Towards high quality, low-carbon ventilation in airtight buildings

AIVC International Workshop

Tokyo, Japan

18-19 May 2023

Workshop description

NILIM and BRI of Japan, together with the Air Infiltration and Ventilation Centre (AIVC) organized a workshop entitled "Towards high quality, low-carbon ventilation in airtight buildings" held on 18-19 May 2023 in Tokyo, Japan.

The 2-day workshop provided the opportunity to Japanese researchers and engineers, as well as international experts visiting Japan, to present and discuss recent developments in relation to ventilation and airtightness. The workshop was organized in 5 thematic sessions.

In the opening session, a representative of the ministry in charge of Japanese policies toward zero carbon buildings in 2030 and 2050 described the latest concrete policy measures including energy efficiency. Latest evolutions in regulations and standards on energy performance and ventilation in Europe and the US were presented.

In the session for IEA EBC Annexes (international collaborative R&D projects), which are relevant to ventilation, latest outputs from 1) technologies for gas-phase air cleaning (Annex 78), 2) side-by-side management methods of indoor air quality and energy efficiency (Annex 86) and 3) personalized environmental control system technologies (Annex 87) were presented.

An airtight building envelope is essential especially in order to avoid heat loss due to air leakages. In non-residential buildings, in addition to wind and stack effects, air pressure caused by HVAC systems may worsen the heat loss due to the air leakages. However, it seems that effective techniques for improving the airtightness in non-residential buildings have not yet been shared enough among Japanese building engineers and researchers. Some existing approaches in Europe, North America and Japan and future perspectives for standardization were discussed in the airtightness session.

In the session on approaches to search for more energy efficient and reliable ventilation systems, the latest standards for testing heat recovery effectiveness in laboratories were reviewed with test examples, in which key characteristics of products influential on the actual effectiveness were demonstrated. Characteristics of the Japanese market of energy recovery ventilators and improvements in the latest products were analyzed. Performance assessment of other energy efficient ventilation strategies and smart ventilation was also discussed.

In the session on the role of ventilation in infection control, a Japanese government proposal in July 2022 on effective ventilation to avoid infections by large aerosol and small floating aerosol diffusion was reviewed with some actual infection case studies. Also, the characteristics of aerosol transmission route of respiratory pathogens and their mitigation strategies were discussed by building physics researchers, collaborating with medical experts in the committee dedicated to the Japanese infection control strategies. Other presentations discussed new developments in ventilation standards and regulations, and advances in measurement techniques.

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Programme

Day 1 – Thursday May 18th 2023					
Opening Chairs: *Takao Sawachi (BRI), Peter Wouters (INIVE)*					
09:00	Welcome on behalf of NILIM	Takahiko Hasegawa (Deputy Director-General, NILIM, JP)			mp4
09:10	Welcome on behalf of BRI and overview of IEA-EBC	Takao Sawachi (EBC Executive Committee Chair, JP			mp4
09:20	Overview of AIVC, TightVent, venticool & IEQ-GA	Arnold Janssens (AIVC Operating Agent/INIVE/UGent, BE)		PPT	mp4
09:30	Japan's Policy toward Carbon Neutrality in the Housing and Building Sectors	Takashi Imamura (Housing Bureau-MLIT, JP)	Abstract	PPT	mp4
09:55	Context and policies for energy and ventilation in Europe, new evolutions in EPBD	Jaap Hogeling (EPB-Center/REHVA/ISSO, NL)	Abstract	PPT	mp4
10:20	Ventilation standards in the US	Iain Walker (LBNL, USA)	Abstract	PPT	mp4
10:45	**Break**				
IEA-EBC Annexes Chairs: *Hilde Breesch (KU Leuven), Kazuhide Ito (Kyushu University)*					
11:15	A general overview of IEA-EBC Annex 78: Supplementing ventilation with gas-phase air cleaning, implementation and energy implications	Pawel Wargocki (DTU, DK)	Abstract	PPT	mp4
11:30	International standardization of testing perceived air quality and the supporting information from in silico model for transport efficiency of acetone from indoor to olfactory epithelium cells	Kazuhide Ito (Kyushu University, JP)	Abstract	PPT	mp4
11:55	An update on IEA-EBC Annex 86: Energy efficient smart IAQ management in residential buildings	Jelle Laverge (UGent, BE)	Abstract	PPT	mp4
12:10	Dallying with DALYs: a harm-based approach to IAQ acceptability	Benjamin Jones (Nottingham University, UK)	Abstract	PPT	mp4
12:35	**Break**				
13:35	IEA-EBC Annex 87: Energy and indoor environmental quality Performance of Personalised Environmental Control Systems (PECS)	Bjarne Olesen (DTU, DK)	Abstract	PPT	mp4
13:50	Personal environment comfort system (PECS) for improving thermal comfort and IAQ in a zero energy building	Shin-ichi Tanabe (Waseda University, JP)	Abstract	PPT	mp4
14:15	Discussion				
Quality assurance of ventilation and heat recovery systems Chairs: *Alireza Afshari (Aalborg University), Masaki Tajima (Toyohashi University of Technology)*					
14:35	Actual effectiveness of energy/heat recovery ventilators in buildings: how is it influenced by key design factors and testing results (airflow, airflow ratio, unit exhaust air transfer ratio)?	Tetsutoshi Kan (Better Living, JP)	Abstract	PPT	mp4
15:00	Latest trends and technologies of energy recovery ventilators in Japan	Junichi Takahashi (Mitsubishi Electric co, JP)	Abstract	PPT	mp4
15:25	**Break**				
15:55	Performance assessment framework for smart ventilation systems	Hilde Breesch (KULeuven, BE)	Abstract	PPT	mp4
16:20	Effect of indoor temperature differences and zoning on the performance of energy efficient ventilation strategies for domestic buildings	Jelle Laverge (UGent, BE)	Abstract	PPT	mp4
16:45	Discussion				

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17:05	**End of Day 1**				

Day 2 – Friday May 19th 2023					
Airtightness Chairs: *Yu Wang (Branz), Hiroshi Yoshino (Tohoku University)*					
09:00	Proposals to promote Airtightness in non-residential buildings in Japan	Kiyoshi Hiwatashi (Taisei Corporation, JP)	Abstract	PPT	mp4
09:25	Trends in building and ductwork airtightness in different countries	Valérie Leprince (Cerema, FR)	Abstract	PPT	mp4
09:50	Airtightness testing of large buildings	Iain Walker (LBNL, USA)	Abstract	PPT	mp4
10:15	Measurement for exterior wall airtightness of high-rise buildings using stack effect/individual air conditioning and outdoor air entering through entrance doors	Yuichi Takemasa (Kajima Technical Research Institute, JP)	Abstract	PPT	mp4
10:40	**Break**				
11:10	Airtightness of large buildings in Japan: current situation and a proposal for the future	Takashi Hasegawa (Eikan-Shoji, JP)	Abstract	PPT	mp4
11:35	ISO 9972: An overview of difficulties with the current standard	Benedikt Koelsch (Cerema, FR)	Abstract	PPT	mp4
12:00	Durability of building airtightness	Valérie Leprince (Cerema, FR)	Abstract	PPT	mp4
12:25	Discussion				
12:45	**Break**				
Role of ventilation in infection control Chairs: *Valérie Leprince (Cerema), U Yanagi (Kogakuin University)*					
13:45	Aerosol transmission route of respiratory pathogens and their mitigation strategies	U. Yanagi (Kogakuin University, JP)	Abstract	PPT	mp4
14:10	Countermeasures against indoor aerosol infection in Japan	Motoya Hayashi (Hokkaido University, JP)	Abstract	PPT	mp4
14:35	Using pathogen-free air to reduce infection risks in buildings (pre-recorded presentation)	Chris Iddon, (UCL, UK)	Abstract	PPT	mp4
15:00	Revision of ISO17772-1 and EN16798-1 Standards dealing with indoor environmental quality	Bjarne Olesen (DTU, DK)	Abstract	PPT	mp4
15:25	**Break**				
15:55	Role of air cleaning in infection control	Pawel Wargocki (DTU, DK)	Abstract	PPT	mp4
16:20	Developing regulations to improve IAQ and ventilation in Belgian buildings	Peter Wouters (INIVE, BE) and Arnold Janssens (UGent, BE)	Abstract	PPT	mp4
16:45	Airtightness and internal air flows in multifamily buildings	Iain Walker (LBNL, USA)	Abstract	PPT	mp4
17:10	Discussion				mp4
17:30	Conclusions				
17:45	**End of Day 2**				

Welcome on behalf of AIVC, TightVent, Venticool and IEQ-GA

Arnold Janssens
Peter Wouters
Operating Agents AIVC - INIVE

AIVC TightVent Europe BUILDING AND DUCTWORK AIRTIGHTNESS PLATFORM venticool the international platform for ventilative cooling IEQ-GA

Welcome on behalf of AIVC (1979 - ...)

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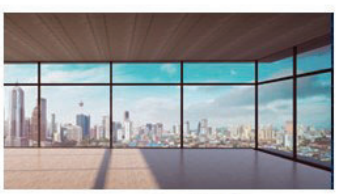
AIVC

Vision and Mission

- The **vision** of AIVC is to be the world's primary information centre on energy efficient ventilation for good indoor air quality in buildings.
- The **mission** of AIVC is to advance the worldwide knowledge and practice of energy efficient ventilation and air infiltration control of buildings, in close collaboration with other leading organisations.
  - Leveraging international technical expertise on ventilation, infiltration and indoor air quality
  - Facilitating information exchange and advanced web-based dissemination strategies between experts in research, industry and policy making.

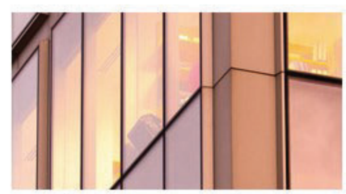
Focus fields and projects



Smart Ventilation

Resilient Ventilative Cooling

Building & Ductwork airtightness



Indoor Environmental Quality

AIVC Projects

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Events

The AIVC holds a conference each year in September/October, a workshop in March/April and several webinars, covering a wide range of topics in the field of infiltration and ventilation in buildings. The conferences and workshops take place in one of the AIVC participating countries. Since 1980, the AIVC annual conferences have been an international meeting point for presenting and discussing major developments and results regarding infiltration and ventilation in buildings.

Click on the links below to know more.

Conferences

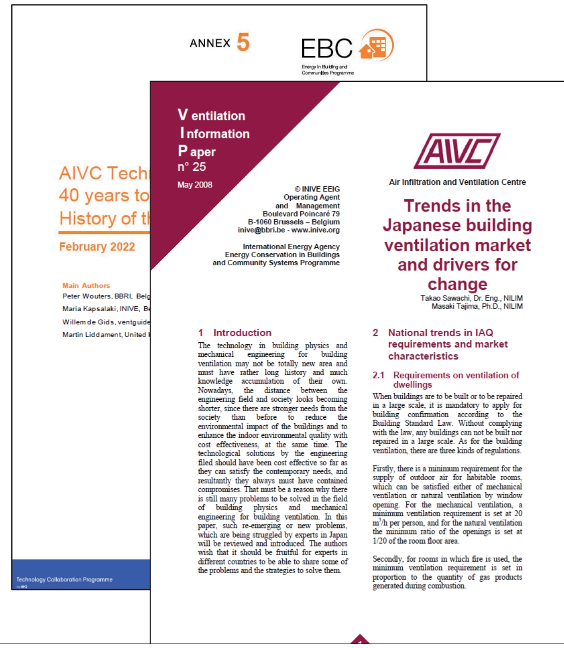
Workshops

Webinars

- **Annual conferences** in collaboration with TightVent and venticool platforms
- **Annual workshops** in collaboration with local hosts on themes of local interest
- **Webinars** presenting results of projects or publications.

Japan and AIVC

- Member country of AIVC since 2006
- AIVC-conference in Japan:
  - 2008, Kyoto, Advanced building ventilation and environmental technology for addressing climate change issues
- Specific dissemination:
  - VIP 25, Trends in the Japanese building ventilation market and drivers for changes (2008)
  - Project 'Energy Recovery Ventilation' (2021-x)



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Workshops

This section gives information on workshops organised or supported by the AIVC

Upcoming Workshops

18 May 2023

18-19 May 2023, Workshop, Tokyo, "Towards high quality, low-carbon ventilation in airtight buildings"

Mark your calendars for the upcoming AIVC 2023 Workshop "Towards high quality, low-carbon ventilation in airtight buildings" to be held on 18-19 May, 2023 in Tokyo, Japan! The workshop will take place at Bellesalle Mita (Mita, Minato-ku, Tokyo 108-6301 (Room 1). The workshop theme is "Towards high quality, low-carbon ventilation in airtight buildings".Information on registration, programme, speakers etc. will follow soon, so stay tuned.

Past Workshops

27 Mar 2019

27-28 March 2019, Symposium, Dublin, "Quality ventilation is the key to achieving low energy healthy buildings"

Sustainable Energy Authority of Ireland (SEAI) together with the Air Infiltration and Ventilation Centre (AIVC) organised a symposium entitled " Quality ventilation is the key to achieving low...

23 Mar 2018

23 March 2018, Workshop, Sydney (AU) - Ventilation for Indoor Air Quality and Cooling

Aiming to inform Australian researchers and engineers on recent developments in the field of ventilation technologies, the workshop gave international experts visiting Australia the opportunity to...

2 other related platforms managed by INIVE

Both platforms have a strong market oriented approach with active involvement of industry and practitioners

More focusing on knowledge generation aspects

AIVC

More focusing on awareness raising and market implementation

TightVent® Europe

BUILDING AND DUCTWORK AIRTIGHTNESS PLATFORM

venticool

…Building and ductwork airtightness…

…Ventilative cooling…

IEQ-GA

- Indoor Environmental Quality – Global Alliance
  - Interdisciplinary, international working group of societies interested in IEQ, to stimulate activities that will help to improve the actual IEQ in buildings
  - Created in 2019, with AIVC as founding member
- 11 full and 2 affiliate members, eg AIVC, ASHRAE, REHVA, ASA, ISHRAE,…
- Example action:
  - Joint task force on COVID-19
  - Website information centre: https://ieq-ga.net/
  - Contact with WHO Engineering Control Expert Advisory Panel (ECAP)

Thank you!

- Presenters
- Organizing committee
- Session chairs

- You: the audience!

AIVC International Workshop
Towards high quality, low-carbon ventilation in airtight buildings

Japan’s Policy toward Carbon Neutrality in the Housing and Building Sectors

18 May 2023

Takashi IMAMURA
Counsellor for Building Regulations, Housing Bureau
Ministry of Land, Infrastructure, Transport and Tourism, JAPAN

国土交通省
Ministry of Land, Infrastructure, Transport and Tourism

Energy in Building and Communities Programme

1. Background

2. Requiring Net Zero Energy Buildings

3. Retrofitting of Existing Buildings

4. Tackling Embodied Carbon

5. Promoting Wooden Buildings

GHG Emission Reduction Goals of Each Country

Country /Region	NDC (2030 goal)	Latest NDC submitted	Net zero by 2050
Japan	-46% (from 2013 levels) Japan will continue efforts to meet the lofty goal of cutting its emission by 50%.	22 October 2021	Declared
EU (Belgium, Denmark, France, Germany, Italy, etc.)	-55% or more (from 1990 levels)	18 December 2020	Declared
U.K.	-68% or more (from 1990 levels)	22 September 2022	Declared
U.S.	-50 to -52% (from 2005 levels)	22 April 2021	Declared
Canada	-40 to -45% (from 2005 levels)	12 July 2021	Declared
Australia	-43% (from 2005 levels)	16 June 2022	Declared
Brazil	-50% (from 2005 levels)	7 April 2022	Declared

Source: Compiled based on the website of UNFCCC and the Ministry of Foreign Affairs of Japan

Synthesis Report of the IPCC Sixth Assessment Report (AR6) Summary for Policymakers (20 March 2023)

B.6 All global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and those that limit warming to 2°C (>67%), involve rapid and deep and, in most cases, immediate greenhouse gas emissions reductions in all sectors this decade. Global net zero CO2 emissions are reached for these pathway categories, in the early 2050s and around the early 2070s, respectively. (*high confidence*)

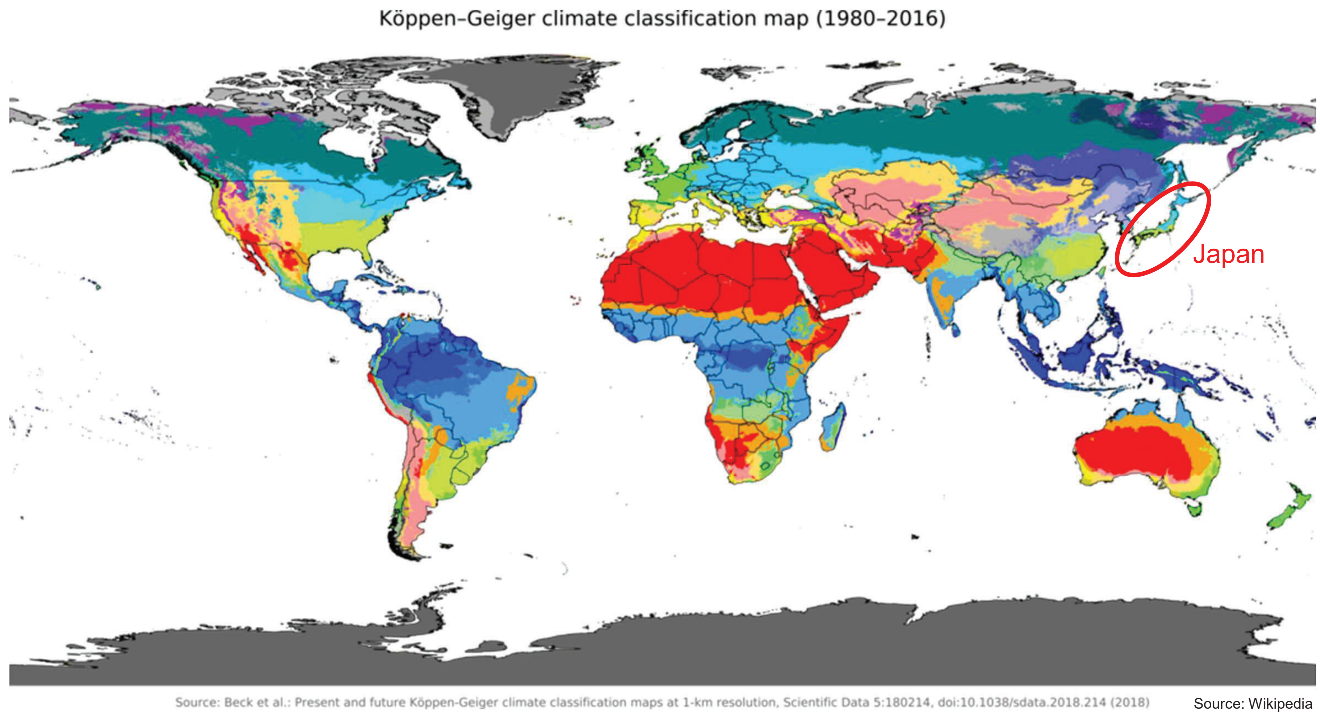
Approved Summary for Policymakers IPCC AR6 SYR

Table XX: Greenhouse gas and CO_2 emission reductions from 2019, median and 5-95 percentiles {3.3.1; 4.1; Table 3.1; Figure 2.5; Box SPM1}

		Reductions from 2019 emission levels (%)			
		2030	2035	2040	2050
Limit warming to1.5°C (>50%) with no or limited overshoot	GHG	43 [34-60]	60 [49-77]	69 [58-90]	84 [73-98]
	CO_2	48 [36-69]	65 [50-96]	80 [61-109]	99 [79-119]
Limit warming to 2°C (>67%)	GHG	21 [1-42]	35 [22-55]	46 [34-63]	64 [53-77]
	CO_2	22 [1-44]	37 [21-59]	51 [36-70]	73 [55-90]

C.1 Climate change is a threat to human well-being and planetary health (*very high confidence*). There is a rapidly closing window of opportunity to secure a liveable and sustainable future for all (*very high confidence*). Climate resilient development integrates adaptation and mitigation to advance sustainable development for all, and is enabled by increased international cooperation including improved access to adequate financial resources, particularly for vulnerable regions, sectors and groups, and inclusive governance and coordinated policies (*high confidence*). The choices and actions implemented in this decade will have impacts now and for thousands of years (*high confidence*).

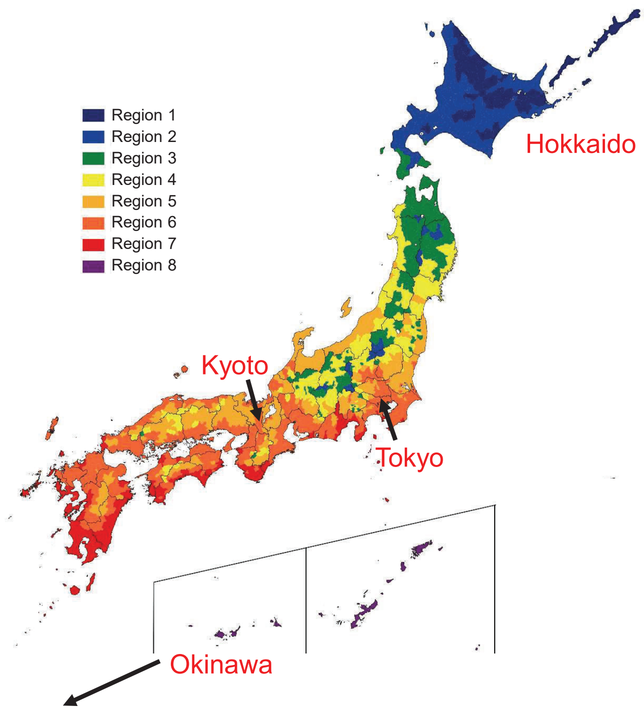
Köppen-Geiger Climate Classification Map



Source: Wikipedia

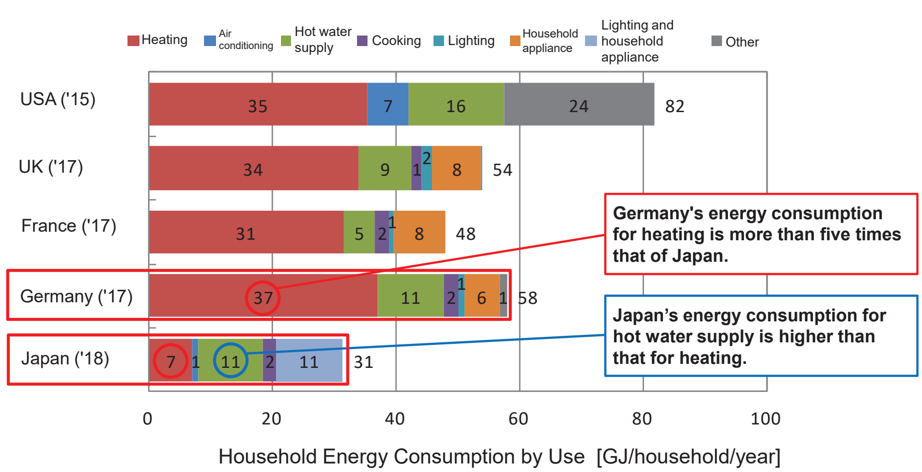
Location of Japan on top of the European Map

Regional Classification of Japan by the Building Energy Efficiency Act



International Comparison of Household Energy Consumption (by Use)

- **Energy consumption per household in Japan is about one-third of that in the U.S. and about a half that in Germany and other European countries.**
- **Japan's average energy consumption for "heating" is particularly low, while consumption of "hot water supply" is higher. Most Japanese people, except for those in northern regions like Hokkaido, heat their homes only when they are at home.**

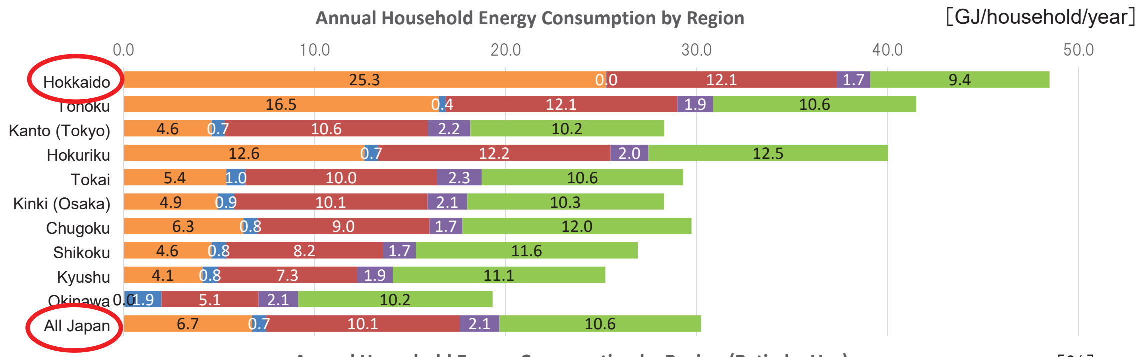


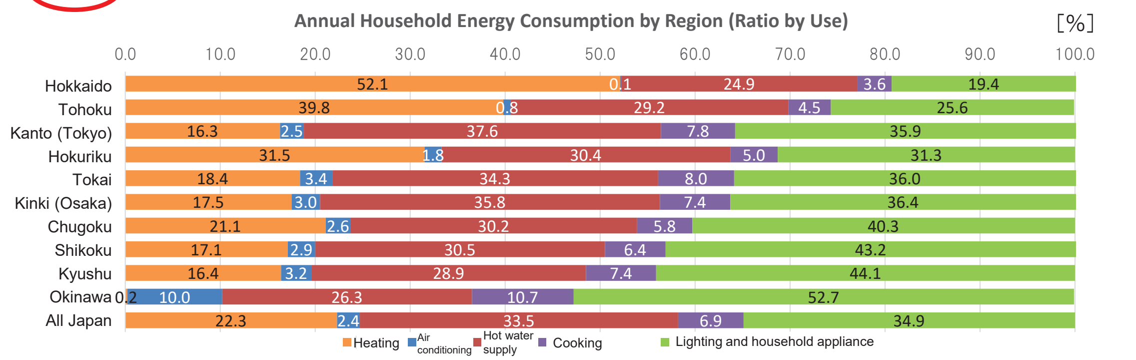
* USA.(Other) includes cooking, lighting, and household appliances.

Source: Compiled by Jukankyo Research Institute Inc. based on statistical data from various countries

Household Energy Consumption in Japan (by Region, by Use)

国土交通省

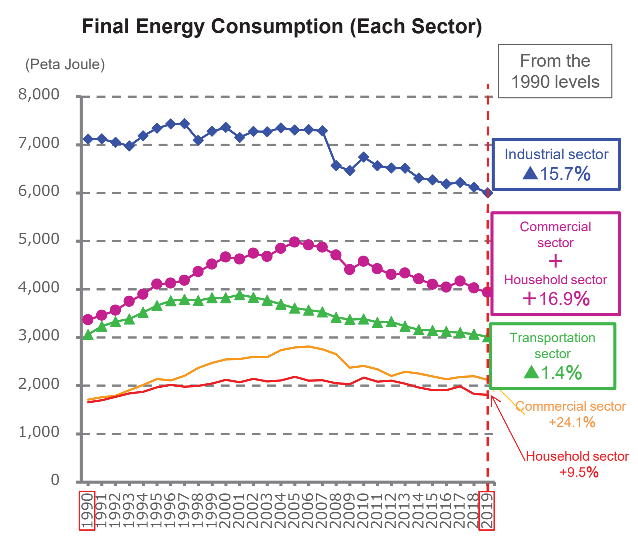


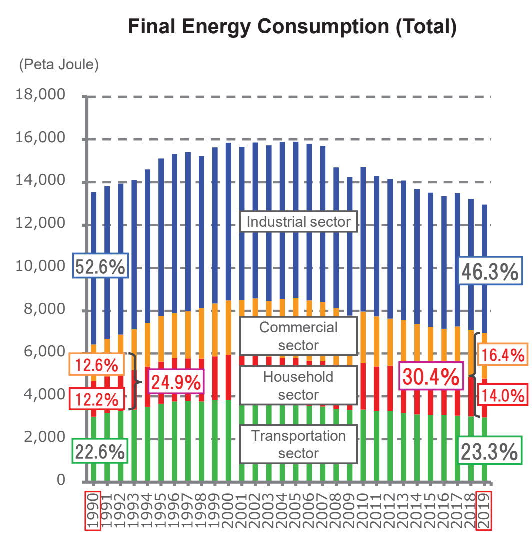


Source: Ministry of the Environment of Japan

Trends in Japan's Energy Consumption by Sector

- While other sectors (industry and transportation) have decreased, energy consumption in the commercial and household sectors have increased significantly (16.9% from the 1990 levels (left Figure)). They accounts for about 30% of total energy consumption (right Figure).
- Drastic reinforcement of energy-saving measures on houses and buildings is essential.

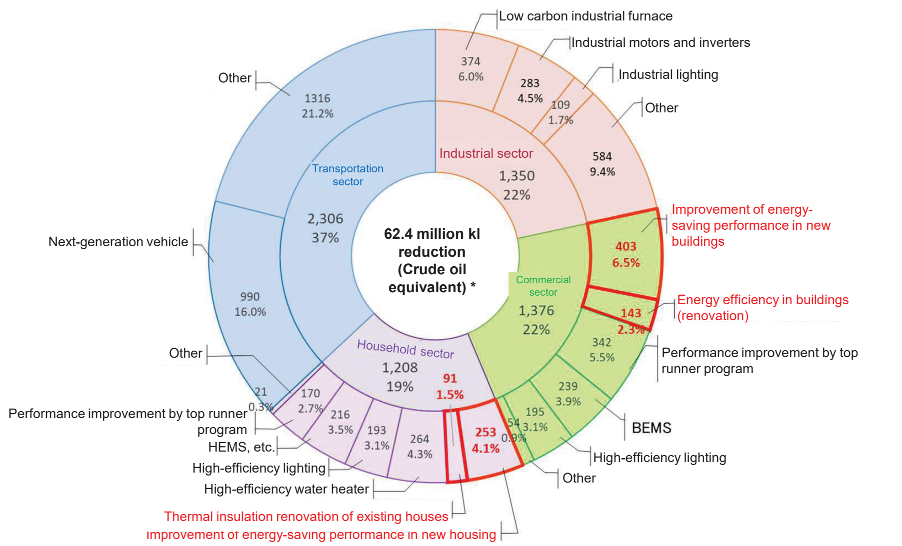




Source: Comprehensive Energy Statistics (ANRE)

Japan’s Reduction Targets in the New “Plan for Global Warming Countermeasures”

(Cabinet Decision on 22 October 2021)



➢ **Reduction targets in the field of houses and buildings**

	Amount of reduction
Newly constructed building	403
Building renovation	143
Newly constructed housing	253
Housing renovation	91
Total	889

* Total does not match due to rounding.

* Reduction target of the previous Plan for Global Warming Countermeasures (May 2016): about 50.3 million kl

Source: Energy Demand and Supply Outlook for FY2030 (Sep. 2021) (Agency for Natural Resources and Energy)

Future Policy for Building Energy Efficiency in Japan

<Basic road map set by the "Plan for Global Warming Countermeasures" (Cabinet Decision in Oct. 2021) >

- **By FY2050,**
  - ✓ Secure the level of Net Zero Energy houses and buildings on stock average.
  - ✓ Introduce renewable energy in common houses and buildings, as long as it is reasonable.
- **By FY2030,**
  - ✓ Require the level of Net Zero Energy for newly constructed houses and buildings.
  - ✓ Install solar power generation equipment for 60% of newly constructed detached houses.

<Near-future policy for building energy efficiency to be implemented by MLIT>

- **Strengthen the Building Energy Efficiency Act (Revised in June 2022 and to be Enforced soon)**
  - ✓ Require compliance with the energy efficiency standards for all the newly constructed buildings, including residential buildings, starting from FY2025.
  - ✓ Upgrade the required energy efficiency standards to the level of ZEH/ZEB standards by FY2030 at the latest.
  - ✓ Strengthen the building energy efficiency display system for residential and non-residential buildings, including existing buildings, when they are sold or leased, starting from FY2024.
- **Promote retrofitting of existing buildings by financial incentives**
  - ✓ Promote retrofitting of existing buildings by all possible financial incentives, including subsidies, tax cuts and low interest loans, but not by regulations at this moment.

Regulatory Measures under the Building Energy Efficiency Act of Japan

	The Original Act (promulgated on July 2015)		The Current Act (promulgated on May 2019)		The Act from FY2025 (promulgated on June 2022)	
	Non-residential	Residential	Non-residential	Residential	Non-residential	Residential
Large (2,000 m² or more)	Obligation of Compliance	Obligation of Notification	Obligation of compliance	Obligation of Notification	Obligation of compliance	Obligation of compliance
Medium (300 m² or more but less than 2,000 m²)	Obligation of Notification	Obligation of Notification	Obligation of compliance	Obligation of Notification	Obligation of compliance	Obligation of compliance
Small (less than 300 m²)	Obligation of Effort	Obligation of Effort	Obligation of Effort + Obligation of Architects' Explanation	Obligation of Effort + Obligation of Architects' Explanation	Obligation of compliance	Obligation of compliance

Energy Efficiency Standards for Buildings in Japan

➢ **The Japanese energy efficiency standards for buildings are the standards that are necessary to ensure the energy-saving performance required for buildings as well as building equipment. They consist of two standards: "primary energy consumption standards" and "envelope insulation standards".**

Primary energy consumption standards
(Apply to both residential and non-residential buildings)

Primary energy consumption shall be equal to or less than the standard value.

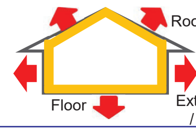
* "Primary energy consumption"
= Air conditioning energy consumption
+ Ventilation energy consumption
+ Lighting energy consumption
+ Hot water supply energy consumption
+ Elevator energy consumption
+ Other energy consumption (OA equipment, etc.)
- Energy creation by solar power generation equipment, etc. (limited to self-consumption)

Envelope insulation standards
(apply only to residential buildings)

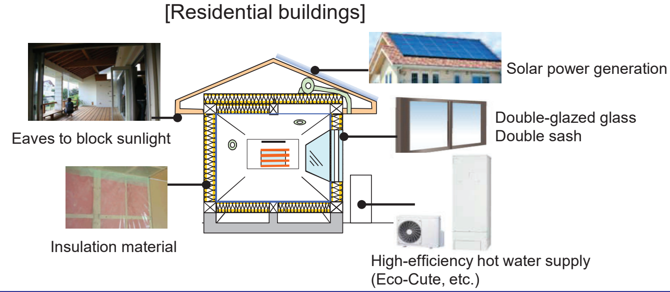
Heat loss per surface area of the "envelope" shall be equal to or less than the standard value.

<Image of heat loss through "envelope">

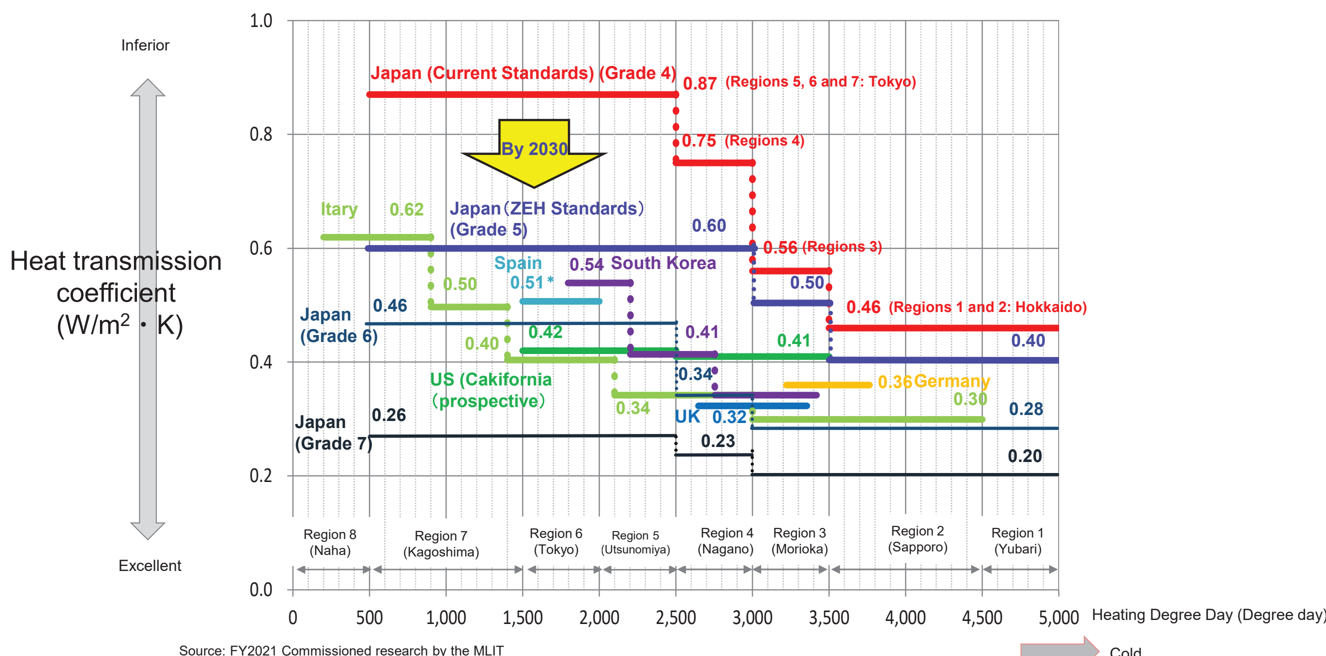
* Envelope average heat transmission coefficient
= Total heat loss / Envelope surface area



Examples of initiatives to improve energy-saving performance



Comparison of Heat Transmission Coefficient Standards (UA Value) for Housing Envelope



Source: FY2021 Commissioned research by the MLIT
"Commissioned research on energy efficiency regulations, standards, etc. in overseas housing and buildings.
* Compiled by Nomura Research Institute based on the energy efficiency standards for homes in various countries.
*Spain: Created in consideration of heating degree days (degree day) in Madrid.

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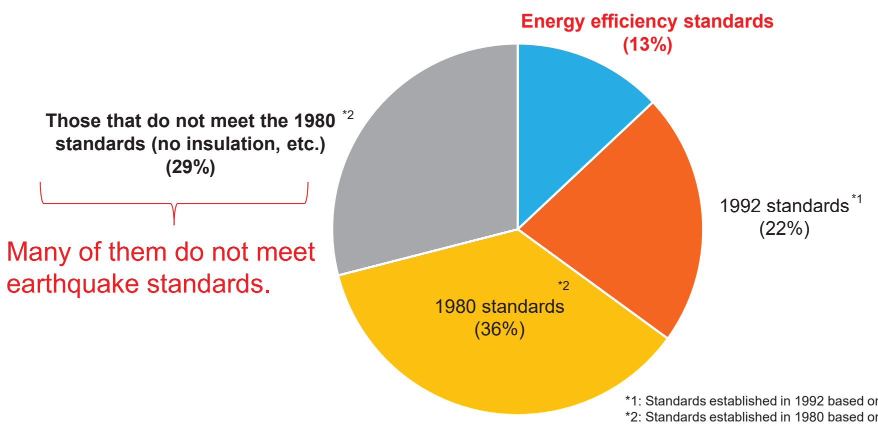
Thermal Insulation Performance of Housing Stock

- **As of FY2019, about 13% of the total housing stock (about 50 million units) complies with the energy efficiency standards, and about 29% of the total housing stock is uninsulated.**
- **According to the Housing and Land Survey (2018), the actual number of thermal insulation renovations for the housing stock in less than five years from January 2014 to October 2018 was about 720,000 units.**

Thermal insulation performance of housing stock (about 50 million units)



*1: Standards established in 1992 based on the Energy Conservation Act
*2: Standards established in 1980 based on the Energy Conservation Act

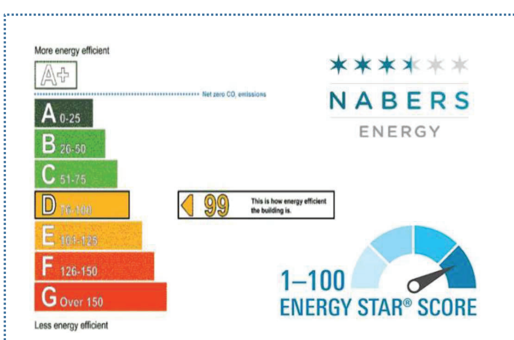
Source: Calculated based on the distribution of housing stock by performance according to the MLIT survey, reflecting the number of renovations according to the Housing and Land Survey and the estimated number of newly constructed housing units by performance based on business operator's questionnaire, etc. (FY2019).

Manga (Cartoons) for Inspiring Consumers to Energy Efficient Houses (January 2023)

Building Energy Efficiency Display System to be Strengthened in April 2024

Revision overview

- ✓ The new measures shall be taken with regard to the obligation of suppliers who sell or lease buildings to make efforts to display their energy consumption performance.
- ✓ The MLIT Minister shall establish the rules of the energy efficiency information of buildings that are to be displayed by sale/lease suppliers.
- ✓ In case the rules are not respected, the Minister is authorized to issue a recommendation that the information should be displayed, make a public announcement of names of such suppliers, and order the suppliers to execute the actions if necessary.



Energy Efficiency Display Systems in the World

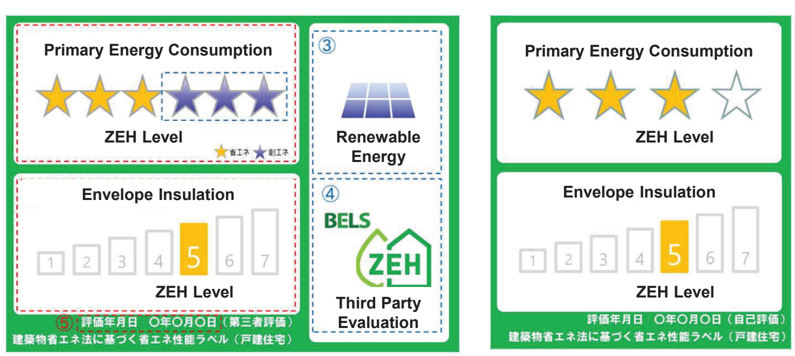


Image of the new Building Energy Efficiency Display System in Japan

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G7 Climate, Energy and Environment Ministers' Communiqué (Sapporo, April 16, 2023)

III. Climate and Energy

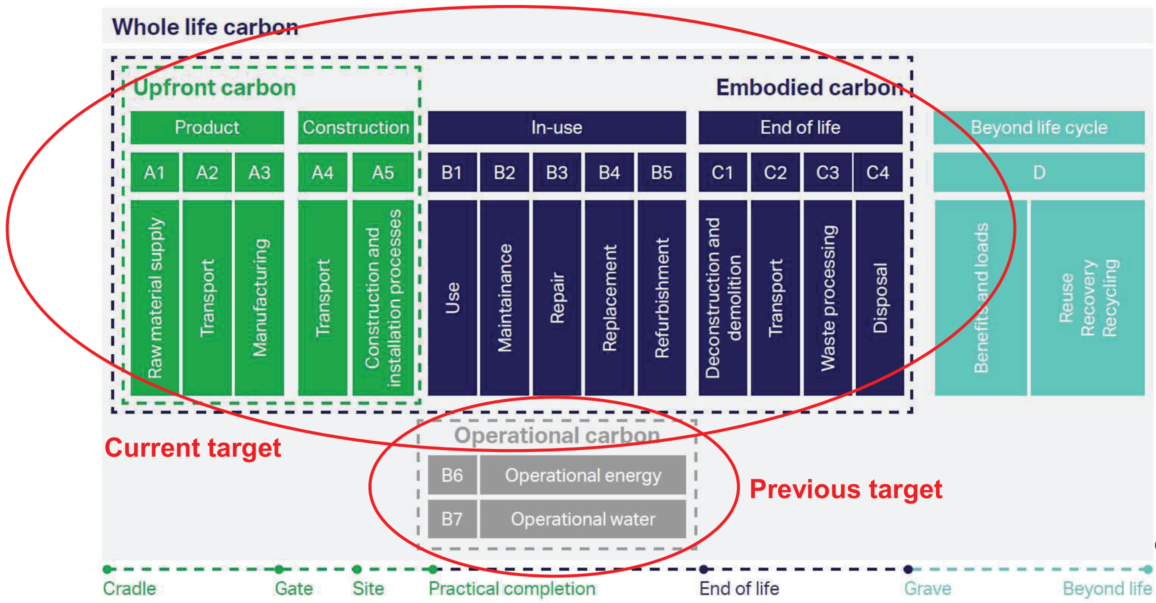
Decarbonizing Industry /Transport /Building Sector

82. Buildings: Noting the importance of decarbonizing buildings' lifecycles in combatting climate change, we recommit to advancing targets to reduce buildings' emissions across their whole lifecycle in line with keeping a limit of 1.5 ° C temperature rise within reach. We highlight the need for improved and climate-adapted building design, enhancing building energy efficiency, including through supporting measures, regulations and international collaboration so that new and renovated near-zero emission and climate resilient buildings are on the path to reach the 2050 net-zero goal. Actions will include improved energy efficiency; fuel switching, electrification and provision of heating and cooling services using renewable energy sources; sustainable consumer choices and the increased digitalization efforts to improve flexibility in building energy management. We will promote reaching zero carbon ready/zero emission new buildings, ideally by 2030 or sooner. We aim to accelerate the phaseout of the installation of new fossil fuel heating systems and the transition to cleaner technology including heat pumps. We also recognize the importance of improved use of sustainable low-carbon materials including wood and end use equipment by using a whole lifecycle buildings approach in design and considering the circularity in the renovation and construction of buildings, as well as decarbonizing the production of conventional materials.

