility or legal classification. Some pollutants such as tobacco smoke are chemical mixtures including pollutants from several different classes. Tobacco smoke contains about 5,000 contaminants, many of which are toxic causing cancer, asthma attacks and allergic reactions, damaging cells (DNA) and being strong irritants. The impacts of chemical mixtures are not explored in this document.

5.1 HEALTH OUTCOMES ASSOCIATED WITH CRITERIA POLLUTANTS

Negative health effects

The U.S. Environmental Protection Agency (USEPA) identified six pollutants as criteria pollutants in the 1970 Clean Air Act: carbon monoxide (CO), nitrogen dioxide (NO_2), ozone, particulate matter (PM), lead, and sulfur dioxide. PM is typically categorized by size with PM_{10} indicating particles less than 10 microns and $PM_{2.5}$ indicating particles less than 2.5 microns in aerodynamic diameter. These six pollutants were shown to have strong associations with negative health and environmental impacts. Except for lead, these criteria pollutants impact indoor air.

5.1.1 HEALTH OUTCOMES ASSOCIATED WITH CHRONIC EXPOSURE

Several authors have used statistical methods to assess relationships between population changes in long term health outcomes with population changes in outdoor concentrations. Chronic $PM_{2.5}$ exposure affects both the respiratory and cardiovascular systems. Pope et al. (2002) predicted incidence rates of all-cause mortality and the average years of life lost per unit increase in $PM_{2.5}$ (Pope et al. 2009). Recent studies have shown that chronic $PM_{2.5}$ exposure can lead to heart disease and thickening of arterial walls (Künzli et al. 2004). $PM_{2.5}$ exposure has also been associated with chronic bronchitis (Abbey et al. 1995) and non-fatal stoke (Brook et al. 2010). The total impact of $PM_{2.5}$ on cardiovascular health is not known. However, recent work by Miller et al. (2007) has shown associations between chronic $PM_{2.5}$ and stroke, an outcome of heart disease, in women. There is evidence that $PM_{2.5}$ exposure is associated with other health outcomes including diabetes and reduced lung function; however, these findings are relatively new and have not been well established. Carbon monoxide (CO) has typically been associated with acute exposures such as CO poisoning deaths, however there is growing concern about possible chronic health effects at levels not previously identified as harmful (Ashley et al. 2005). Chronic ozone and NO_2 exposure have been associated with early death (Samet et al. 1997; Jerrett et al. 2010) and respiratory illness respectively (Hasselblad et al. 1992).

5.2 HEALTH OUTCOMES DUE TO ACUTE EXPOSURES

There are several statistical models used to assess health impacts associated with acute exposures. Initial assessments of the relationship between extremely high exposures during air pollution episodes and illness were easily determined due to rapid and critical outcomes such as death or respiratory problems on a large scale. In homes, high acute exposures to CO have been unequivocally linked to mortality (CDC 2007).

The acute impacts of non-fatal exposures to pollutants are more difficult to determine especially if only a subset of the population is affected. As outdoor concentrations have decreased due to increased regulation, statistical tools became necessary to characterize these relationships (Carracedo-Martinez et al. 2010). Initial large-scale assessments of population impacts of changes in outdoor pollutant concentrations on health used predominantly Poisson regression-based assessments, either parametric or nonparametric, that linked changes in outdoor concentrations to changes in population health outcomes. Poisson-based approaches fit data on exposures and outcomes to a Poisson distribution, a discrete probability distribution that expresses the probability of an outcome independent of the time since the last event. Poisson models, however, have limitations in determining the correct degrees of freedom, which can lead to significant bias. The case-crossover design (CCO), initially proposed by Maclure (1991), by virtue of its design eliminates problems with confounding by personal factors that remain constant within each subject. CCO uses the principles of the more traditional matched pair case-control design, except that instead of comparing pairs of one "case" person and another "control" person matched on key confounding variables, in a CCO design the case and control information come from the same person but at different times. In the CCO, the same person has different exposure levels measured at different times and thus can be used to study effects of acute, time-varying exposures, whereas in a case-control study, each case or control is assigned only one exposure level. Appendix 2 includes tables of studies of the acute health impacts of PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO, and ozone exposure, among others. These studies found a measurable change in the indicated morbidity/mortality outcome within a studied population, as a function of short-term (acute) changes in outdoor concentrations. As Appendix 2 shows, acute exposures are often related to hospital admissions for a variety of causes predominately due to cardiac and respiratory issues. These tables are not all inclusive and several more studies exist linking health outcomes with exposures using both these and alternative statistical models. As Tables A3 and A4 show, acute exposures are often related to hospital admissions for a variety of causes predominately due to cardiac and respiratory issues.

Mortality and morbidity

Exposures to particles are expected to result in changes in morbidity and mortality related to exacerbation of asthma and allergy problems, particularly in case of exposures to pollens and allergens. The acute health symptoms include asthma attacks, cardiovascular or respiratory hospitalizations or emergency visits.

The main health outcomes of interest associated with nitrogen oxides (NO_x) including both nitric oxide (NO) and nitrogen dioxide (NO_2) include respiratory symptoms, bronchoconstriction, increased bronchial reactivity, airway inflammation, and decreases in immune defense leading to increased susceptibility to respiratory infection.

Ozone is harmful for health and exposure to ozone creates risk for a variety of symptoms and diseases associated with the respiratory tract (Koren et al. 1989; Touloumi et al. 1997; Bell et al. 2004).

There are no scientific data showing that exposures to pure CO_2 below 9,000 mg/m^3 will cause negative effects on health; the short exposures up to 18,000 mg/m^3 are neither related with the risk for health (Zhang et al. 2015). There are some limited data that imply that CO_2 levels of 4,500 to 7,200 mg/m^3 can cause negative effects on some aspects of cognitive performance such as decision making or proof-reading (Kajtar and Herczeg 2012; Satish et al. 2012).

Ozone reacts with human skin oils (lipids) on body surfaces. Clothes or skin flakes can produce unwanted contaminants such as carbonyls, dicarbonyls and hydroxycarbonyls which are potentially strong skin and respiratory irritants (Wisthaler and Weschler 2010).

Carbon monoxide is particularly toxic. It can cause so-called carbon monoxide poisoning leading to death and numerous chronic diseases including low birth weight, congenital defects, increased risk of cardiovascular morbidity, asthma, neurological deficits.

5.3 HEALTH OUTCOMES ASSOCIATED WITH AIR TOXICS AND VOCs

Volatile organic carbons (VOCs) are carbon containing compounds that have low enough volatility that they evaporate under normal atmospheric conditions. Air toxics are a set of 187 chemical pollutants identified by the 1990 clean air act as potentially harmful to human health. A large fraction of air toxics are VOCs, but air toxics also include metals, refrigerants, and chlorinated compounds among others. Organic compounds emitted by building materials and furnishing can cause sensory discomfort due to unwanted odours as well as sensory irritation. The exposure has been shown to produce also other acute health effects such as headaches or problems with concentration and fatigue. The contaminants emitted can also cause allergic reactions.

Formaldehyde causes sensory irritation, odour and asthma attacks but has also been classified as carcinogen (nasopharyngeal cancer). Trichloroethylene is suspected of different types of cancer especially kidney and liver. Tetrachloroethylene is expected to cause irritation of mucous membranes, effects on kidneys and liver. Polychlorinated biphenyls (PCBs) and polybrominated diphenyl ethers (PBDEs) are expected to be toxic (endocrine disruptors) and to cause cancer. Benzene and PAHs can cause cancer (benzene blood –leukemia and PAHs lung cancer).

The predominate data on health impacts of VOCs and air toxics come from toxicology studies or historical occupational or accidental exposures. The US EPA maintains a database of toxicicity and epidemiology based studies that have been used to develop guidelines for safe exposures. This database is the Integrated Risk Information System (IRIS) (www.epa.gov/iris/). For each air toxic, and some additional pollutants, the database aggregates all reviewed studies that have been used by the EPA to make decisions about human health impacts from ingestion, inhalation, and dermal exposure. Other standard and guideline publishing organizations, including the World Health Organization (WHO) and the California Office of Environmental Health Hazard Assessment (OEHHA, www.oehha.ca.gov/tcdb/index.asp), publish extensive documentation about existing health studies that are used to set standards and guidelines. It is beyond the scope of this document to address all of the potential outcomes of exposure to air toxics and VOC exposures. The dominant concerns for chronic inhalation are grouped broadly into “cancer” and “non-cancer” risks by most standard/guideline setting bodies. Both chronic cancer and non-cancer impacts have been associated with all major organ systems and the specific outcomes are pollutant specific.

Acute exposures to VOCs and air toxics are predominately associated with irritation and respiratory problems. As an example, Table 7 includes a list of outcomes summarized by OEHHA for the minimum concentration/ exposure duration associated with specific types of irritation due to formaldehyde and acrolein (2 air toxics and VOCs) from laboratory based exposure/response experiments. These concentrations are relatively high and will not typically be reached in non-industrial environments. Table 7 is meant purely as an example of the type of data available. Similar data is available for other air toxics in existing publications of rule making and in databases such as IRIS.

Table 7: Thresholds for specific irritation outcomes of exposure to select aldehydes (formaldehyde and acrolein) (OEHHA 2008) (1ppm formaldehyde=

POLLUTANT	OUTCOME	CONCENTRATION (MILIGRAMS/ M^3)	EXPOSURE DURATION
Formaldehyde	Eye irritation and olfactory symptoms	0.6	Instantaneous
	Conjunctival irritation	1.9	Instantaneous
	Blinking frequency	1.9	Instantaneous
	Eye irritation	2.3	35 mins
	Nose irritation	2.3	35 mins
	Increased eye blinking	3.2	35 mins
	Throat irritation	3.9	35 mins
	Odour sensation	1.9	3 hours
	Eye irritation	1.9	3 hours
	Eye/nose/throat irritation	1.3	Instantaneous
Acrolein	Eye/nose/throat irritation	0.7	1.5 mins
	Severe lacrimation and irritation of the Mucous membranes of the respiratory Tract	7	Instantaneous
	Eye irritation	0.1	Instantaneous
	Eye irritation	0.2	Instantaneous
	Nasal irritation	0.6	Instantaneous
	Depression of respiratory rates	1.4	Instantaneous
	Eye/nasal irritation	0.7	20 mins

5.4 HAZARDS ASSOCIATED WITH MOULD AND MOISTURE IN RESIDENTIAL BUILDINGS

Water (moisture) is not harmful to health per se, but the excessive moisture indoors can result in the presence of contaminants and allergens with potential health impacts.

Germination of moulds depend on the surface type (which need to provide sufficient substrate), availability of nutrients, temperature and moisture. When germination is occurring, mould spores can enter the air can cause allergic reactions in form of bronchial asthma, runny nose or other symptoms. Mould spores and particles containing moulds, even when dead, can still emit toxic chemical compounds so called mycotoxins. Moulds can also emit metabolic volatile organic compounds (mVOCs), which are secondary metabolites producing musty odour typical for houses where moulds are suspected. Exposure to mVOCs can cause immune system activation.