Definition of World Business Council for Sustainable Development, WBCSD

Net-zero buildings: Where do we stand?

Figure 7: Whole life cycle stages, EN15978 (2011)[10]



Carbon Emissions per Life Cycle Stage

Figure 4: Estimated distribution of carbon emissions per life cycle stage

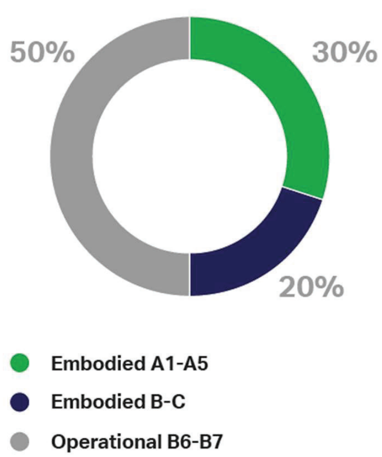
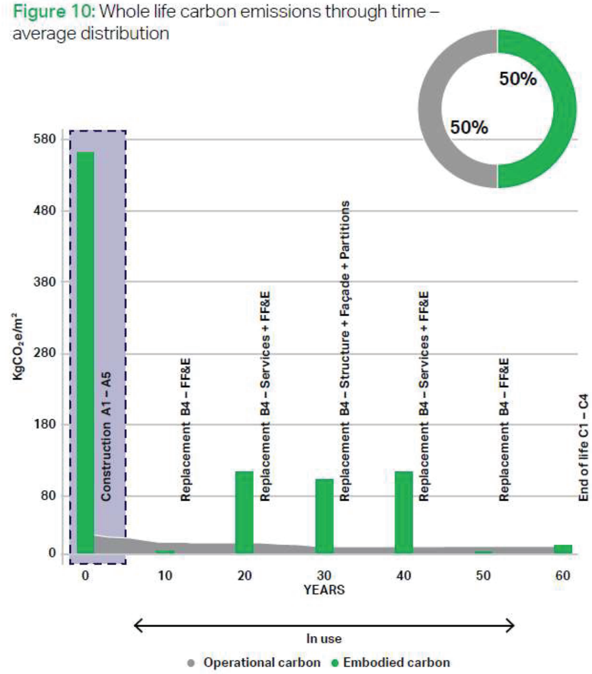
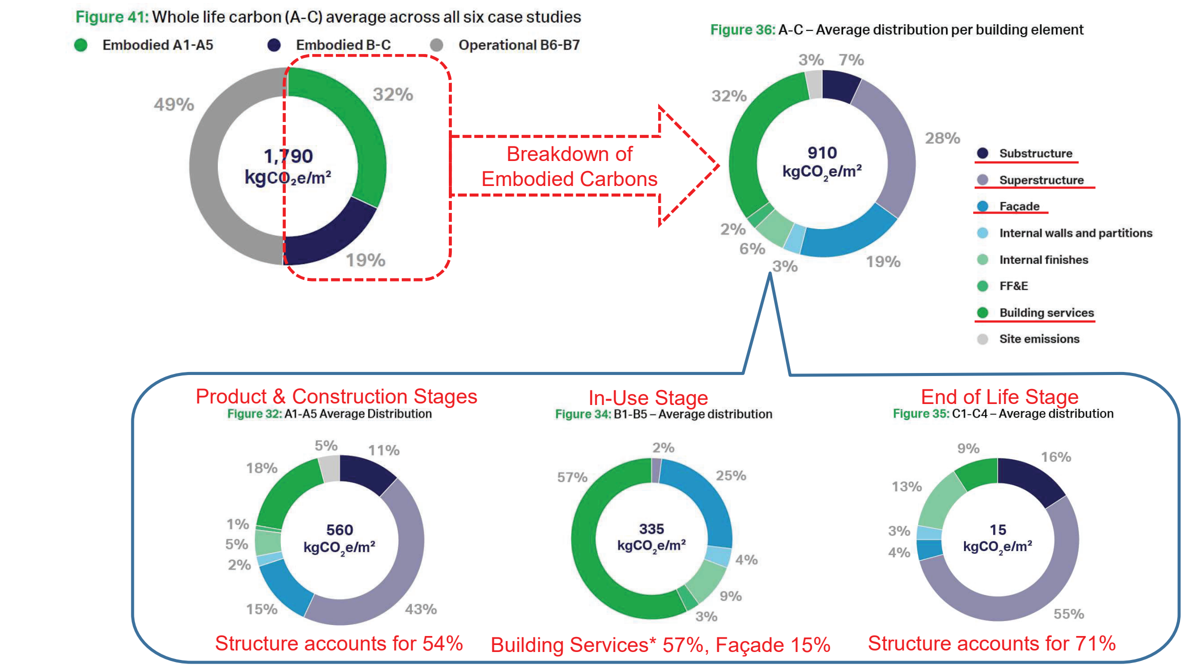


Figure 10: Whole life carbon emissions through time – average distribution



Average Distribution of Embodied Carbons (WBCSD/ARUP 6 Case Studies)

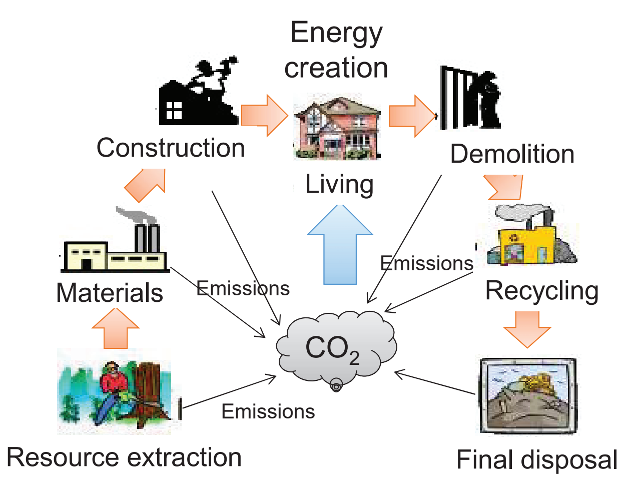


*equipment replacement, refrigerant leakage, etc.

Japan's LCCM (Life Cycle Carbon Minus) Housing -- Beyond Net Zero Energy

Definition of LCCM Housing

Housing that achieves negative CO2 emissions throughout their entire life cycle (from construction to demolition and reuse, etc.) by reducing CO2 emissions at material manufacturing and construction stages in addition to CO2 emissions at the use stage, and by extending the service life.



Envisioned Life Cycle and CO2 Emissions

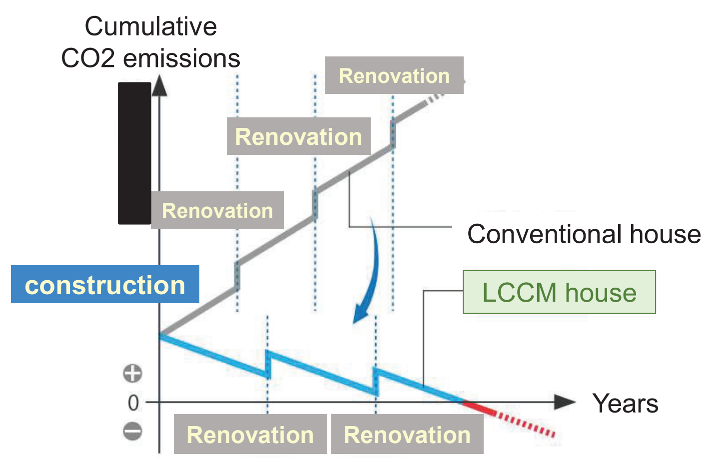


Illustration of CO2 Emissions throughout Whole Life Cycles

1. Background

2. Requiring Net Zero Energy Buildings

3. Retrofitting of Existing Buildings

4. Tackling Embodied Carbon

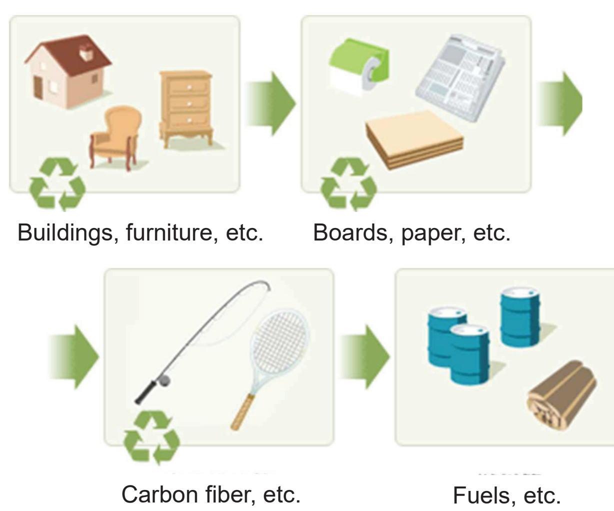
5. Promoting Wooden Buildings

Wood as an “Eco-Material” (Reduction of Environmental Burden)

- Carbon fixation
- Energy consumption
- Recycling

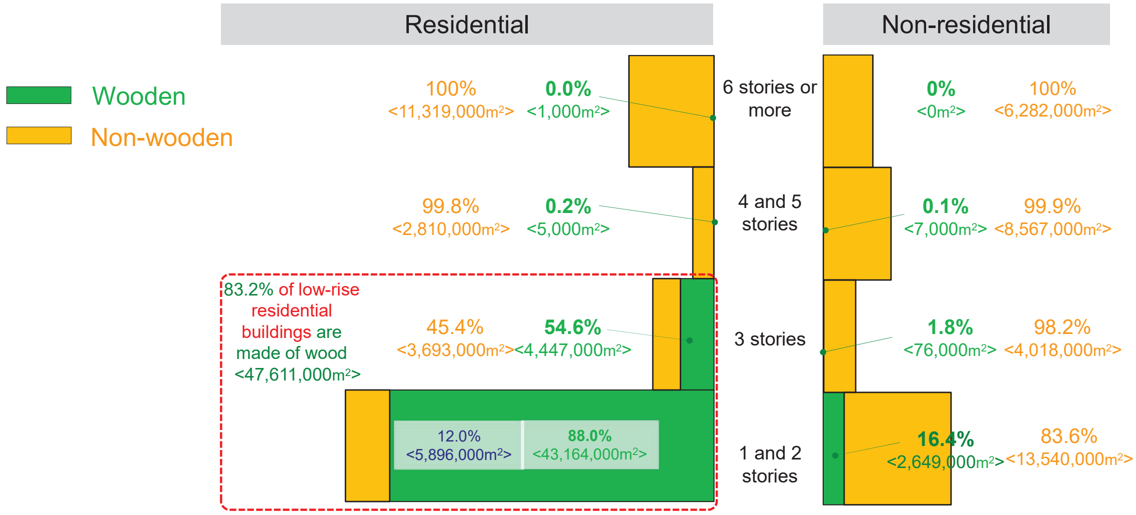
	Wooden	Steel prefabricated	Reinforced concrete
Stored volume of carbon	6 tons of CO_2	1.5 tons of CO_2	1.6 tons of CO_2
CO_2 emissions during manufacture of materials	5.1 tons of CO_2	14.7 tons of CO_2	21.8 tons of CO_2

Stored volume of carbon per house and CO_2 emissions during manufacture of materials



Prepared based on the FY2019 Annual Report on Forest and Forestry in Japan

Percentage of Wooden Buildings among New Buildings (Construction starts in FY2021, floor area)



	Residential		Non-residential		Total	
Wooden	47,617,000m^2	66.8%	2,731,000m^2	7.8%	50,348,000m^2	47.3%
Non-wooden	23,718,000m^2	33.2%	32,408,000m^2	92.2%	56,126,000m^2	52.7%
Total	71,335,000m^2	100%	35,139,000m^2	100%	106,474,000m^2	100%

* New constructions only. Extensions and rebuilding are not included. * Residential buildings include "dedicated residential buildings," "dedicated quasi-residential buildings," and "combined residential and industrial use buildings."

(FY2021 "Construction Starts Statistics")

Immediate Challenges to Promote the Use of Wood in Buildings

- Further rationalizing the building code
  - ✓ Especially, fire protection regulations for mid-rise and high-rise wooden buildings
- Promoting people's better understanding (Dispatching information)
  - ✓ Highlight contribution to carbon neutrality
  - ✓ Clear up the negative image of wood (weak, combustible, etc.)
- Reducing construction cost (Technological development & business efforts)
  - ✓ Wooden is 10-15% more expensive than non-wooden?

Context and policies for energy and ventilation in Europe, new evolutions in EPBD

The IPCC reports on Climate Change: the drivers for European Union to launch policy programs like: EU Green Deal –Fit for 55 by 2030- Renovation Wave and REPowerEU plan (05/2022)

- Jaap Hogeling
- Chair CEN/TC 371 Energy Performance of Buildings
- ISO/TC 163/WG 4: Joint Working Group (JWG) between ISO/TC 163 and ISO/TC 205:Energy performance of buildings using holistic approach

The EPB Center is an initiative of ISSO and REHVA www.rehva.eu and was supported by the EU-Commission

www.epb.center

jaap.hogeling@epb.center

My background

- CEN/TC 371: Energy Performance of Buildings, chairperson since 2004
- Project leader of the EU Mandate/480 to CEN regarding the development of the set of EPB standards.
- Participation in 5 CEN/TC's and 2 ISO/TC's related to Energy Performance of Buildings
- Manager international standards at ISSO, Rotterdam, the Netherlands
- Initiator of EPB Center (an initiative of ISSO and REHVA)
- Fellow of ASHRAE and REHVA
- Officer at **I**ndoor **E**nvironmental **Q**uality **G**lobal **A**lliance board www.IEQ-GA.net

EU Green Deal – Fit for 55 by 2030 Renovation Wave REPowerEU plan (05/2022)

- **drivers for the EPBD revision in 2022/23,**
- **will it affect the use of the set of EPB standards?**
- **A need to revisit the set of EPB standards**

EU Green Deal, Renovation Wave, Fit for 55 by 2030, towards Zero Carbon emission by 2050 drivers to revisit the EPBD

- EPBD: Buildings are acknowledged as one of the key focus areas for the European Green Deal and more specific the Renovation Wave Strategy.
- ambition: at least double annual renovations of EU building stock with focus on **deep renovation to 3%**
- **Basis for the urgent revision of EPBD (version 2018) to direct the national renovation strategies to achieve a decarbonised building stock by 2050**
- **3 focus areas in Renovation Wave:**
  - tackling energy poverty and worst-performing buildings> **towards healthy housing**
  - lead examples: priority for renovation of public buildings
  - **decarbonisation** of energy delivered to and exported from the buildings
- To accomplish this the Commission promotes:
  - MEPS (Minimum Energy Performance Standards) , MS's shall set, and regularly review, these requirements with a view to achieving at least cost-optimal levels, Those requirements shall take account of general indoor climate conditions, in order to avoid possible negative effects such as inadequate ventilation
  - The use of EPC's (Certificates) and Building Renovation Passports, which shall include information on circularity as well as wider benefits related to health, comfort, IEQ, safety…. (art 10)

European green Deal: Carbon/Climate neutral by 2050

- The Building is no longer an energy consumer, but also an energy producer
- Optimize:
  - **Energy efficiency first:** building envelope & building systems
  - **Decarbonize** energy carrier and produce on-site **RENEWABLES**
  - Interaction with the energy grid (hourly/storage..) **Smart Readiness of buildings to become operational (SRI)**
- Step by Step towards Zero CO2
  - We have to show the impact of our components (products) in the energy chain:
    - AC, Heat Pump.. is not longer evaluated as a product, just looking at the product label, but part of the building system in a holistic way
  - We have to address the embodied Carbon as well!

EPBD: Energy Performance Buildings Directive of 2018 revisited in 2022/23: some basic assumptions

- An EU Directive gives guidance to the EU Member States regarding national regulation in a certain field, the EPBD is about energy performance of buildings regulation
- In the revision process and the negotiations between the EU Commission, the EU Parliament , the EU Council of governments and relevant stakeholders the need to regulate EP of buildings and the Indoor Environmental Quality of buildings in the same way
- EPB assessment should be calculated on basis of a methodology which includes IEQ assessment. (rec. 12)
- This shall be addressed for new buildings but more essential for the to renovate existing building stock
- Deep-renovation shall include aspects like IEQ improving the health standards of living conditions especially of vulnerable households.(rec 33)

EPBD: Energy Performance Buildings Directive of 2018 revisited in 2022/23: some basic assumptions

- EU MS's should support EP upgrades that contribute to achieve a healthy IEQ (rec. 35)
- The EP Certificate of buildings should include both : data on EP and IEQ and recommendations to improve the EP and report about LCA GWP (rec. 47a)
- Better high performing EP buildings should avoid overheating having improved IEQ conditions and care about the micro climate around buildings (rec. 52)
- Delegated acts are needed by 2027 on the cost optimality of MEP's towards Zero-emission Buildings, Life Cycle GWP, respecting at the same time minimum Indoor Environmental Quality Standards. (rec. 57)

EPBD: Energy Performance Buildings Directive of 2018 revisited in 2022/23: proposed articles (2023-03) related to IEQ

- Art 1.1 : Zero emission buildings by 2050 taking in to account amongst others: the requirements for IEQ
- Art 1.2 EPBD lays down : the IEQ performance of buildings
- Art 2.37 Digital Building Logbook: includes all relevant building data such as EP, Renovation Passport, SRI, LC GWP and IEQ, **IEQ** is also mentioned in further definitions
- Art 3 National Renovation Plans shall encompass: evidence energy savings, GHG reductions and wider benefits including IEQ
- Art 5.1 setting MEPs: MEP requirements shall take account of Health Indoor conditions based on optimal IEQ… (to be reviewed every 5 years)
- Optimal IEQ levels are also required for New and Deep Renovated buildings within 2 years after EPBD is in force, also taking climate change risks in to account

EPBD: Energy Performance Buildings Directive of 2018 revisited in 2022/23: proposed articles (2023-03) related to IEQ

- Art 10 Renovation Passports: shall comprise information on circularity as well wider benefits related to health, comfort, IEQ, safety, …
- Art 11 Technical Building Systems: Require installation of measuring and control devices for monitoring and regulation IEQ at relevant unit level where technical and economical feasible (where measurable health benefits are taken in account) for the following buildings :
  - Zero Emission buildings
  - New buildings
  - Existing buildings major renovated
  - Non-residential buildings with H&C combined > 70 kW
  - Public buildings

The economic feasibility should take in account the measurable health benefits MS shall ensure that data on IEQ are to be included in the digital building logbook

- B&C systems required for non-res buildings with H&C >240 kW by 2024 and H&C>70 kW by 2029 capable to effective IEQ monitoring to ensure occupants Health and Safety.

EPBD art 11a: IEQ

- 11.1-2 MSs shall set requirements for implementation of adequate IEQ standards in order to maintain a healthy indoor climate. By 24 months after the EPBD is in force measurable indicators based to those in the Levels framework, these indicators shall include:
  - CO2
  - Temperature, thermal comfort
  - Relative humidity
  - Day-light levels
  - Ventilation rate, air change rate per hour
  - Acoustic comfort

EPBD art 11a: IEQ

- **Particulate matter of emissions of indoor sources and target pollutant limits from indoor sources, on VOCs, classified as carcinogenic, mutagenic,** or toxic for reproduction according to Regulation (EC) No 1272/20081, including formaldehyde, shall be reported on the basis of the available data at product level, or direct measurement where available, of the relevant sources in relation to the indoor environment of the building.
- The EU Commission is empowered to adopt a delegated act to supplement this EPBD by establishing a methodology framework for calculating IEQ standards
- Member States shall ensure that new buildings and buildings undergoing major renovation comply with adequate indoor environmental quality standards.

Art 13 SRI: Smart Readiness Indicator

- The Commission shall adopt delegated acts concerning an optional common Union scheme for rating the smart readiness of non-residential buildings.
- The rating shall be based on an assessment of the capabilities of a building or building unit to adapt its operation to the needs of the occupant, in particular concerning **indoor environmental quality** and the grid and to improve its energy efficiency and overall performance.
- Per 2025 for buildings with H&C > 290 kW and per 2030 for >70 kW.

EPBD: Energy Performance Buildings Directive of 2018 revisited in 2022/23: proposed articles (2023-03) related to IEQ

- Art 15a,f One stop shop for energy efficiency in buildings: Supporting awareness and incentives for regulating IEQ
- Art 16 Energy Performance Certificate (EPC) :
  - 16.4: ..shall include recommendations for the cost effective improvement of the energy performance to cost-optimal level and the reduction of whole life-cycle greenhouse gases emissions, **the improvement of indoor environmental quality of a building or building unit**, …..
  - 16.5: The recommendations included in the EPC shall be technically feasible for the specific building and shall provide an estimate for the energy savings and the reduction of operational greenhouse gas emissions over the expected service life of the building **and the improvement of indoor environmental quality performance indicators.**

ANNEX I: COMMON GENERAL FRAMEWORK FOR THE CALCULATION OF ENERGY PERFORMANCE OF BUILDING

- Member States shall describe their national calculation methodology based on Annex A of the key European standards on energy performance of buildings, namely EN ISO 52000-1, EN ISO 52003- 1, EN ISO 52010-1,EN ISO 52016-1, EN ISO 52018-1,**EN 16798-1**, EN 52120-1 and EN 17423 or superseding documents. This provision shall not constitute a legal codification of those standards.
- EN 16798-1: Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics -

EPBD Annex V: Template for EPC's

- In addition, the energy performance certificate shall include the following indicators
  - …..
  - (j) the presence of fixed sensors that monitor the levels of indoor environmental quality;
  - (k) the presence of fixed controls that respond to the levels of indoor environmental quality
  - q) operational fine particulate matter (PM2.5) emissions and performance indicators for the main categories of indoor environmental quality once the relevant provisions apply;

Ventilation Standards in the US

Iain Walker
Scientist
Building Technology & Urban Systems Division

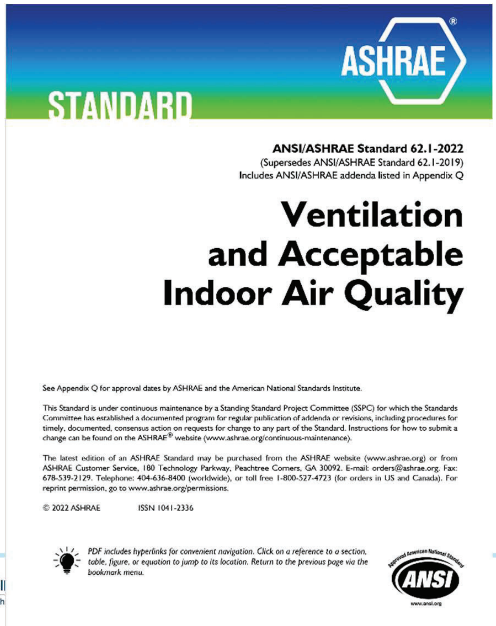
Ventilation or Airtightness Standards?

- Ventilation- Primarily used for **IAQ** reasons
  - Air flow rates
  - Filtration requirements
  - Operation: sound, controls, etc.
- Airtightness- Primarily used for **ENERGY** reasons
  - How leaky is the building envelope?
  - Determines air flows driven by wind and stack effects
  - IECC 3 ACH50 in most of country for residential
  - Area-normalized for commercial (ASHRAE 90.1 0.40 cfm/ft^2 at 75 Pa (7 m^3/h/m^2)

IECC = International Energy Conservation Code

No National building code = state-by-state adoption for regulation, often used in voluntary “above code” programs

US Ventilation Standards



STANDARD

ASHRAE

ANSI/ASHRAE Standard 62.1-2022
(Supersedes ANSI/ASHRAE Standard 62.1-2019)
Includes ANSI/ASHRAE addenda listed in Appendix Q

Ventilation and Acceptable Indoor Air Quality

See Appendix Q for approval dates by ASHRAE and the American National Standards Institute.

This Standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the Standard. Instructions for how to submit a change can be found on the ASHRAE® website (www.ashrae.org/continuous-maintenance).

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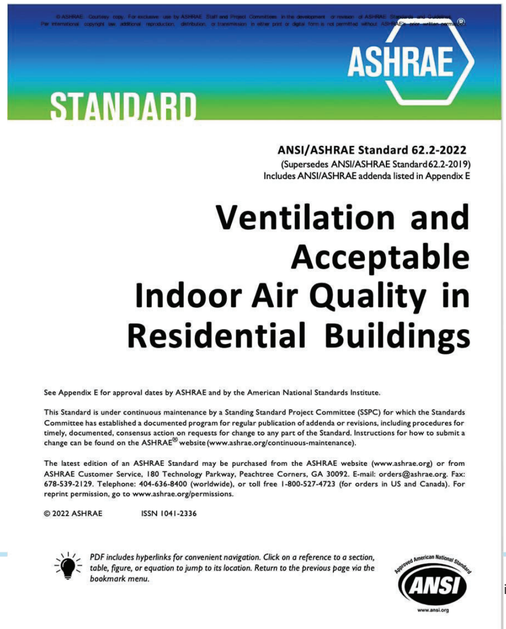
Approved American National Standard ANSI www.ansi.org



STANDARD

ASHRAE

ANSI/ASHRAE Standard 62.2-2022
(Supersedes ANSI/ASHRAE Standard 62.2-2019)
Includes ANSI/ASHRAE addenda listed in Appendix E

Ventilation and Acceptable Indoor Air Quality in Residential Buildings

See Appendix E for approval dates by ASHRAE and by the American National Standards Institute.

This Standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the Standard. Instructions for how to submit a change can be found on the ASHRAE® website (www.ashrae.org/continuous-maintenance).

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ASHRAE 62.2 – 2022 Dwelling Ventilation Rate

- Specifies dwelling ventilation rate based on floor area and number of occupants

$$Qtot\ (L/s) = 0.15 \times Afloor + 3.5 \times (Nbr + 1)$$

- Installed fan size can be reduced by taking credit for infiltration if envelope leakage is measured

$$Qfan\ (L/s) = Qtot - \Phi \times (Qinf \times Aext)$$

- Qinf = infiltration rate calculated using predefined weather and building geometry factors
- Φ = 1 for balanced ventilation, Qinf/Qtot for unbalanced ventilation
- Aext = 1 for detached dwelling units; otherwise, for horizontally attached dwelling units, the ratio of dwelling-unit boundary area that is not attached to garages or other dwelling units to total dwelling-unit boundary area

ASHRAE 62.2 – 2022 Weather Factors for Natural Infiltration

(This is a normative appendix and is part of the standard.)

NORMATIVE APPENDIX B
INFILTRATION EFFECTIVENESS WEATHER AND SHIELDING FACTORS

Table B-1 U.S. Climates

TMY3	wsf	Weather Station	Latitude	Longitude	State
722230	0.42	Mobile Regional AP	30.68	–88.25	Alabama
722235	0.42	Mobile Downtown AP	30.63	–88.07	Alabama
722260	0.39	Montgomery Dannelly Field	32.30	–86.40	Alabama
722265	0.40	Maxwell AFB	32.38	–86.35	Alabama
722267	0.34	Troy Af	31.87	–86.02	Alabama
722268	0.41	Dothan Municipal AP	31.23	–85.43	Alabama
722269	0.36	Cairns Field Fort Rucker	31.27	–85.72	Alabama
722280	0.41	Birmingham Municipal AP	33.57	–86.75	Alabama
722284	0.35	Auburn–Opelika Apt	32.62	–85.43	Alabama

ASHRAE 62.2 – 2022 Local Exhaust from Kitchens and Bathrooms

Table 5-1 Demand Controlled Local Exhaust Airflow Rates

Application	Airflow
Enclosed kitchen	• Vented range hood (including appliance-range hood combinations): 100 cfm (50 L/s) • Other kitchen exhaust fans, including downdraft: 300 cfm (150 L/s) or a capacity of 5 ach
Nonenclosed kitchen	• Vented range hood (including appliance-range hood combinations): 100 cfm (50 L/s) • Other kitchen exhaust fans, including downdraft: 300 cfm (150 L/s)
Bathroom	50 cfm (25 L/s)

Table 5-2 Continuous Local Exhaust Airflow Rates

Application	Airflow
Enclosed kitchen	5 ach, based on kitchen volume
Bathroom	20 cfm (10 L/s)

ASHRAE 62.2 – 2022 Filtration Credit

- Filtration Credit – reduces total air flow requirements, Qtot if filtered air supplied at the following rate:

Qfiltered air = F x Qtot

- Where F is a factor depending on the filter used

Table 4-4 Filtration Factor for Filters with a PM2.5 Efficiency Designation

PM2.5 Efficiency	f_{ftr}
35%	4.3
50%	3.0
70%	2.1
85%	1.8
90%	1.7
95%	1.6

ASHRAE 62.2 – 2022 Variable Ventilation

- Short term Averaging – over 3 hours or less, average ventilation is greater than or equal to constant rate
- Scheduling, real-time control and equivalent ventilation

C3.1 Nonzero Ventilation. The relative exposure for a given time step shall be calculated from the relative exposure from the prior step and the current ventilation using the following equation, unless the real-time or scheduled ventilation is zero:

$$R_i = \frac{Q_{tot}}{Q_i} + \left(R_{i-1} - \frac{Q_{tot}}{Q_i}\right) e^{-Q_i \Delta t / V_{space}} \quad \text{(C-9)}$$

where *Ri* is the relative exposure for time step *i*.

C3.2 Zero Ventilation. If the real-time or scheduled ventilation at a given time step is zero then the following equation shall be used:

$$R_i = R_{i-1} + \frac{Q_{tot} \Delta t}{V_{space}} \quad \text{(C-10)}$$

ASHRAE 62.2 – 2022 Variable Ventilation

- Can use Annual average infiltration or calculated using weather data and "enhanced" infiltration model from ASHRAE Handbook Of Fundamentals.
- Calculations must show:
  1. Annual average exposure less than or equal to that from a continuously operating system.
  2. Peak exposure < 5.

ASHRAE 62.2 – 2022 Existing Homes

- Local exhaust not required to meet minimum air flows – but additional dwelling air flow needed to compensate
- Does not have to meet sound ratings
- Does not have to meet compartmentalization requirements for multifamily
  - Uses "prescriptive" alternative

A5.1 The spaces around accessible penetrations through the dwelling-unit boundary, including but not limited to the following, shall be sealed:

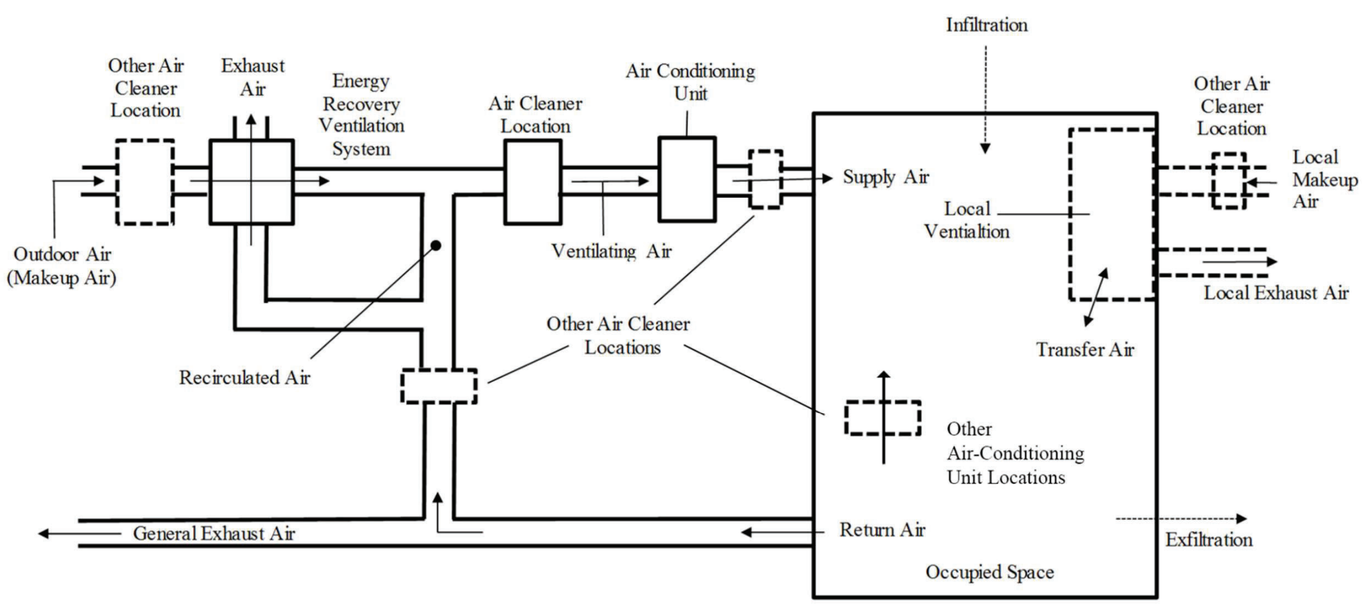
a. Vent and pipe penetrations, including those from water piping, drain waste and vent piping, HVAC piping, and sprinkler heads
b. Electrical penetrations, including those for receptacles, lighting, communications wiring, and smoke alarms
c. HVAC penetrations, including those for ventilation systems

A5.2 Accessible leaks and gaps in the dwelling-unit boundary shall be sealed, including but not limited to the intersections of baseboard trim and floor, the intersections of walls and ceilings, around window trim and dwelling-unit doors, and the termination points of internal chases in attics and crawlspaces.

ASHRAE 62.2 – 2022 Other Requirements

- Air flows must be measure/verified
- Sound: < 1 sone for dwelling unit fans, < 3 sone for local exhaust
- MERV 11 minimum filtration (about 35% of PM2.5)
- Compartmentalization test for Multifamily: < 100 L/s/100m^2
- Duct leakage <6% of fan flow at 25 Pa
- Intakes > 3m from known sources of contamination such as a stack, vent, exhaust hood, or vehicle exhaust
- Exhaust limit for homes with atmospherically vented combustion devices (furnaces, water heaters, boilers, fireplaces) of 75 L/s/100m^2
- No unvented combustion (NEW!)
- CO alarms required

ASHRAE 62.1 – Fully Designed Systems



ASHRAE 62.1 – A lot more design information

- Air balancing
- Air intake separation
- Plenum systems
- Regional Air Quality
- Maintaining pressure control in du
- Erosion and mold growth on surfaces
- Louver design (rain entrainment, (
- Classifying air for recirculation
- Defines "ventilation zones"

Table 5-1 Air Intake Minimum Separation Distance

Object	Minimum Distance, ft (m)
Class 2 air exhaust/relief outlet	10 (3)
Class 3 air exhaust/relief outlet	15 (5)
Class 4 air exhaust/relief outlet	30 (10)
Evaporative heat-rejection equipment exhaust	25 (7.5)
Evaporative heat-rejection equipment intake or basin	15 (5)
Driveway, street, or parking place	5 (1.5)
Garage entry, automobile loading area, or drive-in queue	15 (5)
Garbage storage/pick-up area, dumpsters	15 (5)
Plumbing vents terminating at least 3 ft (1 m) above the level of the outdoor air intake	3 (1)
Plumbing vents terminating less than 3 ft (1 m) above the level of the outdoor air intake	10 (3)
Roof, landscaped grade, or other surface directly below intake	1 (0.30)
Thoroughfare with high traffic volume	25 (7.5)
Truck loading area or dock, bus parking/idling area	25 (7.5)
Vents, chimneys, and flues from combustion appliances and equipment	15 (5)

Table 6-3 Airstreams or Sources

Description	Air Class
Kitchen grease hoods	4
Kitchen hoods other than grease hoods	3
Diazo printing equipment discharge	4
Hydraulic elevator machine room	2
Laboratory hoods	4
Paint spray booths	4
Refrigerating machinery rooms	3

ASHRAE 62.1 – Air flows by Space Type

- ***Breathing Zone*** air flow rates for different applications

	People Outdoor Air Rate R_p		Area Outdoor Air Rate R_a		Default Values Occupant Density		
Occupancy Category	cfm/person	L/s·person	cfm/ft²	L/s·m²	#/1000 ft² or #/100 m²	Air Class	OS (6.2.6.1.4)
Animal Facilities							
Animal exam room (veterinary office)	10	5	0.12	0.6	20	2	
Animal imaging (MRI/CT/PET)	10	5	0.18	0.9	20	3	
Animal operating rooms	10	5	0.18	0.9	20	3	
Animal postoperative recovery room	10	5	0.18	0.9	20	3	
Animal preparation rooms	10	5	0.18	0.9	20	3	
Animal procedure room	10	5	0.18	0.9	20	3	
Animal surgery scrub	10	5	0.18	0.9	20	3	
Large-animal holding room	10	5	0.18	0.9	20	3	
Necropsy	10	5	0.18	0.9	20	3	
Small-animal-cage room (static cages)	10	5	0.18	0.9	20	3	
Small-animal-cage room (ventilated cages)	10	5	0.18	0.9	20	3	
Correctional Facilities							
Booking/waiting	7.5	3.8	0.06	0.3	50	2	
Cell	5	2.5	0.12	0.6	25	2	
Dayroom	5	2.5	0.06	0.3	30	1	
Guard stations	5	2.5	0.06	0.3	15	1	
Educational Facilities							
Art classroom	10	5	0.18	0.9	20	2	
Classrooms (ages 5 to 8)	10	5	0.12	0.6	25	1	
Classrooms (age 9 plus)	10	5	0.12	0.6	35	1	
Computer lab	10	5	0.12	0.6	25	1	
Daycare sickroom	10	5	0.18	0.9	25	3	
Daycare (through age 4)	10	5	0.18	0.9	25	2	
Lecture classroom	7.5	3.8	0.06	0.3	65	1	✓
Lecture hall (fixed seats)	7.5	3.8	0.06	0.3	150	1	✓
Libraries	5	2.5	0.12	0.6	10		
Media center	10	5	0.12	0.6	25	1	
Multiuse assembly	7.5	3.8	0.06	0.3	100	1	✓

ASHRAE 62.1 – Zone Distribution Effectiveness

Zone Air Flow:

Divide ***Breathing Zone*** air flow rates by ***Effectiveness***

Complex calculation procedures for ventilation zones within the building

Table 6-4 Zone Air Distribution Effectiveness (E_z)

Air Distribution Configuration	E_z
Well-Mixed-Air Distribution Systems	
Ceiling supply of cool air	1.0
Ceiling supply of warm air and floor return	1.0
Ceiling supply of warm air 15°F (8°C) or more above space temperature and ceiling return	0.8
Ceiling supply of warm air less than 15°F (8°C) above average space temperature where the supply air-jet velocity is less than 150 fpm (0.8 m/s) within 4.5 ft (1.4 m) of the floor and ceiling return	0.8
Ceiling supply of warm air less than 15°F (8°C) above average space temperature where the supply air-jet velocity is equal to or greater than 150 fpm (0.8 m/s) within 4.5 ft (1.4 m) of the floor and ceiling return	1.0
Floor supply of warm air and floor return	1.0
Floor supply of warm air and ceiling return	0.7
Makeup supply outlet located more than half the length of the space from the exhaust, return, or both	0.8
Makeup supply outlet located less than half the length of the space from the exhaust, return, or both	0.5
Stratified-Air Distribution Systems (Section 6.2.1.2.1)	
Floor supply of cool air where the vertical throw is greater than or equal to 60 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor and ceiling return at a height less than or equal to 18 ft (5.5 m) above the floor	1.05
Floor supply of cool air where the vertical throw is less than 60 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor and ceiling return at a height less than or equal to 18 ft (5.5 m) above the floor	1.2
Floor supply of cool air where the vertical throw is less than 60 fpm (0.25 m/s) at a height of 4.5 ft (1.4 m) above the floor and ceiling return at a height greater than 18 ft (5.5 m) above the floor	1.5
Personalized Ventilation Systems (Section 6.2.1.2.2)	
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with ceiling supply of cool air and ceiling return	1.40
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with ceiling supply of warm air and ceiling return	1.40
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with a stratified air distribution system with nonaspirating floor supply devices and ceiling return	1.20
Personalized air at a height of 4.5 ft (1.4 m) above the floor combined with a stratified air distribution system with aspirating floor supply devices and ceiling return	1.50

ASHRAE 62.1 – IAQ Procedure

- Alternative to fixed air flow table
- Determine emission rates for sources
- Determine air flow rates to nc exceed given concentration limits using a mass balance analysis

Table 6-5 Design Compounds, PM2.5, and Their Design Limits

Compound or PM2.5	Cognizant Authority	Design Limit
Acetaldehyde	Cal EPA CREL (June 2016)	140 µg/m³
Acetone	AgBB LCI	1,200 µg/m³
Benzene	Cal EPA CREL (June 2016)	3 µg/m³
Dichloromethane	Cal EPA CREL (June 2016)	400 µg/m³
Formaldehyde	Cal EPA 8-hour CREL (2004)	33 µg/m³
Naphthalene	Cal EPA CREL (June 2016)	9 µg/m³
Phenol	AgBB LCI	10 µg/m³
Tetrachloroethylene	Cal EPA CREL (June 2016)	35 µg/m³
Toluene	Cal EPA CREL (June 2016)	300 µg/m³
1,1,1-trichloroethane	Cal EPA CREL (June 2016)	1000 µg/m³
Xylene, total	AgBB LCI	500 µg/m³
Carbon monoxide	U.S. EPA NAAQS	9 ppm
PM2.5	U.S. EPA NAAQS (annual mean)	12 µg/m³
Ozone	U.S. EPA NAAQS	70 ppb
Ammonia	Cal EPA CREL (June 2016)	200 µg/m³

ASHRAE 62.1 – IAQ Procedure

- Includes “perceived” IAQ based on % of occupants satisfied with IAQ
- Examples of emission rates, concentration limits and mass balance calculations given in appendices.
- Verification by measurement

Table 7-1 Allowed Laboratory Test Methods

Compound	Allowed Test Methods
VOCs except formaldehyde, acetaldehyde and acetone	ISO 16000-6; EPA IP-1, EPA TO-17; ISO 16017-1; ISO 16017-2; ASTM D6345-10
Formaldehyde, acetaldehyde and acetone	ISO 16000-3; EPA TO-11; EPA IP-6; ASTM D5197
Carbon monoxide	ISO 4224; EPA IP-3

Table 7-2 Direct Reading Instruments Minimum Specifications

	Ozone	PM2.5	Carbon Monoxide
Accuracy (±)	5 ppb	Greater of 5 µg /m³ or 20% of reading	Greater of 3 ppm or 20% of reading
Resolution (±)	1 ppb	5 µg/m³	1 ppm

Table 7-3 Number of Measurements Points

Total Occupied Floor Area, ft² (m²)	Number of Measurements
≤25,000 (2500)	1
>25,000 (2500) and ≤50,000 (5000)	2
>50,000 (5000) and ≤100,000 (10,000)	4
>100,000 (10,000)	6

ASHRAE 62.1 – Natural Ventilation

- Calculation procedure with many requirements
- Based on minimum opening areas

Table 6-7 Minimum Openable Areas: Single Openings [a]

$V_{bz}/A_z \le$, (L/s)/m²	$V_{bz}/A_z \le$, cfm/ft²	Total Openable Areas in Zone as a Percentage of A_z		
		$H_S/W_S \le 0.1$	$0.1 < H_S/W_S \le 1$	$H_S/W_S > 1$
1.0	0.2	4.0	2.9	2.5
2.0	0.4	6.9	5.0	4.4
3.0	0.6	9.5	6.9	6.0
4.0	0.8	12.0	8.7	7.6
5.5	1.1	15.5	11.2	9.8

where

Table 6-8 Minimum Openable Areas: Two Vertically Spaced Openings [a]

$V_{bz}/A_z \le$, (L/s)/m²	$V_{bz}/A_z \le$, cfm/ft²	Total Openable Areas in Zone as a Percentage of A_z					
		$H_{vs} \le$ 8.2 ft (2.5 m)		8.2 ft (2.5m) $< H_{vs} \le$ 16.4 ft (5 m)		16.4 ft (5 m) $< H_{vs}$	
		$A_s/A_l \le 0.5$	$A_s/A_l > 0.5$	$A_s/A_l \le 0.5$	$A_s/A_l > 0.5$	$A_s/A_l \le 0.5$	$A_s/A_l > 0.5$
1.0	0.2	2.0	1.3	1.3	0.8	0.9	0.6
2.0	0.4	4.0	2.6	2.5	1.6	1.8	1.2
3.0	0.6	6.0	3.9	3.8	2.5	2.7	1.7
4.0	0.8	8.0	5.2	5.0	3.3	3.6	2.3
5.5	1.1	11.0	7.1	6.9	4.5	4.9	3.2

ASHRAE 62.1 – Other Requirements

- Time averaging allowed for variable occupancy and/or air flow rate
  - Limited to a time period based on space volume and air flow rates
- Demand control air flow reset permitted based on CO_2
- MERV 8 filters required to protect equipment
- MERV 11 filters on air inlets if in a location where National Guideline for outdoor PM2.5 is exceeded
- Requirements for parking garages – pressure control
- Requirements for smoking – pressure control and transfer air controls and signage
- Requirements for ozone generating devices
- Requires and Operation and Maintenance manual and compliance with O&M requirements

Use in regulation

- ASHRAE 62.1
  - In most jurisdictions using "model energy codes" – i.e., almost universal
- ASHRAE 62.2
  - A few states require it in new construction
  - EPA Energy Star homes
  - DOE Weatherization
  - By default in home energy ratings that are now used in regulations in many states
  - Overall – much less universal than 62.1

Questions/comments

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A general overview of IEA-EBC Annex 78: Supplementing ventilation with gas-phase air cleaning, implementation and energy implications

Outline

- Introduction IEA-EBC Annex 78
- Concept of supplementing ventilation by gas phase air cleaning.
- Testing of gas phase air cleaners
- Energy impacts of using gas phase air cleaning
- Conclusions

Summary

- Operating Agents
  - Bjarne W. Olesen, Technical University of Denmark. Pawel Wargocki, Technical University of Denmark

- Time schedule
  - Preparation phase 01-07-2018 to 30-06-2019
  - Working phase 01-07-2019 to 30-06-2023
  - Reporting phase 01-07-2023 to 30-06-2024

Structure

- Subtask A: Energy benefits using gas phase air cleaning
  - Subtask leader: Alireza Afshari, Denmark
  - Co-leader: Sasan Sadrizadeh , Sweden
- Subtask B: How to partly substitute ventilation by air cleaning
  - Subtask leader: Pawel Wargocki, Denmark
  - Co-leader: Shin-Ichi Tanabe , Japan
- Subtask C: Selection and testing standards for air cleaners
  - Subtask leader: Paolo Tronville, Italy
  - Co-leader: Jinhan Mo, China
- Subtask D: Performance modelling and long-term field validation of gas phase air cleaning technologies
  - Subtask leader: Karel Kabele, Czech
  - Co-leader: Jensen Chang , USA

Concept, ref. ASHRAE 62.1 and EN16798

People Component

Building Component

Breathing Zone Outdoor Airflow

$$V_{bz} = R_p P_z + R_a A_z$$

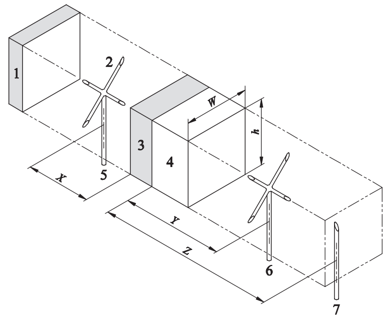
Minimum l/s/Person (R_p)

Number of People (P_z)

Building Area (A_z)

Minimum l/s/m² (R_a)

Concept, supplementing ventilation



Key

1 diffusor and Δp device
2 sampling points – should be of "fork" type or similar with multiple inlet points to make a compounded sample over the whole cross section
3 GPACD under test
4 GPACD section of test duct
5 upstream sampling point for T_U, RH_U, p_U and C_U at X mm before the GPACD
6 Downstream sampling point for T_D, RH_D, p_D and C_D at Y mm after the GPACD
7 Q, air flow rate sampling point at Z mm after the GPACD
W internal width of the test duct along the GPACD section, 3+4
h internal height of the test duct along the GPACD section, 3+4

Figure 1 — Normative section of test stand showing ducting, measurement parameters and sampling points

ISO 10121-1:2014 "Test method for assessing the performance of gas-phase air cleaning media and devices for general ventilation - Part 1: Gas-phase air cleaning media"

- **Clean Air Delivery Rate (CADR)**
  - **CADR = $\varepsilon_{PAQ} \cdot Q_{AP} \cdot (3,6/V)$**
  - where:
  - ε_{clean} or ε_{PAQ} is the air cleaning efficiency
  - Q_{AP} is the air flow through the air cleaner, l/s;
  - V is the volume of the room, m^3.
- **Air Cleaning Efficiency**
  - **$\varepsilon_{clean} = 100(C_U - C_D)/C_D$**

  where:
  - ε_{clean} is the air cleaning efficiency
  - C_U is the gas concentration before air cleaner
  - C_D is the gas concentration after air cleaner.