Moisture on surfaces and in building structures (moisture in the building structure can be the result of poor construction process) can cause hydrolysis reactions causing decomposition. Example of such process includes di-2-ethylhexyl phthalate (DEHP) from PVC flooring hydrolyzing on a moist concrete, which produces 2-ethylhexanol, having mild odour though potentially causing strong irritation. Hydrolysis can produce aldehydes, alcohols and monoesters (carboxylic acids), which can contribute to odour problems and irritation.

5.5 POTENTIAL HAZARDS ASSOCIATED WITH EXPOSURE TO SEMI-VOLATILE COMPONENTS IN RESIDENTIAL BUILDINGS

Semivolatile organic compounds (SVOCs) are compounds that have higher boiling points and lower volatility than VOCs. Unlike VOCs, whose main path of exposure is inhalation, dermal uptake and ingestion are also thought to be important exposure pathways for SVOCs. SVOCs typically have boiling points in the range of 240-400°C and are found in a wide variety of consumer products including flame retardants in furniture, plasticizers and consumer products.

SVOC’s and ventilation?

SVOCs have a high boiling point, but can partition to the air at low concentrations. Once in the air, SVOCs can stick to walls and surfaces, including human skin and dust. SVOCs with large molecular weight and low vapor pressures tend to predominate on surfaces and in and research has indicated that dermal uptake may be on par or greater than inhalation for specific SVOCs (Weschler and Nazaroff 2012). Even removing the initial source from an environment may leave behind substantial reserves of the pollutant on walls and surfaces. Due to these reserves, SVOCs can persist in the indoor environments for long periods of time. The focus of this chapter is ventilation and indoor air pollutants. As shown by Parthasarathy et al. (2012), ventilation is not a good tool for controlling SVOCs in the indoor environment given their low airborne concentrations. We include a brief discussion of their health impacts here, however source control and source removal are the only potential control options currently for this class of pollutants.

SVOCs have been detected in both indoor measurements of air and dust, but also in body burden studies indicating that these compounds are present in human blood and urine (2008). The health outcomes of SVOCs exposures are varied and not known for may compounds. Some SVOCs that have been identified as toxic are dioxins, and polybrominated biphenyls. There are concerns that SVOCs cause allergy symptoms, reproductive development problems, cancer, fetal and child development issues, and are endocrine disruptors (Shaw 2010). Endocrine disruptors mimic hormones in the body and interfere with the bodies normal functioning and development (Casals-Casas and Desvergne 2011; Schug et al. 2011). Some SVOCs that have been identified as endocrine disrupters include polybrominated flame retardants, phthalates, pesticides, and polycyclic aromatic hydrocarbons. Endocrine disrupters have been shown to contribute to cancer, diabetes, obesity, and infertility (De Coster and van Larebeke 2012). Additional information on the range of endocrine disrupting compounds, the evidence for their health effects, proposed mechanisms of action, and the difficulties of assessing the risks, is provided by Casals-Casas et al.(2011).

5.6 HEALTH OUTCOMES ASSOCIATED WITH BIOLOGICAL EXPOSURES

Mould, moisture and health effects

There are several types of biological exposures of concern in the indoor environment including infectious diseases, biological emission of mould in homes, pet dander and pest related allergens, viruses such as colds and the flu can spread though indoor air where they are protected from sunlight and large temperature fluctuations. The high population density in certain indoor environments, such as offices, increases the opportunity for viral spread. Li et al (Li et al. 2007) showed that ventilation has an impact on the spread of viruses and infections in office buildings, although a ventilation rate to protect against these health outcomes could not be determined. Mendell et al (2013) showed that increased ventilation reduced illness related absences in schools. Low relative humidity(RH) due to over ventilation in schools has also been associated increased respiratory infections (Alsmo and Alsmo 2014). Similar studies have not been conducted in the residential environment which tend to have, when normalized by space volume, larger indoor moisture emission rates. Maintaining appropriate levels of humidity in homes is a key aspect for providing good indoor air quality and is impact by ventilation rates.

Biological exposures due to mould and moisture have been associated with respiratory tract infections, bronchitis, asthma development and exacerbation, and allergies(2010; 2011). Biological exposures due to bed dander and dust mites have been associated with allergy outcomes. Bioeffluents have also been associated with irritation due to odours.

PART II: CONTROL STRATEGIES TO REDUCE HEALTH EFFECTS DUE TO INDOOR AIR QUALITY

6
CONTROL STRATEGIES

The primary purposes of ventilation in buildings are to provide a sufficient oxygen supply for the occupants and to remove any hazardous substances or noxious odours in the indoor air. For thousands of years societies have realized the need for ventilation for specific indoor tasks. The first efforts to provide intentional ventilation of residences is unknown, but was likely used to remove combustion gases from indoor heating and cooking such as introducing vents for fires.

Ventilation is provided to bring outdoor air indoors and to move indoor air, and its associated pollutant load, outdoors reducing indoor concentrations and occupant exposures. Ventilation additionally impacts indoor humidity (Moyer et al. 2001) and may impact the spread of airborne infections disease (Hodgson et al. 2009). Ventilation with outdoor air can also bring pollutants of outdoor origin into the home, potentially increasing exposures in highly polluted areas. This part of the Technote will describe the impact of ventilation on home indoor air quality, methods of providing ventilation, and ventilation standards.

Outdoor air brought indoors for ventilation must be thermally conditioned for occupant comfort. Unintentional ventilation can have a significant impact on home energy use (Logue et al. 2013a). Alternative strategies to ventilation should be considered to address indoor air quality issues when possible to reduce energy impacts and avoid pollutants from outdoor air. Because of this, this chapter will also discuss alternatives to ventilation for providing good indoor air quality.

6.1 IMPACTS OF VENTILATION ON INDOOR AIR QUALITY

The path of pollutant sources to health risk is shown in Figure 7 . The primary approach to minimize exposure should be to control the source. Ventilation should only be used to reduce exposure for the emissions that are considered unavoidable. Environmental tobacco smoke for instance, can be seen as an avoidable source in buildings, while radon can be controlled in most cases by design measures rather than by ventilation.

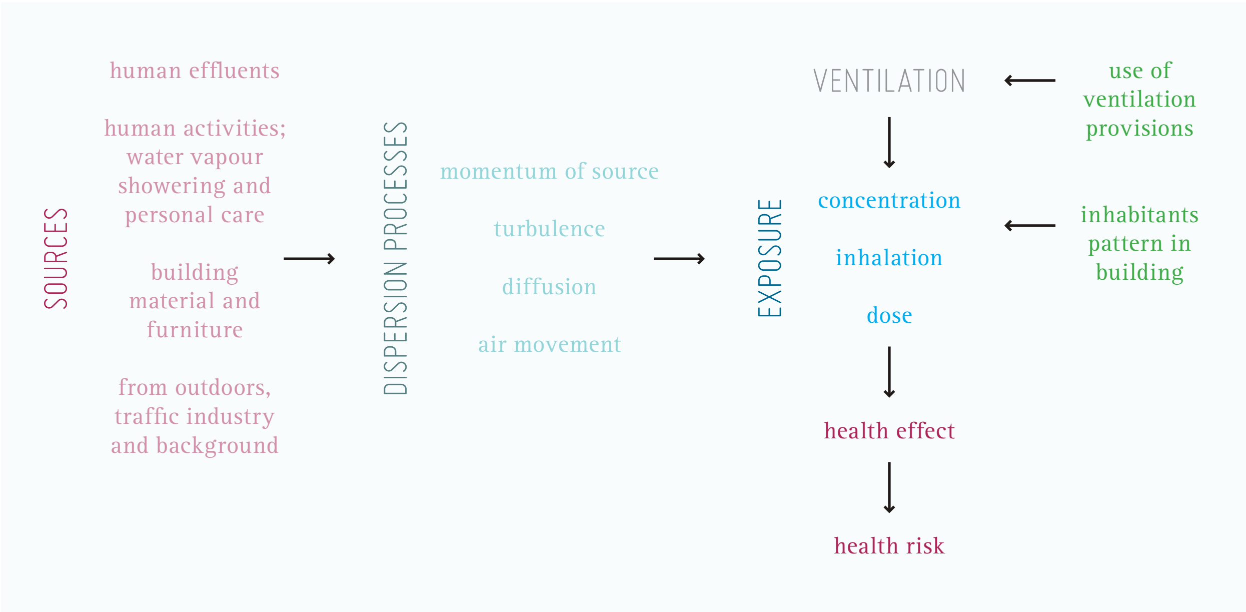

Figure 7: Path from pollutant to health risk (Gids 2012)

Ventilation is not a panacea for all IAQ problems!

The concentration in a room depends on the emission rate of the source, the dispersion processes in the room, contributions from outdoors, and potential loss mechanisms such as chemical losses or deposition. The resulting concentration in the breathing zone of the inhabitants depends on the dilution by ventilation.

Re-supending particles

Ventilation not only dilutes the pollutant but also may act as a transport media to disperse the pollutant over the indoor environment. Figure 7 shows that ventilation is important but absolutely not the only aspect that determines the health risk in buildings. The dispersion process is influenced by several factors: the momentum of the source gives the initial mixing, the turbulence of the source determines the amount of time it takes to mix the pollutant source through the room. Diffusion does not normally play an important role. There are some mechanisms not related to ventilation which may cause the dispersion of fine and ultrafine particles. A significant mass of particles are typically present on carpets or curtains in rooms. Several physical processes can re-suspend particles on surfaces including slamming doors, walking over carpets and the outlets of vacuum cleaners.

Figure 8: Vacuum cleaning can re-suspend particles

Total ventilation and ventilation's impact on concentrations is a function of occupant use of manually operated exhaust fans such as range hoods and use of windows and doors as a source of natural ventilation. Occupant exposure depends on home occupancy patterns. Dose is defined as the inhaled concentration multiplied by the exposure time. There is limited data only at the population level for dose-response relationships. Assessing the health impacts of ventilation on individual occupants or households is currently impossible. Section 4.6 includes a brief discussion on quantifications of the impact of ventilation on health.

6.2 TYPES OF RESIDENTIAL VENTILATION

6.2.1 VENTILATION PROCESSES

For a good understanding of the effectiveness of pollutant removal of different ventilation systems, some insight is needed in the four different flow mechanisms: perfect or complete displacement, perfect or complete mixing, local displacement and local exhaust (see Figure 9). The pollutant source is not indicated in this figures because there can be many types of sources which determine the final exposure of inhabitants.

Displacement ventilation is a form of balanced ventilation in which the supply air "displaces" rather than mixes with the room air. It is well adapted to rooms with high internal thermal sources

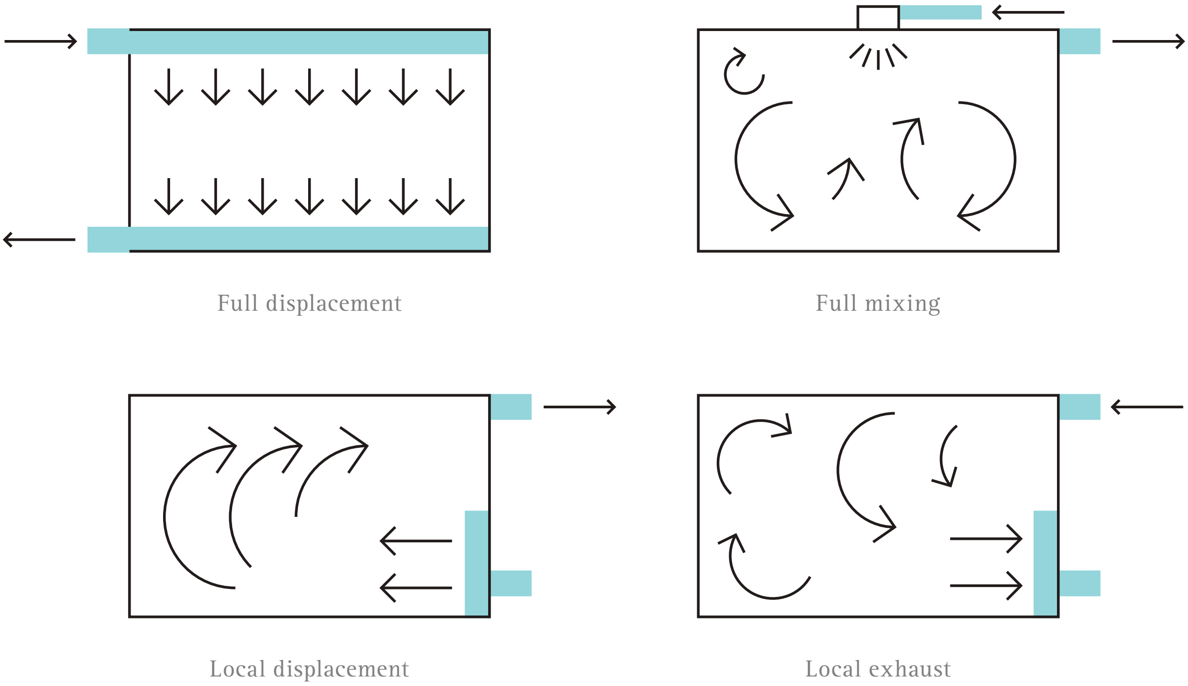

Figure 9: Examples of the four basic principles of ventilation: full displacement, full mixing local displacement and local exhaust

or with specific pollutants sources. Pre-conditioned air at 2-3 K below ambient room temperature is introduced to the space at low level and at very low velocity (typically 0.1 to 0.3 m/s). Perfect or complete displacement is mostly used in cleanrooms, hospital operation theatres and some industrial rooms. It is the most effective mechanism to control and prevent the spreading of pollutants. However, it is difficult to maintain the "designed" flow patterns in practice due to disturbances such as moving people and buoyancy driven flows.

Flow mechanisms and pollutant dispersion

In case of full, complete or perfect mixing, the air is introduced at a velocity that enables mixing with the ambient air thanks to the induction movements it creates. Any pollutant is then assumed uniformly distributed over the whole room. It reduces the contaminant level via dilution. Especially in buildings with low air exchange rates it can take considerable time before the air pollutant level returns to background level, because the pollution has been distributed over the whole room (Wierzbicka et al. 2014). In normal buildings, especially residential buildings, most ventilation systems tend to be close to perfect mixing.
Local displacement ventilation pushes the contaminant away from the breathing zone, as often used in personal ventilation appliances. If done effectively the contaminants will not be inhaled.

Local exhaust is a widely applied and effective mechanism since it is able to extract the contaminants close to the source and hence minimize the exposure.
The most applied example of local exhaust is in homes the range- or cooker-hood.

6.2.1 METHODS OF PROVIDING WHOLE HOUSE OR ROOM VENTILATION

The green AIVC guide

The guide to Energy Efficient Ventilation by the AIVC (Liddament 1996) gives an overview of applied ventilation systems. Different ventilation systems can be seen in Figure 10. For all ventilation systems care must be taken to make sure that provided outdoor air is clean. In polluted areas, air cleaning may be needed for outside air used for ventilation. WHO guidelines for indoor air quality: dampness and moulds gives an overview of whole house ventilation in relation to dampness and mould (WHO, 2009). It stresses not to only to focus on good ventilation design but also proper maintenance.

Adventitious ventilation can be characterized as an unintentional ventilation approach without specific provisions. There are many areas in the world where infiltration and exfiltration through imperfections in walls and roof construction delivers enough ventilation but in new airtight dwellings this is not possible. Natural ventilation by window airing is dependent on operable windows in the façade of the building. If windows in two opposite façades are opened, cross flow may occur. The flows can be relatively high due to wind effects. The high air velocities in the rooms can cause various comfort problems.

Natural ventilation or passive stack ventilation (Figure 10 A) has openings provided in the façade such as windows, vent lights, grilles and slits in habitable rooms that are designed to deliver sufficient outside air to the rooms. The height and control of these inlets is important to minimize draft problems. The use of these provisions is very important to reach acceptable indoor air quality levels. The exhaust is normally designed as passive ducting from the so-called wet rooms, such as toilet room, bathroom and kitchen directly to above room level. This solution effectiveness is influenced by inhabitant use of ventilation provisions depending on weather conditions (when it's cold for example, cold outside air may cause draught problems) The design should account for variations in driving forces, so that minimum flows can be realized during benign weather periods. Stack effect plays an important role, but for high wind speeds the wind dominates the flow.

Mechanical supply and natural exhaust systems (Figure 10 B) uses mechanical supplies in rooms combined with natural exhaust from the wet rooms. An important point of interest is that the dwelling is slightly over pressurized; hence this may lead to exfiltration through the building fabric with possible condensation and mould problems. An advantage of the mechanical supply system is that they are less influenced by weather conditions.

Natural supply and mechanical exhaust systems (Figure 10 C) are less dependent on the inhabitants where the extraction fan is designed and controlled in the right way. The mechanical exhaust is normally from the toilet, bathroom and/or kitchen. The air tightness level plays a role for this system. If inhabitants close or block the purpose provided inlet openings in the façade in very airtight dwellings, a too high under pressure may result in numerous comfort problems, such as noise and draught through unintended openings. Make up air design (air from other rooms) may overcome this problem. The energy in the extracted can be recovered. Only advanced in most cases demand controlled ventilation systems have this option applied.

The balanced system (Figure 10 D) has mechanical exhaust from the wet rooms and mechanical supply to habitable rooms. Balanced systems also allow for the inclusion of a heat or moisture exchanger to reduce the energy loss associated with ventilation. Such a system requires more extensive ducting, and filters are used to protect heat exchangers, which adds a maintenance activity that may be overlooked. This system requires a high level of air tightness since it is designed for balanced mechanical flows and any infiltration and exfiltration flow gives reduced heat recovery.

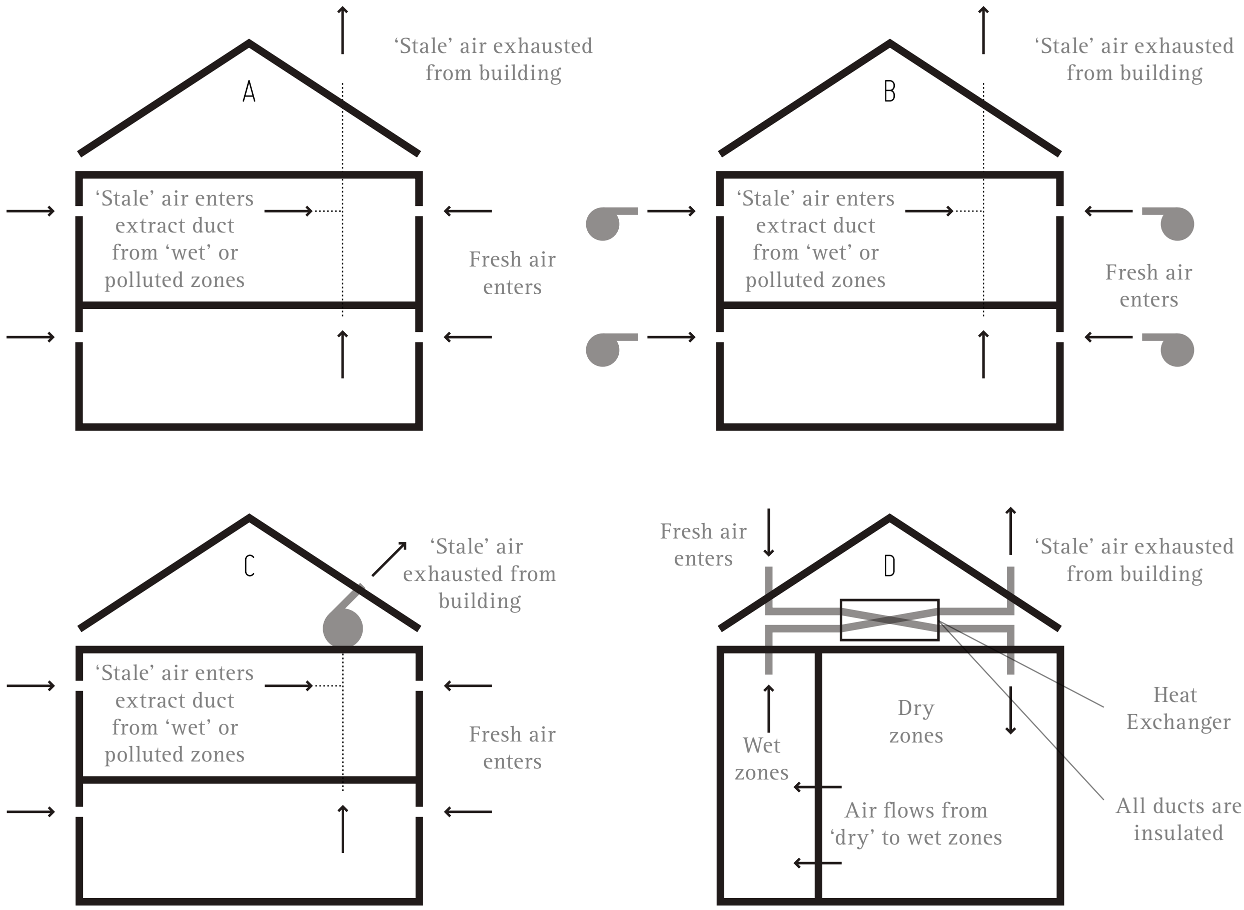

Figure 10: Four principles of ventilation system: A)Passive and natural ventilation, B)Mechanical supply and natural exhaust ventilation, C)Mechanical exhaust and natural supply, and D)Balanced ventilation system.