Methods and standards for testing gas-phase air cleaners

Standard/Protocol	Methods	Challenge Gaseous	Measured Gaseous	Performance index
Air cleaner, Standardization Administration of China (GB/T-18801)	Pulldown	Single species gas e.g.,	Formaldehyde toluene	CADR
Air cleaner, Standardization Administration of China (GB/T-18801)	Singlepass	Single species gas e.g.,	Formaldehyde toluene	Single-pass efficiency
Reduced Energy Use Through Reduced Indoor Contamination in Residential Buildings, NCEMBT (NCEMBT 061101), US report	Pulldown	Eight VOCs mixture	$TVOC_{toluene}$ formaldehyde	CADR
Air cleaner, Japanese Standard Association (JIS C 9615-2007)	Singlepass	NO_2, SO_2	NO_2, SO_2	Single-pass efficiency
Air cleaners of household and similar use, Japan Electrical Manufacturers Association (JEM 1467-1995)	Pulldown	Tobacco smoke	Ammonia, acetaldehyde, and acetic acid	Removal rate
Independent air purification devices for tertiary sector and residential applications - Test methods - Intrinsic performances, Association Française De Normalisation (XP B44-200)	Singlepass	Four VOCs mixture	Acetone, acetaldehyde, heptane, and toluen	Single-pass efficiency, CADR
Test method for assessing the performance of gas-phase air cleaning media and devices for general ventilation (ISO 29464:2017)	Singlepass	VOCs, acids, bases, and others	VOCs, acids, and bases, and others	Single-pass efficiency

Source: Afshari et al. (2022)

Challenges

- Only a few pollutants examined
- No methods for identifying by-products

BYPRODUCT GENERATION INCOMPLETE OXIDATION

- Aldehydes → **formaldehyde**, formic acid, CO
- **Alcohols** → aldehydes → acids → shorter carbon chain alcohols and acids →**formaldehyde**, methanol → CO_2 and H_2O
- Benzene → phenol
- 1-Butanol → butanal (butyraldehyde), butanoic acid, ethanol, acetaldehyde, (propanal (propionaldehyde) and propanol, propanoic acid) → (ethanol, **formaldehyde**) → methanol, **formaldehyde** and formic acid
- Ethanol → methanol, acetaldehyde, **formaldehyde**, acetic acid, formic acid
- Methanol → methyl formate (measured in liquid form only), **formaldehyde**, methylal (formaldehyde dimethyl acetal
- Toluene → benzaldehyde, benzoic acid, cresol, benzyl alcohol, phenol, benzene, formic acid

Source: Mo et al. (2009)

Assessments of perceived air quality

INTERNATIONAL STANDARD **ISO 16000-28**

First edition 2012-03-15

Indoor air —

Part 28:
Determination of odour emissions from building products using test chambers

Air intérieur —

Partie 28: Détermination des émissions d'odeurs des produits de construction au moyen de chambres d'essai

Test Panel
- Trained
- Untrained

Odour
- Acceptance
- Intensity
- Hedonic tone

Examples of diffuser and mask used for odour evaluatio

Figure C.1 — Diffuser

$$\varepsilon_{PAQ} = Q_o / Q_{AP} \cdot (PAQ / PAQ_{AP} - 1) \cdot 100$$

where:
- ε_{PAQ} is the air cleaning efficiency for perceived air quality;
- Q_o is the ventilation rate without air cleaner, l/s;
- Q_{AP} is the ventilation rate with air cleaner, l/s;
- PAQ is the perceived air quality without the air cleaner, decipol;
- PAQ_{AP} is the perceived air quality without the air cleaner, decipol

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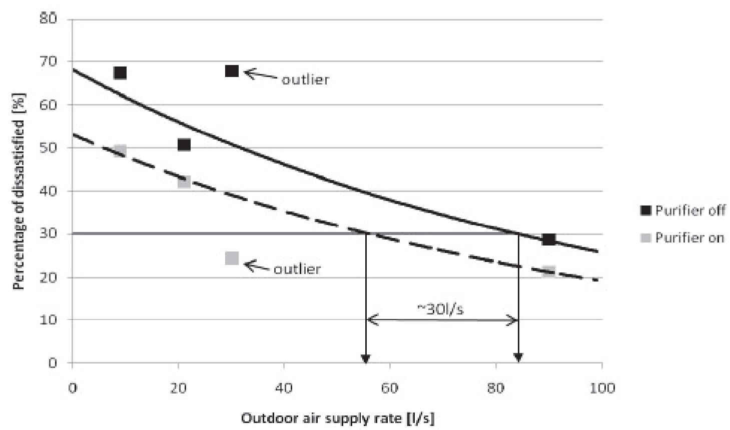
Use of perceived air quality, example



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Energy simulations, example

Source: Bogatsu et al. (2021)

Methods – air cleaner

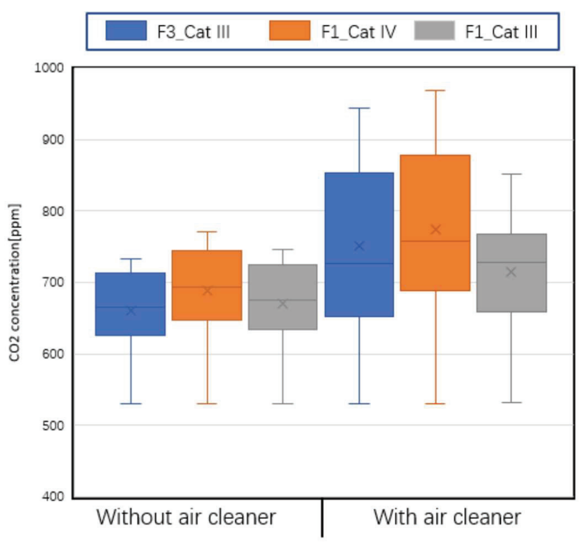
- Stand-alone air cleaner
- Air cleaner supplies clean air without any by-products
- Scenario
  - **F3 building materials and people**
  - **F1 building materials only**
- Improve IAQ from Category IV or III to Category II; PD determined empirically

Category	Level of expectation	PD [%]
IEQ_{I}	High	10
IEQ_{II}	Medium	20
IEQ_{III}	Moderate	30
IEQ_{IV}	Low	40

Source: EN 16798-1:2019

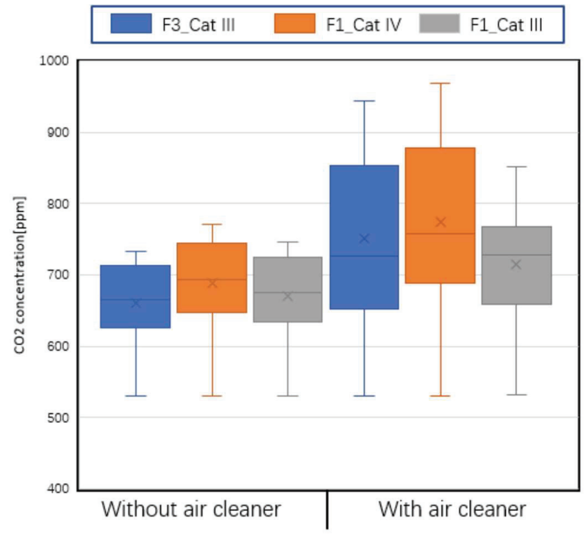
Results – IAQ

- CO_2 concentration below 1200 ppm
- Absolute CO_2 concentration (outdoor 400 ppm)



Results – IAQ

- CO_2 concentration below 1200 ppm
- Absolute CO_2 concentration (outdoor 400 ppm)



Results – Energy

- Including energy use of air cleaner
- Dependent on energy mix

Energy saving potential, F3 Building materials and people

Primary energy factors in Denmark

	Electricity	District heating
BR15	2.5	0.8
Renovation classes of BR15	2.5	1
Building Class 2020	1.8	0.6
Renovation classes of Building Class 2020	1.5	1

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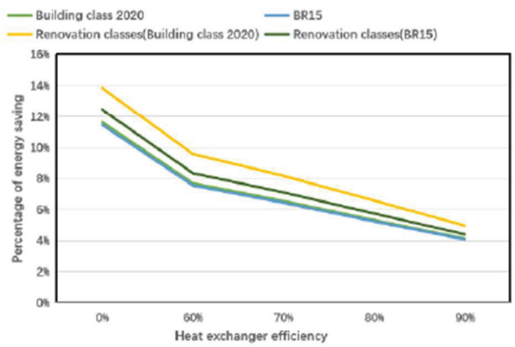
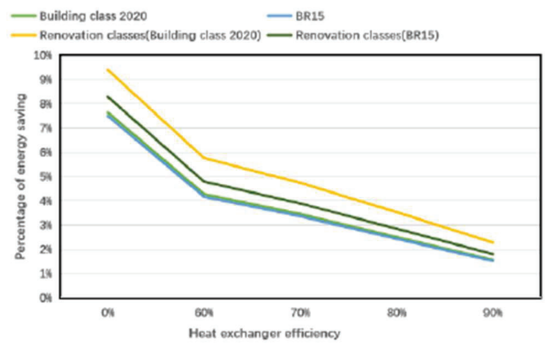
Results – Energy

- Including energy use of air cleaner
- Dependent on energy mix and airflow rate

IAQ Category IV to II



IAQ Category III to II



Energy saving potential, F1 Building materials

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Summary, energy impact

- Simulations for different climates with air cleaner providing CADR resulting in up to 50% reduction in outdoor air supply rate (Cat. II, EN16798)
- Depending on the climate, simulated energy savings reached between 1.9% and 18.2%; the savings were achieved by reducing the energy use for heating, cooling, and transporting the ventilation air

Development of a new standard for testing gas-phase air quality performance

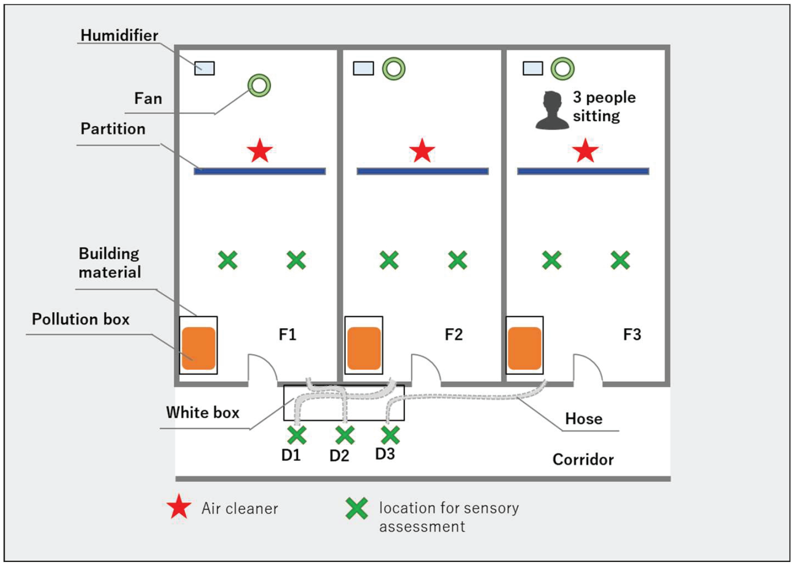
Proposal

- Two-stage-testing
- Stage 1: Pass/no pass with respect to the effect on indoor air quality
- Stage 2: Determine clean air delivery rate (CADR) and compare with equivalent ventilation requirements

- Use sensory assessment of air quality by human panel (ultimately chemical measurements)

- No testing of long-term performance

Experimental validation, setup



Sensory assessments

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Overall protocol

- Portable air cleaners were tested; all operated at close to the maximum capacity
- Air cleaners were challenged with different types of pollutants representing people and building materials
- Conditions under test: ca. 23oC (73oF) and 50%RH
- Up to four levels of ventilation with outdoor air were tested
- Different number of air cleaners were placed in the rooms during testing
- Measurements of air quality were performed with air cleaners idled and in operation

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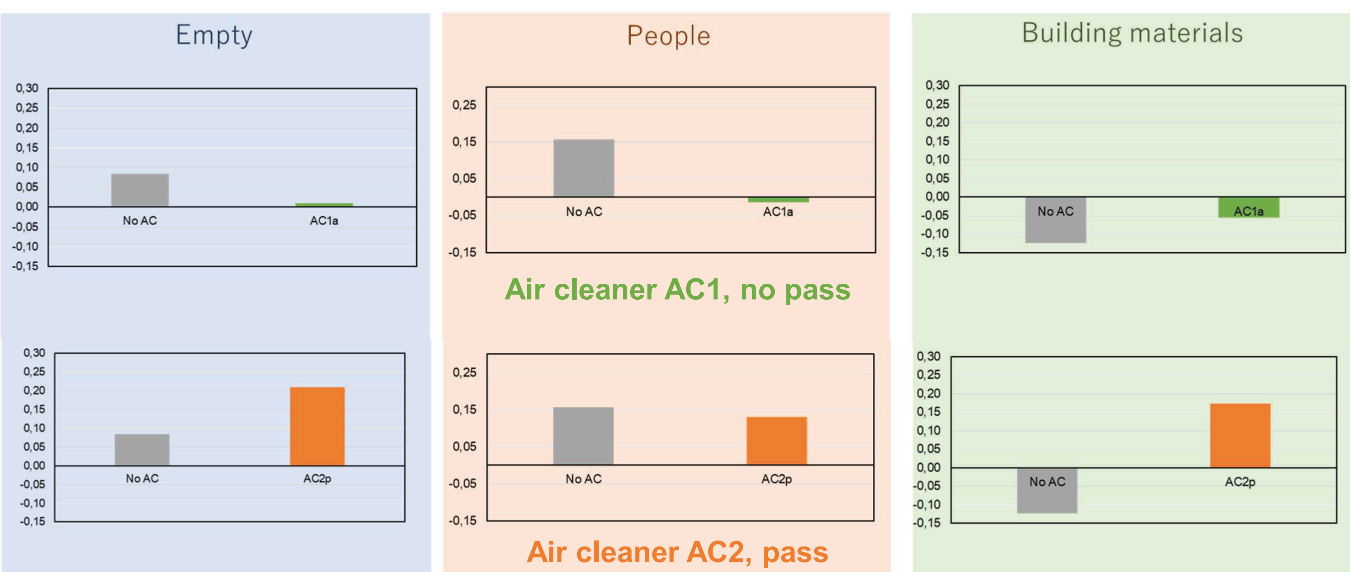
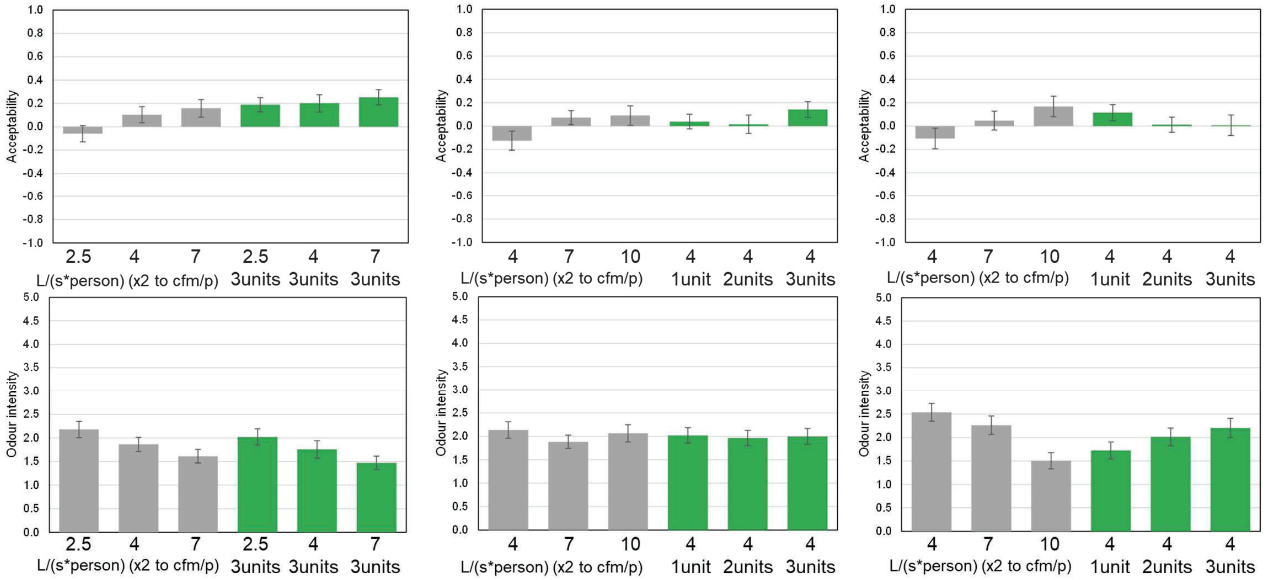
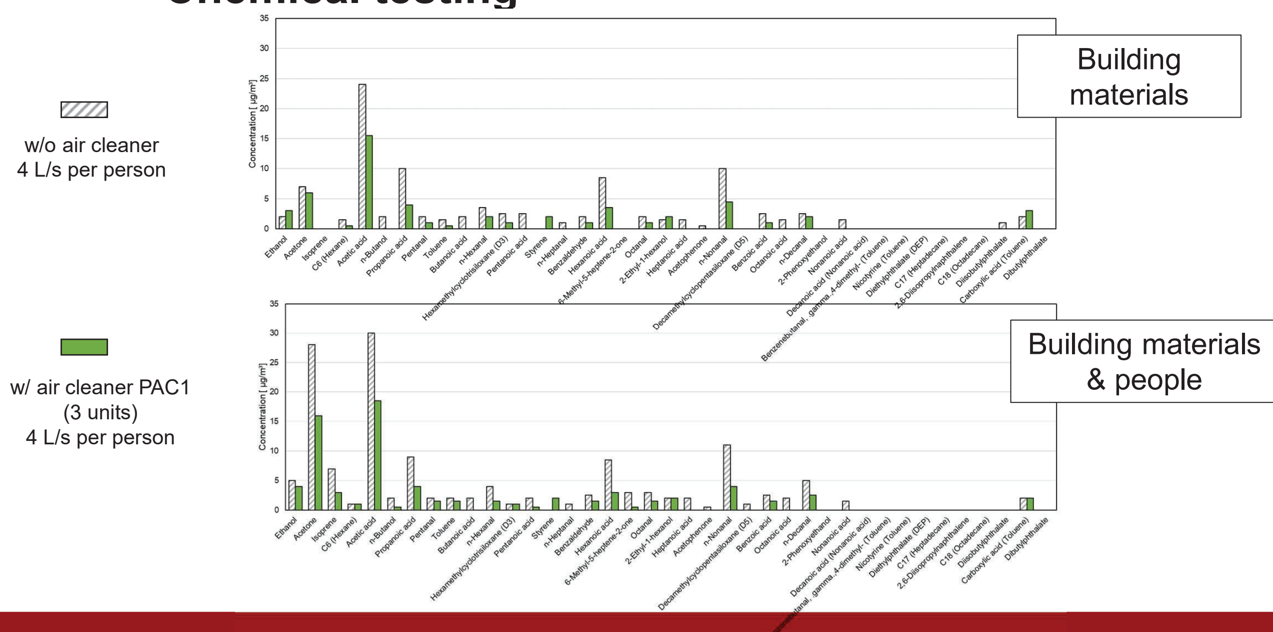
Stage 1 results, passed/not passed



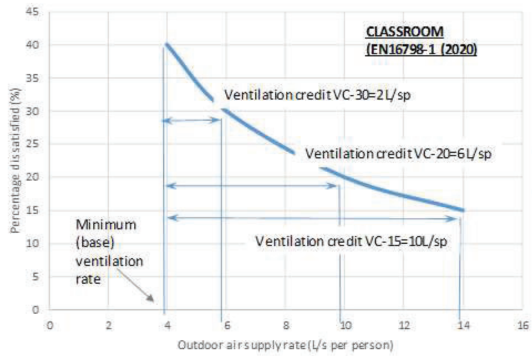
Stage 2 results

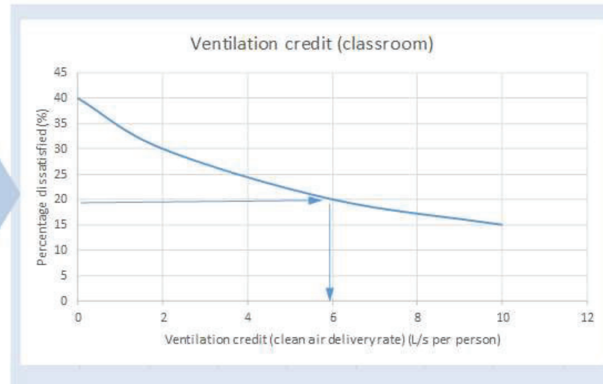


Chemical testing

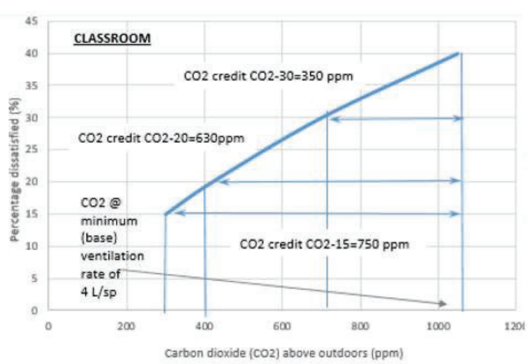


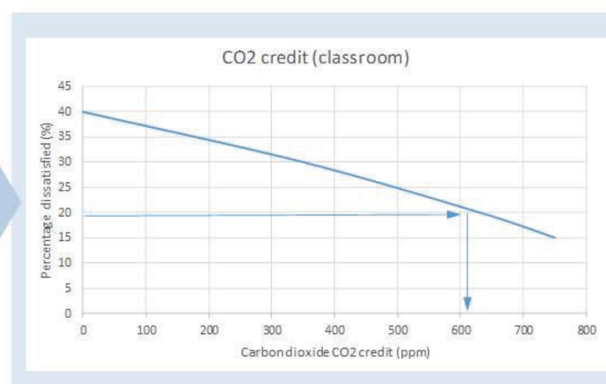
Ventilation credit or CADR?, new concept





CO_2 credit





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Conclusions

- A concept for substituting part of the required ventilation with gas phase air cleaning technology has been presented
- There is a need for new testing standards that considers perceived air quality and human emissions as a source.
- It must be verified that the reduced ventilation rate is still high enough to dilute individual contaminants.
- Adjusted CO_2 criteria must be used to express the indoor air quality and to use for demand-controlled ventilation.

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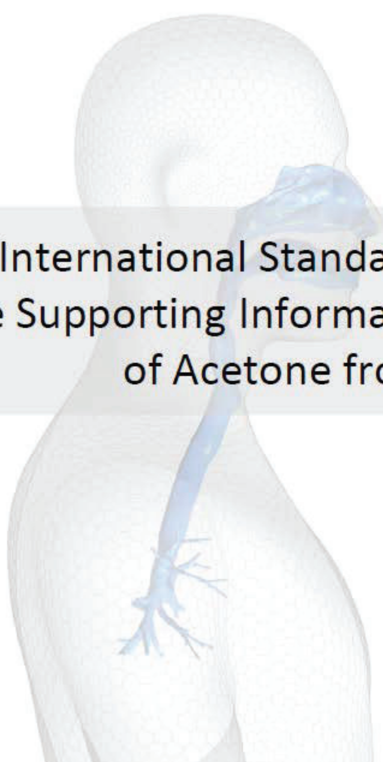
Thank You



International Standardization of Testing Perceived Air Quality and the Supporting Information from *in silico* model for Transport Efficiency of Acetone from Indoor to Olfactory Epithelium Cells

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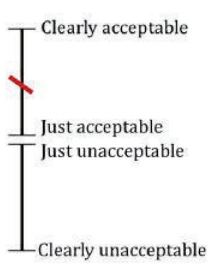
Smell/ Odour in Indoor Environment

- Perceived Air Quality / Bio-effluent
- Convener ISO TC146/SC6/WG25
  - ISO FDIS 16000-44 "Test method for measuring perceived indoor air quality for use in testing the performance of gas phase air cleaners"

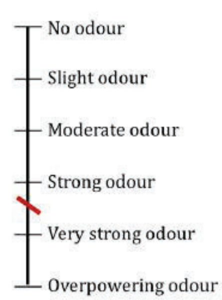
How many sniffs for subjective evaluation?

ISO FDIS 16000-44

- ISO TC146 (Air Quality) /SC6 (Indoor Air) /WG25 (Air Cleaning Technology)
  - Test method for measuring perceived indoor air quality for use in testing the performance of gas phase air cleaners
- Principle for measuring perceived air quality
  - The perceived air quality is determined using subjective evaluations of acceptability and odour intensity. The air assessed by a panel is presented via sniffing device (a funnel).



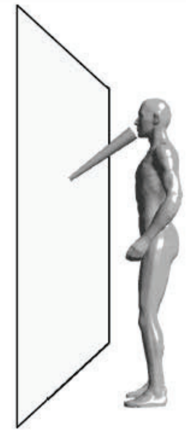
Acceptability scale

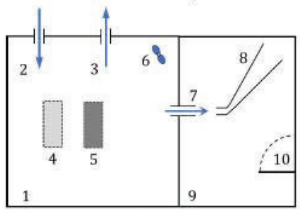


Odour intensity with category scale

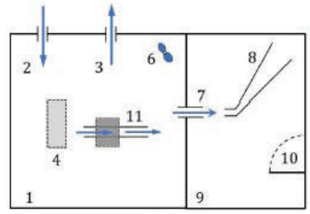
Test Conditions

- The panel member shall enter the front space and assess quality of air presented via sniffing device immediately upon arriving at the measuring point.
- The measurement shall be made after taking one sniff of the air.
- Only one measurement shall be made at a time, either acceptability or perceived odour intensity

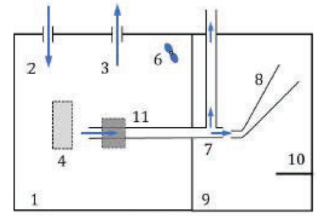




A test room for
a standalone air cleaner



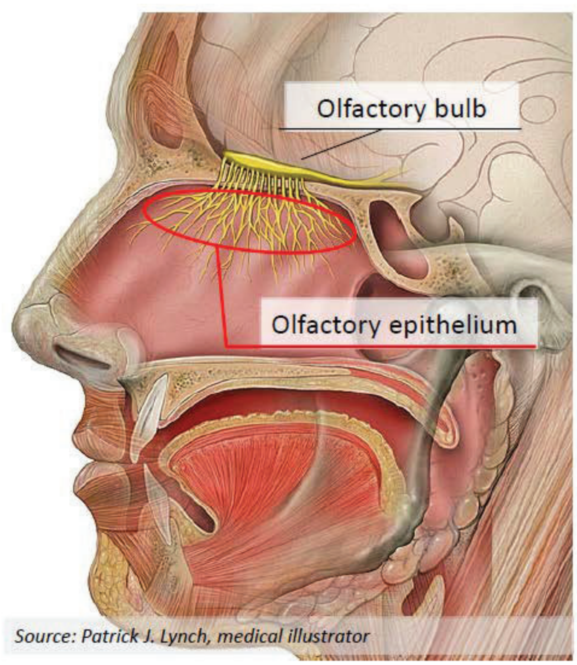
A test room for
a in-duct air cleaner



A test room for
a in-duct air cleaner (single-pass condition)

1	test chamber	7	tube or duct
2	clean and temperature/humidity conditioned air supply inlet	8	sniffing device
3	exhaust outlet	9	front/anterior space in which human panel enter
4	emission source	10	Doors where panel enters
5	An air cleaner	11	in duct air cleaner
6	mixing fan		

Perception of Odour/ Smell



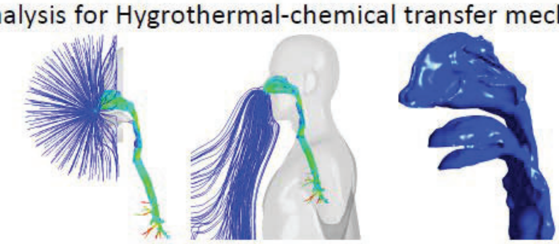
Sensory experiment

- Direct volunteer participant(s) evaluation/ high sensitivity
- Ethical constraints

Odor Intensity level	
extremely strong	6
very strong	5
strong	4
distinct	3
weak	2
very weak	1
no odor	0

CFD based *in silico* Approach

- Analysis for physico-chemical mechanism
- Analysis for Hygrothermal-chemical transfer mechanism



Modeling the Wall Surface Decomposition/Deposition Flux of Scalar

- Heterogeneous reaction between Scalar and wall surface
- The surface deposition of the local scalar concentration close to the surface (molecular theory)

$$Js = -\gamma \frac{\langle v \rangle}{4} C_o \Big|_{y=\frac{2}{3}\lambda}$$

γ [-] : mass accommodation coefficient/Reaction probability

- The flux model to enable an increased length scale at the surface

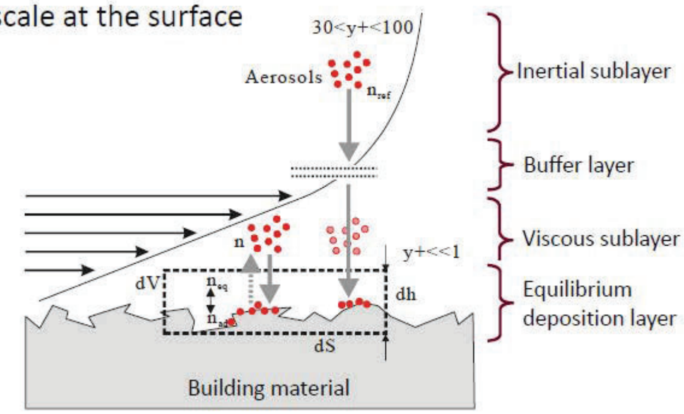
$$Js = -\frac{\gamma \cdot \frac{\langle v \rangle}{4}}{1 + \gamma \cdot \frac{\langle v \rangle}{4} \cdot \frac{\Delta y_1}{D_o}} \cdot C_o \Big|_{y=\Delta y_1}$$

(damping due to molecular diffusion in viscous sub layers)

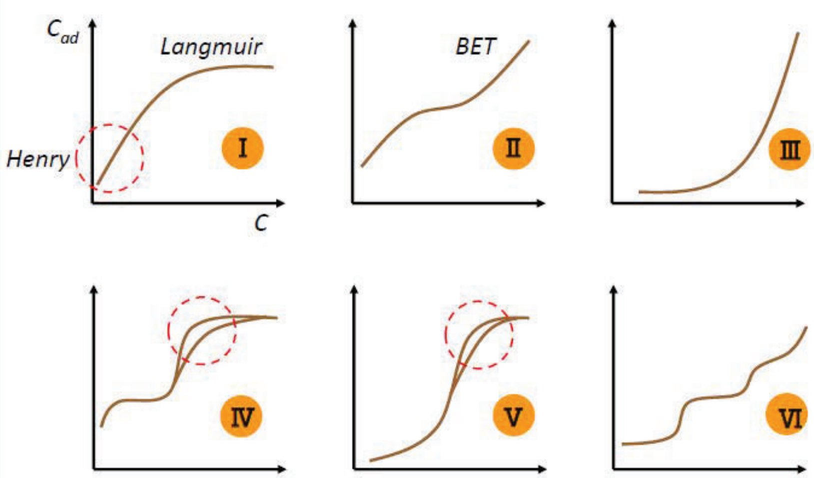
$< v >$ [m/s] : Boltzmann velocity for targe scalar

λ [m] : mean molecular free path (order of the 10^{-8}

Δy_1 : distance to the first computational cell ($< y^+ = 1$)



Variety of Adsorption Isotherm



Classification of Adsorption Isotherm

IUPAC (*International Union of Pure and Applied Chemistry*)

Henry type

$$C_{ad} = k_h \cdot C_{eq} = k_h \cdot C$$

Langmuir type

$$C_{ad} = \frac{C_{ad\,0} k_l C}{1 + k_l C}$$

BET type

$$C_{ad} = \frac{C_{ad\,0} k_{BET} C_r}{(1 - C_r)(1 - C_r + k_{BET} C_r)}$$

Freundlich type

$$C_{ad} = k_f C^{1/n}$$

Physiologically Based Pharmaco-Kinetic (PBPK) model

Reaction Diffusion System

Lumen-Tissue Boundary (Flux Conservation)

$$D_a \frac{\partial C_a}{\partial n} = D_t \frac{\partial C_t}{\partial n}$$

partitioning

$$C_t = P_{t:air} C_a$$

Mucosa + Epithelial

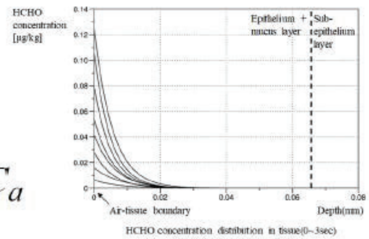
$$\frac{\partial C_t}{\partial t} = -\frac{(V_{\max 1C})C_t}{K_{m1} + C_t} - K_f C_t - K_b C_t + D_t \nabla^2 C_t$$

Michaelis–Menten kinetics; Diffusion Term

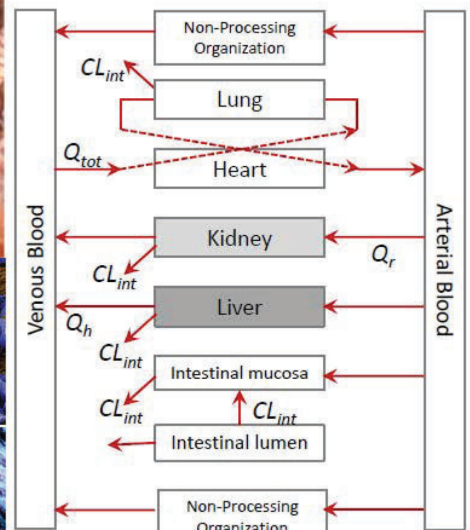
$$C_b = P_{b:t} C_t$$

Sub-mucosal

$$\frac{\partial C_b}{\partial t} = -K_f C_b - K_b C_b - (Q_b / V_b) C_b + D_b \nabla^2 C_b$$



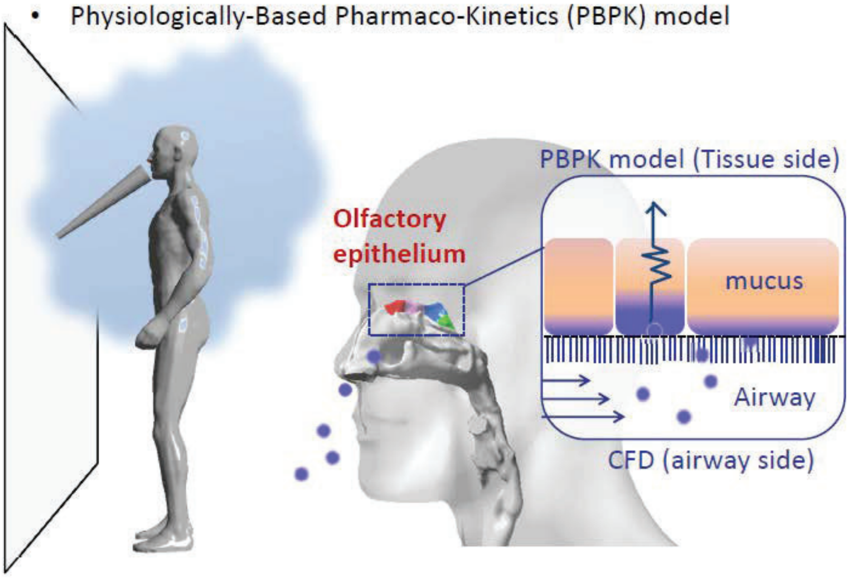
PBPK for Local Tissue/Sites



PBPK for Whole-Body

In Silico Human Model for ISO FDIS 16000-44

- Integrated analysis of flow, heat, moisture, odorous (chemical) substance
- Physiologically-Based Pharmaco-Kinetics (PBPK) model



Reaction-Diffusion equation in 3 layers

Subepithelial tissue: $$\frac{\partial C_b(x,t)}{\partial t} = \frac{\partial^2 C_b(x,t)}{\partial x^2} - \frac{Q_b}{V_b} C_b(x,t)$$

C_{sub}

Epithelial tissue: $$\frac{\partial C_t(x,t)}{\partial t} = D_t \frac{\partial^2 C_t(x,t)}{\partial x^2}$$

C_{epi}

Mucus: $$\frac{\partial C_m(x,t)}{\partial t} = D_m \frac{\partial^2 C_m(x,t)}{\partial x^2}$$

$C_{m,0}$

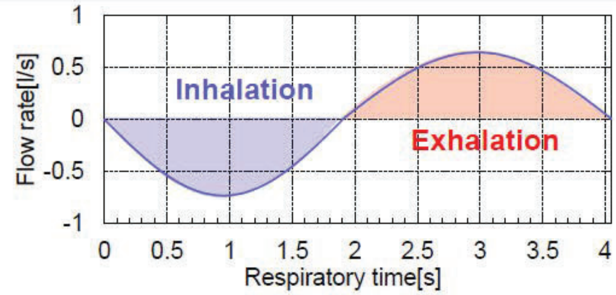
Airway lumen (CFD): $$\frac{\partial \overline{C_a}}{\partial t} + \frac{\partial \overline{U_i C_a}}{\partial x_i} = \frac{\partial}{\partial x_i}\left\{\left(D_a + \frac{\nu_t}{\sigma_t}\right)\frac{\partial \overline{C_a}}{\partial x_i}\right\}$$

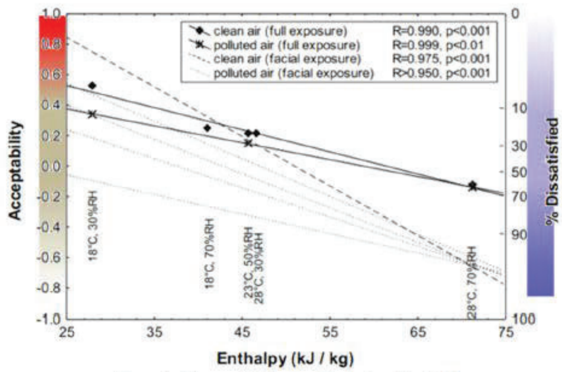
Adsorption equilibrium

$$\begin{cases} C_{sub} = P_{epi,sub} C_{t,n} \\ C_{epi} = P_{m,epi} C_{m,n} \\ C_{m,0} = P_{m:air} C_{air,0} \end{cases}$$

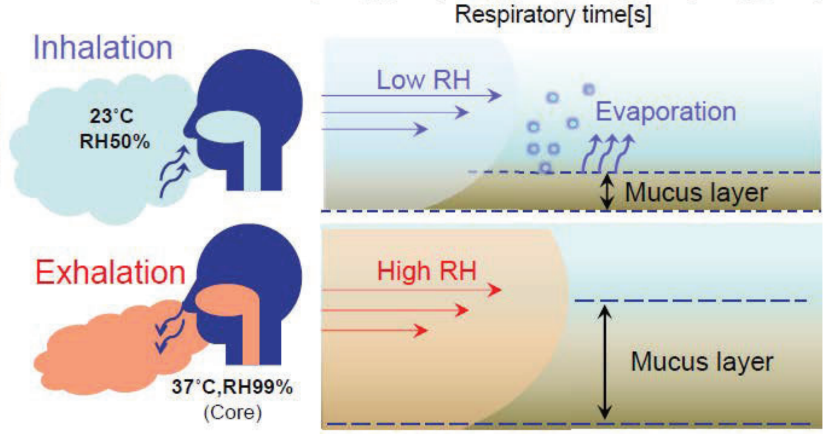
Thermo-Regulation / Heat and Mass Transfer

- Enthalpy of indoor air will affect odour perception
- As the enthalpy of indoor air increases, acceptability decreases and the % dissatisfied increases.