Adventitious ventilation and natural ventilation by window opening is mostly used in very mild climates with limited heating and cooling needs. Mechanical supply combined with natural exhaust, and natural supply in combination with mechanical exhaust are mostly used in moderate climates because of draft problems at outside temperatures lower than 5oC (Mansson 1995, IEA Annex 27)[i]. Advanced ventilation systems are applied in moderate and severe climates because they can save energy in combination with heat recovery and can prevent draught problems.

Russell et al.(2007) reviewed specific market technologies for providing ventilation in residential buildings with a focus on North America. Their work provides a good overview of existing technologies. Historically designed ventilation in homes has only included flues or chimneys to remove combustion pollutants and manually operated windows and doors. Many homes now also include manually operated bath and kitchen exhaust fans. Continuous or semi-continuous ventilation has not been a design feature of homes until recently. Most home ventilation has been provided via unintentional air infiltration through building cracks and leaks. For many homes, especially older homes, infiltration and exfiltration through imperfections in walls and roofs deliver sufficient ventilation. Newer homes have been built increasingly tighter. Homes that are too tight, that have insufficient leaks, may not provide sufficient ventilation for occupants. Other methods of ventilation include passive, mechanical, and hybrid ventilation systems.

Adventitious ventilation delivers no pollutant control

With adventitious ventilation control of pollutants is of course not possible. Natural ventilation by window airing dilutes pollutants produced in rooms on the windward side by mixing and transports to the leeward side rooms, where they leave the building. For pollutant removal it is in most cases very effective as long as the driving force is above a minimal level. The energy penalty may not be overlooked.

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[i] **Evaluation and Demonstration of Domestic Ventilation Systems – State of the Art**
Mansson L-G (ed.)
Sweden, Stockholm, Swedish Council for Building Research, 1995, Report A12:1995, 136 pp

Open windows are very effective for pollutant control but comfort and energy need attention

Mechanical supply, mechanical exhaust and balanced ventilation mix the pollutants in the room that are being produced, and after mixing and dilution they are extracted in the toilet, bathroom and kitchen. The removal of pollutants is limited due to the fact that they are theoretically always already mixed before leaving the building. Both exhaust and supply ventilation have particular advantages. Supply ventilation can control the flow path of air from the outdoors to indoors and allows for the use of air cleaning or filtration technologies. Without proper maintenance however, filters can become clogged and may reduce the flow or cease the flow of supply systems. Anecdotal evidence exists of clogging of the supply side of balanced ventilation systems indicating the improper maintenance, such as not changing filters, could result in failure of supply mechanical ventilation systems. Supply systems can push indoor air through building wall structures and can potentially lead to mould and moisture issues in the home. Exhaust systems pull air through the intended and unintended openings in the building envelope. Unintended openings provide a minor level of filtration of outdoor particles, but can potently move pollutants from the wall structure in to the space. Since exhaust systems draw air out of the space, no air cleaning or filtration can be applied. The exhaust-only systems may fail in homes that are too tight if intended air inlets are not properly used.

Mechanical exhaust is normally done from wet rooms including the toilet, bathroom, laundry room and kitchen. In US homes, air may also be supplied to the central ducting system that distributes heating and cooling to the home while in Europe this is less common. In Europe so called demand controlled ventilation systems are becoming quite common in regions with moderate climates. Hybrid systems are typically a combination of a mechanical system and a passive system with the mechanical system activating if there is insufficient airflow from the passive system alone.

6.2.3 TASK VENTILATION

Task ventilation refers to ventilation that is associated with a specific activity. Traditionally task ventilation has been manually operated with a user turning ventilation on during specific activities. This differs from whole house/room ventilation in that it is not running on a regular basis independent of home activities. The two most common forms of task ventilation are bathroom or WC ventilation and cooker/range hoods.

6.2.3.1 BATHROOM OR WC

Bathroom fans remove bioeffluents, moisture and pollutants generated in bathroom activities such as personal care product use and showering. Bath fans tend to be run for occupant comfort or moisture control rather than indoor air quality. Controlling mould and moisture reduces the likelihood that there will be a resulting health issue however. The bathroom is also a potential source of VOCs due to product use and chlorinated tap water (Kerger et al. 2000). WHO Guidelines for indoor air quality: dampness and mould stresses that moisture control, including ventilation, is the main method for containing mould and mites. Attention is needed not only in the design phase but also sustained maintenance is important (WHO 2009).

The purpose of bathroom ventilation, whether it should include the control of VOCs, is a question of debate. Further research is needed to determine which episodic activities in bathrooms may lead to acute exposures and how to use bathroom fans to avoid these exposures. There is very limited research on effective bathroom ventilation configurations (Tung et al. 2009; Tung et al. 2010). The research that does exist has focused on novel bathroom exhaust systems.

6.2.3.2 RANGE/COOKER HOOD

Effective cooker/range hoods may reduce pollutants during cooking

Every home has a kitchen and kitchens can be the biggest source of pollutants in a house. A major source of contaminants in the kitchen is cooking. Contaminants are produced both by the cooking fuel as well as the food being cooked. Range or cooker hoods are designed to exhaust or capture pollutant streams from cooking prior to the pollutants entering the rest of the home. It is not easy to assess the effectiveness of a range hood for a typical homeowner. Range hoods are also a design feature for many homes meaning they are not always selected for optimal indoor air quality. Range / cooker hoods are typically manually operated by the homeowner with noise being cited as the most common reason for not using them. Range hoods can have different positions from under and/or in between a cabinet, as a chimney, integrated in a microwave oven or even as downdraft based systems. Figure 11 illustrates the variety of types and positions of cooker hoods.

Figure 11: Different positions and types of cooker hoods

There are two major types of range/cooker hoods, exhaust and recirculating. Exhaust cooker hoods are always preferred to recirculation hoods because recirculation hoods, in most cases, even if they are designed with some filtration, re-emit a large fraction of pollutants back into the occupied space. Better recirculation hoods are coming onto the market that include particle filters and systems to capture pollutants and odour, but there are currently no systems that effectively handle all cooking pollutants.

Both the US and Europe have established energy efficiency and noise standards for range hoods. The CE mark is a mandatory conformity marking for cooker hoods sold within the European Union. The Energy Star label is a voluntary energy efficiency label in the US. Both programs set energy efficiency standards for the fan used in a given range/cooker hood but neither of these labels address how effective the hood is at exhausting pollutants from the space or reducing exposures.

Significant research has gone into assessing the effectiveness of range hoods and suggesting methods for improving range hoods. The Lawrence Berkeley National Lab in California, USA and other research institutions have measured range hood effectiveness in both real homes and laboratory settings (Delp and Singer 2012; Rim et al. 2012; Singer et al. 2012; Lunden et al. 2015). They identified a set of design characteristics and occupant behaviors that could maximize range hood capture efficiency. They suggested that occupants cook on back burners and run their range hoods on high to maximize capture efficiency of effective hoods. Standards are currently under development for assessing range/cooker hood capture efficiency for hood labeling purposes.

TNO (the Netherlands) tested the fine dust emissions of cooker hoods at several exhaust flow rates and cooker hood geometries. At the lowest exhaust flow the peak PM1 (particulate matter with an aerodynamic diameter less than 1 micron) concentration was more than a factor 20 higher than the ambient concentration. Increasing the flow rate to 83 dm^3/s reduced the peak concentration to 300 $\mu g/m^3$. In another option, the exhaust hood was modified by adding a damp buffer. This simple measure reduced the PM concentration by more than a factor of three.

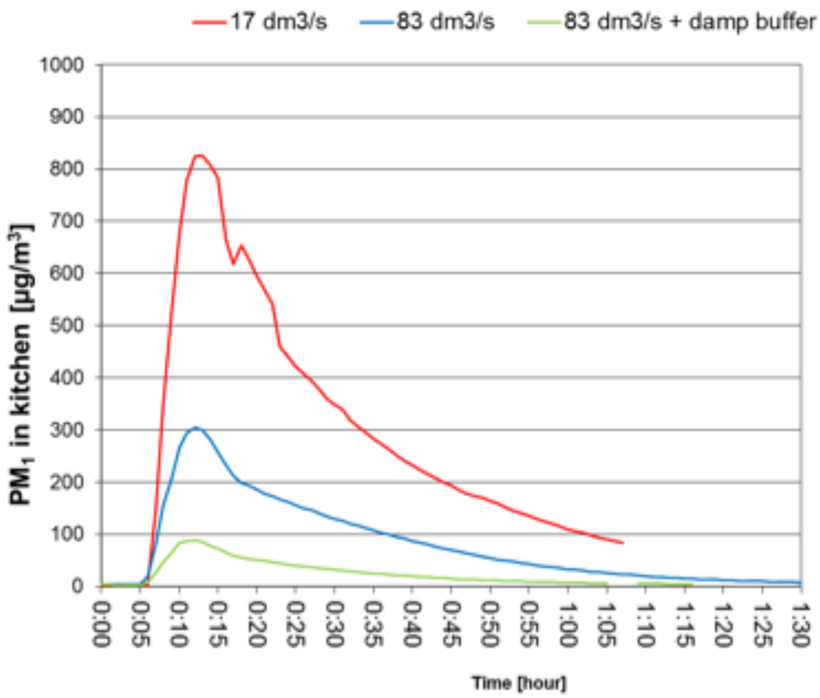

Figure 12: Effect of flow rate and the presence of a damp buffer under the cooker hood on PM1 concentration in a kitchen during frying of 100 ml oil at 180°C.

The effects of disturbance of persons in front of the cooker hood can be significant as shown by the study by Simon (Simon 1984) see Table 8. The ratio of capture efficiency with and without interference globally is 75%.

Table 8: The effect of interference in front of cooker hoods (from (Simon 1984))

AIR FLOW (M^3/H)	WITH INTERFERENCE DEVICE	WITHOUT INTERFERENCE DEVICE
450	0.74	0.97
300	0.66, 0.67	0.89, 0.90
200	0.46, 0.49	0.95, 0.96
100	0.38, 0.39	0.67, 0.71
‘optimal’ 300	0.94	-

6.2.4 HOME DEPRESSURIZATION AND BACKDRAFTING

Backdrafting may cause comfort and IAQ problems

One major concern with exhaust-based systems, including both task and whole house or room ventilation, is the potential for home depressurization. Fan performance is a function of both the fan characteristics and pressure drop the fan must overcome to vent a given unit of air via a given vent. As homes become tighter or when multiple fans are attempting to exhaust air at the same time the fans may not perform as intended. Additionally, in homes with naturally drafting combustion appliances, there is the potential for backdrafting where combustion gases may spill back into the space. Rapp et al conducted an excellent review of the science of backdrafting and of the effectiveness of back draft tests (Rapp et al. 2013; Rapp et al. 2015). Their work determined that existing backdrafting tests have far too many false positives.

One solution for home depressurization is to provide supply air for all exhaust fans in the home. The best method for doing this is still an area of debate. Depressurization is good to avoid moisture damage due to convection in cold attics.

6.2.5 VENTILATION CONTROL STRATEGIES

Currently home ventilation systems have rudimentary controls that do not take indoor air quality into account. Most whole house or room ventilation is continuous while task ventilation is manually controlled by the occupant based on perceived indoor air quality. Some whole house ventilation systems are designed to limit the energy impacts of ventilation, but systems are not optimized to provide the best indoor air quality.

Demand control for bioeffluents not for health

Demand control approaches typically use sensors to identify when more or less ventilation is needed. Demand control is generally based on home occupancy with higher ventilation rates when the home is occupied. CO_2 concentration is one potential indicator of occupancy that can be used to control ventilation (Gids and Wouters 2010). An alternative method is humidity control based ventilation; this is automatic control of the airflow according to humidity level through a mechanical sensor (France, Belgium, Spain, Germany and Poland) (Savin and Laverge 2012). Demand controls making use of "VOC" or multi-gas sensors are relatively new. The sensors used are predominately semiconducting metal oxide (SMO) sensors. These are used in the car industry for vehicle cabin air quality monitoring (AQM) and are now finding their way into demand control ventilation systems for buildings. They are sensitive to several pollutants (CO, NO_2, HC, O_3) but are not very selective in sensing. An alternative with better selectivity is Infra Red-optical sensors (Galastis and Wlodarski 2012).

The optimal control solution will be a function of home location and pollutant sources. Table 11 summarizes how demand control could impact ventilation controls for specific rooms of the home. Table 9 and 10 list indoor and outdoor pollutant sources and their optimal control strategies. The tables also list how demand control could play an important role in ventilation control for controlling these specific sources. As cheaper, more reliable sensors enter the market, there is more and more potential to incorporate demand control into ventilation strategies.

Table 9: Main outdoor sources and preferred measures

MAIN OUTDOOR SOURCE	POLLUTANT	PREFERRED CONTROL MEASURE	DEMAND CONTROL OPTION	ALTERNATIVE CONTROL MEASURER
Traffic, industry, traffic	$PM_{2.5}$, Ozone, NO_2	Filtering of supply air (only $PM_{2.5}$)	Optical sensor	Air purifiers (only $PM_{2.5}$)
Humid climates	Moisture	Dehumidification of supply air	Moisture, SMO or infra-red optical gas	Local dehumidification

Table 10: Main indoor processes and measures to be preferred

MAIN INDOOR PROCESSES	POLLUTANT	PREFERRED CONTROL MEASURE	DEMAND CONTROL DETECTION SENSOR	ALTERNATIVE CONTROL MEASURER
Open combustion	$PM_{2.5}$, Acrolein	Avoid open combustion for example by using induction range or closed combustion devices. In case of cooking use a very efficient hood	Optical sensor CO_2, SMO or infra-red optical gas	Extra supply of fresh air (large volumes needed and energy consumed!), air purifiers for $PM_{2.5}$
Burning candles	$PM_{2.5}$, Acrolein	Replace by electric candles	Optical sensor CO_2, SMO or infra-red optical gas	Extra supply of fresh air, air purifiers
Construction failures and faults	Moisture (mould)	Insulated cold bridges, use of moisture barriers, built in moisture/ dry construction phase (especially in bathrooms)	Humidity	Local dehumidification, extra heating
Construction, furniture and wet cleaning substances	Formaldehyde	Avoid materials with high emitting formaldehydes, for example N.A.F. (no added formaldehyde) or U.L.E.F (ultra-low-emitting-formaldehyde)		Extra supply of fresh air, dehumidification in humid climates (formaldehyde emission increases due to moisture)

Table 11: Rooms and the state of the art ventilation measures in residential buildings

ROOMS	POLLUTANT	VENTILATION MEASURES (STATE OF THE ART)	DEMAND CONTROL DETECTION OPTIONS
Toilet	Odour of feces, urine, moisture	Exhaust ventilation, a minimal level is needed to have dominant airflow underneath the door of the toilet.	Presence (light switch), CO_2, humidity, SMO (Semiconducting Metal Oxide), timer
Kitchen, stove	Cooking, gas burner	Exhaust ventilation, cooker hood (no specific efficiency), operable windows	CO_2, humidity, SMO, timer
Shower	Moisture (mould)	Exhaust ventilation	Presence (light switch), CO_2, humidity, SMO, timer
Bed rooms, living room	Odour of persons	Extract ventilation, supply of ventilation	CO_2, humidity, SMO, timer

6.3 REVIEW OF EXISTING RESIDENTIAL VENTILATION STANDARDS

Backdrafting may cause comfort and IAQ problems

People spend the majority of their time in residences (Klepeis et al. 2001), making indoor air quality an increasing concern. It has been widely recognized that the health burden of indoor air is significant (Edwards et al. 2001; de Oliveira et al. 2004; Weisel et al. 2005). Current ventilation standards are set to protect the health and provide comfort for residents, but the majority rely heavily on engineering judgement due to the limited existence of scientific justification. This section will describe current and potential methods for estimating required flow rates for ventilation and provide an overview of important existing standards.

6.3.1 HUMAN EFFLUENTS AND CARBON DIOXIDE

Sweating seems to be the main body odour source determining perceived indoor air quality (Gids and Wouters, 2008). Odours create discomfort, as good air quality is often perceived as the absence of odour. In many cases occupants become used to odours that can be well perceived by someone entering the room. Judgment of a visiting test panel (Fanger et al. 1988) can be used to assess the odour intensity.

Pettenkofer Zahl bases for ventilation standards

Carbon dioxide (CO_2) is not a major health driver for indoor air exposure in residences. CO_2 is a marker for bioeffluents of people and can be related to the nuisance of odour. CO_2 has been the basis for almost all ventilation requirements in buildings since the work of Pettenkofer (1858). He recognized that while CO_2 was harmless at normal indoor levels and not detectable by persons, it was a measurable pollutant that ventilation standards could be designed around. From this study he proposed the so-called "PettekoferZahl" of 1000 ppm as a maximum CO_2 level to prevent odours from human effluents. He assumed an outside concentration of about 500 ppm. He advised to limit the difference in CO_2 between inside and outside to 500 ppm. This is equivalent to a flow rate for an adult of about 10 dm^3/s per person. This amount is still the basis of ventilation requirements in many countries. Later Yaglou (1937), Bouwman (1983), Cain (1983) and Fanger (1988) conducted further research on a "odour nuisance driven" ventilation approach based on CO_2 as a marker.

Table 12: Generally used CO_2 limits in spaces (Gids 2011)

PLACE	CO_2 CONCENTRATION (%)	CO_2 CONCENTRATION (PPM)
Outdoors	About 0,04	400
Comfort	0,10-0,15	1000-1500
Maximum Allowable Concentration (MAC)	0,5	5000
Bomb shelters	Maximum 2	Maximum 20000
Submarine	Maximum 3	Maximum 30000
Mortality level	10%	100.000

A recent study indicates that CO_2 itself might influence the cognitive performances of people (Satish et al. 2012). In case the performance of people is the most important parameter in rooms such as classrooms, lecture-rooms and even in some cases offices, CO_2 levels should determine the ventilation level rather than nuisance and/or comfort. In order to develop standards based on CO_2 for cognitive performance, an acceptable level of exposure would have to be established. Based on this study, maintaining a level of around 1000 ppm appears to have no impairment on performance (Satish et al. 2012).

6.3.2 BASIS FOR FUTURE VENTILATION STANDARDS

6.3.2.1 VENTILATION FOR HEALTH

Pollutants are emitted in or enter into the space where the occupants then inhale them. Ventilation provides one option for removing pollutants to reduce exposure either by removing the pollutants at source, such as with cooker hoods, or by diluting air in the home via whole house ventilation. Ventilation is not the only control option for reducing exposures and may not be the right tool in many situations.

In order to design a ventilation or pollutant control strategy based on health, there must be a clear understanding of the pollutants to control, indoor sources and source strengths of those pollutants, and acceptable levels of exposure in the home. A European Collaborative Action developed a method for determining the ventilation requirement to achieve good indoor air quality as a function of these pollutants (Bienfait et al. 1992).

Most important pollutants indoors

Chapter 4.5.1 of part I describes the pollutants that appear to drive the chronic health risks associated with exposure to indoor air. Those pollutants are:

- Fine particles ($PM_{2.5}$)
- Second-hand tobacco smoke (SHS)
- Radon
- Ozone
- Formaldehyde
- Acrolein
- Mould/moisture related pollutants

Currently there is insufficient data about source strengths and specific source contributions to exposure in homes to design a ventilation standard based on health. There is significant variability in source characteristics from home to home and the appropriate ventilation rate for a home may need to take indoor sources and occupant behavior into account. This is an ongoing area of research. Future ventilation standards may rely on health outcomes to establish sufficient ventilation rates.

6.3.2.2 VENTILATION FOR COMFORT

As described above, odours can play an important role in comfort and wellbeing. Another aspect of comfort is thermal comfort. Ventilation can influence thermal comfort by transporting cooled, heated, humidified or dried air. The turbulence and air speed caused by ventilation can influence the perceived thermal comfort. High infiltration or air change rates can create discomfort (Liddament 1996).

Calculating required ventilation rates for comfort and health requires different approaches. Ventilation for comfort is mostly based on odour reduction and temperature/humidity control, while for health the strategy is based on reduction of exposures. A proposal of the concerted action guidelines (CEC 1992) is to separately calculate the ventilation rate needed for comfort and health. The highest ventilation rate should be use for the design.

6.3.3 EXISTING VENTILATION STANDARDS

6.3.3.1 UNITED STATES VENTILATION STANDARDS: ASHRAE 62.2

The American Society of Heating, Refrigerating and Air Conditioning Engineer's (ASHRAE's) Standard 62.2 is the most widely accepted residential ventilation standard in the United States. ASHRAE developed Standard 62.2 "Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings" to address indoor air quality (IAQ) issues (ASHRAE 2010). ASHRAE 62.2 is now required in some building codes, such as California's Title 24, and is treated as a standard of practice in many energy efficiency programs and by organizations that train and certify home performance contractors. The standard specifies an overall, residence-level outdoor air ventilation rate as a function of floor area (a surrogate for material emissions) and the number of bedrooms (a surrogate for occupant-related emissions) and requires bathroom and cooking exhaust fans. The focus of the standard generally is considered to be the overall ventilation rate. This emphasis has been based on the idea that risks indoors are driven by continuously emitted, distributed sources such as formaldehyde from furnishings and bioeffluents (including odours) from humans. The required level of whole residence mechanical ventilation was based on the best judgment of experts in the field, but was not based on any analysis of chemical pollutant concentrations or other health-specific concerns.

6.3.3.2 EUROPEAN VENTILATION STANDARDS

There are a variety of ventilation standards in various European countries. Dimitroulopoulou (2012) provides an overview of existing standards in table format for 14 countries (Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Netherlands, Norway, Portugal, Sweden, Switzerland, United Kingdom) along with a description of modeling and measurement studies done in each country. All countries specified flow rates for whole house or specific rooms of the home. Airflow was specified in at least one standard for the following rooms: living room, bedroom, kitchen, bathroom, toilet Most standards only specified airflow for a subset of rooms.