(Fang L, Clausen G, Fanger PO, *Indoor Air*, 1998)



Thermo-Regulation model for Skin Surface and Core Temperature Control

- Heat Balance of Human Body

$$M = Q_{sk} + Q_{res} + S = (Q_{cv} + Q_r + E_{sk}) + (C_{res} + E_{res}) + S_{cr} + S_{sk}$$

$$M = 0.0014M(34-\theta_a) - 0.000017M(5867-p_a) - 0.00305(5733-6.99M-p_a) + 0.42(M-58.2) + f_{cl}\alpha_c(\theta_{cl}-\theta_a) + \varepsilon\cdot\sigma\cdot f_{cl}\frac{A_r}{A_D}\{(\theta_{cl}+273)^4-(MRT+273)^4\}$$

Comfort equation (by Fanger)

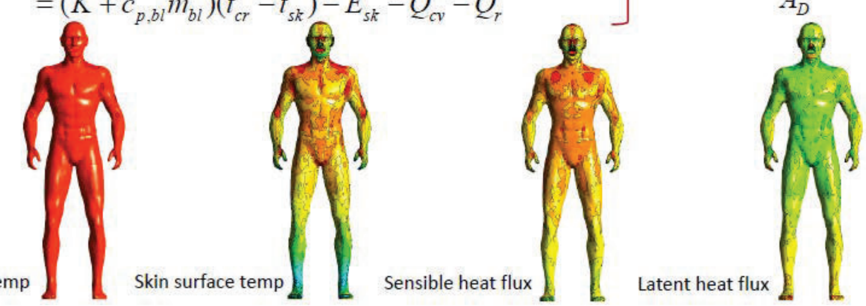
- Heat storage in Core and Skin (Gagge's two node concept)

$$S_{cr} = M - C_{res} - E_{res} - K(t_{cr}-t_{sk}) - c_{p,bl}m_{bl}(t_{cr}-t_{sk}) = M - C_{res} - E_{res} - (K + c_{p,bl}m_{bl})(t_{cr}-t_{sk})$$

$$S_{cr} = \frac{(1-\alpha_{sk})m\cdot c_{p,b}}{A_D}\frac{dt_{cr}}{d\theta}$$

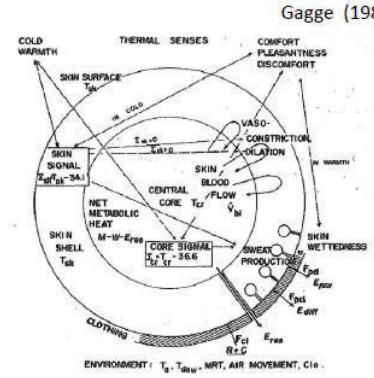
$$S_{sk} = K(t_{cr}-t_{sk}) - c_{p,bl}m_{bl}(t_{cr}-t_{sk}) - E_{sk} - (Q_{cv}+Q_r) = (K + c_{p,bl}m_{bl})(t_{cr}-t_{sk}) - E_{sk} - Q_{cv} - Q_r$$

$$S_{sk} = \frac{\alpha_{sk}\cdot m\cdot c_{p,b}}{A_D}\frac{dt_{sk}}{d\theta}$$



Core temp | Skin surface temp | Sensible heat flux | Latent heat flux

Gagge (1986



Hygrothermal Transfer Modeling in Respiratory Tract

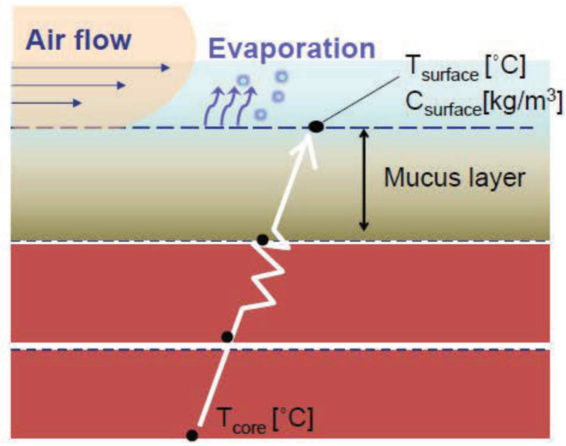
- Total heat balance equation of airway wall

$$\underbrace{k_m \frac{\partial T}{\partial x}}_{conduction} = \underbrace{\left(k_{air} + k_{air,t}\right)\frac{\partial T}{\partial x}}_{sensible\ heat} + \underbrace{L\left(D_{air} + D_{air,t}\right)\frac{\partial C}{\partial x}}_{latent\ heat}$$

- Water vapor concentration on mucus surface

$$C_{surface} = \rho_{air}\left(\frac{0.622e}{p-0.378e}\right)\ [\mathrm{kg/m^3}]$$

$$e = 0.61078\exp\left(\frac{7258.2T_{surface}}{T_{surface} + 237.3}\right)\ [\mathrm{kPa}]$$

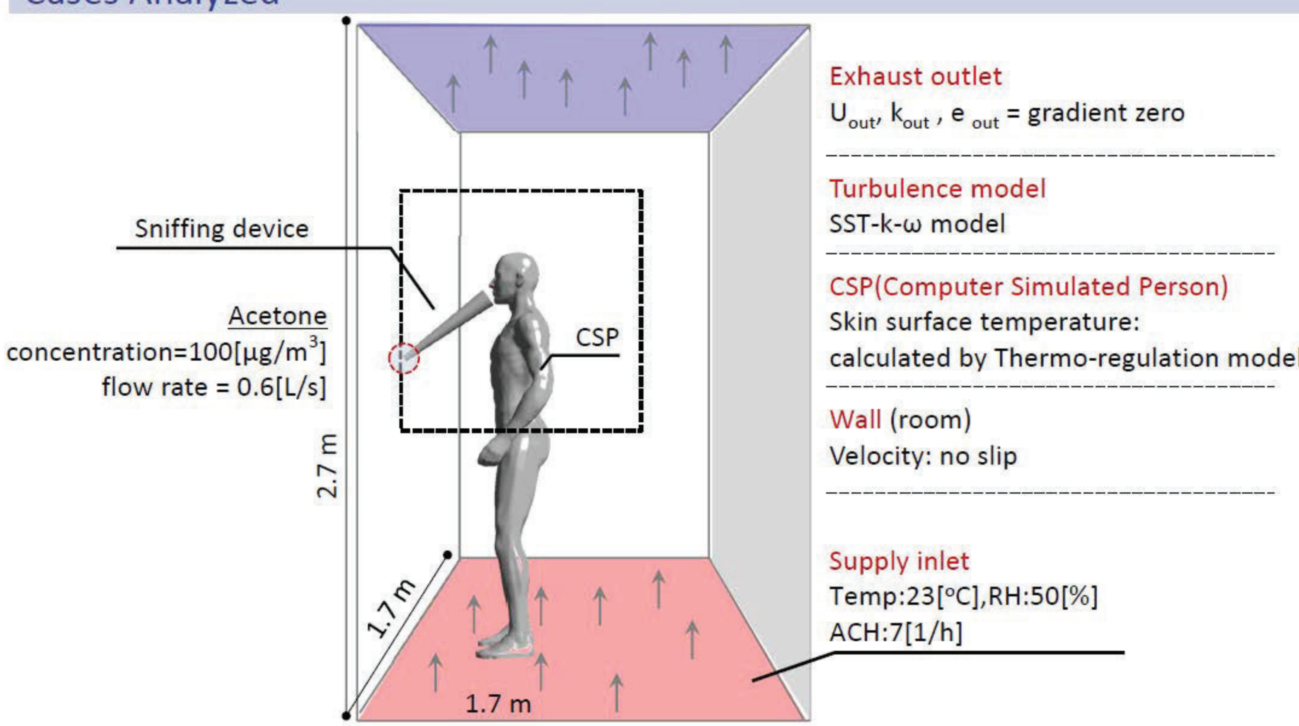


$$S_{cr} = \frac{(1-\alpha_{sk})m \cdot c_{p,b}}{A_D}\frac{dt_{cr}}{d\theta}$$

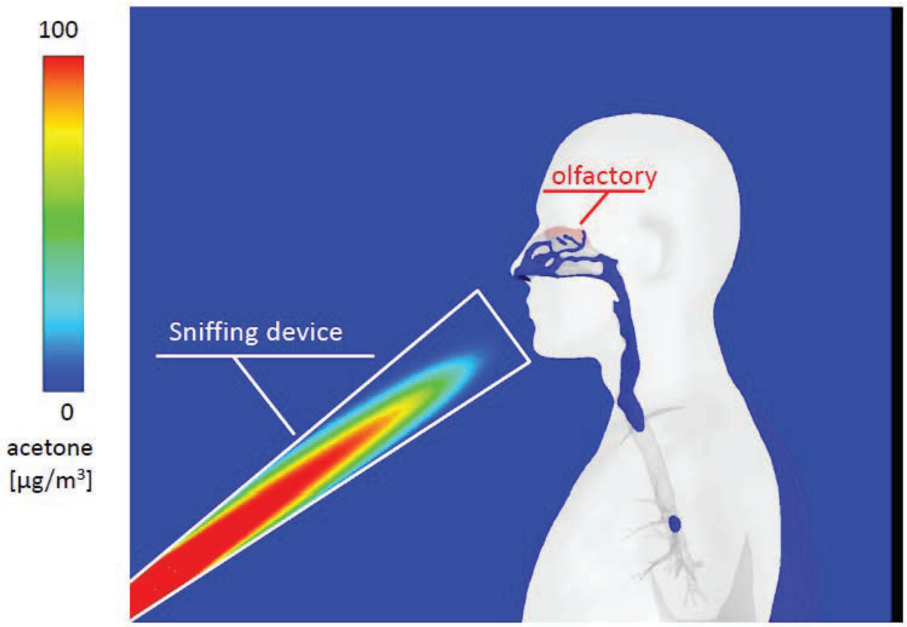
$$S_{sk} = \frac{\alpha_{sk} \cdot m \cdot c_{p,b}}{A_D}\frac{dt_{sk}}{d\theta}$$

CSP with Thermo-regulation (Gagge's two node concept)

Cases Analyzed

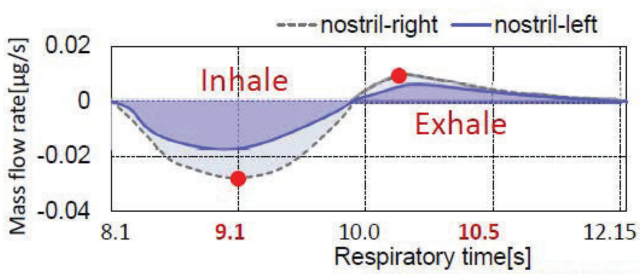


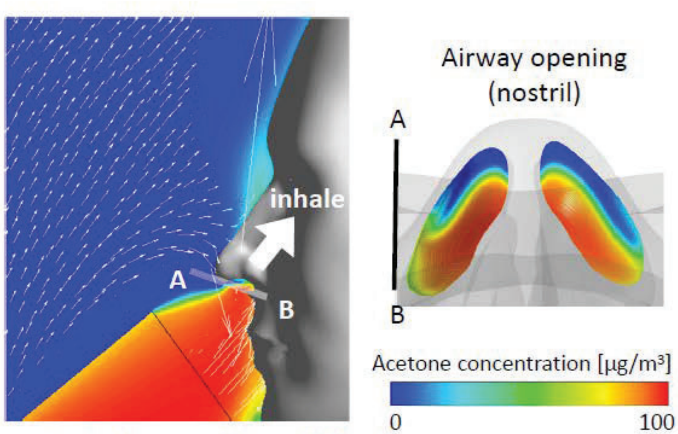
Transient *Acetone* Concentration Distribution



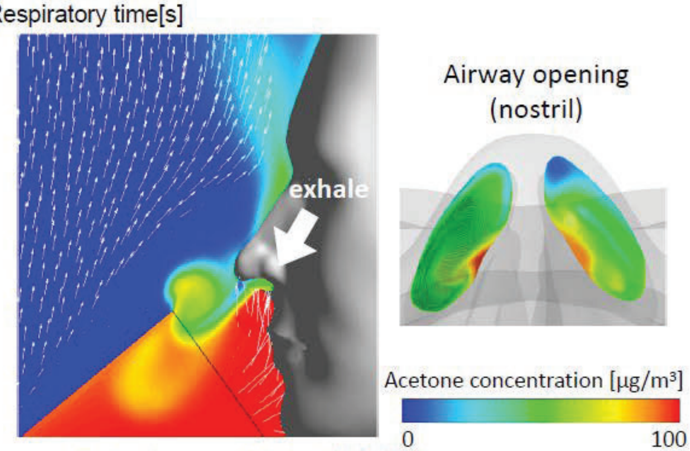
Center cross section of in Silico human (*x*=1.35m)

Inhaled/Exhaled *Acetone* Concentration via Right/Left-Nostril



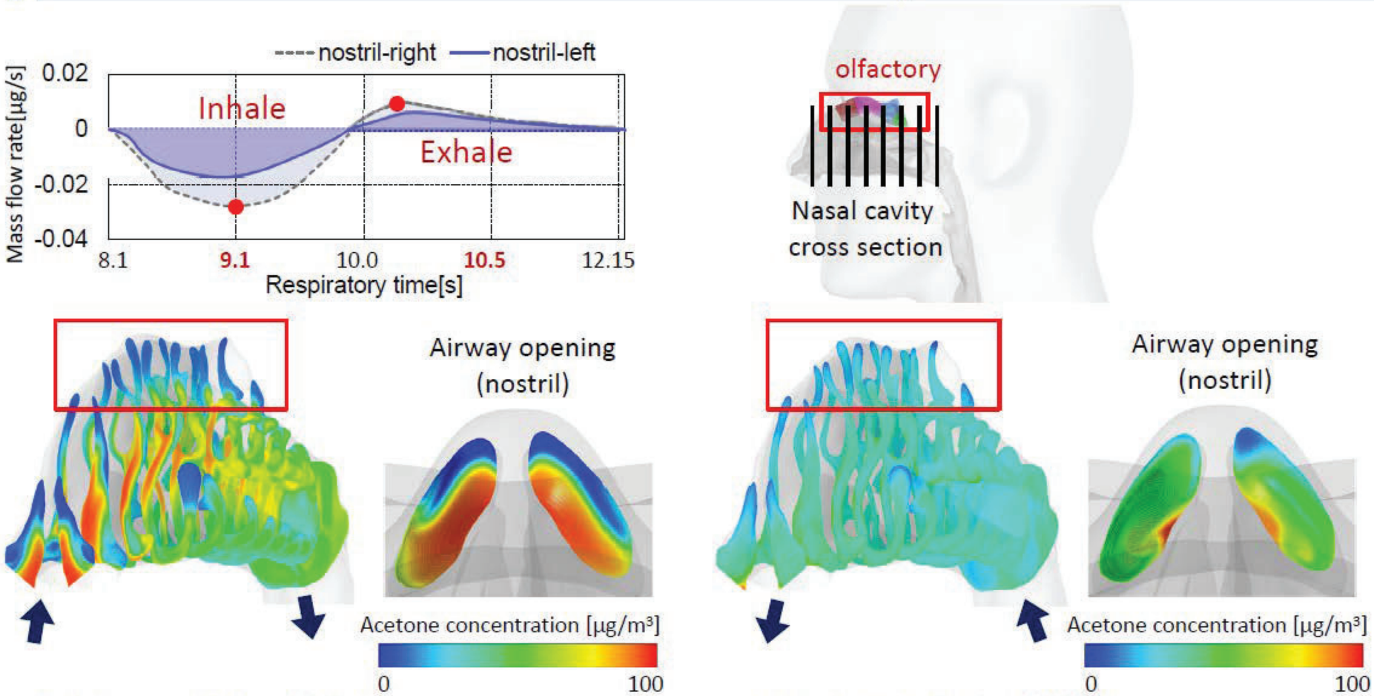


Inhale condition (9.1s)



Exhale condition (10.5s)

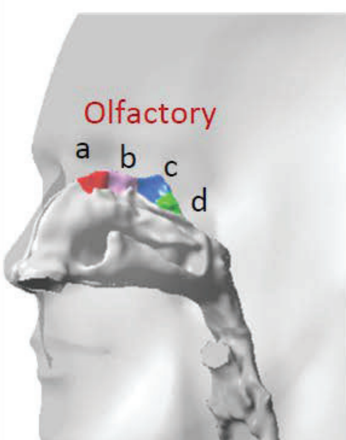
Acetone Concentration Distributions in Nasal Cavity



Inhale condition (9.1s)

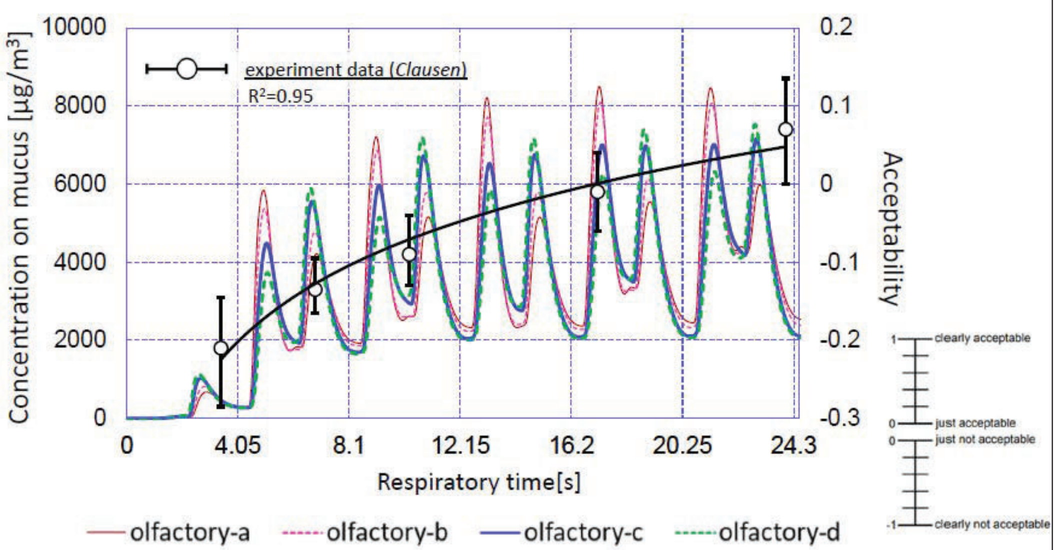
Exhale condition (10.5s)

CFD-PBPK Analysis – *Acetone* concentration on mucus layer



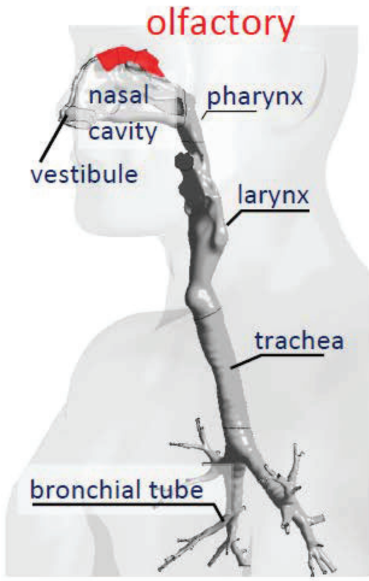
Surface area [cm²]

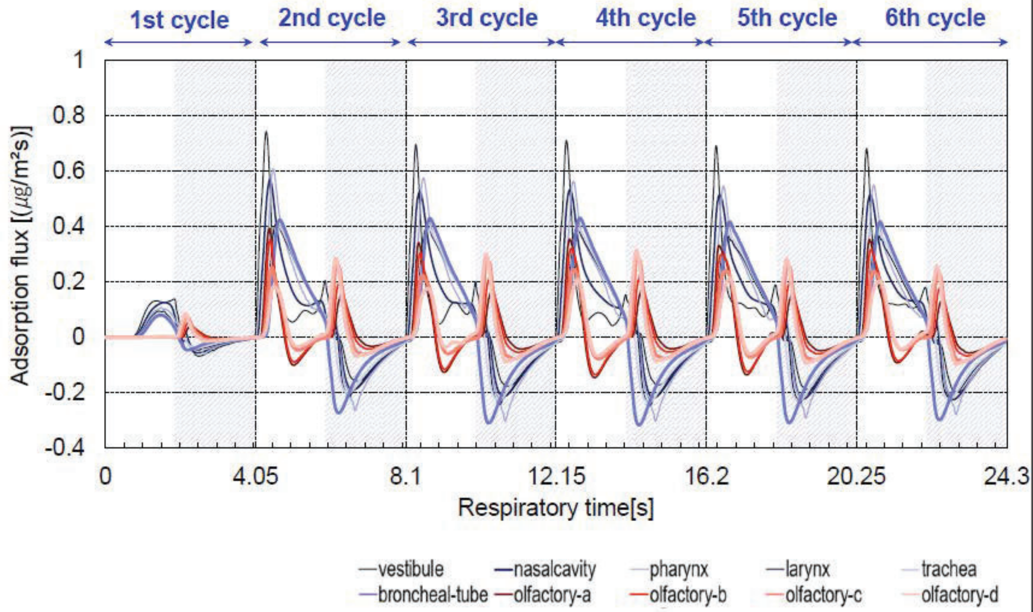
a	b	c	d
3.94	4.40	5.14	2.08



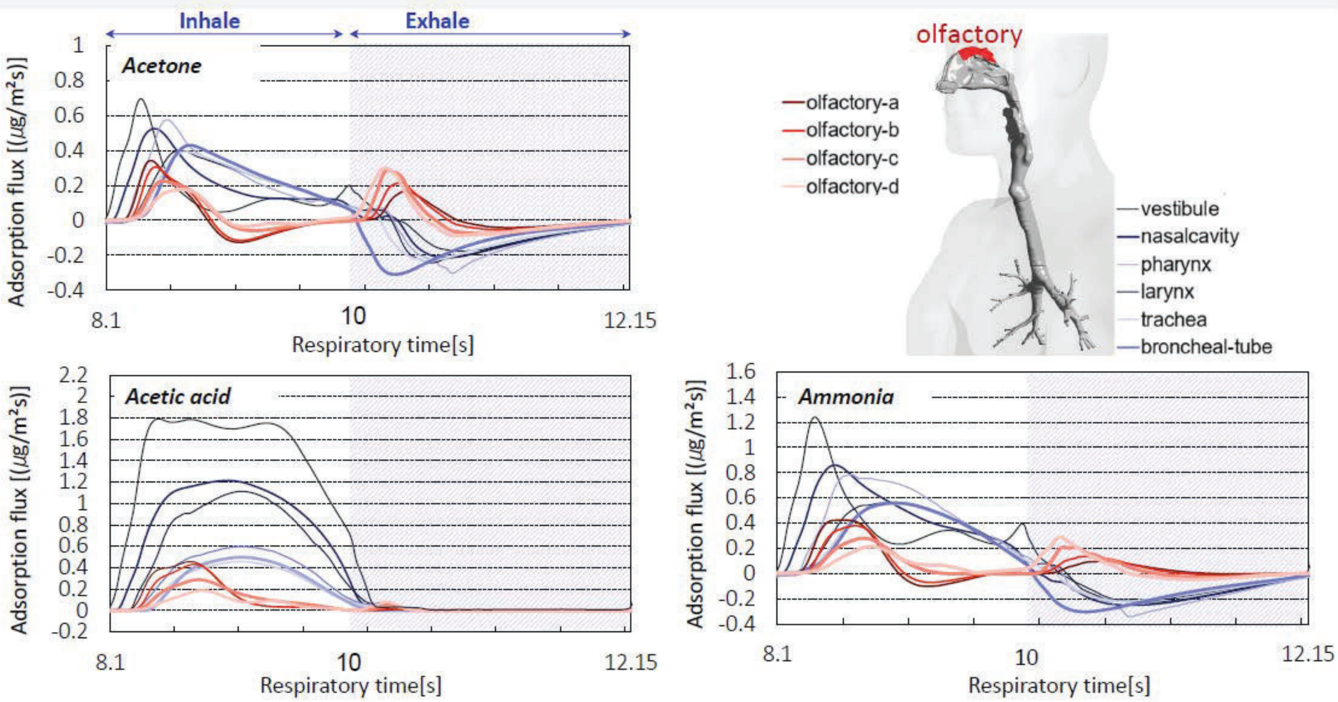
Clausen G (2000) Sensory evaluation of emissions and indoor air quality. In: Proceedings of healthy buildings 2000, vol 1, Espoo, pp 53–62

CFD-PBPK Analysis – *Acetone* Adsorption Flux on Mucus Surface

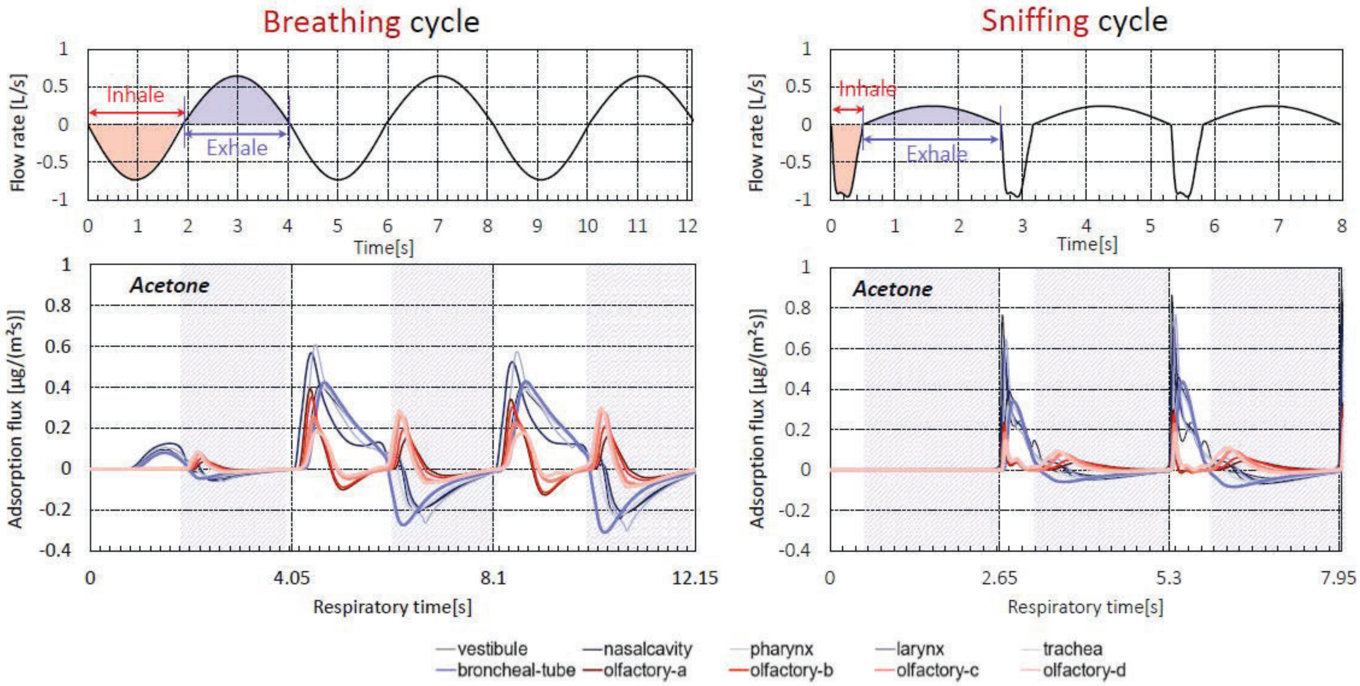




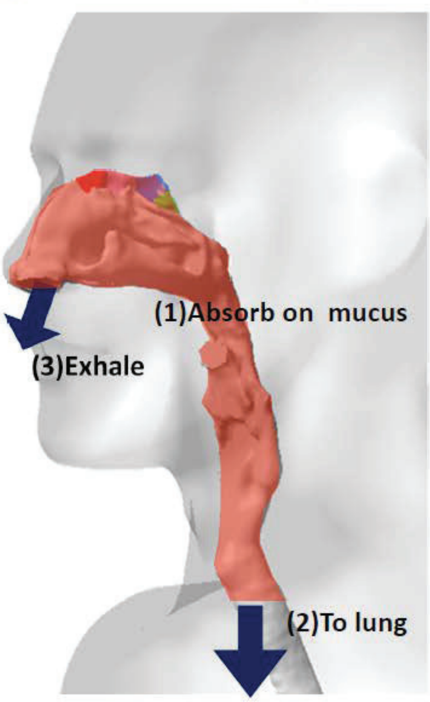
Adsorption Flux of *Acetone*, *Acetic acid*, and *Ammonia* on Mucus Surface

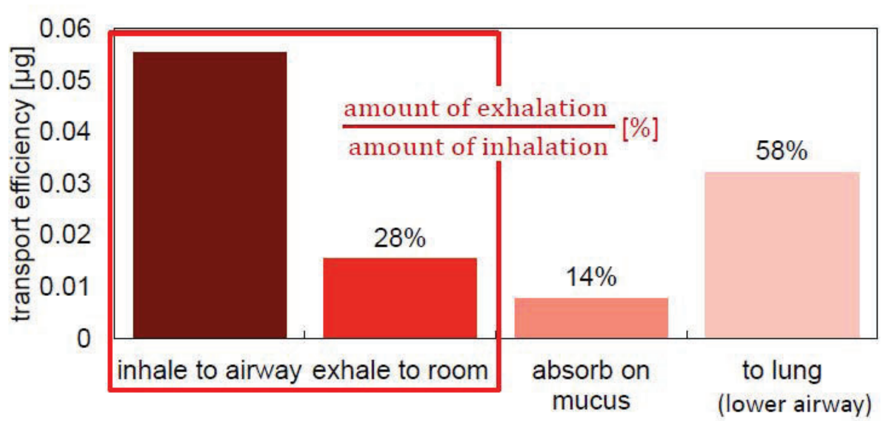


Breathing or Sniffing Cycle

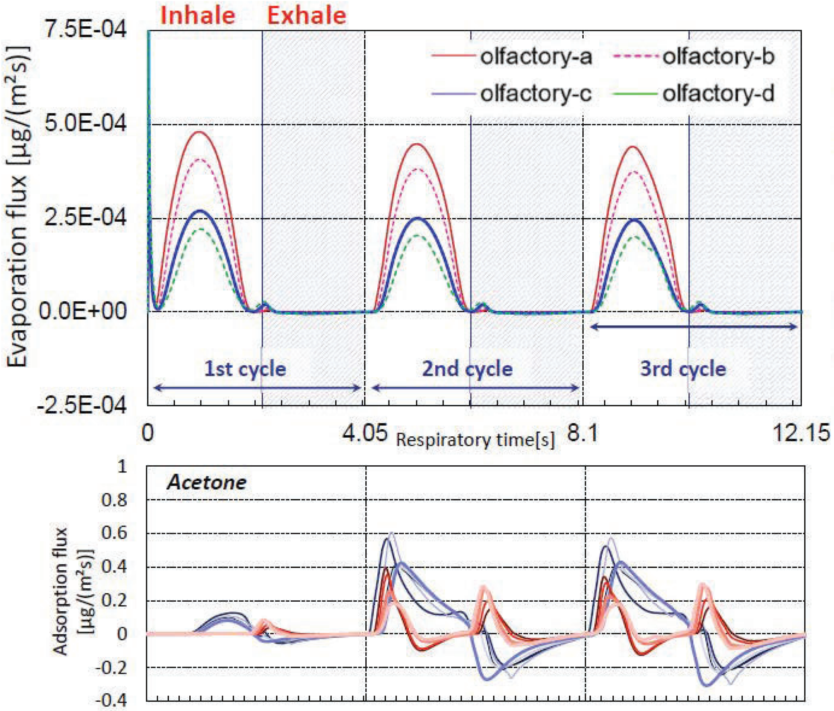


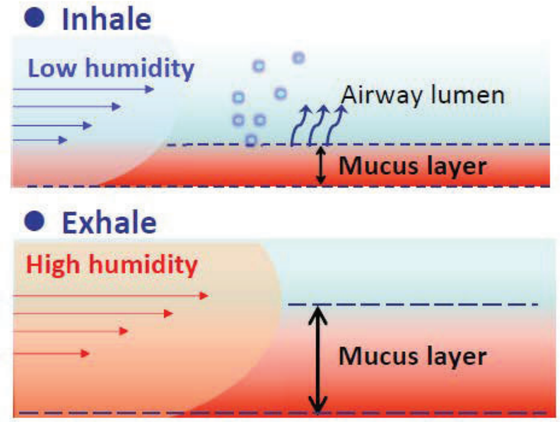
CFD-PBPK Analysis – Contribution Ratio of *Acetone* Distribution





Hygrothermal Analysis – Evaporation flux on mucus surface





In Silico Human model or Volunteer Participants for Smell/ Odour Evaluation

- At present, adsorption flux (of chemical compounds) and sensible/latent heat flux to olfactory epithelial tissue may be analyzed quantitatively, but their combined effect on acceptability and perceived odour intensity evaluation could not be analyzed.
- Olfactory fatigue is also numerically unpredictable.
- Hence, still we do not know how many sniff/breath would be appropriate to odour evaluation.

an update on IEA-EBC Annex 86

energy efficient IAQ management strategies in residential buildings

Jelle Laverge

IEA-EBC Annex 86

Energy Efficient IAQ Management in residential buildings

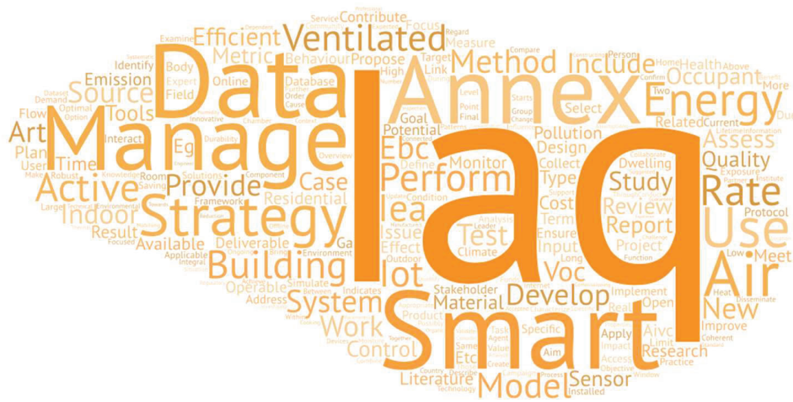
AIVC Workshop 2023 Tokyo

EBC
Energy in Buildings and Communities Programme

Context

IAQ is an important constraint for energy efficiency optimisation in buildings

There is no consensus on a framework to rate IAQ as a basis for this optimisation



EBC
Energy in Buildings and Communities Programme

Scope and Goals

Provide a framework to improve energy efficiency of IAQ management for

Residential buildings

both new construction and refurbishment

To select metrics to assess energy performance and indoor environmental quality of an IAQ management strategy and study their aggregation
To improve the acceptability, control, installation quality and long-term reliability of IAQ management strategies by proposing specific metrics for these quality issues
To set up a coherent rating method for IAQ management strategy that takes into account the selected metrics
To identify or further develop the tools that will be needed to assist designers and managers of buildings in assessing the performance of an IAQ management strategy using the rating method
To gather existing or provide new standardized input data for the rating method
To study the potential use of smart materials as (an integral part of) an IAQ management strategy
To develop specific IAQ management solutions for retrofitting existing buildings
To benefit from recent advances in sensor technology and cloud-based data storage to systematically improve the quality of the implemented IAQ management strategies, ensure their operation and improve the quality of the rating method as well as the input data
To improve the availability of these data sources by exploring use cases for their providers
To disseminate about each of the above findings.

EBC
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Workplan

6 Subtasks

ST 1 and 2: methodology

ST 3 and 4: application to technology

ST 5: new opportunities through IoT

ST 6: dissemination and management

Subtask 1 Metrics and development of an IAQ management strategy rating method

This subtask is devoted to the development of a general rating method for the benchmarking of the performance of IAQ management systems. In addition to relevant metrics, a set of appropriate tools, consistent modeling assumptions and monitoring protocols are also proposed.

Subtask 2 Source characterization and typical exposure in residential buildings

This ST creates consistent input values for the assessment method developed in ST 1 and control strategies in ST 4. It starts from information available in literature, adding new experimental results where needed and reviewing and developing models (empirical, semi-empirical or physical models) for characterizing relevant residential sources.

Subtask 3 Smart materials as an IAQ management strategy

This ST identifies opportunities to use the building structure and (bio-based) building materials (focussing on hemp concrete) and the novel functional materials inside it to actively/passively manage the IAQ, for example, through active paint, wallboards, textiles coated with advanced sorbents or hemp concrete, and quantifies their potential based on the assessment framework developed in ST 1.

Subtask 4 Ensuring performance of smart ventilation

This subtask focuses on practical conditions that assure reliable, cost effective and robust implementation of smart ventilation. This includes both installation and operation. A poor performance of smart ventilation systems can not only lead to waste of energy and aggravated IAQ. It can also create a bad reputation of smart ventilation among relevant stakeholders - designers, installers as well as occupants. This, in the end, can lead to adoption of more primitive, less efficient (in terms of energy use) and less effective (in terms of IAQ) forms of IAQ management. The subtask defines a smart ventilation according to the AIVC

Subtask 5 Energy savings and IAQ: improvements and validation through cloud data and IoT connected devices

This subtask is exploring the potential of the new generation of IoT connected devices (both standalone and embedded in eg. AHU's) for smart IAQ management. What can we learn from big data? Can we benchmark system energy and IAQ performance based on this data? How can we make sure that the data is available and can be accessed? Can we update what we think we know about what happens in dwellings based on what we see in big data rollouts? What are the best protocols and ontologies? How to create viable services out of the data/business plans? How can we integrate data with smart grids?

Subtask 6 Dissemination, management and interaction

The final subtask assures the close alignment of the activities within the annex and the interaction with the AIVC. This subtask includes the outreach of the annex, eg. by managing the dedicated section of the IEA EBC webpage. It uses the different platforms that the AIVC provides to interact with the broader target audience. This task will also ensure the continuation of the link with (the results from) other ongoing and ended annexes, especially annex 68.

EBC
Energy in Buildings and Communities Programme

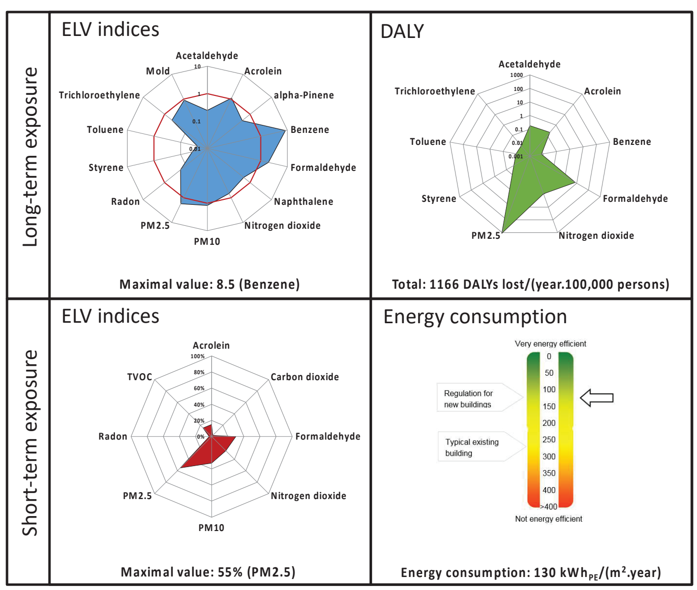
Rating?

3 cases

Comparing cases

Ranking options / engineering case

Across buildings / generic options



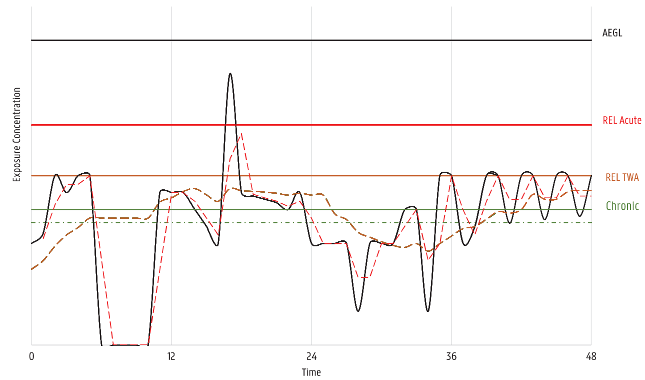
Methodological issues

Conflicts of longterm vs shortterm effects

Resillience?

SBS?

Acceptibility of IAQ?



Methodological issues

Conflicts of longterm vs shortterm effects

Resillience?

SBS?

Acceptibility of IAQ?

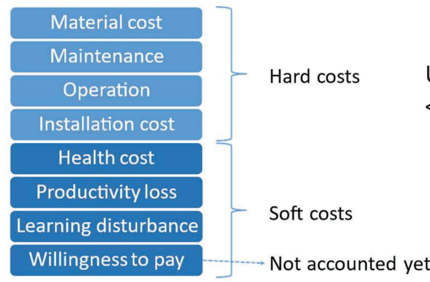
Methodological issues

Conflicts of longterm vs shortterm effects

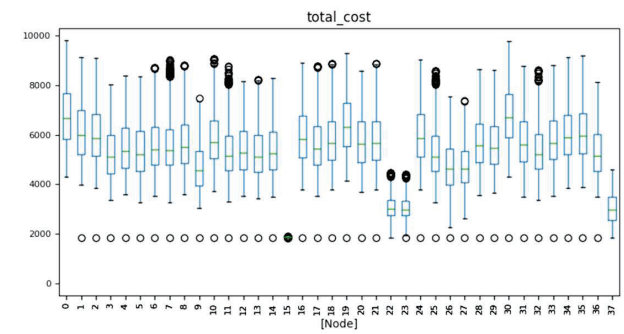
Resillience?

SBS?

Acceptibility of IAQ?



Update on total cost
<> Boulanger et al.



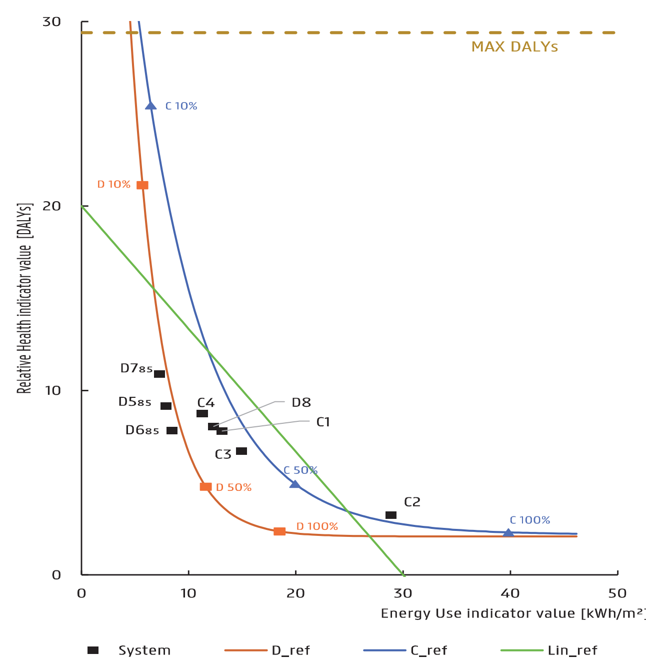
Methodological issues

Conflicts of longterm vs shortterm effects

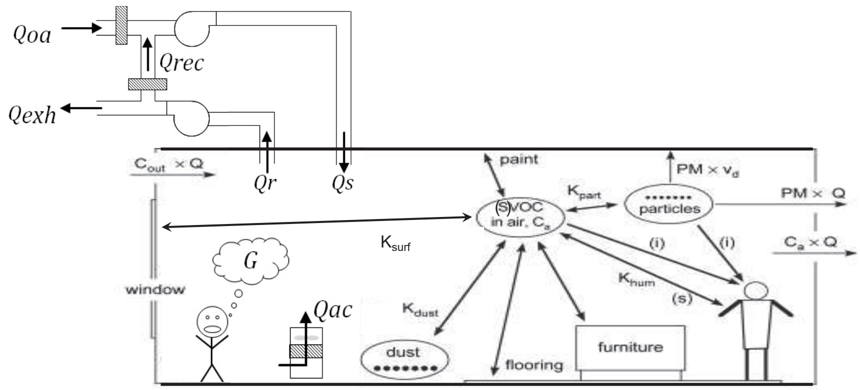
Resillience?

SBS?

Acceptibility of IAQ?



Rating Ecology



Mash-up of Weschler et al. & Dols, 2020, https://doi.org/10.6028/NIST.TN.2095

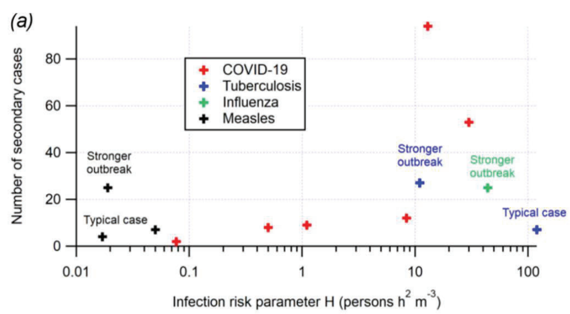
Back to cases 2 and 3

Input variables

Standard conditions & physics?

Standardised scenarios?

Rating Ecology



Back to cases 2 and 3

Input variables

Missing dose-response curves?

Standard conditions & physics?

Standardised scenarios?

EBC
Energy in Buildings and Communities Programme

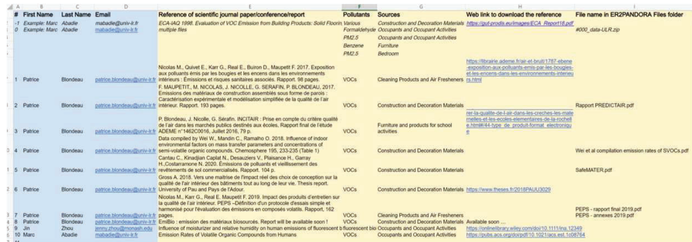
A2.1b Review of emission rate studies for PANDORA database

https://db-pandora.univ-lr.fr/

ST2

1st step: Updating PANDORA with data from 2014-2022

--> EMISSION RATES from published papers/reports and Annex86's data (*Link to TEAMS files)*



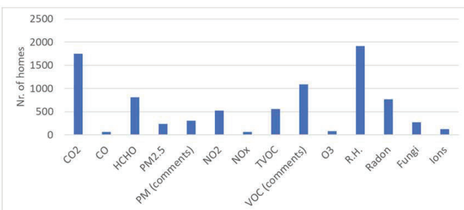
#	First Name	Last Name	Email	Reference of scientific journal paper/conference/report	Pollutants	Sources	Web link to download the reference	File name in ER2PANDORA Files folder
-1	Example: Marc	Abadie	mabadie@univ-lr.fr	ECA-IAQ 1998. Evaluation of VOC Emission from Building Products: Solid Floorin	Various	Construction and Decoration Materials	https://gut-prodis.eu/images/ECA_Report18.pdf	
0	Example: Marc	Abadie	mabadie@univ-lr.fr	multiple files	Formaldehyde	Occupants and Occupant Activities		#000_data-ULR.zip
					PM2.5	Occupants and Occupant Activities		
					Benzene	Furniture		
					PM2.5	Bedroom		
1	Patrice	Blondeau	patrice.blondeau@univ-lr.fr	Nicolas M., Quivet E., Karr G., Real E., Buiron D., Maupetit F. 2017. Exposition aux polluants émis par les bougies et les encens dans les environnements intérieurs : Émissions et risques sanitaires associés. Rapport. 98 pages.	VOCs	Cleaning Products and Air Fresheners	https://librairie.ademe.fr/air-et-bruit/1787-ebene-exposition-aux-polluants-emis-par-les-bougies-et-les-encens-dans-les-environnements-interieurs.html	
2	Patrice	Blondeau	patrice.blondeau@univ-lr.fr	F. MAUPETIT., M. NICOLAS, J. NICOLLE, G. SERAFIN, P. BLONDEAU. 2017. Emissions des matériaux de construction assemblés sous forme de parois : Caractérisation expérimentale et modélisation simplifiée de la qualité de l'air intérieur. Rapport. 193 pages.	VOCs	Construction and Decoration Materials		Rapport PREDICTAIR.pdf
3	Patrice	Blondeau	patrice.blondeau@univ-lr.fr	P. Blondeau, J. Nicolle, G. Sérafin. INCITAIR : Prise en compte du critère qualité de l'air dans les marchés publics destinés aux écoles. Rapport final de l'étude ADEME n°1462C0016, Juillet 2016, 79 p.	VOCs	Furniture and products for school activities	rer-la-qualite-de-l-air-dans-les-creches-les-maternelles-et-les-ecoles-elementaires-de-la-rochelle.html#/44-type_de_produit-format_electronique	
4	Patrice	Blondeau	patrice.blondeau@univ-lr.fr	Data compiled by Wei W., Mandin C., Ramalho O. 2018. Influence of indoor environmental factors on mass transfer parameters and concentrations of semi-volatile organic compounds. Chemosphere 195, 233-235 (Table 1)	VOCs	Construction and Decoration Materials		Wei et al compilation emission rates of SVOCs.pdf
5	Patrice	Blondeau	patrice.blondeau@univ-lr.fr	Cantau C., Kinadjian Caplat N., Desauziers V., Plaisance H., Garray H.,Costarramone N. 2020. Émissions de polluants et vieillissement des revêtements de sol commercialisés. Rapport. 104 p.	VOCs	Construction and Decoration Materials		SafeMATER.pdf
6	Patrice	Blondeau	patrice.blondeau@univ-lr.fr	Gross A. 2018. Vers une maitrise de l'impact réel des choix de conception sur la qualité de l'air intérieur des bâtiments tout au long de leur vie. Thesis report. University of Pau and Pays de l'Adour.	VOCs	Construction and Decoration Materials	https://www.theses.fr/2018PAUU3029	
7	Patrice	Blondeau	patrice.blondeau@univ-lr.fr	Nicolas M., Karr G., Real E. Maupetit F. 2019. Impact des produits d'entretien sur la qualité de l'air intérieur. PEPS –Définition d'un protocole d'essais simple et harmonisé pour l'évaluation des émissions en composés volatils. Rapport, 162 pages.	VOCs	Cleaning Products and Air Fresheners		PEPS - rapport final 2019.pdf PEPS - annexes 2019.pdf
8	Patrice	Blondeau	patrice.blondeau@univ-lr.fr	EmiBio : emission des matériaux biosourcés. Report will be available soon !	VOCs	Construction and Decoration Materials	Available soon ...	
9	Jin	Zhou	jenny.zhou@monash.edu	Influence of moisturizer and relative humidity on human emissions of fluorescent b	fluorescent bio	Occupants and Occupant Activities	https://onlinelibrary.wiley.com/doi/10.1111/ina.12349	
10	Marc	Abadie	mabadie@univ-lr.fr	Emission Rates of Volatile Organic Compounds from Humans	VOCs	Occupants and Occupant Activities	https://pubs.acs.org/doi/pdf/10.1021/acs.est.1c08764	
11								

--> New: if you have unpublished data you want to share → please also fill the Teams files.