The basis for ventilation requirements varies from country to country with requirements based on number of people, floor area, number of rooms, room type, unit type or some combination of these inputs. Brelih and Olli (2011) aggregated ventilation standards for 16 countries in Europe (Bulgaria, Czech Republic, Germany, Finland, France, Greece, Hungary, Italy, Lithuania, Netherlands, Norway, Poland, Portugal, Romania, Slovenia, United Kingdom). They used a set of standard homes to compare resulting air exchange rates (AERs) calculated from these standards. They compared required airflow rates for the whole house and task ventilation. Required whole house ventilation rates ranged from 0.23-1.21 ACH with highest values in the Netherlands and lowest in Bulgaria.
Minimum range hood exhaust rates ranged from 5.6-41.7 dm^3/s.
Minimum exhaust rates from toilets ranged from 4.2-15 dm^3/s.
Minimum exhaust rates from bathrooms ranged from 4.2-21.7 dm^3/s.

There seems to be a standard consensus between most standards that a whole house ventilation rate is required with additional higher levels of ventilation for rooms where pollutant emitting activities may occur, such as kitchens and bathrooms, or where people spend the majority of their time, such as living rooms and bedrooms.

6.3.3.3 STANDARDS IN PRACTICE

New home construction is ostensibly built to meet requirements specified in the country in which the home is built. Ventilation devices are selected that meet required flow rates. Flow rates can be affected by more than just the device selected. Backpressure from the vent attached to a given fan, improper installation and clogged filters can result in drops in fan performance. Currently there is no commissioning requirement in either the US or European standards. Commissioning is mandatory in Sweden since 1991. Commissioning is the process of measuring actual building performance to determine if they meet requirements (Stratton and Wray 2013). Commissioning requires additional resources and may be considered cost prohibitive. Due to the lack of commissioning, actual flows may not meet prescribed or designed values. Stratton et al (2012) measured flow rates in 15 California, US homes and found that only 1 met the ASHRAE 62.2 Standard completely. Measurements across Europe have also indicated that many homes fail to meet prescribed standards (Dimitroulopoulou 2012). Commissioning should potentially be added to existing standards to assure compliance in homes.

6.4 OTHER MEASURES TO IMPROVE INDOOR AIR QUALITY

To design for good indoor air quality it is important to reduce the generation and the spread of pollutants in the home. Ventilation is just one available tool to do so. This section will briefly describe other methods that have an impact on indoor air quality. Tables 9,10 and 11 contain suggestions for methods to reduce exposure for specific sources.

6.4.1 SOURCE CONTROL

Material emission standards as well as banning of specific chemicals in materials are intended to limit the sources of pollutants in the home. The following steps should be taken to reduce the sources and source strengths of pollutants in the home:

Control strategy

1. Avoid materials containing known or suspected pollutants including endocrine disruptors (Vandenberg 2012)
2. Reduce moisture production in buildings to minimize mould and mildew (Bornehag et al. 2001)
3. Avoiding open combustion with fuels, consider replacement with closed combustion systems
4. Physically separate living areas from areas that may contain stored pollutant sources such as garages and basements.

6.4.2 AIR CLEANING: STAND-ALONE AND WHOLE HOUSE

Air cleaning is a method by which particulates and gaseous pollutants may be removed from the air by passing the contaminated air through a filter or other medium. This captures the pollutants while allowing clean air to pass through. Air cleaning is most effective at controlling pollutants (especially particulates) associated with specific air quality problems. It is not a substitute for the ventilation necessary to meet the metabolic needs of occupants, since filtration does not replenish oxygen or normally remove metabolic carbon dioxide from the air stream. Infiltration has a major influence on the remaining pollutants when filtering the supply air. Studies (Jacobs 2015) in several offices show that the effects of improving filter quality above M6 in the supply air is limited for $PM_{2.5}$ concentration due to infiltration.
Various filtration and air cleaning technologies are available. The energy and health impacts of these technologies vary widely. The ASHRAE Position Document on Filtration and Air Cleaning characterizes these technologies and their applications (ASHRAE 2015). The document provides an excellent resource for understanding existing filtration and air cleaning technologies. The committee found that the body of literature on effective filtration and air cleaning as an alternative to ventilation is limited.

Air cleaning and filtering

Simulation studies conclude that applying filters in dwellings can reduce the exposure to ambient $PM_{2.5}$. Hanninen (2005) predicts an exposure reduction of 25% if dwellings are supplied with supply air filters reducing the infiltration to the same level as in offices. Raja (2011) studied the effect of stand-alone filtration on asthmatic children. The unit, which provided 9 air changes per hour (ACH) with 1.7 fresh ACH through a 95% efficient particulate matter filter, was tested for 14 weeks in the bedrooms of twenty asthmatic children between ages 5 and 16. Measurements of indoor air quality and pulmonary function showed statistical improvement with the unit running as compared with the placebo mode both with and without ventilation. A recent review on the effects of air filtration (Fisk 2013) considered the recently published literature and the results of prior reviews (IOM 2000; Reisman 2001; McDonald et al. 2002; Wood 2002; Sublett et al. 2010; Sublett 2011). It concluded that particle filtration could be modestly effective in reducing adverse allergy and asthma outcomes, particularly in homes with pets. It also concluded that particle filtration systems that deliver filtered air to the breathing zone of sleeping allergic or asthmatic persons might be more consistently effective in improving health than use of room or whole-house filtration systems. The review additionally concluded that the limited available evidence suggests that particle filtration in buildings (homes, offices and schools) is not very effective in reducing acute health symptoms (SBS symptoms) in persons without asthma and allergies(ASHRAE 2015).

6.4.3 ENCLOSURE

An enclosure keeps a selected hazard "physically" away from the occupant. Enclosed equipment, for example, is tightly sealed and it is typically only opened for cleaning or maintenance. An example is a boiler or a closed wood stove, which has its own air supply and exhaust. The enclosure itself must be well maintained to prevent leaks. Isolation places the hazardous process "geographically" away from the user.

7
RESEARCH NEEDS

Two workshops were held to develop priorities for indoor air quality research, implementation and policies supporting health and comfort in highly energy efficient buildings (Wargocki, 2015). At the first workshop, organized by the Air Infiltration and Ventilation Centre (AIVC) with the support of the Joint European Medical Research Board and held in Brussels in 2012, experts from the following disciplines took part: ventilation, medicine, epidemiology, building systems and building policies. Legislators and other stakeholders involved in building design, construction and operation were invited. During two days of presentations and discussions, research issues that must be addressed to ensure that the indoor environment in highly energy efficient buildings is healthy and comfortable were identified. Both new buildings and those that have undergone or will undergo energy retrofits were considered. The discussions addressed a wide number of issues related to basic human requirements, technical solutions, policies and training programs that support implementation. The outcome of the workshop was used to draft a first list of research priorities, which was reviewed, supplemented and approved by the workshop participants. In the next step, the list of research priorities was subjected to external review by the participants of the special workshop held at the AIVC 2012 conference in Copenhagen (Denmark). One aim of this additional workshop was to supplement the agenda with new topics that might have been overlooked during the first workshop. Another aim was to prioritize the topics listed and estimate how much effort would be required for their accomplishment. The participants in this second workshop came from different professional backgrounds, including research, practice and legislation.

This chapter presents a list of challenges, tasks and research needs that should be addressed to make sure that IAQ and health of building occupants are not compromised identified in these workshops. They are based on opinions rather than on a systematic review of literature and the intention was not to duplicate similar endeavours reported previously (Fisk et al. 2002; Mendell et al. 2002; IOM 2011; Phillips and Levin 2013). One of the aims was to increase awareness of the potential health problems in buildings due to exposures to contaminants and of the potential solutions for improving indoor air quality and health. The particular focus was on highly energy efficient buildings to anticipate the future challenges being a result of gradual change of building stock into green alternative with low energy use. Nevertheless, the topics identified during the workshops are relevant for the entire building stock. They can be used in preparing an agenda for research on energy efficiency, IAQ and health in buildings, and to identify solutions to potential problems.

7.1 SELECTION PROCESS

An agenda for appropriately addressing the issues related with health and ventilation in buildings is particularly important given that building stock is undergoing a very dramatic and substantial change, both as regards actions having the aim to retrofit the existing buildings so that they can match future requirements and challenges as well as the newly constructed buildings. This change addresses mainly the need to reduce the energy use in building stock estimated to be responsible for 40% of all energy use, but also to some extent climatic changes and the need to renovate the building stock so it is resilient towards extreme weather events. The energy that is used in the buildings mainly serves the purpose of maintaining indoor environmental quality and is used namely for heating, cooling, ventilating and lighting the buildings, as well as to support domestic hot water production, electrical appliances, cooking and other activities occurring in the buildings. The research agenda needs to identify the most critical aspects that need to be addressed setting the priorities and outlining the steps that will have to be taken to avoid any negative consequences of the worldwide effort to impose rigorous limits on energy use in buildings.

Workshops on IAQ research

The list with topics identified during the first workshop was later subjected to external review, revisions and supplementation during another workshop held at the one of the AIVC conferences. These conferences are held on annual basis to create a meeting point for individuals from academia and practice, and for those preparing legislation, that deals with energy, IAQ and ventilation in buildings. The workshop was open to any participant of the conference and was attended by 30 participants representing the areas mentioned above, approximately half of whom were researchers; one participant was responsible for preparing legislation. The workshop participants additionally prioritized the identified issues.

The topics identified during both workshops and thus considered as essential and requiring clarification in connection with ventilation-health relationship in buildings were clustered along the following main themes, which form a general conceptual framework for achieving high IAQ in buildings that do not create any health risks:

1. Performance criteria that define good IAQ in buildings, including the expectations of building users, the conditions that promote well-being and healthy living, and the conditions that have been linked to potentially harmful effects.

2. Processes, solutions and technologies for minimizing the release and propagation of air pollutants that have been linked to harmful effects on humans, and the precursors for such pollutants, including the careful selection of building materials, furnishing and consumer products, and the use of technologies for the dilution and removal of air pollutants, such as ventilation, airborne particle filtration and gas-phase air cleaning.

3. Building design methods that ensure good IAQ in the built environment, including fault-free manufacture and installation of the systems that ensure good air quality in buildings.

4. Procedures and actions ensuring appropriate and judicious use, operation and maintenance of buildings and all of the building systems installed in them.

7.2 BASIC RESEARCH NEEDS

Priority in research needs

Basic research needs for achieving good indoor air quality in buildings with low risk for health (with a particular focus on highly energy efficient buildings) are listed in the following starting with the needs that should be addressed at first and considered to have the highest priority:

1. Studying the impact of user behaviour on the control of indoor air quality.
2. Development, implementation and harmonization of new, advanced and harmonized methods for monitoring indoor air quality, and health and comfort effects in buildings.
3. Definition of ventilation parameters and requirements for buildings that are harmonized across all relevant policies, regulations and standards.
4. Identification of pollutants of concern especially in highly energy efficient buildings.
5. Determination of occupant expectations of highly energy efficient buildings in relation to indoor air quality and whether they differ from those of traditional and retrofitted buildings.
6. Investigation of differences in health risks in traditional buildings, energy retrofitted buildings and new highly energy efficient buildings.
7. Examination of the impact of non-building related variables (gender, age, social and work status) on health and comfort requirements.
8. Development of an improved and simplified toxicological characterization of building related pollutants.
9. Identification of sources of pollutants of concern in indoor environment.

7.3 SOLUTIONS FOR ACHIEVING GOOD IAQ

Tasks and issues that need to be addressed in relation to solutions, processes and technologies required for achieving good indoor air quality in buildings with particular focus on highly energy efficient buildings and reducing health risks are listed in the following starting with the tasks having the highest priority:

1. Evaluation of new advanced ventilation strategies based on health and comfort criteria.
2. Identification of barriers that block innovation in the building process having the goal of achieving good indoor air quality.
3. Identification of methods that will encourage the active involvement of building occupants in creation of healthy and comfortable indoor air quality (methods affecting occupants' operational habits and activities).
4. Studying the potential of flexible building design to account for and respond to variables influencing indoor air quality.
5. Comparison of performance of natural ventilation, mechanical ventilation, ventilation on demand and any other ventilation solutions in particular in the context of highly energy efficient buildings, taking into account the purpose and circumstances of their use.
6. Development and implementation of harmonized methodology for measurements and health based evaluation of chemical emissions from building materials and consumer products, and comprehensive performance classes of products including the evaluation of the impact of the labelling of building materials and consumer products in the context of healthy, comfort and highly energy efficient buildings.

7.4 NEEDS FOR POLICY AND FOR THE PROPER MANAGEMENT AND IMPLEMENTATION

The list identifying the needs for policy and for proper managements and implementation of solutions for achieving good indoor air quality in particular in highly energy efficient buildings, to reduce health risks is presented in the following starting with the items that have been considered to have the highest priority:

1. Development of ways to increase the responsibility of building contractors, designers, producers, constructors and installers.
2. Development of tools and methods for ensuring a robust and performance-based design, operation and maintenance of building systems while maintaining good indoor air quality and energy efficiency.
3. Development of framework for quantification of health and comfort outcomes in terms of public health and economic criteria.
4. Development of guidelines for operating buildings in multi-objective settings, together with user-friendly manuals and control interfaces for building occupants.
5. Development of ad hoc educational and training programs for different stakeholders (architects, designers and engineers to installers and facility managers) involved in building processes including their certification.
6. Development of long-term economic incentives for creating healthy and comfortable indoor environments, in the form of add-on values rather than penalties.

7.5 GENERAL COMMENTS

The impact of occupant behaviour on the control of indoor environmental quality is clearly assigned the highest priority. This somewhat reflects debate between stakeholders and scientists involved in the research, construction, design and operation of buildings on the importance of human behaviour. There are new data documenting that occupant's actions, attitudes and behaviours are important, perhaps even dominating in the process of creating healthful and comfortable built environments (e.g., Leaman and Bordass 1999; Leaman and Bordass 2007; Andersen et al. 2009). These data indicate that even most advanced policies, technologies and regulations will only be effective if they address occupant behaviour. Consequently it is strongly encouraged that the focus in future should be on the real reasons that certain actions are taken, and occupants' motivation to perform them, on identification of those aspects of the control of indoor environmental quality in highly energy-efficient buildings that should be delegated to occupants, and to what extent (e.g., (Paciuk 1989)), an on ways of engaging and motivating occupants to be more responsible for the environments in which they live and work.

It is also strongly advised to benchmark the health risks of occupants of traditional buildings, energy retrofitted buildings and new highly energy-efficient buildings and to investigate thoroughly the building related exposures and sources responsible for the health effects observed. It is believed that these investigations would create a true reference point (benchmark) for future development of buildings as comparable data will be collected using similar, standardized and harmonized measuring protocol. Such a reference is essential and will enable assessing the performance, effectiveness and success of any proposed mitigation technologies. There is actually a paucity of such reference/benchmark at present.

Relevant new policies should be developed supporting implementation of actions focused on achieving high IAQ and the existing policies must be revised. These policies must be aligned and integrated with the relevant regulations and standards, and any crosscutting and overlapping criteria must be identified. Besides, the successful implementation requires continuous training of the stakeholders involved in building design, operation and maintenance.

The identified new research initiatives will require substantial funding, this is justified by the obvious benefits of reducing morbidity, mortality and the costs of medical care and by the economic consequences of improved performance and learning (e.g., (Kats et al. 2003; De Oliveria Fernandes et al. 2009; Fisk et al. 2011; Jantunen et al. 2011b; Logue et al. 2011a; Wargocki 2011; Wargocki et al. 2014)). Implementing the research agenda will additionally address current gaps in knowledge, building on rather than attempting to repeat what has been done in the past.

The agenda with topics identified through workshops needs proper dissemination, not only in the form of scientific debate, but also in a way that can be easily comprehended by the general public. Developing an open-source internet-enabled database with search engine capabilities in research projects and benchmark measurements investigating the impact of indoor environmental quality on health and comfort in modern and traditional buildings would be one means of dissemination and would also aid the process of rapidly identifying problems and prioritizing them, so it would be a very useful tool for advancing the science in this area of research. The public must be able to understand the implications of certain actions and behaviours and the need for specific solutions and undertakings, which may otherwise be considered as costly and unjustified. Communication and dissemination is crucially important when the intention is to delegate more responsibility to building occupants, which it is argued above is essential for the successful operation of building systems. It is therefore crucial that the occupants of buildings should be fully informed and instructed on how best to operate a highly energy efficient building and in the use of the different technologies, so that their health and comfort are not compromised.

Research needs continue to evolve beyond this set. Issues arise continually from the impact of outdoor air on indoor air quality to the use of integrated smart controls. Research groups like the AIVC will continue to follow these trends and respond accordingly.

8
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9

APPENDIX 1: POLLUTANT IN THE RESIDENTIAL ENVIRONMENT

9.1 CONCENTRATIONS OF CHEMICAL POLLUTANTS

The following is summarized from Logue, JM, McKone, TE, Sherman, MH, Singer, BC. (2011). Hazard assessment of chemical air contaminants measured in residences. Indoor Air 21(2): 92-109. LBNL-3650-E.

Over 260 pollutants have been measured in residential indoor air in the US and European Countries. Logue et al (2011a) aggregated concentration data in homes from 79 studies to establish representative mid-range and upper bound concentrations in homes. The review was focused on the U.S. but also covered data from other industrialized countries. The review focused first on studies that measured pollutant concentrations relevant to chronic exposures. Many studies reported results from integrated samples collected over periods of 24 hours or more in occupied homes. Some reported concentrations measured over shorter periods in homes that were unoccupied or measured during periods when no substantial pollutant-generating activities were occurring. A second set of studies was identified to obtain data on elevated short-term and peak concentrations resulting from pollutant generating activities. These data included time-resolved or short-term sampling at times and/or for rooms in which pollutant generating activities were occurring. The activities were in some cases scripted and in some cases occupant initiated.

Logue et al. used the ISI web of knowledge database as the main search engine and reviewed proceedings from the 2009 Healthy Building Conference held in Syracuse, NY and the 2008 Indoor Air conference held in Lyngby, Denmark. This search yielded over 150 articles. Articles were chosen that had measurements taken in the last 15 years (1995-2010) from industrialized nations that were thought to be comparable to the United States. This search yielded 79 articles that were relevant to acute and chronic exposure in residences. These studies are listed in Table A1.

The review considered all chemical contaminants measured in residential air regardless of source with the exception of radon and chemical mixtures such as second hand smoke (SHS). The contaminants considered thus include some emitted purely from indoor sources, some that enter predominantly from outdoors, and some having both indoor and outdoor sources.

Based on these 79 reports, Logue et al. compiled a database of summary statistics for chronic-exposure relevant concentrations for SVOCs, VOCs, metals, and criteria pollutants and calculated weighted summary statistics for each pollutant. When calculating summary statistics, Logue et al. weighted statistics from individual studies by the number of unique measurements in each study. Typically this was the number of homes in which measurements were made, though some studies included repeat measurements for some homes. This approach was used in a previous compilation effort (Dawson and McAlary 2009). Results include the total number of studies measuring the pollutant; the total number of unique measurements of a pollutant across all studies and weighted arithmetic mean, 25th, 50th, 75th, and 95th percentile values. Available data for VOCs varied from compound to compound. Each VOC listed has at least one study with mean or median values reported. Benzene was measured in more studies (15) than any other VOC. Fewer data were found for SVOCs. Naphthalene was reported in nine studies, but for some of the SVOCs only a Top of Range, TOR, value was reported. Since SVOC data are so limited, TOR values are included in the data summary. The summary chronic exposure relevant (long-term) concentration data and Limited acute exposure relevant (short-term) data from Logue et al. an be found in LBNL-3650E (homes.lbl.gov/sites/all/files/hazard-assessment-lbnl3650e.pdf).

Table A 1: Publications with chronic and acute exposure relevant concentrations

PUBLICATIONS WITH CHRONIC EXPOSURE RELEVANT CONCENTRATIONS

(Arhami et al. 2009)	(Jia et al. 2008a)	(Piechocki-Minguy et al. 2006)
(Batterman et al. 2009)	(Jia et al. 2008b)	(Raw et al. 2004)
(Baxter et al. 2007a)	(Jo and Lee 2006)	(Raymer et al. 2009)
(Chao 2001)	(Johnson et al. 2004)	(Rehwagen et al. 2003)
(Croxford et al. 2006)	(Johnson-Restrepo and Kannan 2009)	(Rudel et al. 2003)
(Cyrys et al. 2000)	(Kinney et al. 2002)	(Saborit et al. 2009)
(Dodson et al. 2008)	(Kirchner et al. 2009)	(Sakai et al. 2004)
(Edwards et al. 2001)	(Kornartit et al. 2010)	(Seaman et al. 2007)
(Fromme et al. 2004)	(Leaderer et al. 1999)	(Sexton et al. 2004)
(Garcia-Algar et al. 2003)	(Lee et al. 1998)	(Simons et al. 2007)
(Garrett et al. 1999)	(Lee et al. 2002)	(Sorensen et al. 2005)
(Geyh et al. 2000)	(Levy 1998)	(Strandberg et al. 2006)
(Gilbert et al. 2005)	(Long et al. 2000)	(Stranger et al. 2009)
(Gilbert et al. 2006)	(Malkin-Weber et al. 2009)	(Toms et al. 2009)
(Gordon et al. 1999)	(Marchand et al. 2008)	(Topp et al. 2004)
(Guo et al. 2009)	(Miller et al. 2009)	(Turpin et al. 2007)
(Gustafson et al. 2007)	(Missia et al. 2008)	(Weisel 2006)
(Harrad et al. 2006)	(Na et al. 2004)	(Weisel et al. 2005)
(Heroux et al. 2009)	(NYDOSH 2006)	(Williams et al. 2009)
(Hodgson et al. 2000)	(Offermann 2009)	(Zhu et al. 2005)
(Janssen et al. 2005)	(Park and Ikeda 2006)	(Zipprich et al. 2002)
(Jarvis et al. 2005)	(Phillips et al. 2005)	(Zota et al. 2005)

PUBLICATIONS WITH ACUTE EXPOSURE RELEVANT CONCENTRATIONS

(Buonanno et al. 2009)	(Gordon et al. 2008)	(Pagels et al. 2009)
(Coleman et al. 2008)	(He et al. 2004)	(Park et al. 2008)
(Dutton et al. 2001)	(Kerger et al. 2000)	(Singer et al. 2006)
(Fortmann et al. 2001)	(Morawska et al. 2003)	(Stranger et al. 2007)
(Franklin et al. 2006)		

9.2 RADON IN HOMES

Radon is a radioactive gas that is emitted due to the breakdown of naturally occurring uranium in certain types of rock and soil. These type of rock and soil may also be used in building materials such as concrete and brick. There are strong spatial variations in indoor concentrations based on regional variations in the soil radium content and parameters that impact how easily radon can move into the indoor environment such as soil and building conditions. Radon enters the home through gaps and cracks in the foundation, by permeating through foundations, and from materials used in the home that may have high levels of radium. Concentrations tend to be highest in basements due to entry from adjacent soil. Radon has been shown to increase incidences of lung cancer in homes with high levels of exposure and is therefore of concern.