--> Implementation not started yet, later this year.

A2.1a „Registry" of IAQ monitoring studies

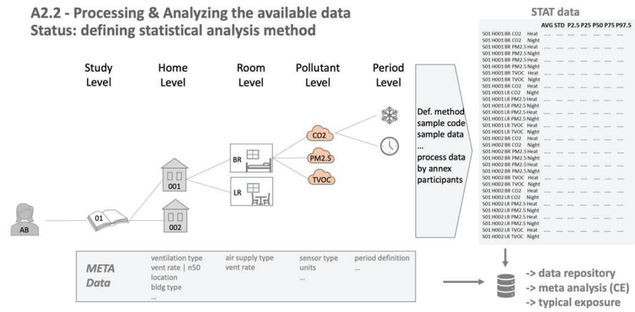
Big Thank you for all entries so far!



>40 monitoring studies from:

Australia	Norway
Austria	Portugal
Belgium	Singapore
Chile	Slovakia
Denmark	Spain
France	Switzerland
Italy	Sweden
Germany	UK
Mexico	USA
Netherlands	

A2.2 - Processing & Analyzing the available data
Status: defining statistical analysis method



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ST5

Rating Ecology

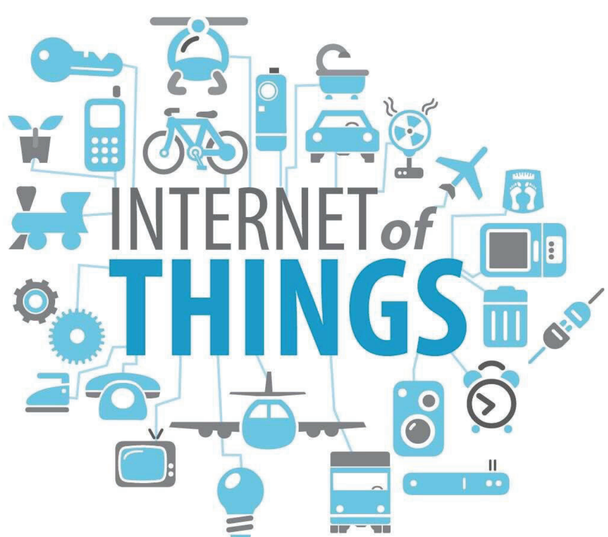
Back to cases 2 and 3

Input variables

Missing dose-response curves?

Standard conditions & physics?

Standardised scenarios?



Rating Ecology

Back to cases 2 and 3

Input variables

Missing dose-response curves?

Standard conditions & physics?

Standardised scenarios?

Annex I
(informative)

Basis for the criteria for indoor air quality and ventilation rates

I.1 Default design ventilation air flow rates

I.1.1 General

Due to health reasons the total minimum airflow rate during occupancy expressed as l/s per person should never be below 4 l/s per person (Table I.3) and the WHO Guideline values in Annex M is met. The default air flow rates given in this Annex I are design ventilation air flow rates.

The default air flow rates given in this Annex assume complete mixing in the room (concentration of pollutants is equal in extract and in occupied zone). For non-residential buildings ventilation rates should be adjusted by the ventilation effectiveness in accordance with prEN 16798-3 if the air distribution differs from complete mixing.

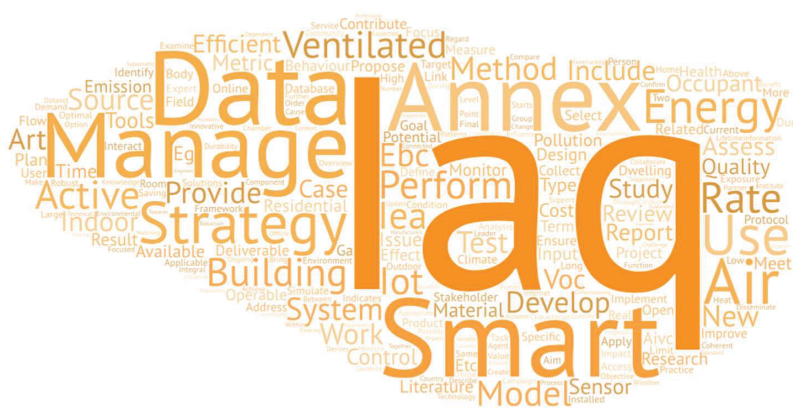
Conclusions

There is no consensus on a framework to rate IAQ as a basis for energy efficiency optimisation in residential buildings

To successfully get there, we need to

- Advance methodologically to define constraints and cost functions
- Provide a 'rating ecology'

Thanks to AIVC for partnering with us to collect your input



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IEA-EBC Annex 86

Energy Efficient IAQ Management in residential buildings

Jelle.Laverge@UGent.be

University of Nottingham

UK | CHINA | MALAYSIA

Dallying with DALYs:

A Harm Based Approach to IAQ Acceptability

Dr Benjamin Jones
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People

Benjamin Jones
University of Nottingham

Giobertti Morantes Quintana
University of Nottingham

Constanza Molina
Pontifical University of Santiago, Chile

Max Sherman
University of Nottingham
& Lawrence Berkeley National Laboratory

Effects

Section 1

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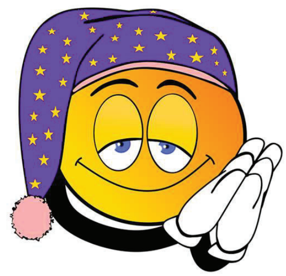
Thought experiment

Perfectly mixed contaminant. Two people. Different activities. Different ages.
Which person is harmed the most?

8 years old

80 years old



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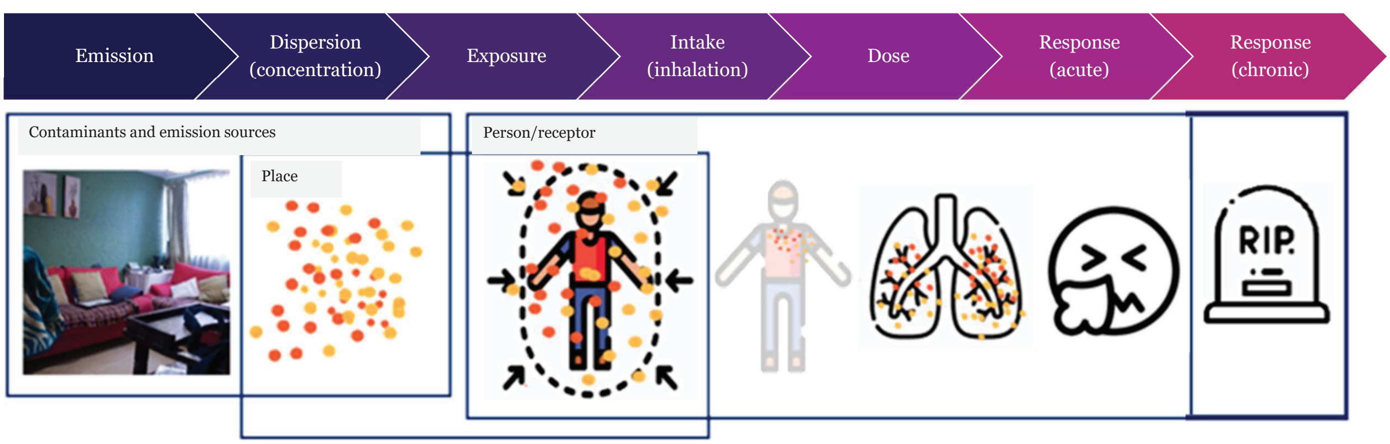
Lifetime effects



Acute: short term, normally <24h
Chronic: long term, normally >24h

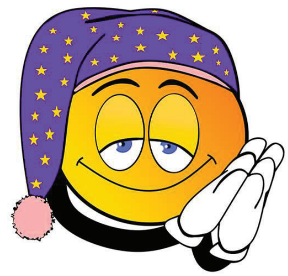
Different metrics for different response rates

Thought experiment

Perfectly mixed contaminant. Two people. Different activities. Different ages.
Which person is harmed the most?

8 years old

80 years old



Harm matters!

Paradigm

Section 2

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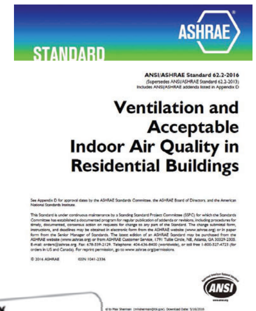
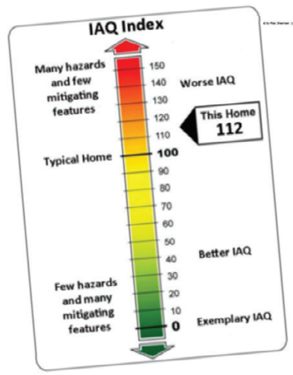
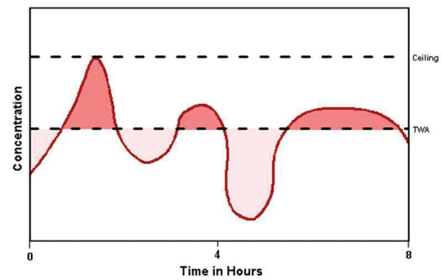
Existing

1. The olfactory paradigm
2. Ratings systems
3. IAQ indices
4. Threshold limit values
5. Exposure limit values







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Lists of Limit Values: disagreements

Recommended thresholds for $PM_{2.5}$

- WHO
  - Mean concentration of <15μg/m³ per day
  - Mean concentration of <5μg/m³ per year
- U.S. National Ambient AQ Standards
  - Mean concentration of <35μg/m³ per day
  - Mean concentration of <12μg/m³ per year
- WELL Buildings
  - Threshold of 15 μg/m³ measured at least once per hour at a resolution of 10μg/m³ or finer

Some Drawbacks and Questions

1. Not clear how a change to any of these metrics, say by 10%, would affect occupant health and comfort.
2. Easier to deal with acute risks rather than chronic risks. Thresholds work for acute exposures and time frames. For the chronic they do not.
3. An indication of the relationship between dose and health consequences is required.
4. Shouldn't all thresholds cause the same magnitude of harm?
5. There's no such thing as zero risk, but risk can be *acceptable*.
6. How can we account for harm at a population scale and determine appropriate solutions, ignoring outliers?
7. Therefore, can we determine ***contaminants of concern***, that have a direct effect on health ***and*** are commonly found in indoor air?

Some Drawbacks and Questions

How can we *actually* measure harm?

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Harm

Section 3

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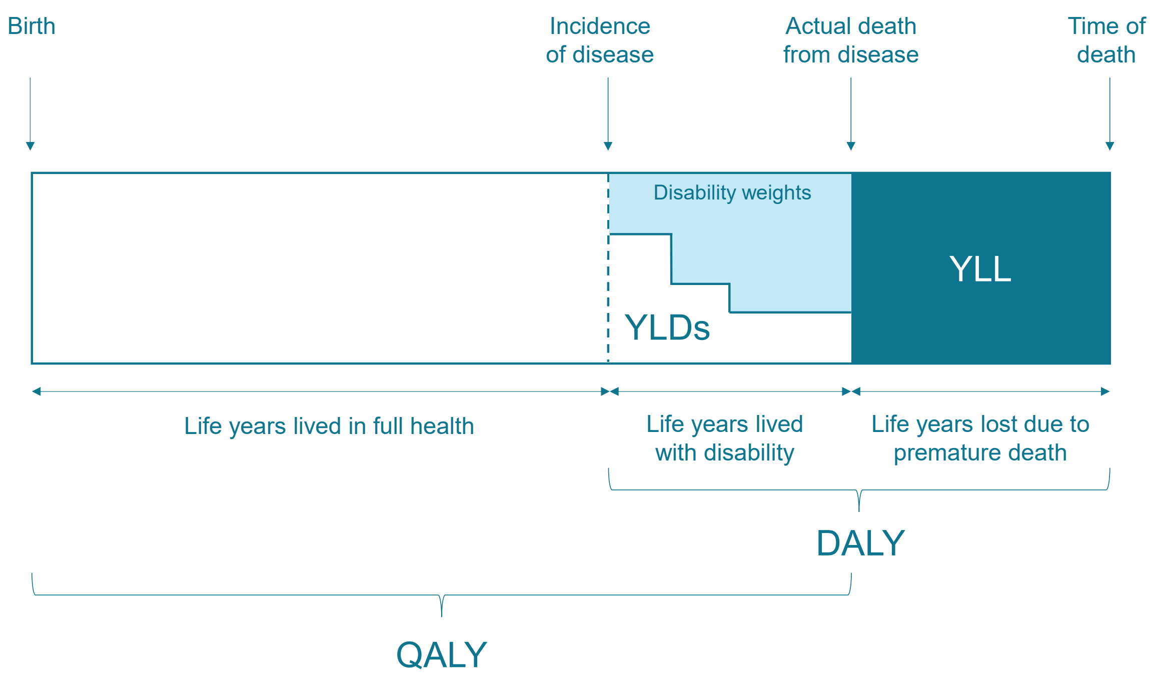
Disability Adjusted Life Years (DALY)



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DALY

- Can rely on toxicological or epidemiological data (epi data is usually acceptable in stage 4 countries)
- Can account for the relative importance of a healthy life at different ages, placing greater value on years lived in young adulthood (9 to 54 years of age)
- YLL is a function of the number of deaths from a disease and the population life expectancy
- YLD is a function of age of onset, the duration, severity, and two statistical constants, C and β
- Cumulative for different diseases that occur from exposure to a contaminant

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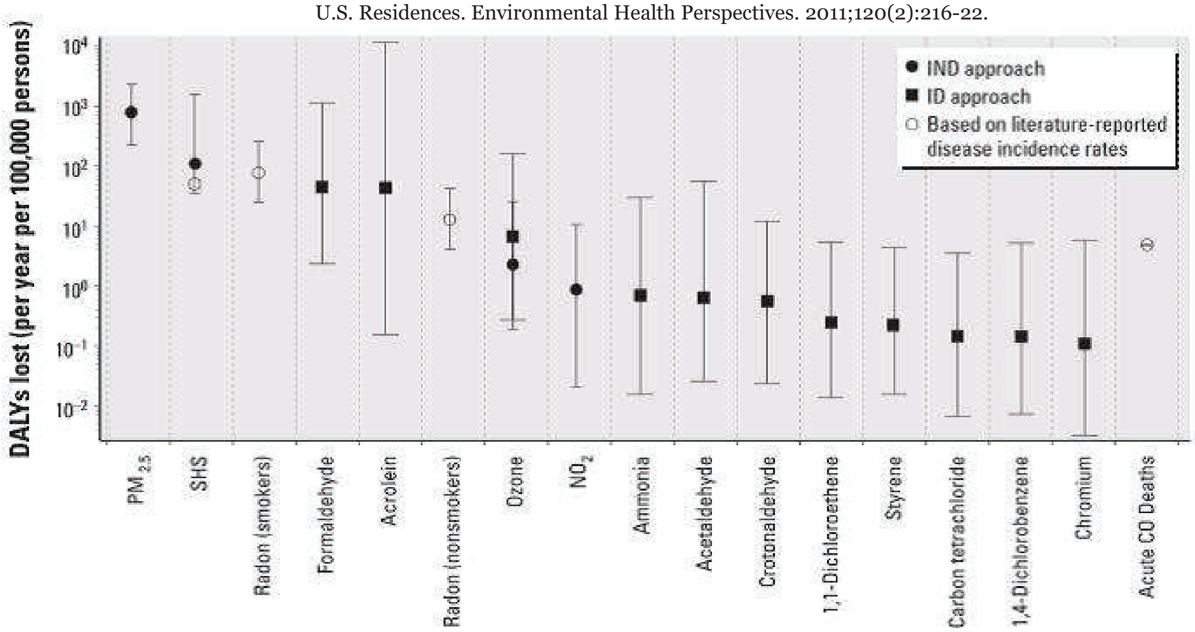
Previous work: DALYs lost per year per 100,000 population

Logue JM, Price PN, Sherman MH, Singer BC. A Method to Estimate the Chronic Health Impact of Air Pollutants in U.S. Residences. Environmental Health Perspectives. 2011;120(2):216-22.



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Analysis

Section 4

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Our analysis

- International approach: identified uncertainty in a number of contaminants in homes in wealthy and western countries
- Quantify uncertainty in *all* parameters
- Use two calculation methods
  1. Epi-harm method
     epidemiological-based C-R functions to quantify disease incidence
  2. Tox-harm method
     toxicological data to quantify disease effects
- Both methods produce a **Harm Intensity** metric with units of DALY per unit-concentration
- Harm intensity pooled when Epi and Tox data available
- Household concentrations *N*=827 datasets

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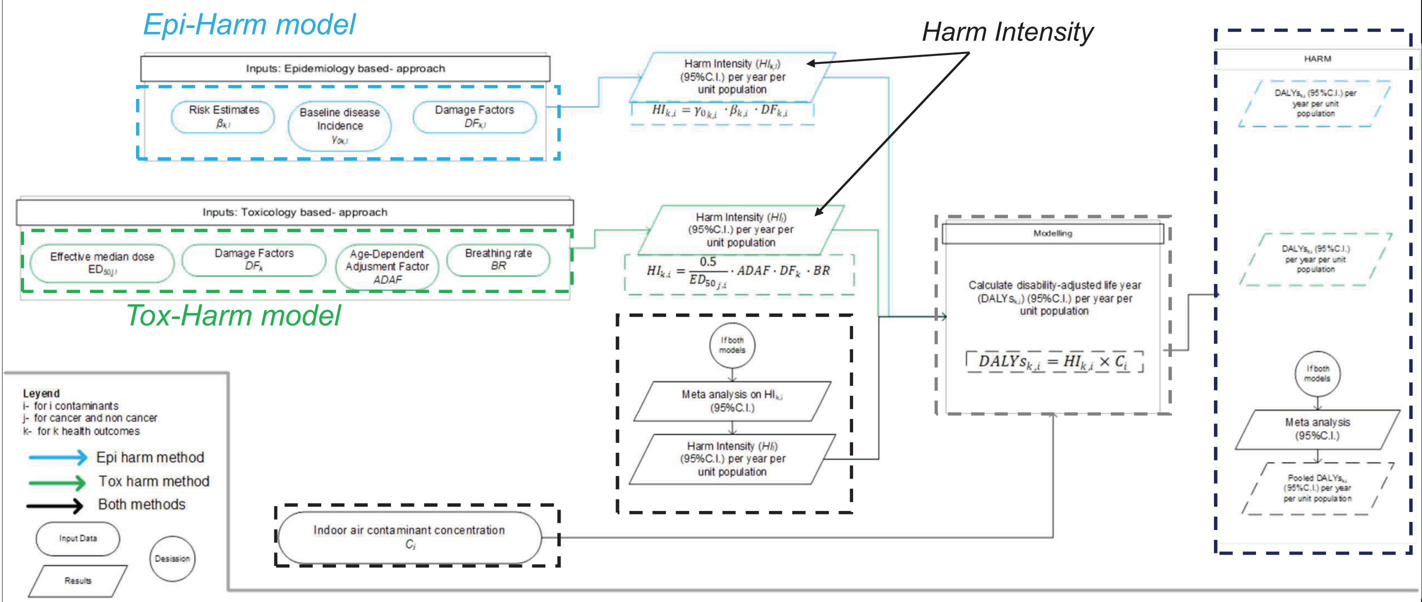
Current research framework: Epi harm and Tox harm methods



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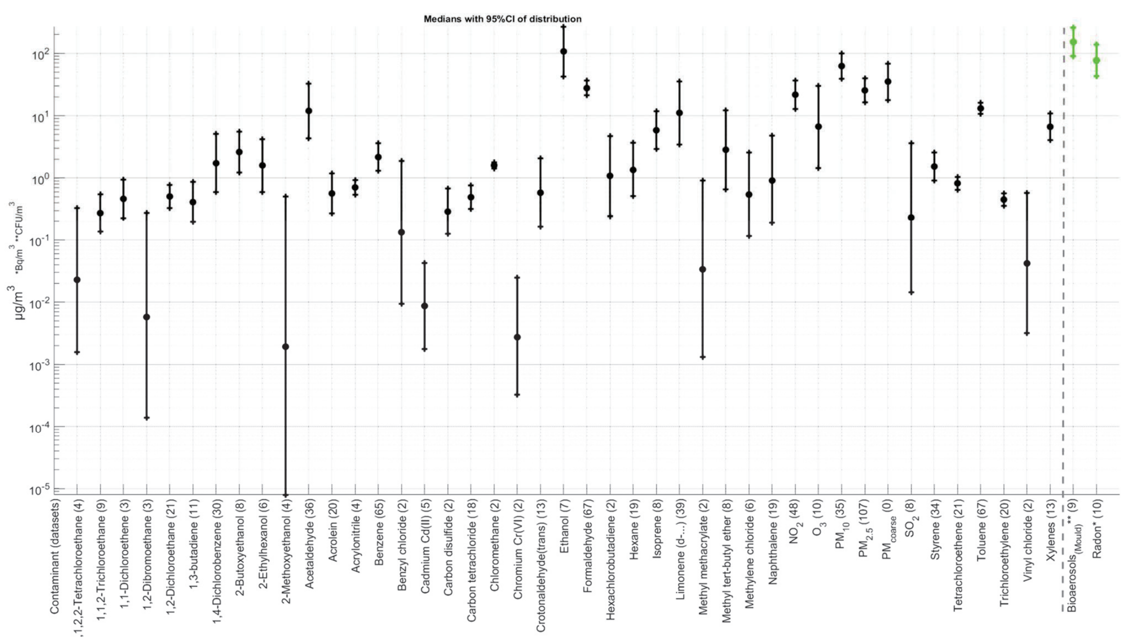
Concentrations

Through literature review: 123 studies *(827 datasets)*

The most reported contaminants: $PM_{2.5}$, Formaldehyde, Toluene, Benzene, and NO_2

The most abundant contaminants: Ethanol, PM_{10}, Formaldehyde, $PM_{2.5}$ and NO_2



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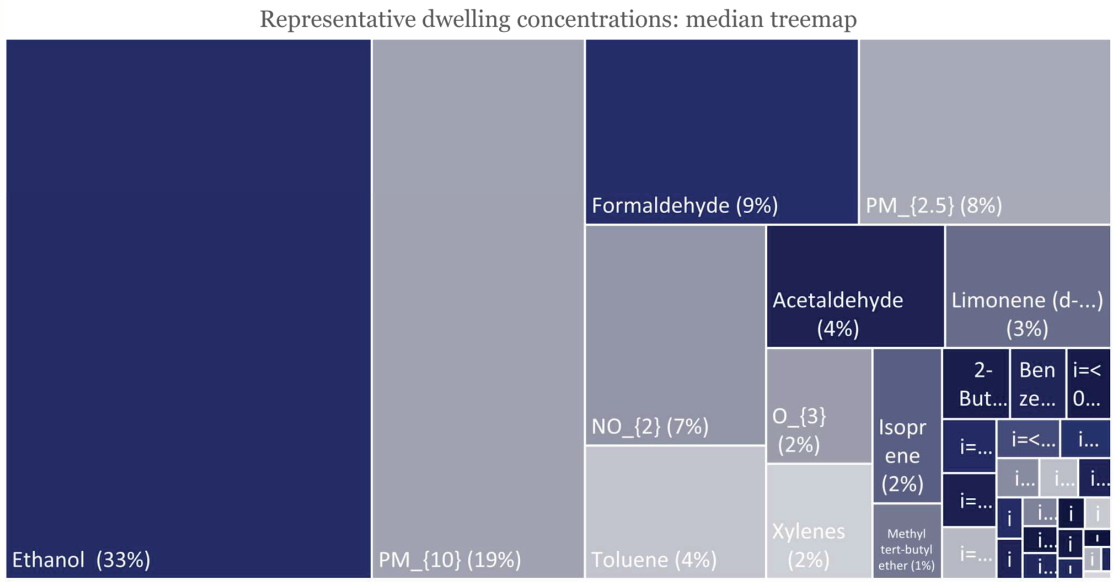
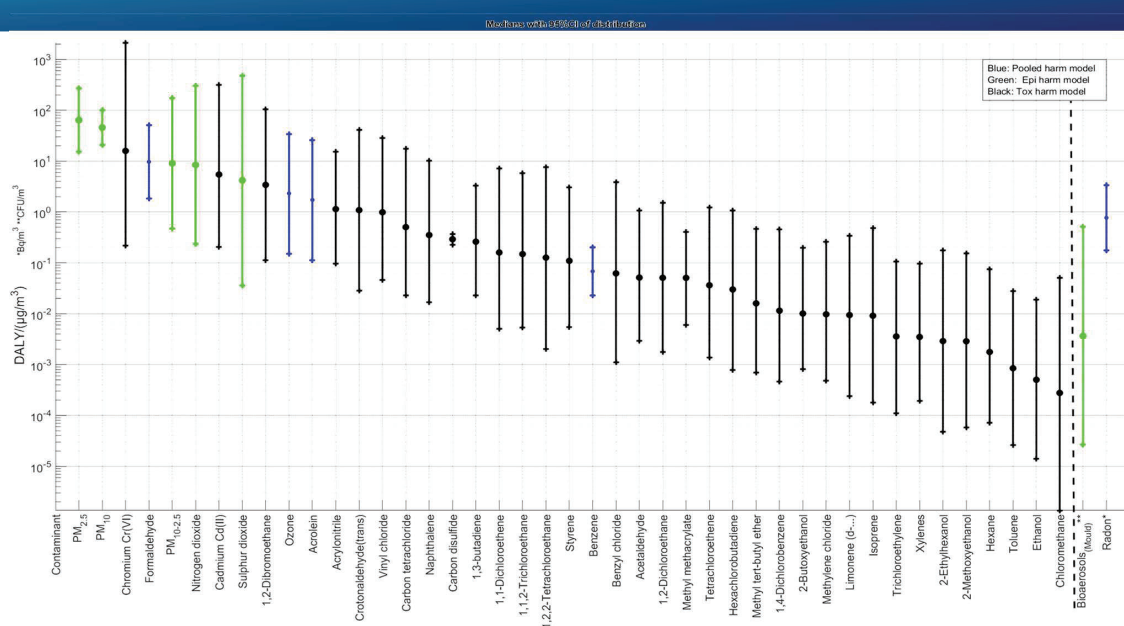


Harm intensity

$PM_{2.5}$ has the highest Harm Intensity:

$6.4 \cdot 10^2$ DALY/(µg/m³) (95%C.I. $1.5 \cdot 10^1$-$2.7 \cdot 10^2$)



Harm Intensities, per 100,000 population (as DALY per unit-concentration).

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Total harm

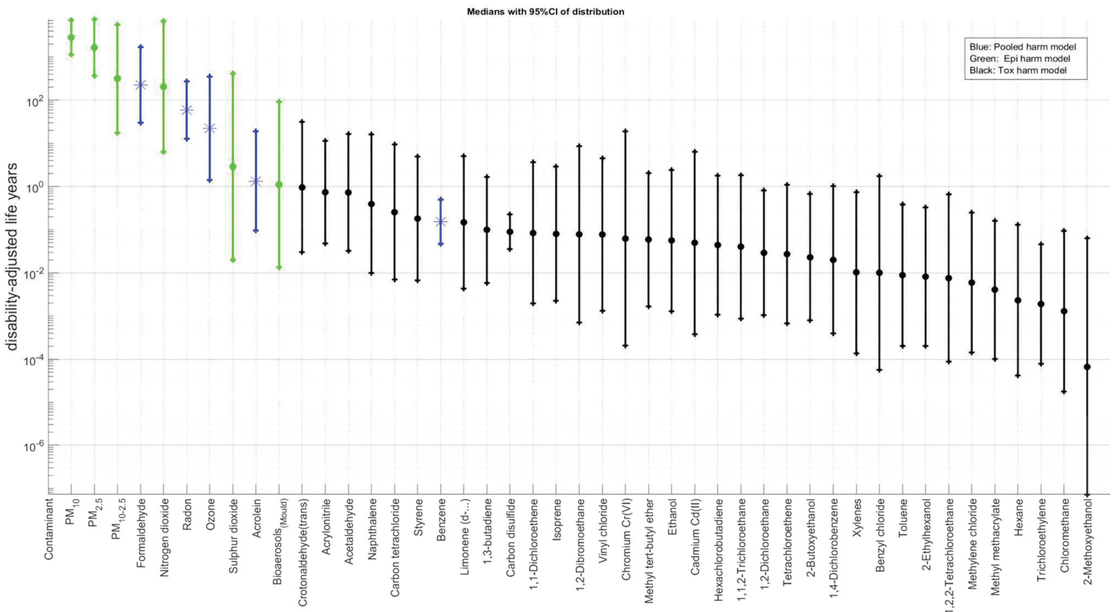
The contaminants with the **highest** median **DALY loss** estimates are

PM_{10}: 2.8$\cdot 10^3$
(95%C.I. $1.1\cdot10^2$-$7.1\cdot10^3$)]

and

$PM_{2.5}$: $1.7\cdot10^3$
(95%C.I. $3.6\cdot10^2$-$7.6\cdot10^3$)

Contaminants of concern include: particle matter, formaldehyde, NO_2, Radon and Ozone.



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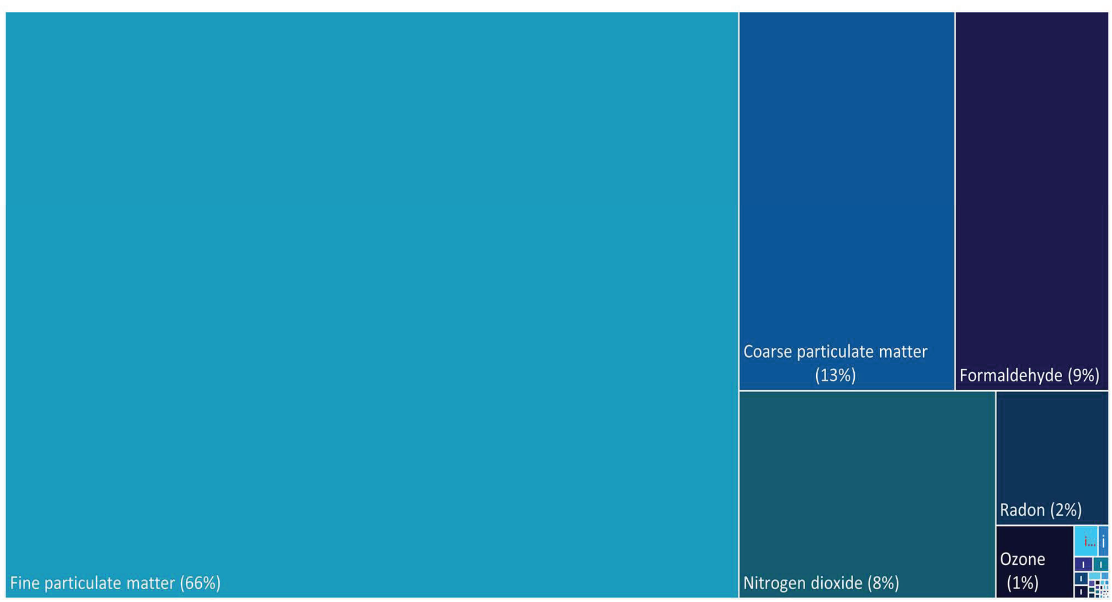
Total harm

$PM_{2.5}$ amounts to 2/3 of the expected total harm from chronic exposure to the 45 indoor contaminants considered

Contaminants of concern include: particle matter, formaldehyde, NO_2, Radon and Ozone.



Total Harm: Median DALYs, hierarchically-ordered (DALYs per 100,000 population)

Acceptability using a harm budget

- Sets an *acceptable* threshold for contaminant harm
- Derived from contaminants of concern
- Use concentrations from a reference scenario (California home study) and harm intensities
- Addendum to ASHRAE 62.2

REF: C Singer, WR Chan, Y-S Kim, FJ Offermann, IS Walker, Indoor air quality in California homes with code-required mechanical ventilation, Indoor air 30 (5) (2020) 885–899.

Summary

Section 5

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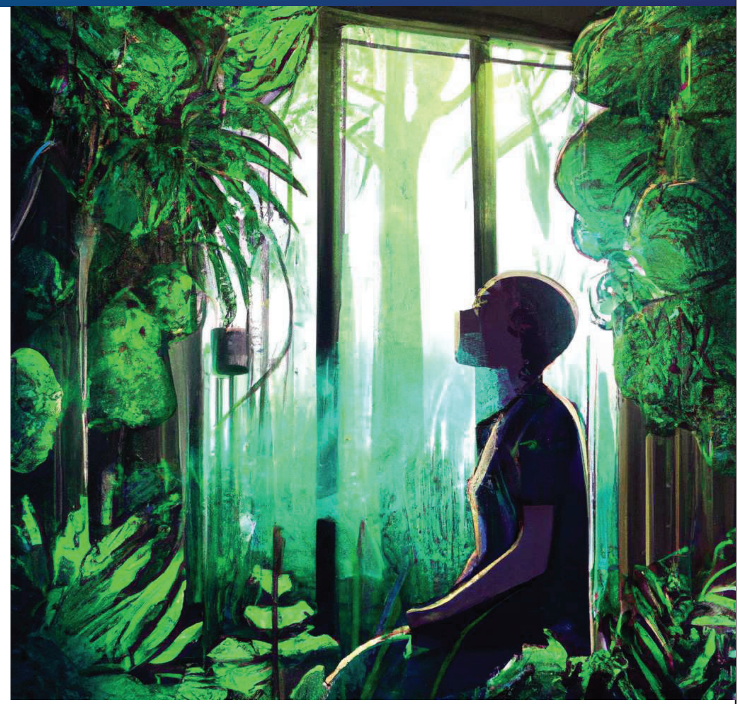
Summary

1. IAQ standards and guidelines should reflect the harm contaminants *actually* cause
2. Dwellings should mitigate against harm from $PM_{2.5}$, PM_{10}, HCHO, and NO_2
3. Harm intensities can be applied to other building types
4. Other building types require separate concentration analyses



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End

Indoor Air Quality

IEA EBC Annex 87

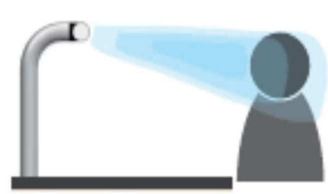
Energy and Indoor Environmental Quality Performance of Personalised Environmental Control Systems (PECS)

Bjarne W. Olesen and Ongun Berk Kazanci
Intl. Centre for Indoor Environment and Energy, Technical University of Denmark

AIVC Workshop, May 2023, Tokyo

WHAT IS PECS?

- Personal Environmental Control System (PECS) with the functions of heating, cooling, ventilation, lighting and acoustic has advantages of controlling the localized environment at occupant's workstation by their preference instead of conditioning an entire room.
- This improves personal comfort, health and energy efficiency of the entire heating, ventilation and air-conditioning (HVAC) system substantially.
- Personalized ventilation will also protect against cross contaminations, which are critical in open plan offices and work places with close distance.



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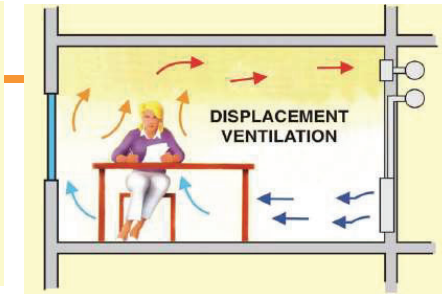
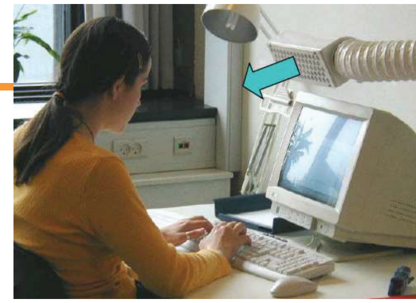
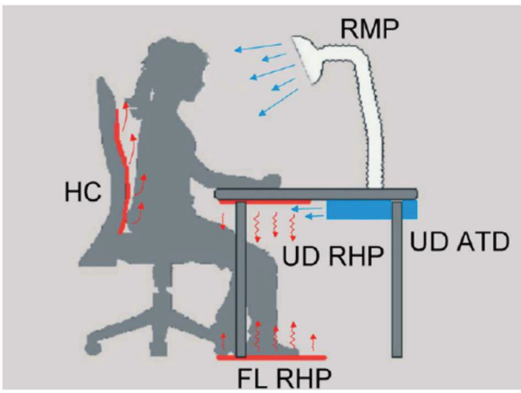




Source: Melikov 2010



Source: Watanabe et al. 2010

Source: Zhang et al. 2010

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Why PECS?

- Has several benefits compared to ambient (total volume) conditioning systems
  - Improved comfort, health and productivity
  - Higher satisfaction with the indoor environment, due to
    - Improvements in the immediate indoor environment experienced by the occupants
    - Possibility of personalized control
  - Potential energy savings
  - Increasing focus on individual differences between people → PECS can address these individual differences
  - Even more relevant due to COVID-19 (pandemic-proofing)

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Why PECS?

- Not entirely new – significant amount of research exists
- Despite the proven benefits
  - No design guide or manual for such systems and their integration in building HVAC systems
  - Far from ”solved”, still several issues to be addressed
  - Not at the level of a common solution in buildings
  - Very limited ”real world” and commercial examples

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Meetings

- 2022 Preparation phase
  - May 20th, 2022 Rotterdam
  - October 17-18th, Copenhagen
- 2023-2025 Working Phase
  - 1. meeting of the working phase of IEA EBC Annex 87, 19th and 20th of May 2023, Tokyo
  - 2. meeting in September 11-12, 2023 (Lausanne, Switzerland, before CISBAT2023 Conference)
- 2026 Reporting Phase

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OBJECTIVES

- Establish design criteria and operation guidelines for PECS
- Quantify the benefits regarding health, comfort and energy performance.
- Control concepts and guidelines for operating PECS in spaces with general ambient systems for heating, cooling, ventilation and lighting.

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SCOPE

- Includes all types of PECS for local heating, cooling, ventilation, air cleaning, lighting and acoustic.
- Includes desktop systems, which are mounted on desks or integrated in a furniture
- Chairs with heating/cooling and ventilation.
- Wearables, where heating/cooling and ventilation are included in garments or devices attached to occupants' body.
- Not including cars

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TARGET AUDIENCE

- Manufacturers (who need design guidelines)
- Building owners and consultants (who need information on performance, advantages, problems, operation, how PECS is operated together with other building systems)
- Users (need same info as building owners and for home workplaces)
- Standardisation Bodies (revision of standards for indoor environmental quality).

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Activities

- Seminar in CLIMA2022 (ca. 30 people attended)
  - https://clima2022.org/extra_content/seminar-new-iea-ebc-annex-on-personalized-environmental-control-systems-pecs/
- Topical session in AIVC2022 (ca. 45 people attended)
  - https://aivc2022conference.org/topical-session-08/
- AIVC Webinar on Monday, 12th of Dec 2022
  - Registration link:
  - https://inive.webex.com/inive/j.php?RGID=rd4ce219c23589874419137a1bff98911

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Subtask A: Fundamentals

- **Leader**
  - **Mariya P. Bivolarova, Technical University of Denmark, Denmark**
- **Co-leader:**
  - **Dolaana Khovalyg, EPFL, Switzerland**
- **Activity A1:** Definition and identification of the requirements of PECS in terms of localized and background Indoor Environmental Quality (IEQ) i.e., thermal, air quality, lighting, and acoustics.
- **Activity A2:** Outline the benefits of PECS regarding comfort, health and productivity based on literature and new research.
- **Activity A3:** Outline the minimum energy cost requirements for PECS.

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Subtask B: Applications and Technologies

- **Leader:**
  - **Kai Rewitz, RWTH Aachen University, Germany, pending**
- **Co-leader**
  - **Joyce Kim, University of Waterloo, Canada**
- **Activity B1:** Summarize the working principles, capabilities and limitations of existing PECS, based on literature.
- **Activity B2:** Identify future development and improvement suggestions for PECS for optimal energy, IEQ and cost performance.

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Subtask C: Control, operation and system integration

- **Leader:**
  - **Joon-Ho Choi, University of Southern California, USA**
- **Co-leader**
  - **TBD**

- **Activity C1:** Identify and summarize existing methods for controlling PECS (including sensors used for control).
- **Activity C2:** Develop guidelines on integrating PECS with ambient conditioning systems in buildings.

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Subtask D: IEQ and Energy Performance evaluation

- **Leader:**
  - **Douaa Al-Assad, KU-Leuven, Belgium**
- **Co-leader**
  - **Marco Perino, Politecnico di Torino, Italy**
- **Activity D1:** Collection of existing methods of studying and testing PECS.
- **Activity D2:** Identification of generic power requirements for PECS to achieve energy savings compared to ambient conditioning systems.
- **Activity D3:** Development of universal and standardized ways of evaluating and reporting performance of PECS.

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Subtask E: Policy and advisory actions

- **Leader:**
  - **Rajan Rawal, CRABSE, CEPT University, India**
- **Co-leader:TBD**
- **Activity E1:** Summary of national and international building codes and standards regarding PECS.
- **Activity E2:** Develop ways of overcoming current barriers for a wide implementation of PECS in buildings.
- **Activity E3:** Provide input to existing national and international standards about requirements, characteristics, and performance of PECS.

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DELIVERABLES

1. Guidebook on requirements for PECS
2. State-of-the-art report on PECS
3. Guidebook on PECS design, operation and implementation in buildings (including integration of PECS with ambient conditioning systems)
4. Report on test methods for performance evaluation of PECS
5. Universal criteria about requirements, characteristics, and performance of PECS to be used in national and international standards

Technology Collaboration Programme
by iea

EBC

Participating countries

- Australia, Belgium, Brazil, Canada, China, Denmark, Finland, France, Germany, Italy, Netherlands, Republic of Korea, Singapore, Switzerland, Turkey, USA

Further information

- www.iea-ebc.org/projects/project?AnnexID=87

Personal Environment Comfort System (PECS) for Improving Thermal Comfort and IAQ in a Zero Energy Building

Shin-ichi Tanabe, Prof. Dr., FASHRAE
Waseda University
President, Architectural Institute of Japan

T Innovation Center

WASEDA University

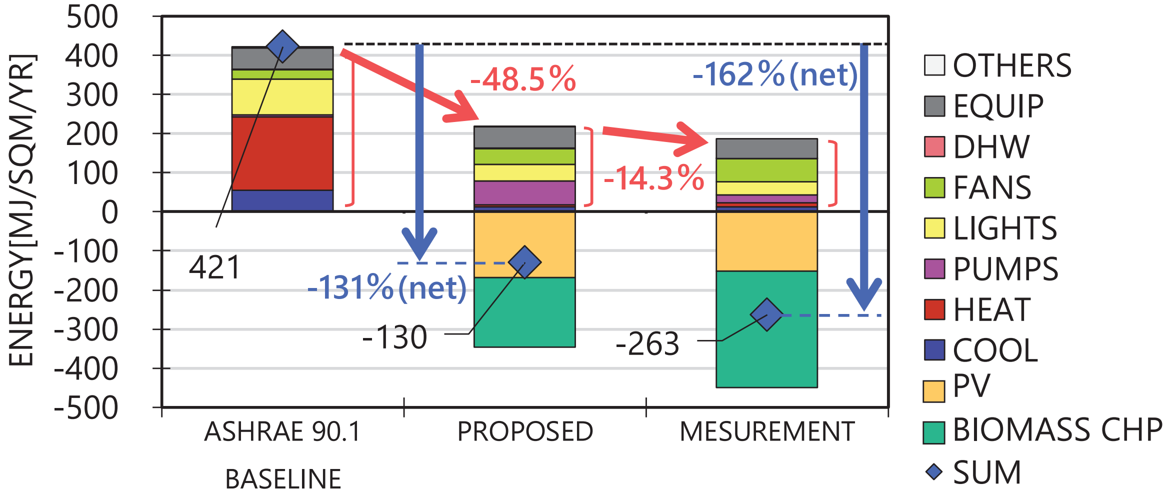
T Innovation Center

WASEDA University

Location	Tsukubamirai-city, Ibaraki, Japan
Hight	2-story building (15.5m)
Target office	2^{nd} floor with Activity Based Working (ABW)
Floor Area	Office building: 4,750m^2 Laboratory building: 6,050m^2
Energy System	Groundwater heat exchange Wood biomass heat and power supply system (CHP) PV panels 200 kW Battery power storage 4,600kWh

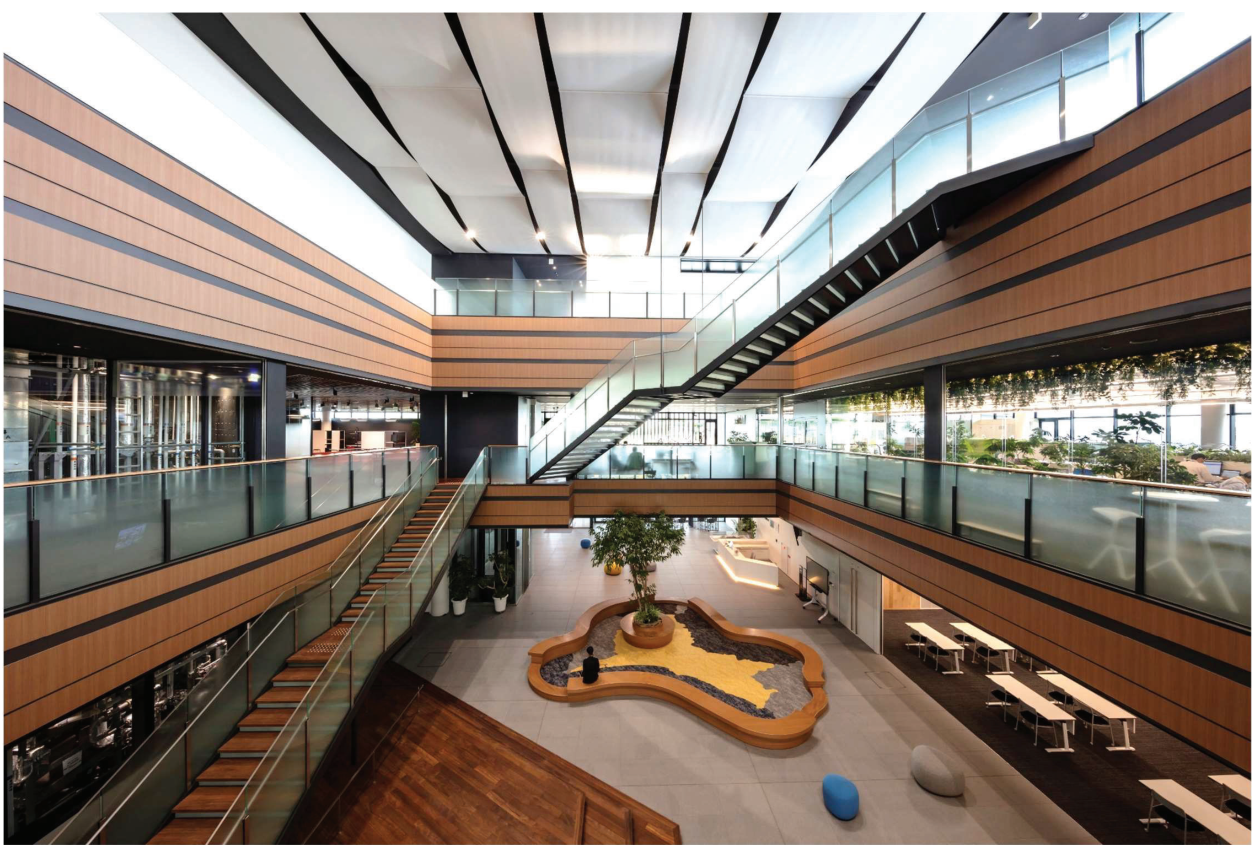
Net Zero Energy

WASEDA University



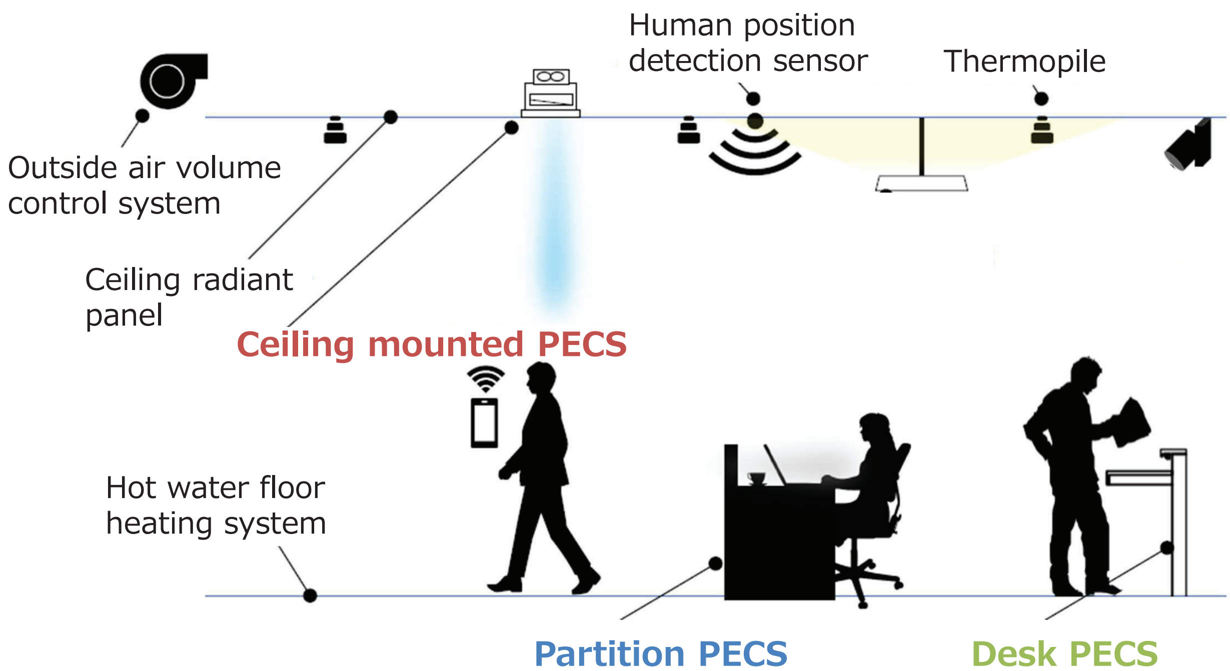
✓ **Net Zero Energy and Emission were achieved during 2021.**

WASEDA University



Three Types of PECS

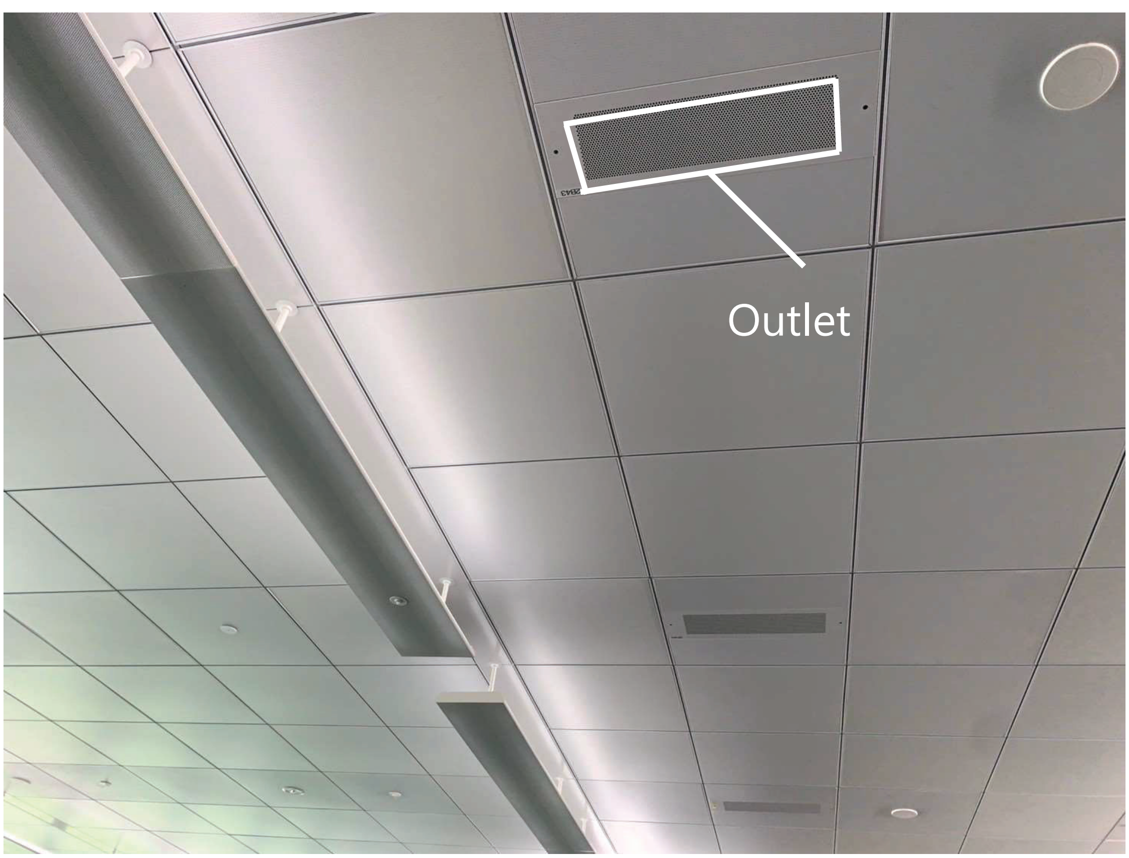
WASEDA University



Energy Efficiency: using groundwater as a cold heat source in summer and exhaust heat from biomass CHP as a heat source in winter

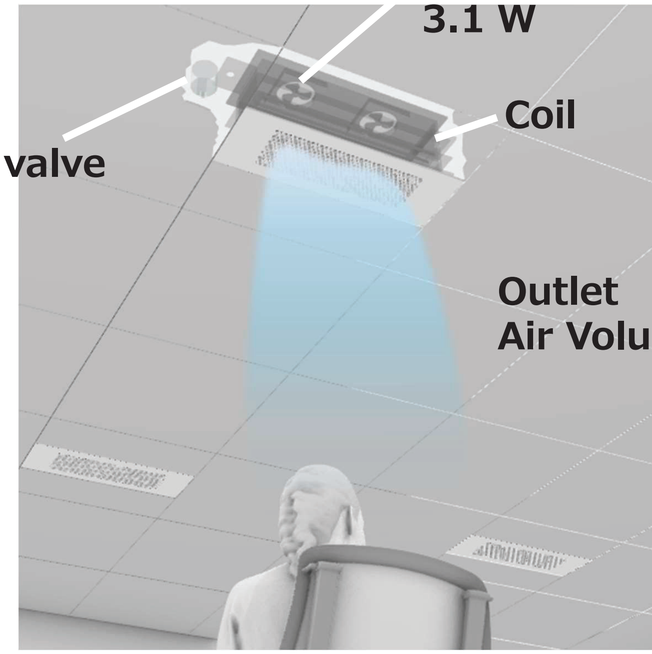
Ceiling installed PECS

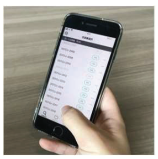
WASEDA University



Ceiling installed PECS

WASEDA University

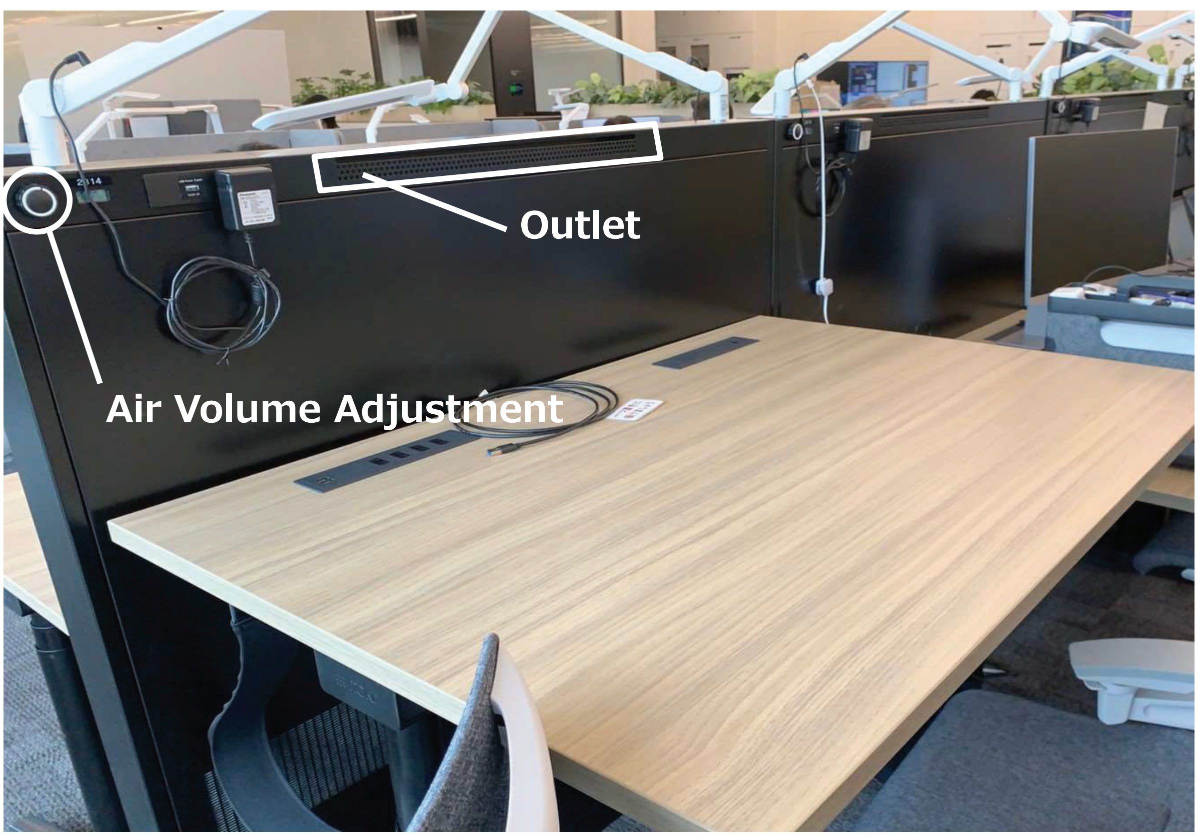




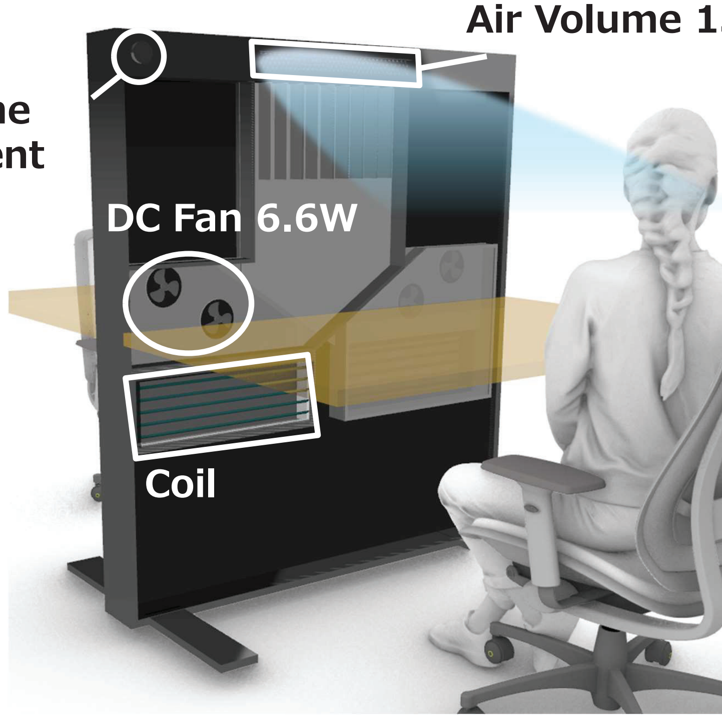
Cooling capacity 470W

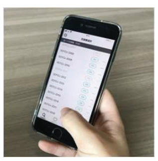
Partition PECS

WASEDA University

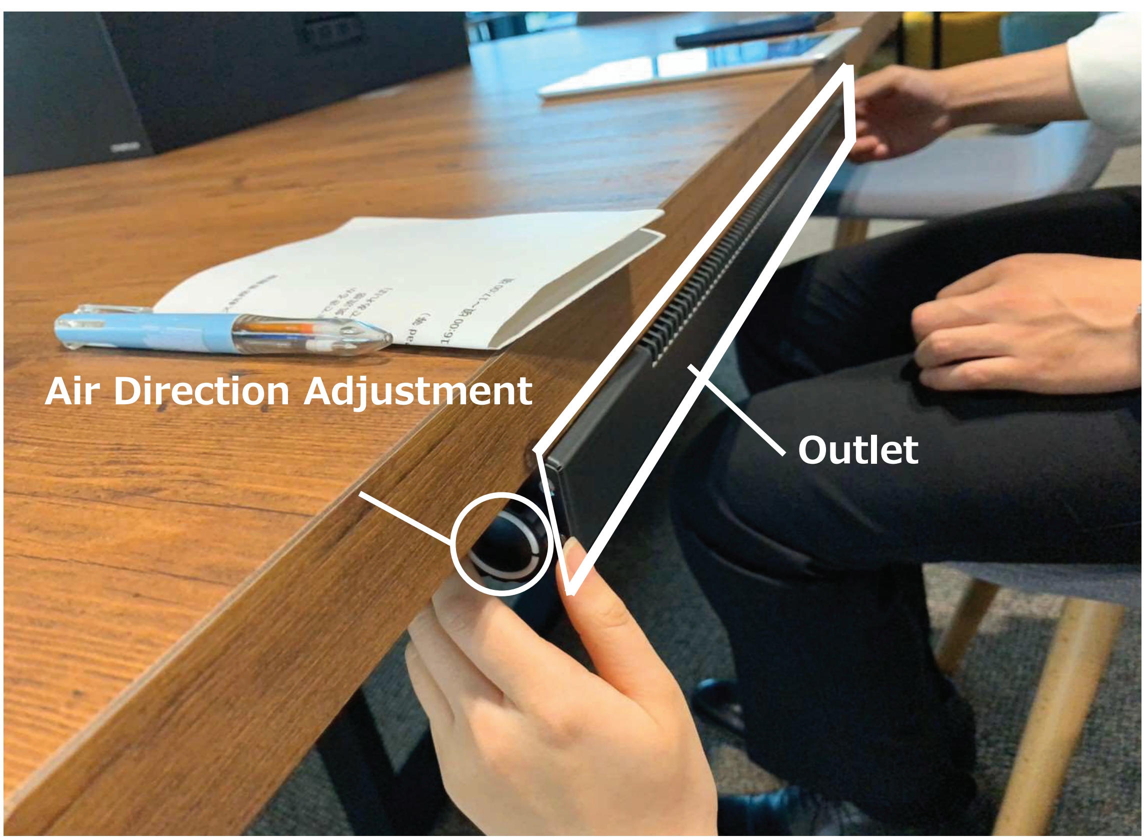


Partition PECS



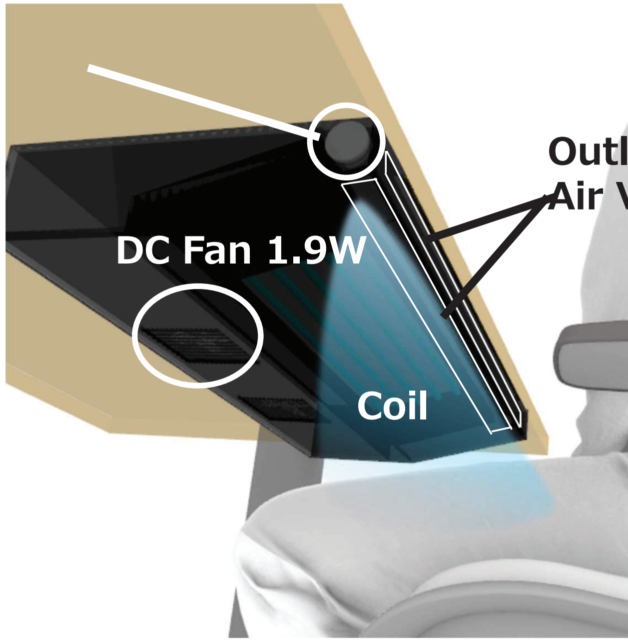


Desk PECS

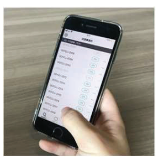


Desk PECS

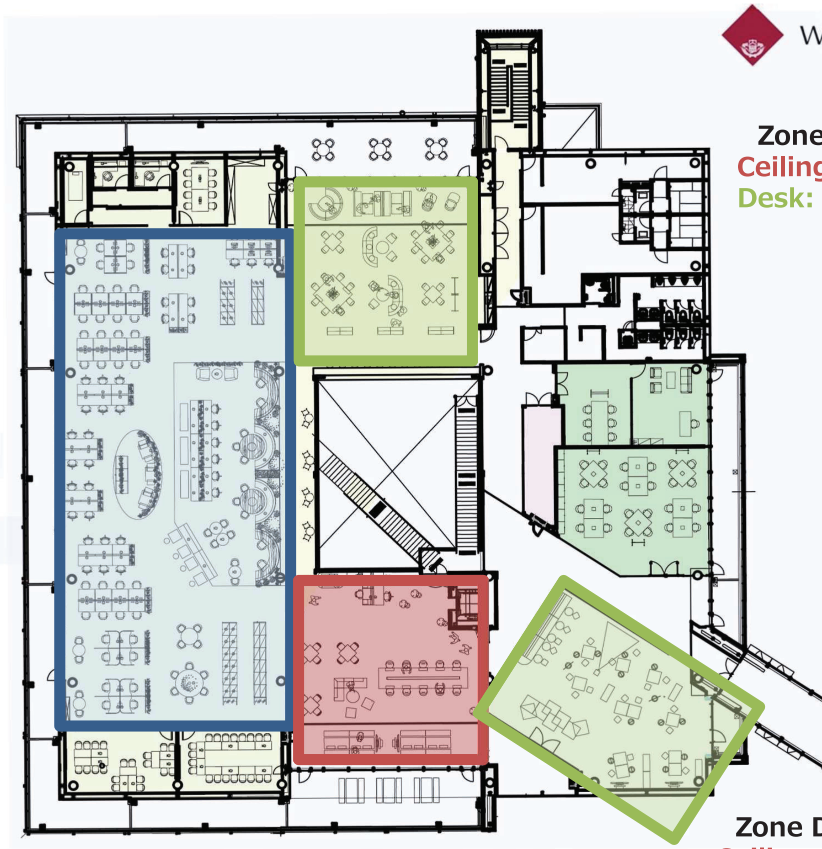
Air Direction Adjustment



Outlet Air Volume 50m³/h



Cooling capacity 70W



Zone A (634m²)
Ceiling: 57 units
Partition: 30 units
Desk: 28 units

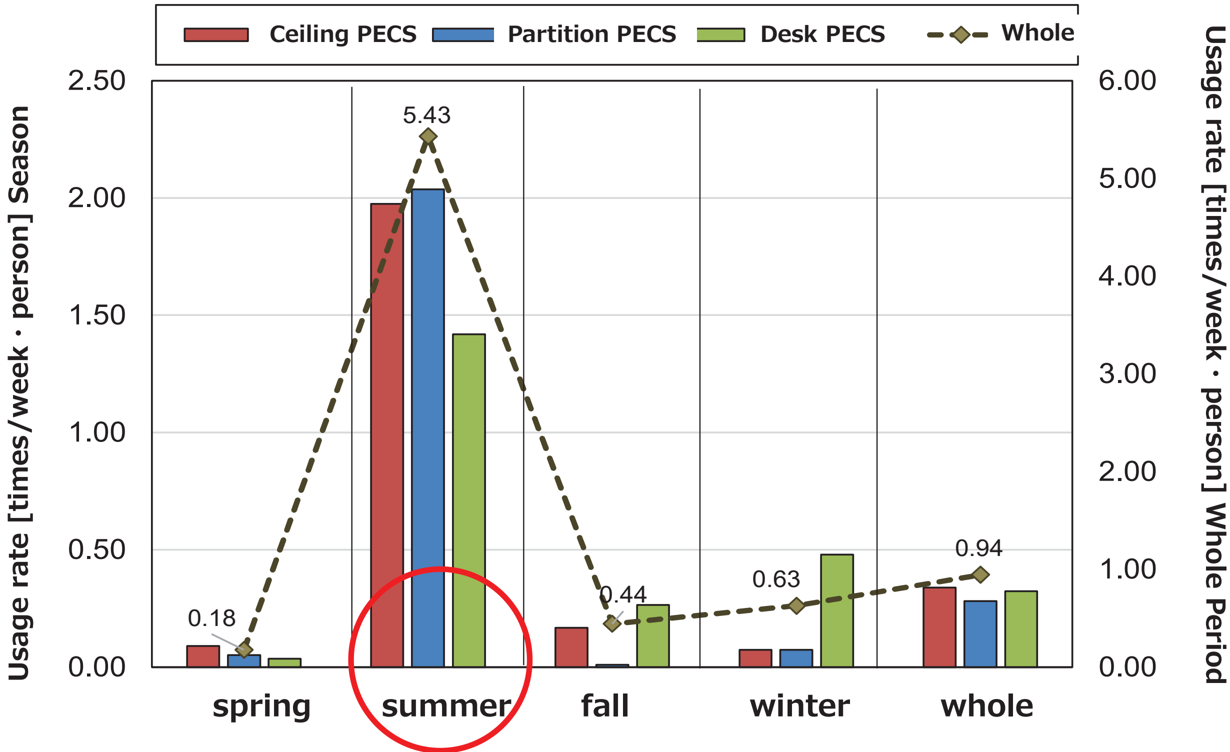
Zone B (194m²)
Ceiling: 34 units
Partition: 10 units
Desk: 18 units

Zone C (204m²)
Ceiling: 36 units
Desk: 8 units

Zone D (274m²)
Ceiling: 38 units

Season Usage Rates of PECS

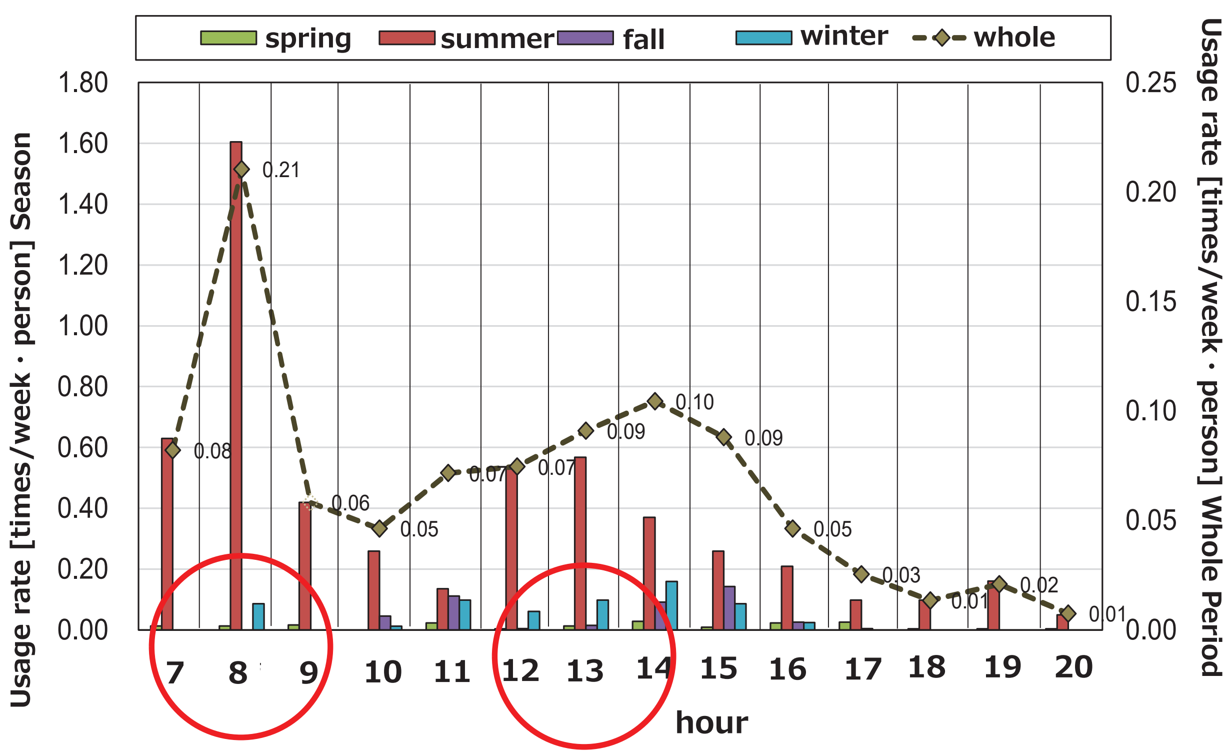
WASEDA University



✓ **During summer usage rates of PECS are higher and during winter they use desk type PECS for warming.**

Daily Usage Rate of PECS

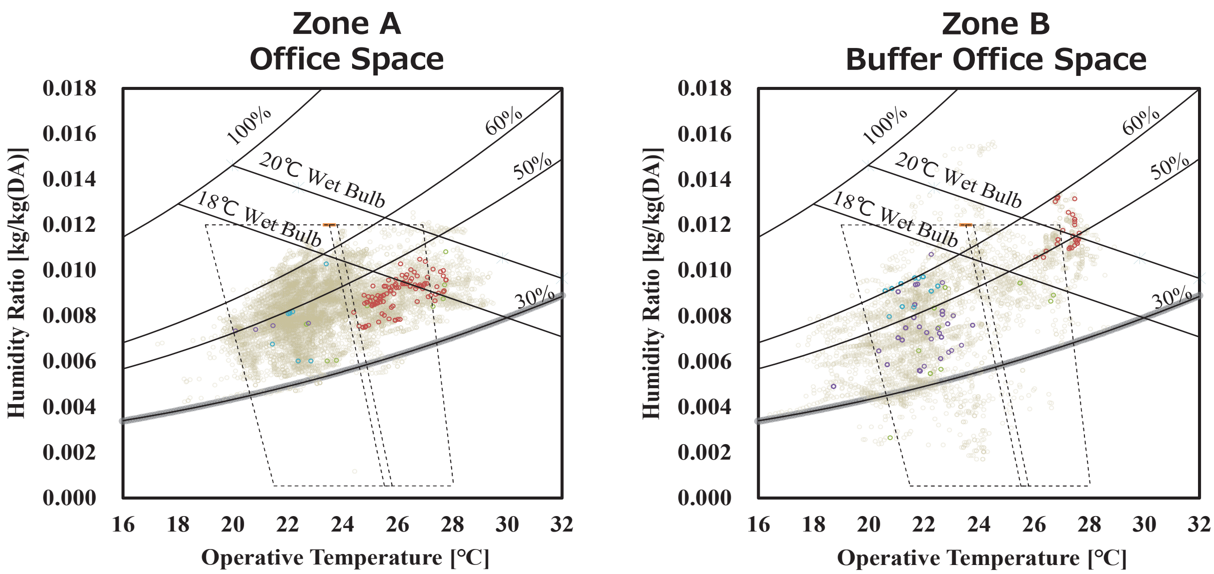
WASEDA University



✓ **More use in the morning and after lunch due to high metabolic rate.**

Ambient Thermal Conditions

WASEDA University



- : w/o PECS
- : Spring with PECS
- : Summer with PECS
- : Fall with PECS
- : Winter with PECS

✓ In office space (Zone A), they use PECS in the morning and after lunch due to high metabolic rate.

✓ Buffer office space (Zone B), they use PECS to compensate thermal sensation.

Percentage of Satisfied

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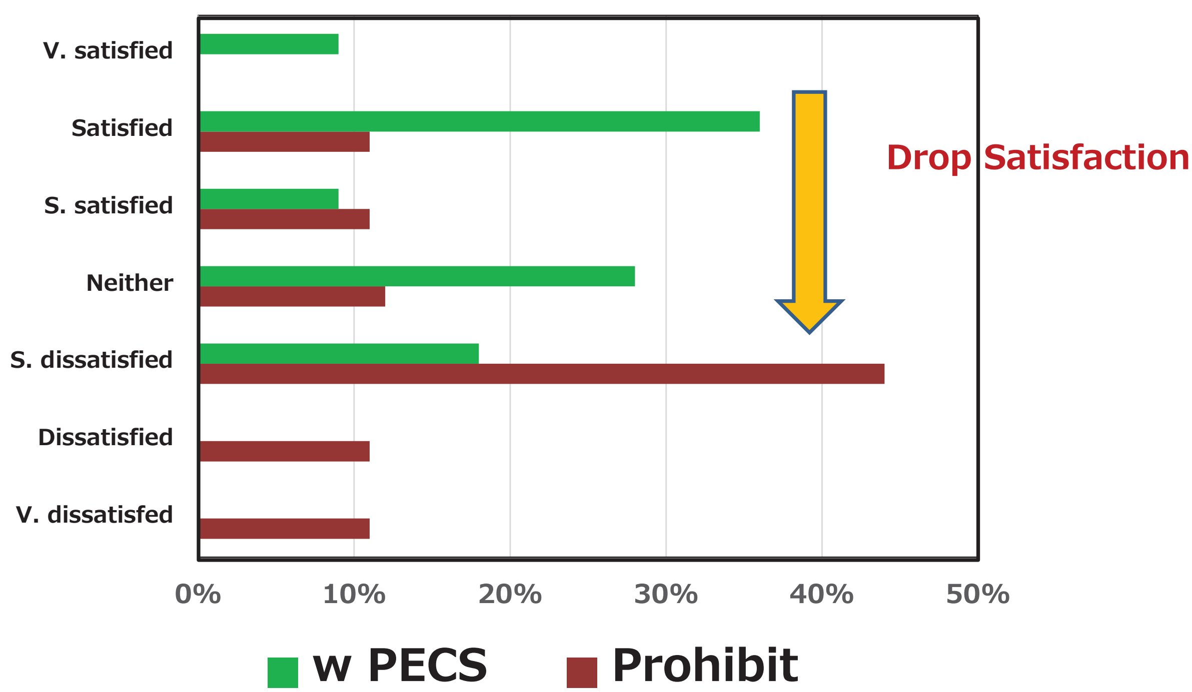


We prohibit to use PECS system during certain period.

Conclusions

WASEDA University

T Innovation Center opened in January 2020
- ✓ In office building unit net Zero Energy and Emission were achieved during 2021.
- ✓ Three types of PECS are installed in the different area.
- ✓ System specifications are described.

Usages of PECS are investigated
- ✓ During summer usage rates of PECS were higher and during winter they use desk type PECS for warming.
- ✓ They used PECS more in the morning and after lunch due to high metabolic rate.
- ✓ In office space (Zone A), they used PECS in the morning and after lunch.
- ✓ Buffer office space (Zone B), they used PECS to compensate thermal sensation.

We prohibited to use PECS system during a certain period.
- ✓ Percentage of dissatisfied significantly increased w/o PECS.

Acknowledgments

WASEDA University

Presented Project and Research are conducted in collaboration with the following companies and universities:

Takasago Thermal Engineering Co., Ltd.
Mitsubishi Jisho Design
Takenaka Cooperation
Kandenko Co., Ltd.
Yamato Co., Ltd.
Kanshinetsu Branch, Takasago Thermal Engineering Co., Ltd.
Shin-ichi Tanabe, Waseda University
Masanari Ukai, Waseda University
Yasunori Akashi, The University of Tokyo
Shohei Miyata , The University of Tokyo

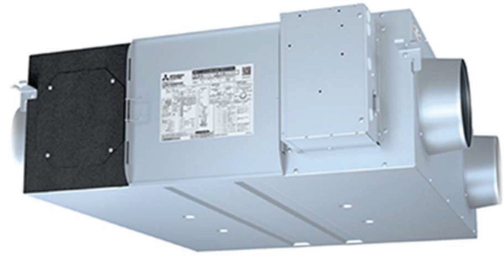
Actual effectiveness of energy/heat recovery ventilators in buildings: how is it influenced by key design factors and testing results(airflow, airflow ratio, unit exhaust air transfer ratio)?

Tetsutoshi Kan, Center for Better Living
Satoru Mineno, AE-Solutions Inc.
Takao Sawachi, Building Research Institute

Agenda

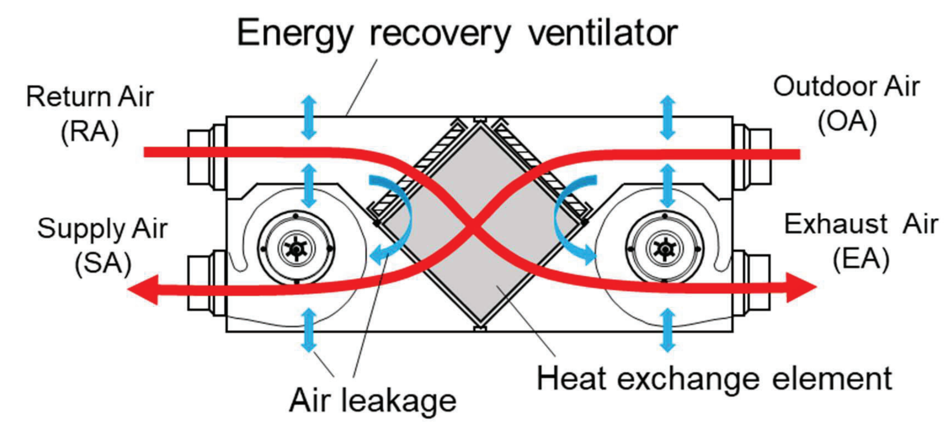
1. Introduction
2. Test results and discussion
3. Correction formula for total effectiveness of energy recovery ventilator and accuracy verification
4. Confirmation of energy saving performance of energy recovery ventilator in HVAC system
5. Conclusions

Introduction

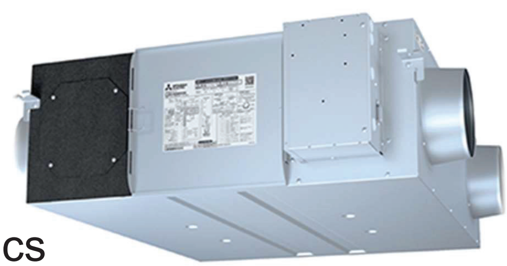


Energy recovery ventilator (ERV) :
> Supply outdoor air to indoor
> Exhaust indoor air to outdoor
> Supply air and Exhaust air exchange heat and moisture via heat exchange element

Reducing air-conditioning load (Energy- saving)



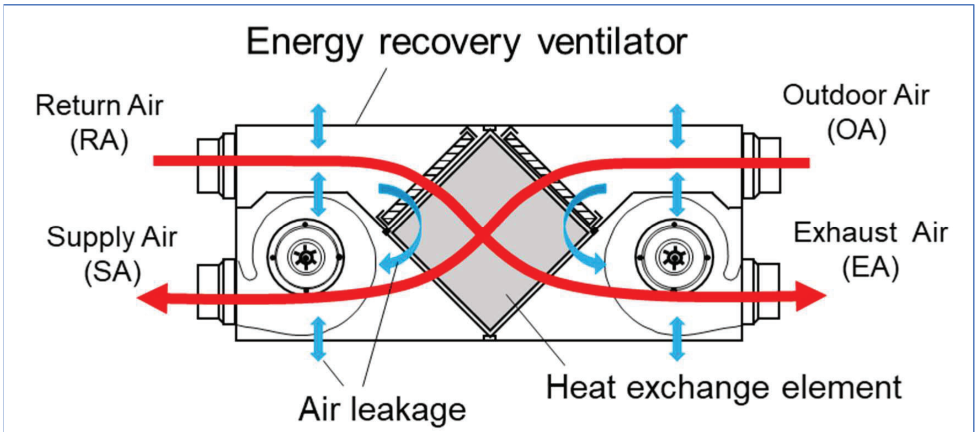
Introduction



Performance values of
Energy recovery ventilator (ERV) :

1. Airflow - static pressure characteristics
2. Gross effectiveness (Total effectiveness etc.)
3. Unit exhaust air transfer ratio (UEATR) or Net supply airflow ratio (NSAR)

   NSAR = 100-UEATR



Air leakage:
Depend on airtightness
>Throw the housing gap
> Throw the inside gap

Introduction

The performance value (The total effectiveness etc.) is not a constant value, but influenced by airflow rate, airflow ratio, unit exhaust air transfer ratio (UEATR).

Airflow, airflow ratio, UEATR are affected by ventilation equipment system in building and condition of operating.

In the design of heat recovery ventilation system in buildings, It is important to design airflow rate, airflow ratio, and UEATR to be appropriate in order to maximize the energy saving effect of the energy recovery ventilation systems.

Introduction

We conducted an experimental study to confirm how the total effectiveness of energy recovery ventilator is influenced by airflow rate, airflow ratio, and UEATR.

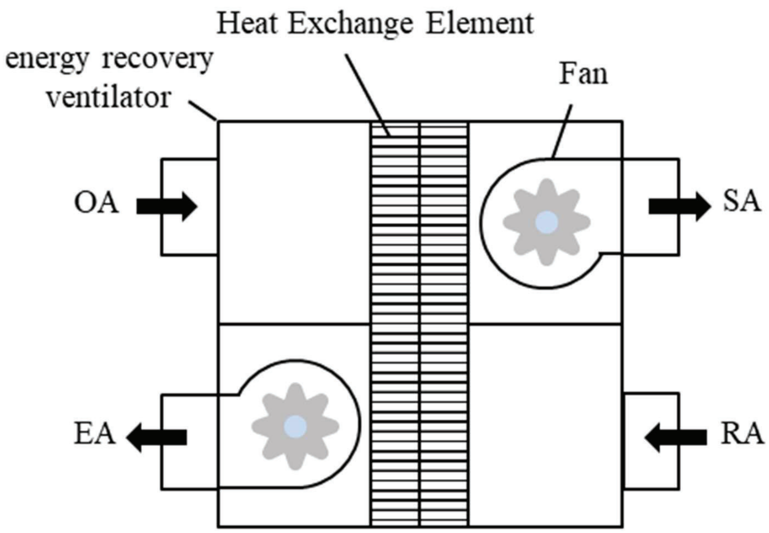
⇧

Purpose of experiment

2. Test results and discussion

Test method：JIS B 8628:2017 (ISO16494:2014)

Specimens: Plate type energy recovery ventilators



" The image is a product example and has nothing to do with the data that follows."