Radon concentrations are reported in terms of radioactivity per unit area. The standard metric for radon concentrations is becquerel (Bq) per cubic meter (m^3) of air (Bq/m^3). Becquerel is a measurement of the rate of disintegration of atoms per second, 1 Becquerel = 1 disintegration of atoms per second.

The World Health Organization (WHO) published average radon concentrations for several countries which are included in Table A 2 (WHO 2002). These values are averages for each country, but there will likely be large variation in concentrations from home to home.
The US has identified areas of the country where concentrations are likely to be higher and suggests that all homes should be measured to determine if remediation is needed.

Table A 2: Country average radon concentration in homes (Bq/m^3) as reported by the World Health Organization. (WHO 2002)

COUNTRY	AVERAGE CONCENTRATION
Czech Republic	140
Finland	123
Germany	50
Ireland	60
Lithuania	37
Norway	51-60
Russia	19-205
Sweden	108
Switzerland	70
United Kingdom	20
USA	46

9.3 PRESENCE OF DAMPNESS AND MOULD IN HOMES

The presence of mould and moisture in homes has long been identified as a health concern. Mould releases fungi and bioaerosals into the environment that can have negative health impacts. As summarized by McLaughlin (2013):

"Fungi are ubiquitous heterotrophic organisms that are prominent bioaerosols, in the range of approximately 1-30 μm in diameter (Jones and Harrison 2004). They account for approximately >20% of all organic aerosol emissions (Yamamoto et al. 2012), and they have a diverse impact on human life. Fungal proliferation in buildings causes structural discoloration and deterioration as well as unpleasant odours. Physiologically, aberrant mould growth has been positively linked to exacerbated respiratory diseases such as asthma, eczema and bronchitis (Mendell et al. 2011). Specific types of mould such as Candida and Aspergillus are also prominent causes of morbidity in patients that are immunocompromised (Johnston et al. 2013)".

McLaughlin et al. aggregated studies of concentration in homes in the US, UK and Australia and found typical indoor concentrations of fungi ranging from 10^2-10^3 (colony forming units) CFU/m^3 and problematic mould concentrations elevated by moisture problems ranged from 10^3 to as high as 10^5 CFU/m^3 in particularly moisture damaged environments.

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APPENDIX 2: STUDIES ASSOCIATING ACUTE EXPOSURES WITH HEALTH OUTCOMES

Table A 3: Case-crossover studies associating acute exposures with health outcomes

REFERENCES	POLLUTANTS	OUTCOME	LOCATION(S)	TIME FRAME
(Bhaskaran et al. 2011)	NO_2,PM_{10}	MI	Wales and England UK	2003-2006
(Dennekamp et al. 2010)	CO, PM_{10}, $PM_{2.5}$	OHCA: all cardiac	Melbourne, Australia	2003-2006
(Ensor et al. 2013)	ozone, $PM_{2.5}$	OHCA: all cardiac	Houston, TX	2004-2011
(Henrotin et al. 2010)	ozone	ICVE	Dijon, France	1985-2001
(Kaplan et al. 2012)	CO, NO_2, $PM_{2.5}$, SO_2	HA: abdominal pain	Edmonton/Montreal, Canada	1992-2002
(Levy et al. 2001)	PM_{10}	OHCA: all cardiac	King County, WA, USA	1988-1994
(Li et al. 2011)	CO, NO_2, $PM_{2.5}$, SO_2	HA: Asthma	Detroit, MI, USA	2004-2006
(MacIntyre et al. 2011)	NO, $PM_{2.5}$, wood smoke	Otitis media	Southwestern Canada	1999-2000
(Medina-Ramon et al. 2006)	ozone, PM_{10}	HA: COPD, pneumonia	36 US cities	1986-1999
(Mustafic et al. 2012)	CO,NO_2, PM_{10}, $PM_{2.5}$, SO_2	MI	varied-Meta Analysis	1988-2011
(O'Donnell et al. 2011)	$PM_{2.5}$	stroke: ischemic	Ontario Canada	2003-2008
(Peters et al. 2001)	$PM_{2.5}$	HA: MI	Boston, MA, USA	1989-1996
(Pope et al. 2006)	$PM_{2.5}$	stroke: acute ischemic	Wasatch Front in Utah	1994-2004
(Pope et al. 2008)	$PM_{2.5}$	HA: heart failure	Wasatch Front in Utah	1993-2006
(Rich et al. 2010)	$PM_{2.5}$	MI	New Jersey, USA	2004-2006
(Rosenthal et al. 2013)	NO, ozone, $PM_{2.5}$, PM_{10}, SO_2, UFP	OHCA: MI, all cardiac, other	Helsinki, Finland	1998-2006

REFERENCES	POLLUTANTS	OUTCOME	LOCATION(S)	TIME FRAME
(Samoli et al. 2011)	PM_{10}, SO_2	HA: Asthma (Pediatric)	Athens, Greece	2001-2004
(Schwartz 2004)	ozone, PM_{10}	mortality	14 US cities nationwide	1986-1993
(Silverman et al. 2010)	$PM_{2.5}$	OHCA: all cardiac	New York City, NY	2002-2006
(Szyszkowicz et al. 2010)	ozone	Cellulitis	Edmonton, Canada	1992-2002
(Villeneuve et al. 2012)	NO_2	stroke	Edmonton, Canada	2003-2009
(Wellenius et al. 2005)	CO, NO_2, PM_{10}, SO_2	stroke: ischemic	9 US Cities nationwide	1986-1999
(Wellenius et al. 2005)	$PM_{2.5}$	stroke: acute ischemic	Boston, MA, USA	1998-2001
(Wichmann et al. 2013)	PM_{10}, $PM_{2.5}$	OHCA: all cardiac	Copenhagen, Denmark	1994-2010
(Zanobetti and Schwartz 2005)	PM_{10}	HA: MI	21 US cities	1985-1999
(Zanobetti and Schwartz 2006)	BC, CO, NO_2, $PM_{2.5}$	HA: MI, pneumonia	Boston, MA, USA	1995-1999

HA=hospital admission, OCHA=out of hospital cardiac arrest, ICVE= recurrent ischemic cerebrovascular event, COPD=chronic obstructive pulmonary disease, MI=myocardial infarction, BC=black carbon, CO=carbon monoxide, NO_2=nitrogen dioxide, UFP=ultra fine particles, NA= not applicable

Table A 4: Poisson distribution acute health impact studies form Clean Air Act CBA (EPA 1999).

REFERENCES	POLLUTANTS	OUTCOME	LOCATION(S)	TIME FRAME
(Burnett et al. 1999)	NO_2, ozone, SO_2, CO, $PM_{2.5}$	HA: Varied causes	Toronto, CA, USA	1980-1994
(Burnett et al. 1997)	ozone, SO_2, NO_2	HA: All Respiratory/ Cardiac	Toronto, CA, USA	Summers 1992-1994
(Cody et al. 1992)	ozone	HA: Asthma	Central and Northern, NJ, USA	Summers 1988-1989
(Krupnick et al. 1990)	ozone	Acute respiratory symptoms	Los Angeles, CA, USA	1978-1979
(Moolgavkar et al. 1997)	NO_2, ozone, SO_2, CO	HA: pneumonia/ COPD	Minneapolis St. Paul, MN, USA	1986-1991
(Ostro 1987)	$PM_{2.5}$	RAD, Work loss day	Nationwide, USA	1976-1981
(Ostro et al. 1991)	$PM_{2.5}$	Asthma status	Denver, CO, USA	1987-1988
(Ostro and Rothschild 1989)	$PM_{2.5}$	MRAD	Nationwide, USA	1976-1981
(Schwartz 1997)	CO	HA: cardiovascular	Tucson, AZ, USA	1988-1990
(Schwartz 1999)	CO	HA: cardiovascular	Eight U.S. counties	1988-1990
(Schwartz 1994c)	ozone	HA: pneumonia	Minneapolis St. Paul, MN, USA	1986-1989
(Schwartz 1995)	ozone	HA: All Respiratory	New Haven, CT, USA	1988-1990
(Schwartz and Morris 1995)	CO	HA: ischemic heart disease, congestive heart failure	Detroit, MI, USA	1986-1989
(Schwartz 1994a)	$PM_{2.5}$	Lower Respiratory Symptoms	Birmingham, AL, USA	1986-1989
(Schwartz 1994b)	ozone	HA: pneumonia/ COPD	Detroit, MI, USA	1986-1989
(Sheppard et al. 1999)	CO, $PM_{2.5}$	HA: Asthma	Seattle, WA, USA	1987-1994

REFERENCES	POLLUTANTS	OUTCOME	LOCATION(S)	TIME FRAME
(Stieb et al. 1996)	ozone	HA: Asthma	New Brunswick, Canada	1984-1992
(Thurston et al. 1994)	$PM_{2.5}$, ozone	HA: All Respiratory	Toronto, Canada	1986-1988
(Weisel et al. 1995)	ozone	HA: Asthma	Central and Northern NJ, USA	Summers 1986-1990
(Whittemore and Korn 1980)	ozone	Asthma Attack	6 communities in southern CA, USA	three 34 week periods 1975

HA=hospital admission, MRAD=minor restricted activity day, RAD = restricted activity day, COPD=chronic obstructive pulmonary disease, CO=carbon monoxide, NO_2 =nitrogen dioxide, UFP=ultra fine particles, NA= not applicable, SO_2=sulfur dioxide