2. Test results and discussion

Specimens: Sample A (for non-residential buildings)
Sample B (for residential buildings)

Table　Description of the energy recovery ventilators

	Sample A	Sample B
Heat exchange element type	Plate type	
Constitution	Energy recovery ventilator	
Shape of inlet and outlet	Designed for duct connection	
Classification by airvolume	Medium size ($500m^3/h$)	Small size ($250m^3/h$)
Instalation	Ceiling hanging type	
Appliction	Non-residential buildings	residential buildings
Motor and fan	Built-in (two motors and fans)	

2. Test results and discussion

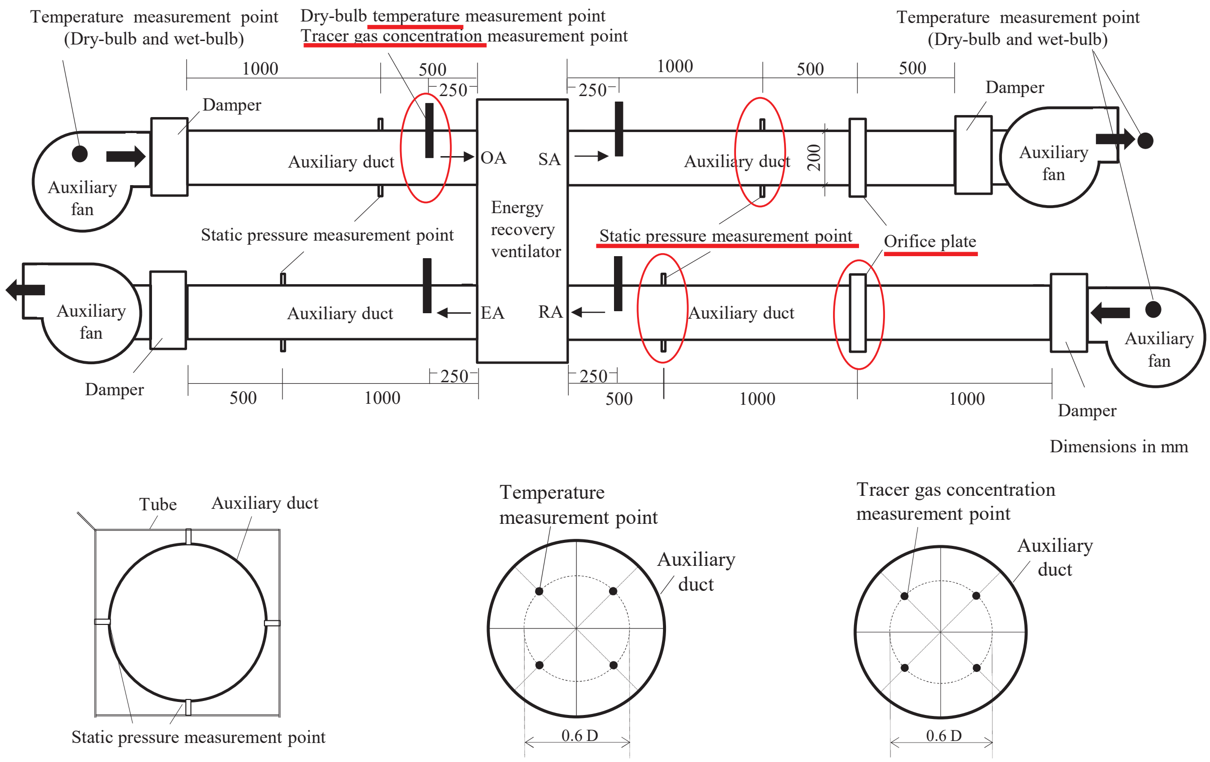


Fig　Schematic diagram of measurement apparatus

2. Test results and discussion

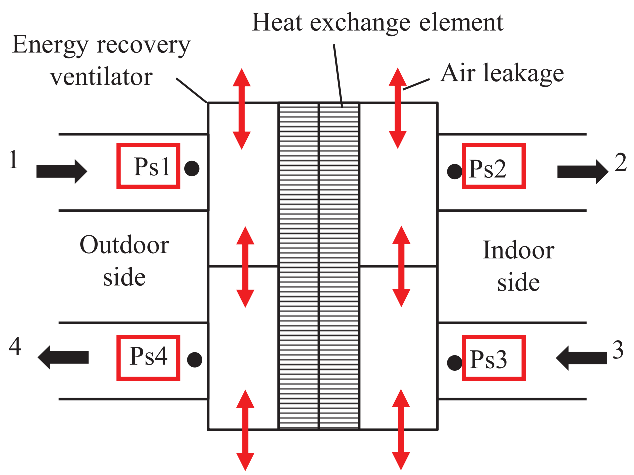
2. Test results and discussion

Table Measurement instruments and their performance

Measurement quantity	Measurement instrument	Uncertainty (JSCC calibration results)	Note
Temperature	Quartz thermometer PTR-111 (TOKYO DENPA CO.,LTD)	0.01˚C (at 0 ˚C)	
Dry-bulb temperature Wet-bulb temperature	Platinum resistance thermometer (Yashimasokki.co,.ltd AAClass)	-	0.12˚C (at 0˚C)(1)
Static pressure	MKS Baratron 220DD	3Pa (at 100kPa)	
Atmospheric pressure	Digital barometer R-30 (SANOH CO.,LTD)	0.5hPa (at 1000hPa)	
Tracer gas concentration	Infrared gas analyzer IR400（Yokogawa Electric Corporation)	-	±0.025% (at 5%)(2)
Airflow rate	Orifice plate (OHNISHI NETSUGAKU CO.,LTD)	-	

Note
(1):Uncertainty due to comparative calibration with PTR-111
(2):Repeatability shown in the specifications

2. Test results and discussion



1 Outdoor air ; OA 2 Supply air ; SA
3 Return air ; RA 4 Exhaust air ; EA

Ps1 Static pressure (OA) Ps2 Static pressure (SA)
Ps3 Static pressure (RA) Ps4 Static pressure (EA)

Symbols for the static pressure at inlets and outlets.

2. Test results and discussion

Table Static pressure measurement requirements and Airflow rate measurement points

Test setup	Test item	Static pressure measurement requirements	Airflow rate measurement points
Two room setup	Thermal performance test	Ps1 < 0Pa, Ps3 < 0Pa |(|Ps1|-|Ps3|)| <= Max (10Pa, Max(|Ps1|,|Ps3|)×5%) |(|Ps2|-|Ps4|)| <= Max (10Pa, Max(|Ps2|,|Ps4|)×5%)	200, 300, 400, 500m^3/h
Ducted setup	Thermal performance test	For the maximum and minum airflow rate |(|Ps1|-|Ps3|)| <= Max (10Pa, Max(|Ps1|,|Ps3|)×5%) |(|Ps2|-|Ps4|)| <= Max (10Pa, Max(|Ps2|,|Ps4|)×5%) For each intermediate test point Max(|Ps1|, |Ps2|, |Ps3|, |Ps4|) - Min(|Ps1|, |Ps2|, |Ps3|, |Ps4|) <= Max(10Pa, Max(|Ps1|,|Ps2|, |Ps3|, |Ps4|)×5%)	200, 300, 400, 500m^3/h

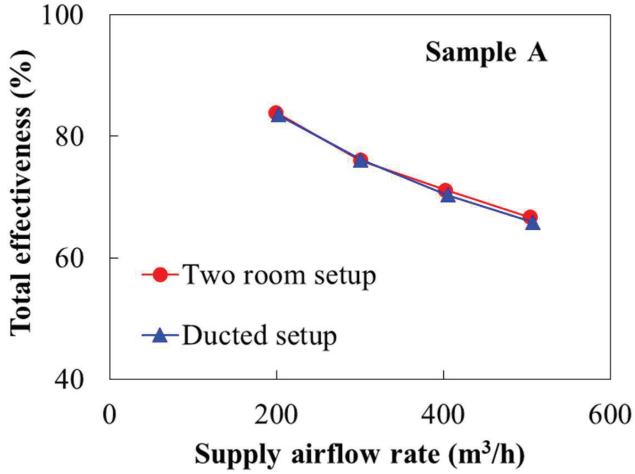
2. Test results and discussion

Table Temperature condition of thermal performance tests

Parameter		Heating	Cooling
Temperature of outdoor air (˚C)	Dry-bulb	5.0	35.0
	Wet-bulb	3.0	31.0
Temperature of return air (˚C)	Dry-bulb	20.0	27.0
	Wet-bulb	15.0	20.0

2. Test results and discussion (Sample A)

Influence of airflow rate (supply ≒ return)



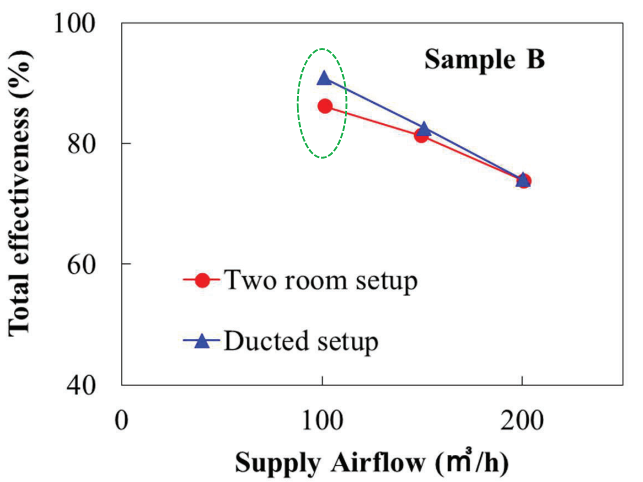
	Supply airflow rate	Return airflow rate	Airflow ratio	Total effecteveness
	m^3/h	m^3/h	-	%
Two room setup	199.5	212.4	0.94	83.9
	300.6	321.6	0.93	76.0
	403.0	412.3	0.98	71.1
	504.2	504.3	1.00	66.7
Ducted setup	202.1	203.9	0.99	83.5
	301.0	317.8	0.95	76.1
	405.2	407.3	1.00	70.3
	507.2	498.1	1.02	65.8

Sample A had relatively good air leakage performance, and there was no significant difference between the Two room setup and Ducted setup. The airflow ratio is approximately 1.0.

This result shows, if the airflow rate is small, the total effectiveness will be higher. At the supply airflow rate of 200m^3/h, the total effectiveness is about 84%. At the supply airflow rate of 500m^3/h, the total effectiveness is about 65%.

2. Test results and discussion (Sample B)

Influence of airflow rate



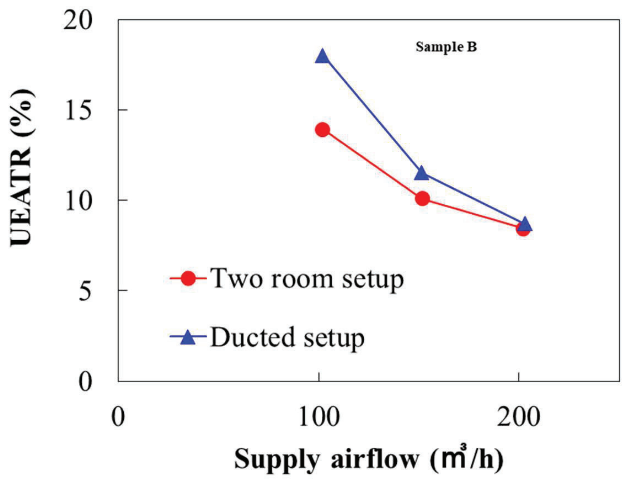
	Supply airflow rate	Return airflow rate	Airflow ratio	Total effecteveness
	m^3/h	m^3/h	-	%
Two room setup	101.3	108.3	0.94	86.2
	149.8	162.1	0.92	81.3
	200.6	207.2	0.97	73.8
Ducted setup	101.1	130.0	0.78	90.9
	151.1	170.1	0.89	82.6
	200.2	207.5	0.96	74.1

This is test result of Sample B.
Same with A, if the airflow rate is small, the total effectiveness will be higher.
But at the airflow rate about 100m^3/h, the total effectiveness is different between Two room setup and Ducted setup. This is due to the difference in the airflow ratio. Airflow ratio of two room setup is 0.94, compare to this the airflow ratio of ducted setup is 0.78. In the ducted setup, the return airflow rate lager than the supply airflow rate. We suppose another reason to cause such results is the difference in air leakage.

$$\text{Airflow ratio} = \frac{\text{Supply airflow rate}}{\text{Return airflow rate}}$$

2. Test results and discussion

Trace gas test result (Sample B)



This is trace gas test result of Sample B.
At the airflow rate about 100m^3/h, the UEATR of Ducted setup is 18.0%, larger than UEATR of Two room setup (13.9%).
The reason of causing this difference is when the airflow rate small (the static pressure is large), the air leakage rate of each part of the energy recovery ventilator is different.
Similarly, it causes the difference of airflow ratio.

	Supply airflow rate	Return airflow rate	Airflow ratio	UEATR
	m^3/h	m^3/h	-	%
Two room setup	102.0	119.0	0.86	13.9
	151.7	165.5	0.92	10.1
	202.2	211.0	0.96	8.4
Ducted setup	102.1	129.8	0.79	18.0
	151.6	172.5	0.88	11.5
	203.0	210.7	0.96	8.7

3.Correction formula and verification of accuracy

In order to properly evaluate the energy saving effect of energy recovery ventilator installed in a building for ventilation system design, the correction formula for total effectiveness of energy recovery ventilator was reviewed and proposed.

The total effectiveness values of energy recovery ventilator In the catalog were corrected by airflow rate, airflow ratio, and NSAR (NSAR =100-UEATR).

3.Correction formula and verification of accuracy

$$\eta'_t = \eta_t \times C_{tol} \times C_{eff} \times C_{bal}$$

η'_t : *is the corrected total effectiveness* [%]

η_t : *is the total effectiveness listed in the catalog* [%]

C_{tol} : *is the correction coefficent considering the total effectiveness tolerance listed in the catalog* [−]. The default value is 0.95.

C_{eff} : *is the correction coefficent considering the net supply air flow ratio(NSAR)* [

NSAR = 100 − UEATR

C_{bal} : *is the corrected coefficent due to the airflow ratio* [−].

3.Correction formula and verification of accuracy

$$C_{eff} = 1 - \frac{\left(\frac{1}{\varphi} - 1\right)(1 - \eta_t)}{\eta_t}$$

C_{eff} : *is the corrected coefficent considering the net supply air flow ratio(NSAR*

NSAR = 100 − UEATR

η_t : *is the total effectiveness listed in the catalog* [%]

φ: *is the net supply airflow ratio* (*NSAR*) [%].

3.Correction formula and verification of accuracy

$$C_{bal} = \frac{\eta_{t,d}}{\eta_t}$$

C_{bal} : *is the corrected coefficent due to the airflor ratio* [−].

$\eta_{t,d}$: *is the corrected total effectiveness considering the airflow ratio in the building* [%]

η_t : *is the total effectiveness listed in the catalogue* [%]

3.Correction formula and verification of accuracy

$$\eta_{t,d} = 1 - e^{\left[\frac{e^{\left(-N_d{}^{0.78} \cdot R_{vnt,d}\right)} - 1}{N_d{}^{-0.22} \cdot R_{vnt,d}}\right]}$$

$$R_{vnt} = \begin{cases} \dfrac{V_{d,SA}}{V_{d,RA}} & (V_{d,RA} > V_{d,SA}) \\ \dfrac{V_{d,RA}}{V_{d,SA}} & (V_{d,RA} \le V_{d,SA}) \end{cases}$$

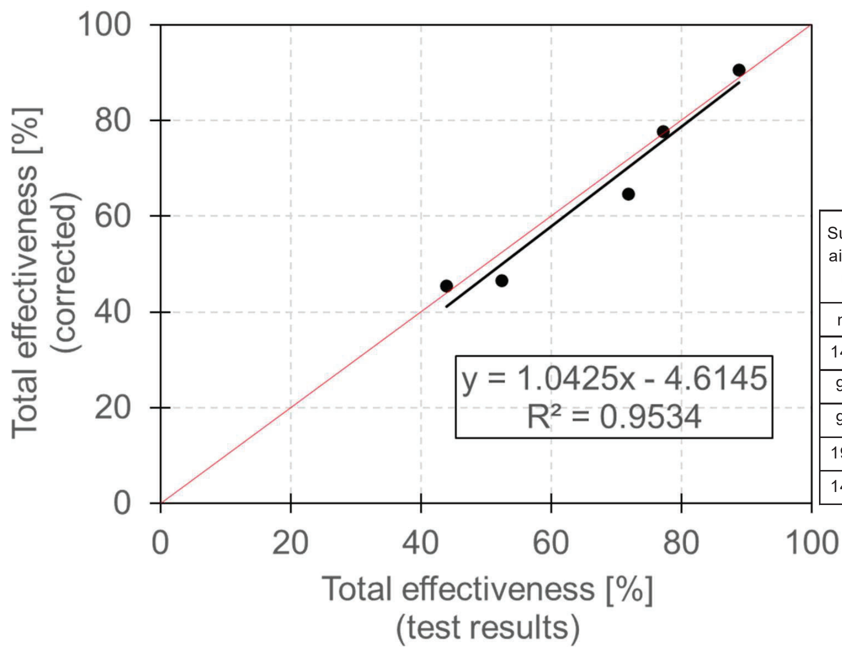
$\eta_{t,d}$: *is the corrected total effectiveness considering the airflow ratio in the building design* [%]

$V_{d,SA}$: *is the supply airflow rate in the building design* $[m^3/h]$

$V_{d,RA}$: *is the return airflow rate in the building design* $[m^3/h]$

N_d : *is the heat transfer unit number in the energy recovery ventilator* [−]

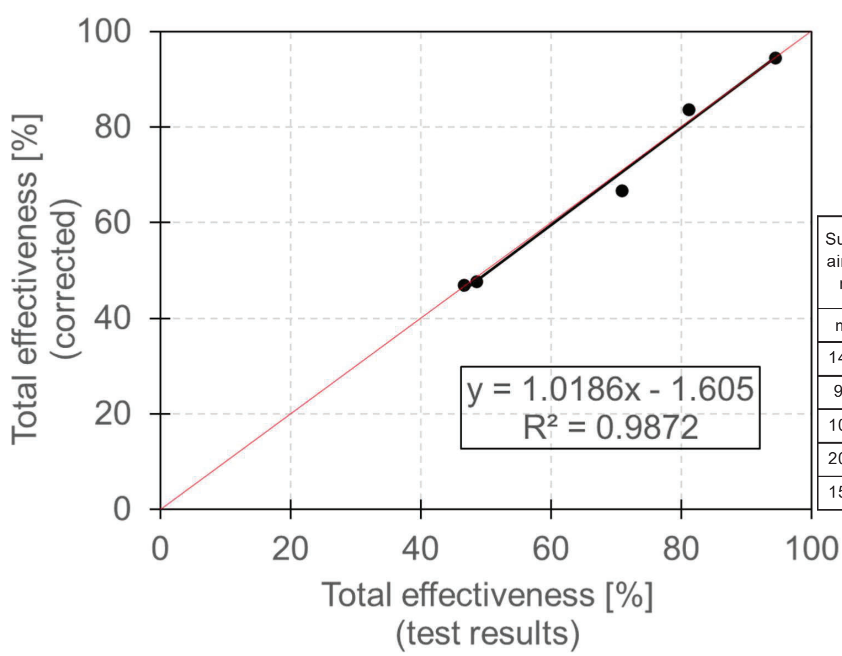
3.Correction formula and verification of accuracy



Supply airflow rate	Return airflow rate	NSAR	Airflow ratio	Total effectivenees (corrected)	Total effectiveness (test results)
m^3/h	m^3/h	%	-	%	%
147.7	197.6	88.0	0.75	77.1	77.7
99.7	198.6	82.3	0.50	88.8	90.6
98.7	74.5	83.3	1.32	71.8	64.7
197.1	99.0	90.9	1.99	43.9	45.5
147.4	73.4	88.2	2.01	52.4	46.6

Comparison of test results and corrected total effectiveness (Cooling condition)

3.Correction formula and verification of accuracy



Supply airflow rate	Return airflow rate	NSAR	Airflow ratio	Total effectivenees (corrected)	Total effectiveness (test results)
m^3/h	m^3/h	%	-	%	%
149.9	200.5	88.0	0.75	81.2	83.7
99.9	199.6	82.3	0.50	94.4	94.6
101.1	75.6	83.3	1.34	70.8	66.7
201.6	100.2	90.9	2.01	46.6	47.1
150.3	74.8	88.2	2.01	48.5	47.8

Comparison of test results corrected total effectiveness (Heating condition)

4. Energy saving performance in HVAC system

In Japan, there are calculation programs to estimate energy consumption performance at the design stage. The program runs on the website and is available through the website of Building Research Institute.

Energy Consumption Performance Calculation Program
https://building.lowenergy.jp/

Until 2023, the total effectiveness of energy recovery ventilator for non-residential buildings was calculated using fixed values for "Airflow rate" and "NSAR";
from 2024, the calculation method was changed to use the correction formula for total effectiveness of energy recovery ventilator.

As described in this presentation, we examined the energy saving performance of energy recovery ventilator when the total effectiveness is calculated by correction coefficient proposed.

4. Energy saving performance in HVAC system

Comparison of old and new calculation methods

	Airflow ratio	NSAR
Present calculation method	0.50	0.85
New calculation method (using correction formular)	Variable	Variable

Case study

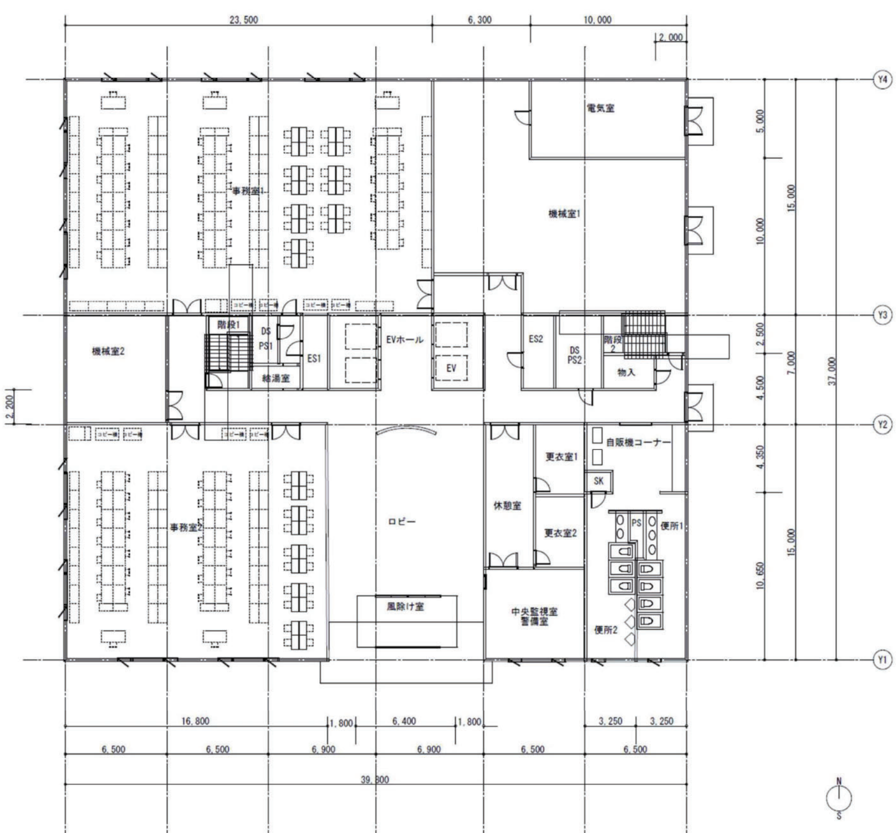
	Package air conditioner + Energy recovery ventilator
Present calculation method	Case A
New calculation method (using correction fomular)	Case A'

4. Energy saving performance in HVAC system

Building outline

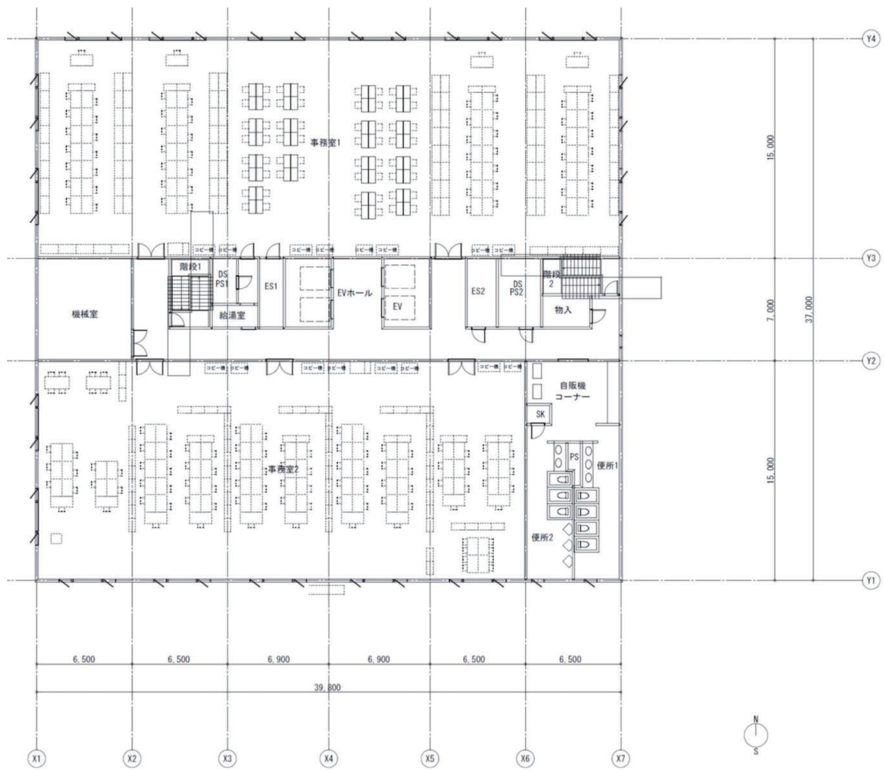
Building location	Tokyo
Number of floors	7
Building use	office
Building strcture	steel reinforced concrete construction
Total floor area	10,358.3 m^2

4. Energy saving performance in HVAC system



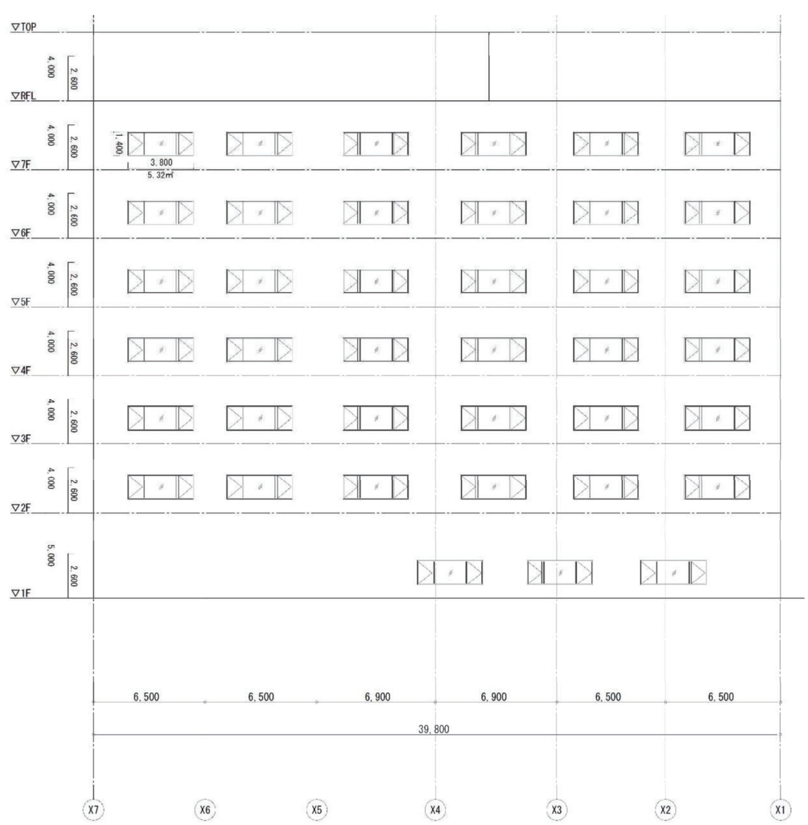
1st floor plan

4. Energy saving performance in HVAC system



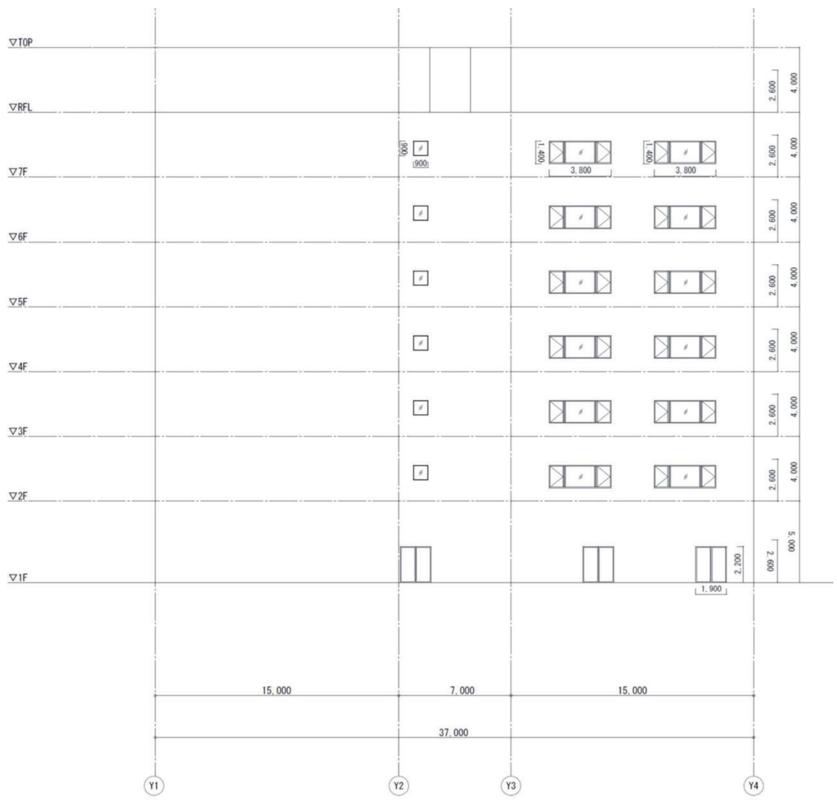
2nd to 7th floor plan

4. Energy saving performance in HVAC system



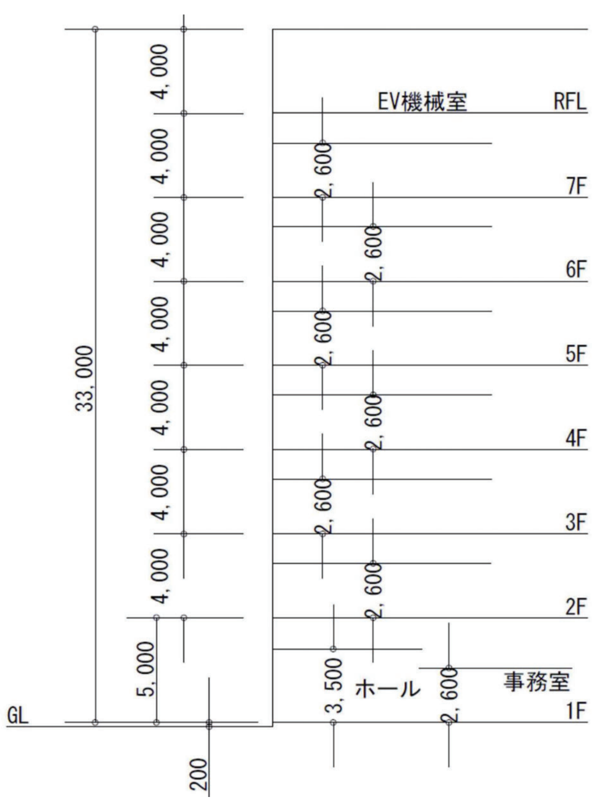
North side elevation

4. Energy saving performance in HVAC system



East side elevation

4. Energy saving performance in HVAC system



RF	63.5m²
7F	1,472.60m²
6F	1,472.60m²
5F	1,472.60m²
4F	1,472.60m²
3F	1,472.60m²
2F	1,472.60m²
1F	1,459.16m²
延べ床面積	10,358.26m²

Cross section and floor space

4. Energy saving performance in HVAC system

Building skin insulation performance

	Thermal convection rate W/m^2K
Outer wall	0.59
Rooftop	0.32
Ground floor	0.80
Window	1.60

4. Energy saving performance in HVAC system

Dry and wet bulb temperature conditions

	Summer		Winter	
	Dry-bulb (˚C)	Relative humidity (%)	Dry-bulb (˚C)	Relative humidity (%)
Outside air condition	34.7	53.5	1.8	40.1
Office room air condition	26.0	50.0	22.0	40.0

4. Energy saving performance in HVAC system

Internal heat gains

	Lighting (W/m^2)	Office equipment (W/m^2)	Large office equipment (W)	People	Heat gain / Person (W/Person)	
					SHG	LHG
Office room 1	34.7	18.8	53.5	120	1.7	40.1
Office room 2	26.0	10.5	50.0	100	6.6	40.0

4. Energy saving performance in HVAC system

Air conditioning performance (Case A, Case A')

	Heating capacity (kW/m^2)	Cooling capacity (kW/m^2)	COP (Heating condition)	COP (Cooling condition)
Package air conditioner	0.118	0.133	3.39	2.96

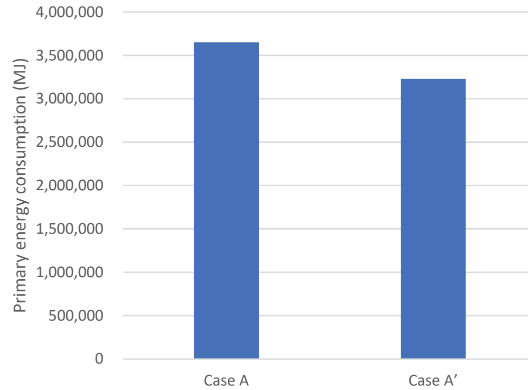
Performance values of Energy recovery ventilators (Case A, Case A')

	Total effectiveness (%)	NSAR (%)	Ratio of supply airflow rate to return airflow rate	Specific fan power
Eenergy recovery ventilator	70	92	1.25	0.51

4. Energy saving performance in HVAC system

Case	Primary energy consumption of the entire air conditioning system (MJ)
Case A	3,650,298
Case A'	3,228,859

Reduction (MJ)	421,439
Reduction rate	11.5%

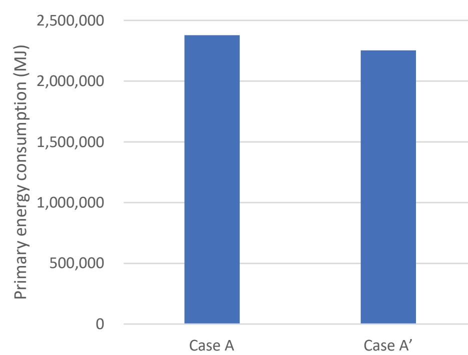


Comparison of Case A and Case A'

4. Energy saving performance in HVAC system

Case	Primary energy consumption of the entire air conditioning system (MJ)
Case A	2,378,448
Case A'	2,254,092

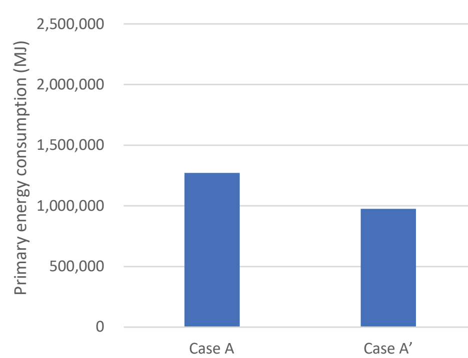
Reduction (MJ)	124,356
Reduction rate	5.2%



Comparison of Case A and Case A' (Cooling condition)

Case	Primary energy consumption of the entire air conditioning system (MJ)
Case A	1,271,850
Case A'	974,768

Reduction (MJ)	297,082
Reduction rate	23.4%



Comparison of Case A and Case A' (Heating condition)

5. Conclusions

1.Total effectiveness depends on the airflow, the airflow ratio, and the UEATR. And UEATR depends on the static pressure differential across the ventilators.

2.The total effectiveness of energy recovery ventilator operating in the building often differs from the total effectiveness in the energy recovery ventilator catalogs.

3. In order to properly evaluate the energy saving effect of energy recovery ventilator installed in a building for ventilation system design, it is necessary to correct the total effectiveness of energy recovery ventilator in the catalogs.

4.We proposed a correction formula that corrects the total effectiveness of energy recovery ventilator in the catalogs according to the airflow rate, airflow ratio, and NSAR. And using the correction formula was examined the energy saving performance of energy recovery ventilator in an office building.

5.The total effectiveness of energy recovery ventilator in the catalogs are also useful for product comparisons.

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Latest Trends and Technologies of Energy Recovery Ventilators in Japan

Mitsubishi Electric Corporation

Nakatsugawa Works

Junichi Takahashi , Hidemoto Arai, Masaru Takada

換気は、やっぱり 三菱電機

N23HMGT0013

1. **Ventilation and Air Conditioning Situation in Japan**
   - Overview of Ventilation and Air Conditioning in Japan
   - Ventilation and Air Conditioning Regulations in Japan
   - The building design and construction situation

2. **Technological Trends of ERVs (Static Type) in Japan**
   - Product type
   - Air volume control
   - Multiple unit control/network
   - Interlock control with air conditioners
   - Installation/Maintenance

1-1 Ventilation and Air Conditioning Situation in Japan

Overview of Ventilation and Air Conditioning in Japan

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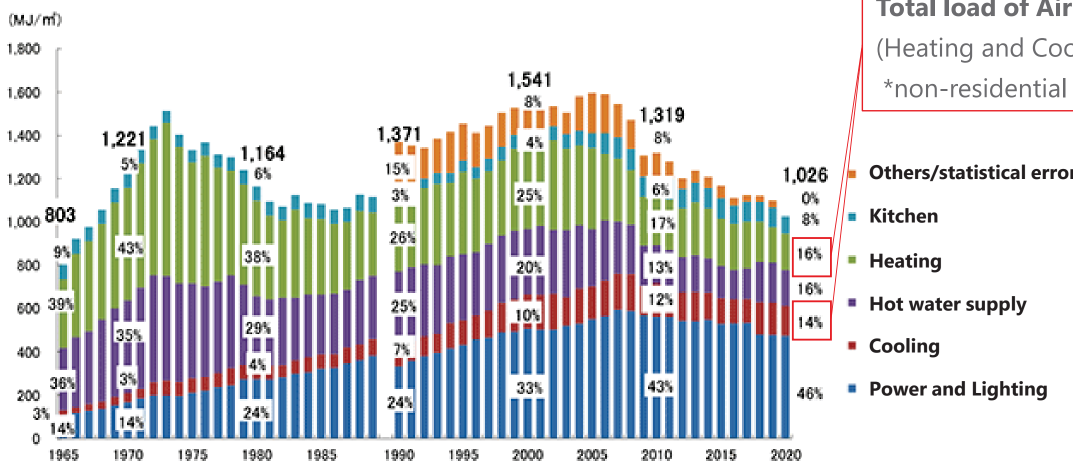
Energy Use in Building by Applications

Below is the bar chart showing energy Consumption ratio through year in business dept. in Japan.
Air Conditioner takes up high ratio.

Total load of Air Conditioning
(Heating and Cooling) : **30%**
*non-residential sector



Source: Agency for Natural Resources and Energy White Paper on Energy 2022 [No. 212-1-9] Changes in unit energy consumption by business and other sectors https://www.enecho.meti.go.jp/about/whitepaper/2022/html/2-1-2.html

Energy Saving of Air Conditioning System is
High Priority in Japan same as other countries.

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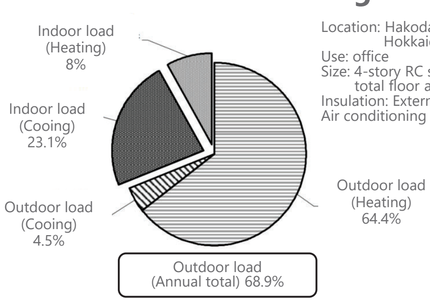
Three Types of Air Conditioning Load

We cannot live without air conditioning system. Therefore, in order to save energy, we must think about reducing power consumption by reconsidering the load on air conditioning system.

Total Air Conditioning Load



Location: Hakodate City, Hokkaido
Use: office
Size: 4-story RC structure
total floor area: 4,045 m2
Insulation: External wall insulation
Air conditioning method: FCU

Graph
Annual air conditioning load ratio
(Non-use of outside air load reduction technology)

Source: Research on the effectiveness of environmental load reduction technology in cold regions -Effects of ERVs and outside air intake control in highly insulated buildings-Hokkaido Development Technology Research Conference (2004) <https://thesis.ceri.go.jp/db/documents/public_detail/24379/>

01 Indoor Generated Heat
Energy loss from heat generated by lightning, human, electronics, bath, kitchen, etc.

02 Indoor Penetration Heat
Energy loss from heat coming from walls or drafts of buildings with poor airtightness and insulation.

03 Ventilation Outdoor Air Load
Energy loss occurring when outside air enters when ventilating.

Ventilation outdoor air load takes a big part of energy loss in air conditioning system.

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1-2 Ventilation and Air Conditioning Situation in Japan

Ventilation and Air Conditioning Regulations in Japan

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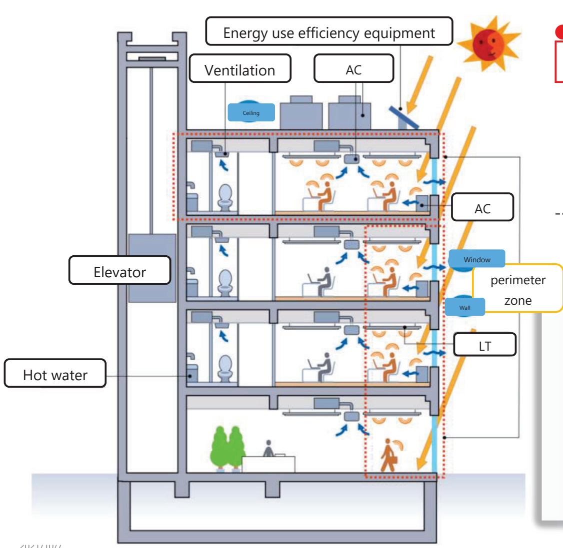
Regulations related to ventilation and air conditioning (laws, guidelines, etc.)

Laws and regulations related to energy conservation

Law/Regulation	Overview
Act on Rationalizing Energy Use	Laws related to energy-saving performance of equipment Example) Top-runner standards; stipulating performance and power
Building Energy Efficiency Act	Law on energy efficiency performance of all buildings. Buildings cannot be built unless the total energy consumption of insulation performance and equipment (air conditioning, ventilation, lighting, hot water supply, elevators, etc.) is below the specified value.



●Primary energy consumption

- \+ Primary energy consumption of air conditioning equipment(AC)
- \+ Primary energy consumption of ventilation equipment
- \+ Primary energy consumption of lighting equipment(LT)
- \+ Primary energy consumption of hot water supply equipment
- \+ Elevator primary energy consumption
- \+ Other (OA equipment, etc.) primary energy consumption
- − Amount of reduction in primary energy consumption by energy use efficiency equipment

= Primary energy consumption

Ventilation fans and ERVs must also be taken into account

In order to achieve **ZEB/ZEH**, it is necessary to further **reduce energy consumption in the field of air conditioning and ventilation**.

<Efforts toward carbon neutrality in 2050>

Strengthening drastic efforts is essential

Aiming to secure ZEH/ZEB-level energy-saving performance for new construction

Aiming to secure ZEH/ZEB-level energy-saving performance on average for stock

2030年 ・・・・・ 2050年 ・・・・・

ZEH/ZEB: Net zero energy house/building

2021/10/7

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Regulations related to ventilation and air conditioning (laws, guidelines, etc.)

Health and air quality laws and regulations

Law/Regulation	Building type	Required ventilation	Ventilation considerations
Building Standards Act * Minimum requirement	All Buildings	(1) 20 m^3/h/person or more, (2) (Non-residential) 0.3 to (residential) 0.5 times/h or more, whichever is greater	
Act on Maintenance of Sanitation in Buildings * Obligation to make efforts	Specific (large) buildings (*1)	30 m^3/h/person	• Mandatory maintenance of ventilation equipment (proper cleaning, inspection, etc.)
	Facilities that do not correspond to specific buildings	30㎥/h/person Required ventilation (assuming 350 ppm outside air)	• Require maintenance of ventilation equipment (proper cleaning, inspection, etc.) • If the required ventilation volume is insufficient, reduce the number of people in the room.
Guidelines for Improving "Closed Spaces with Poor Ventilation"	All Buildings	30 m^3/h/person, or CO_2 conc. of 1000 ppm or less (*2)	

After COVID-19, there is a **movement to increase the ventilation volume to 30m^3/h/person** as a countermeasure against infectious diseases.

(*1) Specific buildings under the Building Standards Act are buildings with a total floor area of 3,000㎡ or more that are used by a large number of people and are used for purposes such as entertainment venues, department stores, assembly halls, amusement centers, and shops. refers to (excluding school)
(*2) When using mechanical ventilation. CO_2 concentration is used as an indicator of air pollution and ventilation volume.

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1-3 Ventilation and Air Conditioning Situation in Japan

The design of the building and construction situation

Trend of the design of building

Increase in intelligent buildings and smaller office compartments due to the impact of COVID-19

Environmental change	Changes of environment and needs
Intelligentization of small and medium-sized buildings	Changes in working styles (spread of remote work) have led to diversification of offices (satellite offices, etc.). → Japanese office building developers have announced the "intelligentization of small and medium-sized buildings".
Increasing the rate of adopting smaller office rental units and the individual decentralization method	Due to the spread of telecommuting and remote work due to the impact of Covid19, office rental units are becoming smaller. → Increased willingness to adopt separate decentralized ventilation and air conditioning systems.

There is a **growing need for high value-added decentralized air conditioning and ventilation equipment** for small and medium-sized buildings.

Ventilation equipment is also evolving in product types and functions suitable for **" decentralized " (small size, multiple unit installation)**

Product type	• Static type ERVs which is suitable for small product sizes are the mainstream, and there are a variety of product types (according to various buildings, securing installation locations)
Air volume control	• Realizes energy saving by air volume adjustment and sensor control
Group control of multiple units	• Improved controllability by operating multiple units
Interlocking with air conditioner	• Detailed zone control unique to decentralized ventilation and air conditioning
Improved installation workability	• Easy installation workability is important for multiple installations

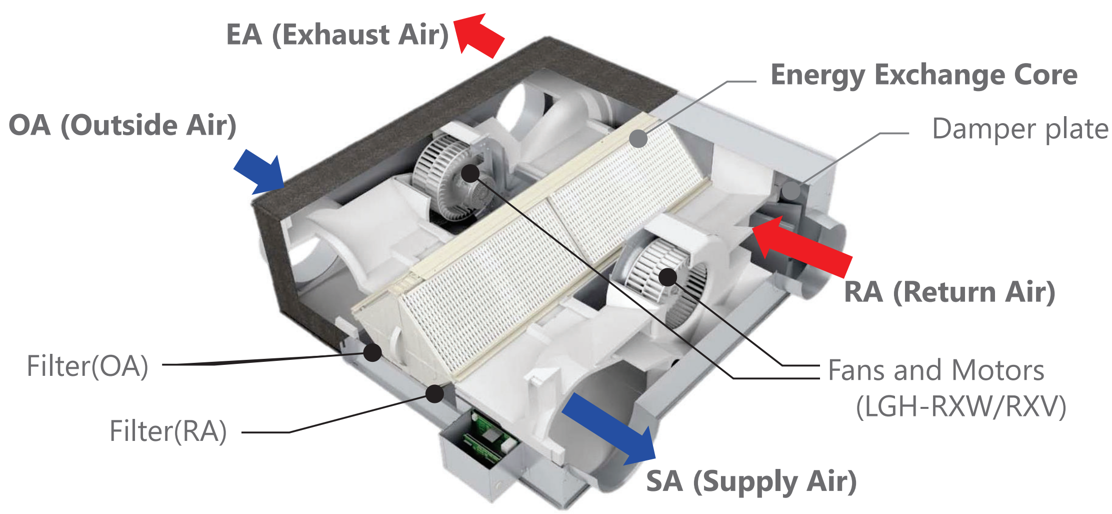
2-1

Technological Trends of ERVs (Static Type) in Japan

Product Type

Energy Recovery Ventilator (ERV) : ventilator with a heat exchange unit

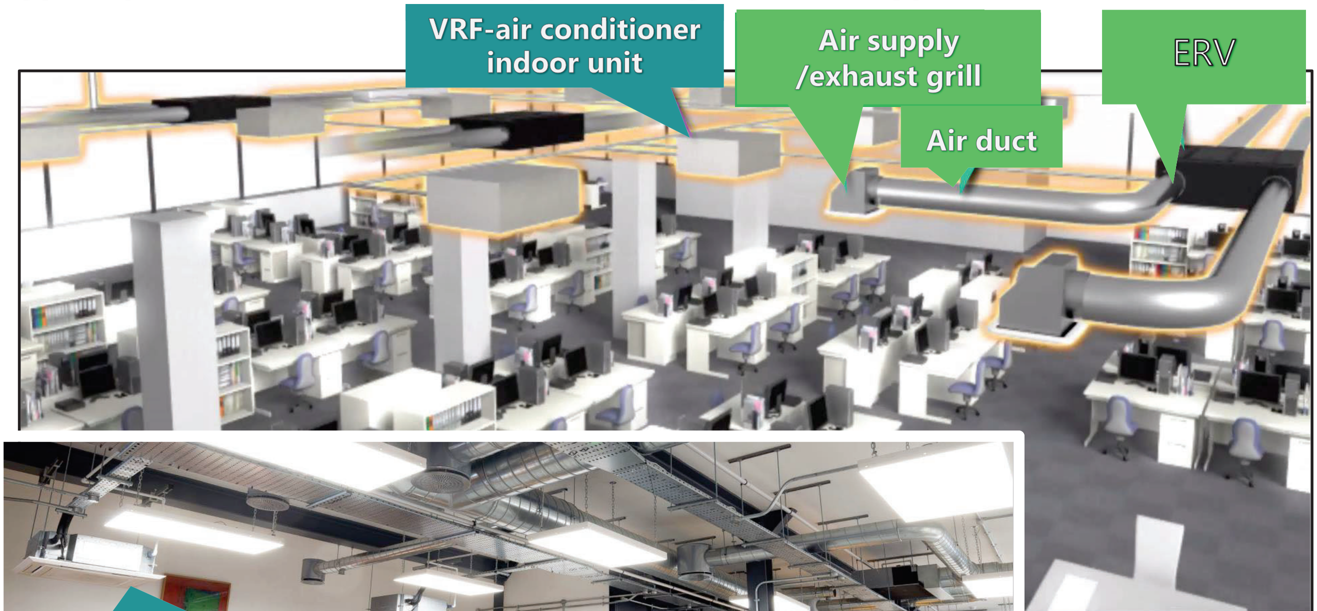
Registered product name " **LOSSNAY** " is an ERV which was developed by **Mitsubishi Electric**.



3 Major Components **Supply Fan, Exhaust Fan , and Energy Exchange Core**

- ERV simultaneously intakes fresh air and exhausts dirty air
- Energy Exchange Core returns both sensible heat and latent heat.

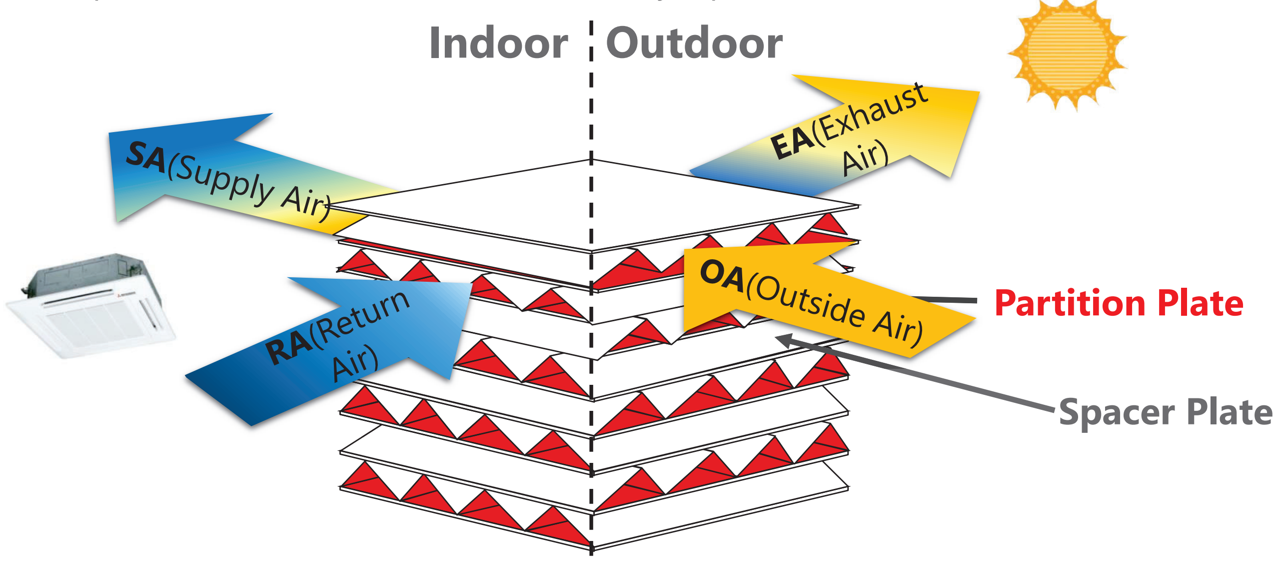
Typical product installation example (Ceiling concealed type)



VRF:
Variable Refrigerant Flow

Structure of Energy Exchange Core

Two paths ventilation Core is constructed by 2 parts



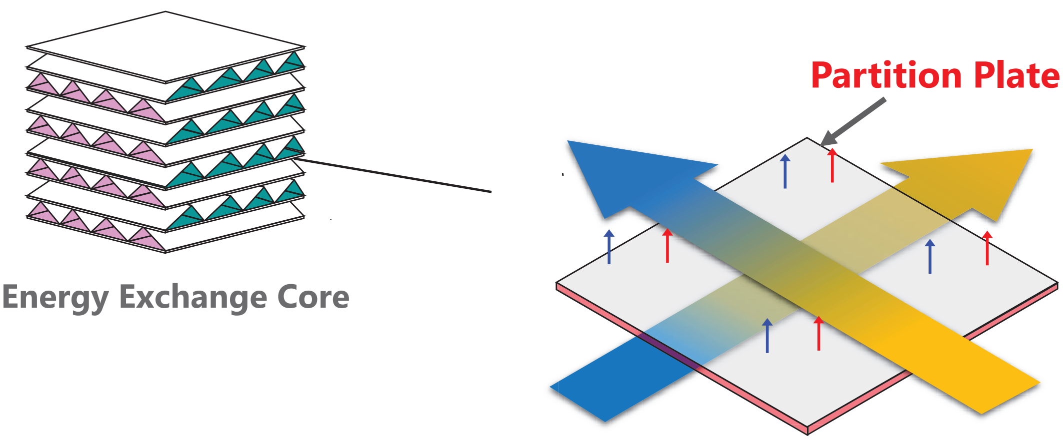
Spacer Plate	: Make supply air and exhaust air
Partition Plate	: Separated SA and EA, heat exchange

Heat exchange technology of Energy Exchange Core

Total Enthalpy = Sensible Heat (Temp.) + Latent Heat (Humidity)

<The Baisic Principle of Physics>

- **Sensible Heat** tends to transfer from higher to lower temp.
- **Latent Heat** tends to transfer from higher to lower absolute humidity.

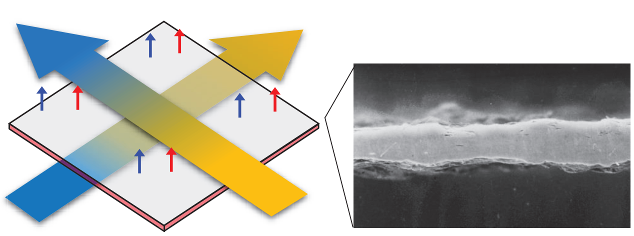


Technologies for static type ERV core materials

Species of Partition plate

Materials	Heat transfer rate 1)	Moisture Transfer Rate 2)	Air permeability 3)	Benefits
Paper based	0.06 W/mK	12kg/m²/day	＞10,000 sec	Cost saving
Plastics	0.15～0.3 W/mK	9-10kg/m²/day	＞10,000 sec	Washable Suitable for wet condition

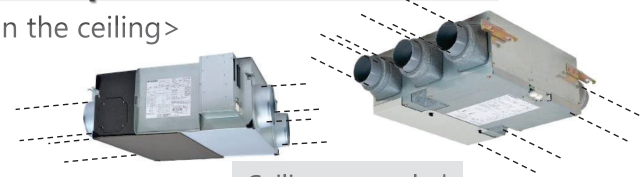
1) JSME Data Book：Heat Transfer (Fourth Edition) P321-322
2) Measured by ISO 15106-2 (Mocon Method)
3) Measured by JIS P8117 (Oken Method)



In Japan, **paper is the main material for partition plate.**
...Because it has good moisture permeability and is relatively inexpensive.
Resin partition are limited to applications under high humidity

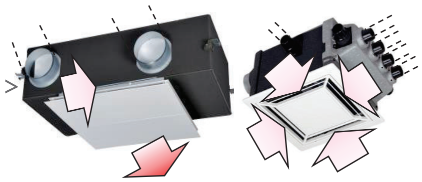
Various product installation forms

<In the ceiling>

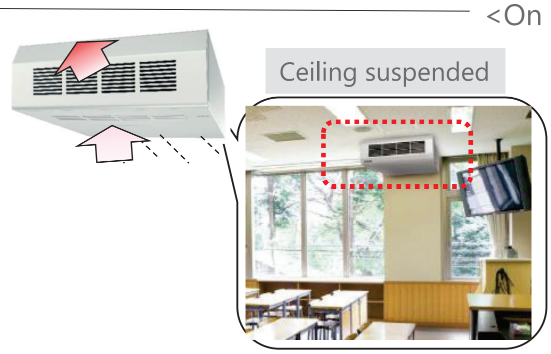


Ceiling concealed

<On the ceiling>



Ceiling suspended



Ceiling Cassette

<On the wall>

Wall mount

<In the machine room>

Floor standing
In the wall

(Japanese model information)

2-1 Product – ERV (Energy Recovery Ventilator)
MITSUBISHI ELECTRIC Changes for the Better

ERV product lineup (by Mitsubishi Electric Corp)

Product Type		Air volume [m³/h] (200, 400, 600, 800, 1000, 2000, …, 10000)	Energy Recovery	Constant air volume	CO_2 sensor control	Bypass ventilation	Humidification
Wall mount			○				
Ceiling Cassette			○	○	○	○	
Ceiling Concealed	Standard		○	○	○	○	
	With Humidifier		○		○	○	○
	With heating and Humidifier		○	○	○	○	○
Ceiling suspended			○		○		
Floor Standing			○			○	○

1,000 m^3/h or less in any product type

Some models in this table do not have the function

(Japanese model information)

2-2 Technological Trends of ERVs (Static Type) in Japan

Air Volume Control

Method of air volume control

1) Control of individual products :

- **Constant air volume control** by adjusting motor output (see p. 22)
- **Multi-stage air volume control** (see p. 23)
  Easy to adjust the air volume after unit installation. Positive pressure and negative pressure management, etc. Both low power consumption and high static pressure adjustment can be achieved even if the duct is long.
- **Air volume control for energy-saving by connecting CO_2 sensor** (see p. 24-29)
  Air volume control by CO_2 concentration level. Because it is a decentralized system, each unit can be operated according to detected CO_2 concentration of each location individually. By using a smart switch and extra sensor, it is possible to control airflow rate by the CO_2 concentration at any position.

2) Control of multiple products :

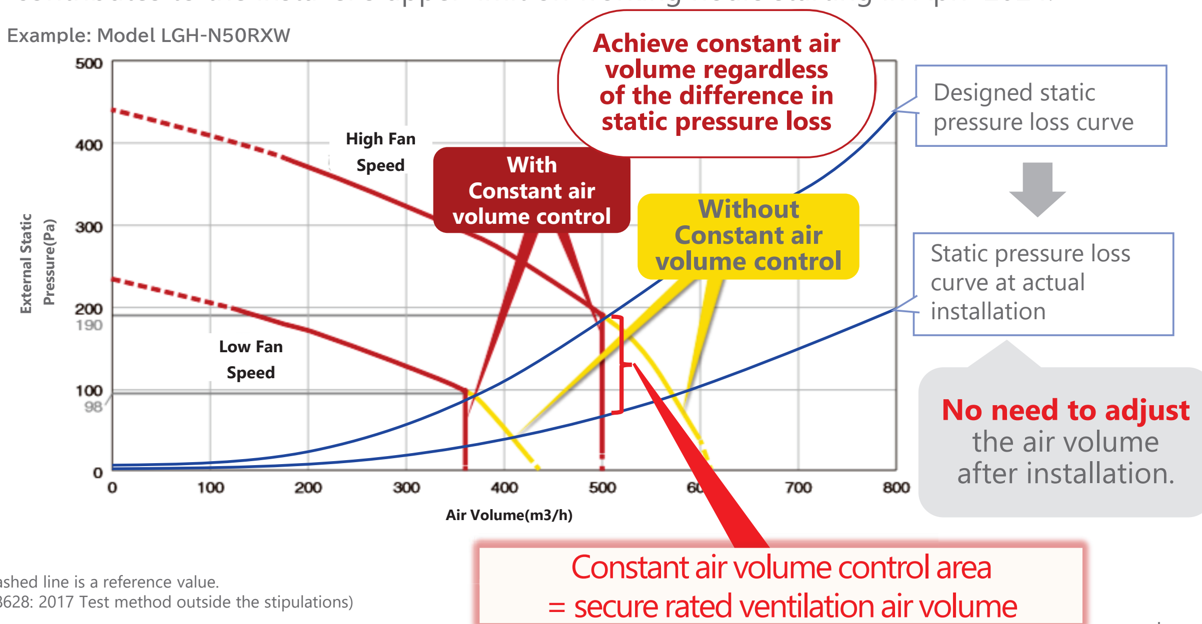
- **System controller** makes the airflow rate change, turn on/off, in each multiple unit.
  Several hundreds of AC units and ERV can be controlled.

Constant air volume control

Automatically adjusts the ventilation air volume against static pressure loss **to ensure the air volume required by the design.**

By reducing the time and effort of adjusting the air volume at the site during installation, ERV contributes to the installer's upper limit on working hours starting in April 2024.

Example: Model LGH-N50RXW



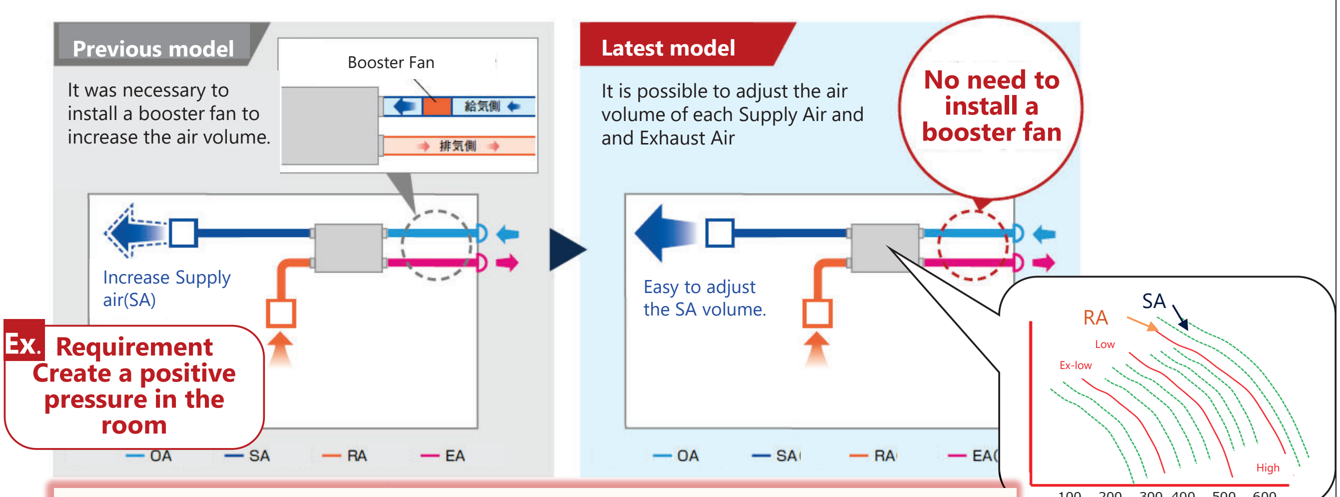
*The dashed line is a reference value.
(JIS B 8628: 2017 Test method outside the stipulations)

2-2 Air volume control for individual products

Multi-stage air volume control

Detailed settings such as adjustment of the air pressure balance in the room space are possible.

1) It is possible to select from eleven levels of ventilation air volume and set to 3 fan speeds (High, Low, Extra-Low).
2) It is possible to adjust the ventilation air volume of each supply air and exhaust air and tune the air pressure balance.



Installation and adjustment of booster fans and dampers were required
⇒ **Easier to install and adjust as it is no longer needed**

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Example of high school in Hokkaido (Sapporo)

CO_2 concentration on ventilating by opening the door between classes

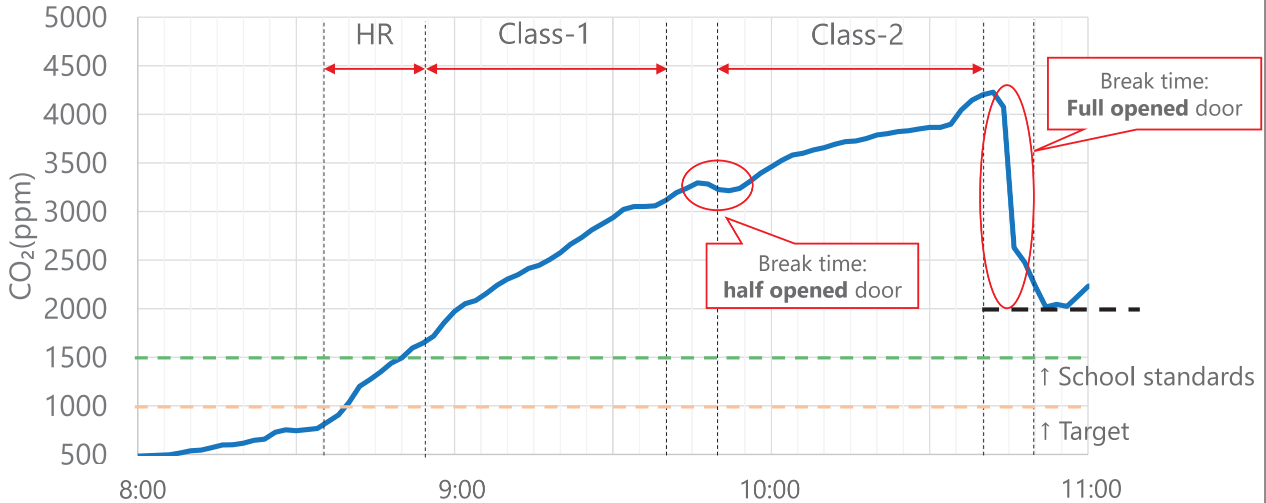

Fig. Change of CO_2 concentration in the classroom (28.January.2021. 33 students)

CO_2 concentration of **2,000 ppm** even when the door is opened.
⇒ **Clearly lack of ventilation**.
… because The door and windows are hard to open due to the **snow and cold climate**,
The number of **teachers and students cannot be reduced**. ⇒ **CO_2 concentration rises**

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Example of Nightclub in Tokyo (Ginza)

CO_2 concentration when the number of guests had been limited by reducing seats due to COVID-19

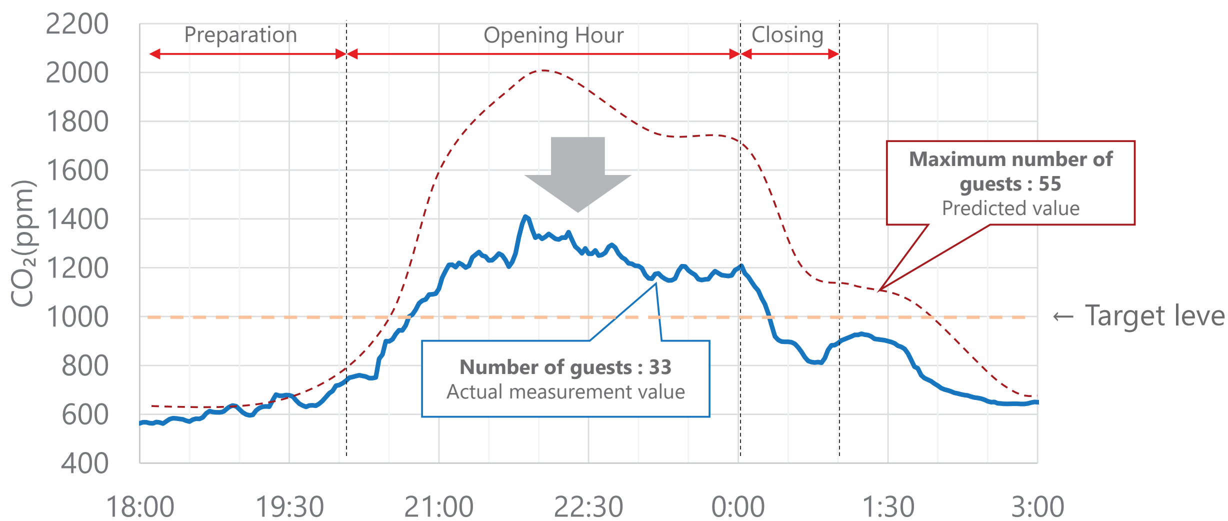

Fig. change of CO_2 concentration inside the shop (7. August. 2020)

CO_2 concentration of **1,400 ppm** even if the number of people is limited
⇒ It is necessary to **adjust the ventilation volume while monitoring the CO_2 concentration**

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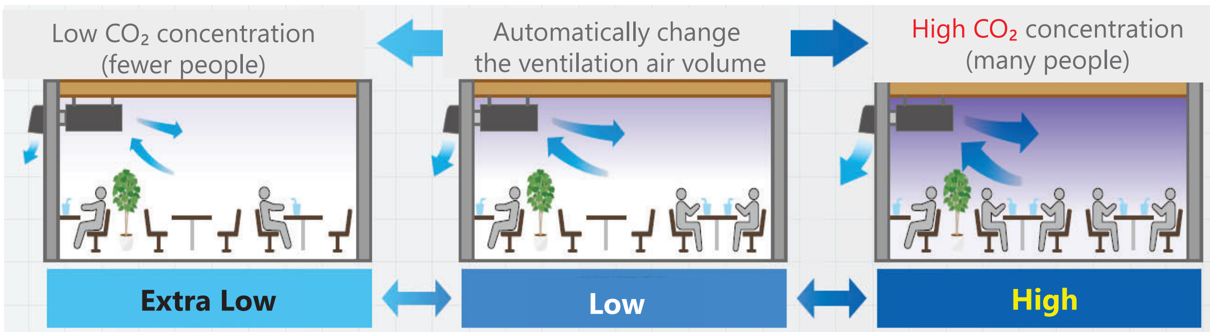
Air volume control for energy-saving by connecting CO_2 sensor

Realizes **energy-saving operation by adjusting the ventilation air volume in conjunction with the CO_2 sensor**

- It is assumed that **the number of workers in the office will decrease** as telework and satellite offices become common.
- By **minimizing the amount of outside air intake** according to the indoor CO_2 concentration, the **air conditioning load is reduced, and energy is saved**.



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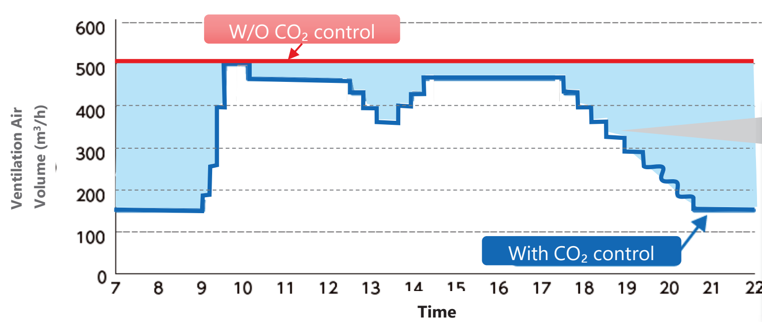
Changes for the Better

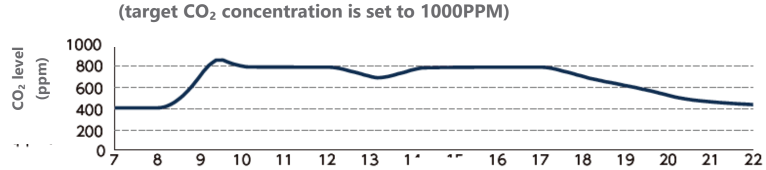
Air volume control for energy-saving by connecting CO_2 sensor

Result of ventilation air volume of ERV by changing indoor CO_2 concentration (Calculated)



* When the CO_2 sensor specified by Mitsubishi Electric is installed (target CO_2 concentration is set to 1000PPM)

Air volume can be adjusted in 11 steps automatically according to the indoor CO_2 concentration.



Calculation condition

Indoor and Outdoor Air Conditions

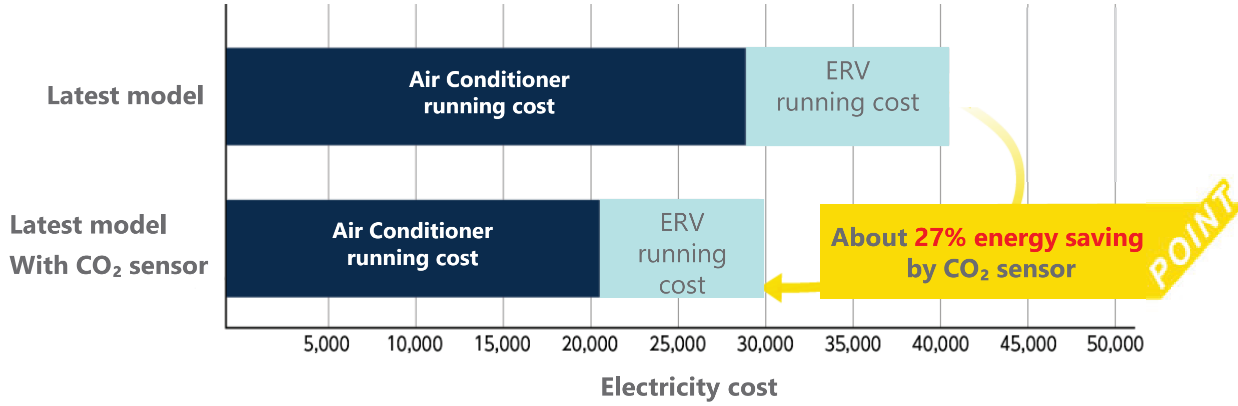
	Summer	Winter
OA	35℃ 75.3%	5℃ 71.9%
RA	27℃ 52.8%	20℃ 58.9%

Time and operating conditions for Air Conditioning and Ventilation(ERV)

Time	Air Conditioning	ERV(Previous model)	ERV(Latest model)
		CO_2-Sensor connected	
8:00-20:00	ON	Variable air volume by detected CO_2 level (Fan speed:3 steps, Automatic learning : OFF)	Variable air volume by detected CO_2 level (Fan speed:11 steps)
20:00-8:00	OFF		

Air volume control for energy-saving by connecting CO_2 sensor

Calculation of Cost of electricity in AC and ERV <Ceiling concealed type>



Air volume control by using CO_2 sensor not only **saves the ERV operating power input,** but also **reduces the air conditioning load by improving energy exchange efficiency of ERV and minimizing the amount of outside air intake.**

Calculation condition
- Target room size 243㎡ (≒9.5x9.5x2.7m)
- Maximum number of people in the room: 12 (occupancy rate 67% for 18 people calculated based on the standard number of people of 5㎡/person)
- Seasonal days and temp and humid conditions: Summer: 3.5 months (75 weekdays, 32 holidays), Winter: 3 months (60 weekdays, 30 holidays)
- Equipment information: Air-Conditioner: Heating COP 3.6, Cooling COP 3.19, ERV LGH-N50RVX x 1 unit
- Ventilation frequency: 2.1 [times/h] (at maximum fan speed) ・Target CO_2 concentration setting: 1000ppm ・Electricity cost: 27 [¥/kWh]

Visualization of the effect of air volume control

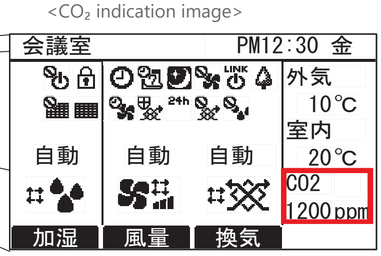
Display the indoor CO_2 concentration due to visualize the effect of air volume control

On the remote controller

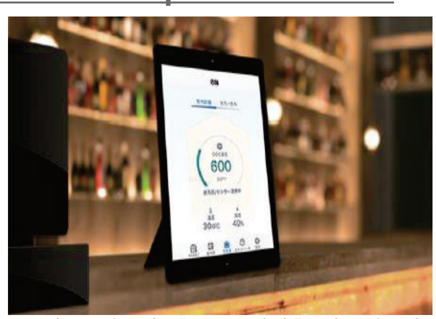
<ERV remote controller>

(PGL-62DR2)

<CO_2 indication image>



On the smartphone or tablet*



*When using the “smart switch” and setting the IoT linkage function

On the product indicator

(SKU-40EXC)

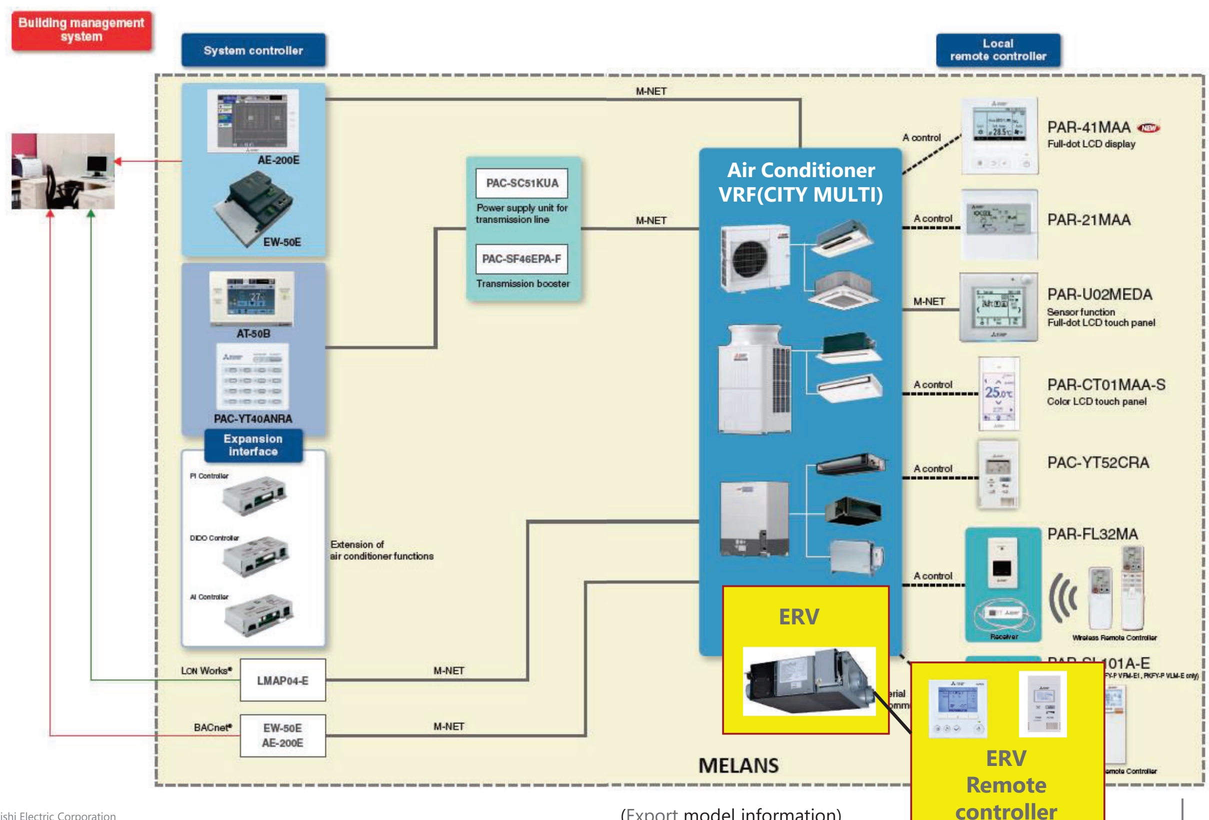
(Japanese model information)

2-3

Technological Trends of ERVs (Static Type) in Japan

Multiple unit control/network

Mitsubishi Electric unique transmission network(M-NET)



(Export model information)

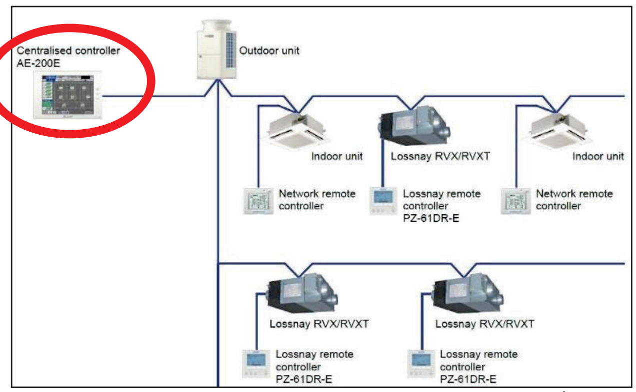
Using system controller to make the airflow rate change in multiple products

AE-200 (System controller)

- Up to 200 AC-indoor units and ERV can be managed (when using 3 units of EW-50J)
- With the built-in web server function, it is also possible to manage from a PC
- Functionality can be expanded with a license (option)
- E-mail notification is possible when an abnormality occurs
- Yearly/weekly schedules are provided as standard

< Points >

- Visualize the wasteful operation of air conditioners with the energy management function
- Using an extension controller, it is possible to manage air conditioning in a wide type of buildings.(from small to medium-sized buildings)



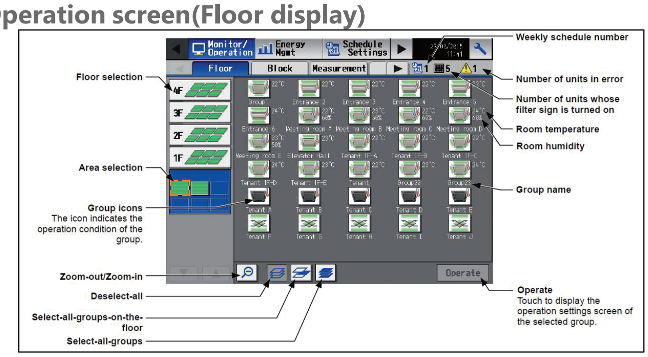
(Export model information)

2-3 Control of multiple products System controller
MITSUBISHI ELECTRIC Changes for the Better

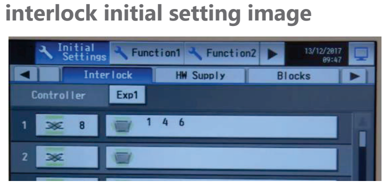
Using system controller to make the airflow rate change in multiple products

AE-200 (System controller)

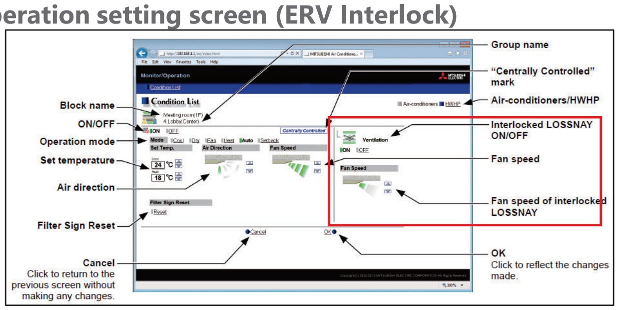
Operation screen(Floor display)



ERV interlock initial setting image



Operation setting screen (ERV Interlock)



(1) ERV Interlock

ON	OFF	Error	Interlocked LOSSNAY ON *1 *6	Interlocked LOSSNAY OFF *6

(2) ERV independent (non interlock)

ON	OFF	Error	Schedule set *2	Schedule disabled *2

Energy-saving ON *1	HOLD ON	Night purge ON/OFF *2	Operation suspended *4
		ON (Yellow) / OFF (Gray) *3	

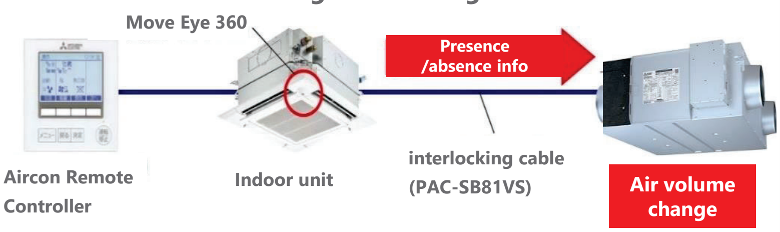
(Export model information)

2-4 Technological Trends of ERVs (Static Type) in Japan

Interlock control with air conditioners

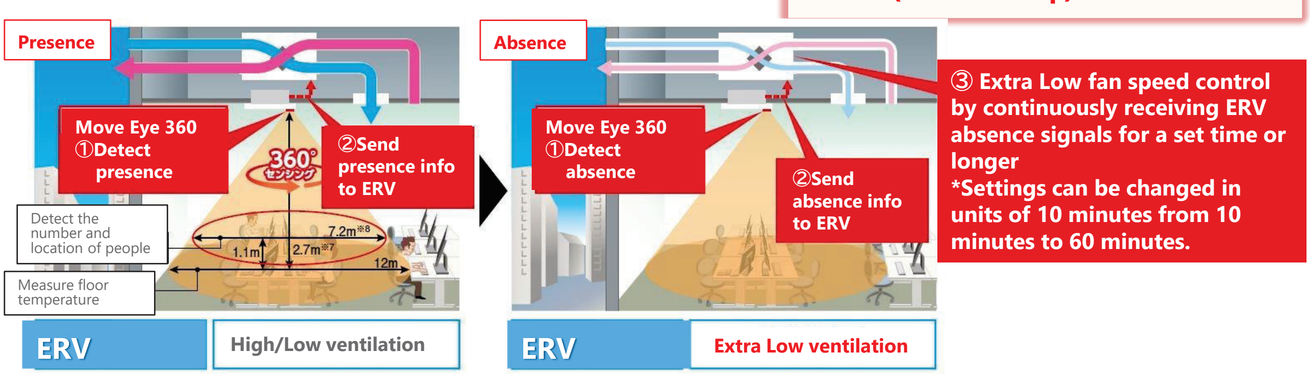
Realizes energy-saving operation by **adjusting the ventilation air volume** in "not crowded" cases by interlocking with the human motion sensor of the air conditioner

In the case of interlocking with Package Air Conditioner



- The motion sensor **"Move Eye 360"** is equipped in our air conditioning indoor unit
- ERV are linked to AC and **automatically Control the ventilation air volume based on the presence /absence of people** in the room

➡ When no one is present, ERV changes automatically to the minimum ventilation volume (*does not stop)



*Move Eye: A sensor that determines the presence of people in a room by detecting their position and movement. Registered trademark of Mitsubishi Electric <Export model: i-see sensor>

2-5 Technological Trends of ERVs (Static Type) in Japan

Installation/Maintenance

Facilitate adjustments and setting changes after unit installation

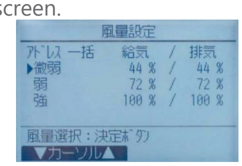
Even **after the ERV is installed, you can select and operate the air supply and exhaust air volume** from a maximum of eleven levels by using the ERV Remote Controller (PGL-62DR).

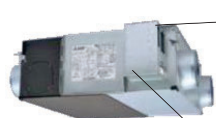
⇒ **No need to access the ERV unit**

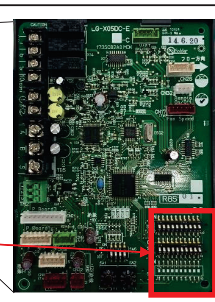
Detailed fan speed adjustment

It is possible to change 3 air volume (High Low Extra-Low) from the main operation screen.

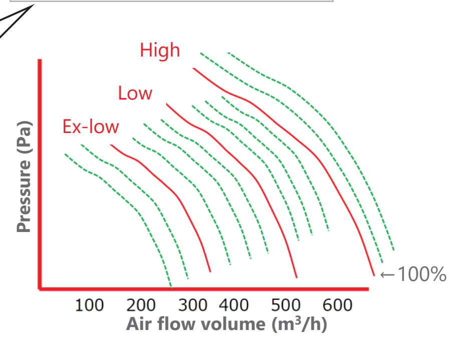
The air volume of each of the 3 speed can be adjusted in 7% increments on the dedicated air volume setting screen.







Conventional ERV was set by the DIP switch on the circuit board in the product.

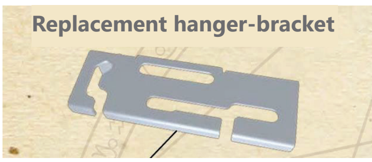


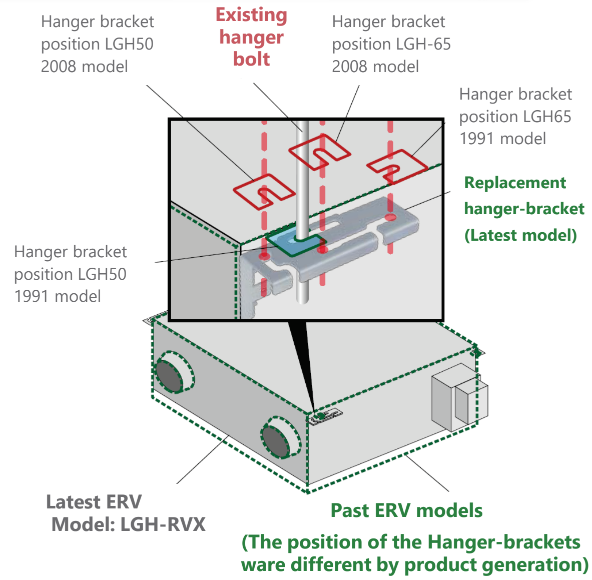
(Japanese model information)

Hanger bracket for replacement

It has been 50 years since we launched our ERV, and it has been adopted in many buildings.

Equipped as standard with replacement hanger-brackets that can be connected to existing hanger bolts (right figure).
It reduces the on-site installation work such as anchor re-drilling, enabling cost reduction and shortening of the installation period.

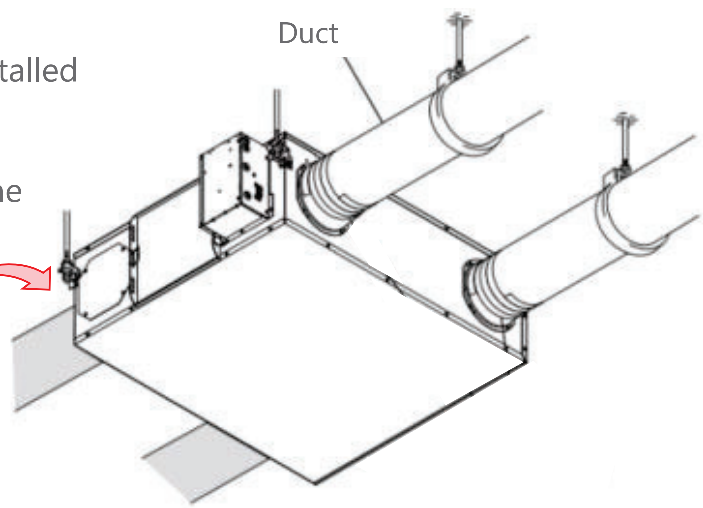


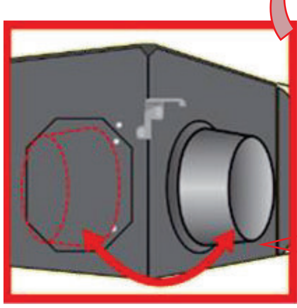


General life of building : **50 to 100 years**
Expected life of ERV : **13 years** (depreciation years)
⇒ **ERV maybe replace at least once or twice during the life of the building**

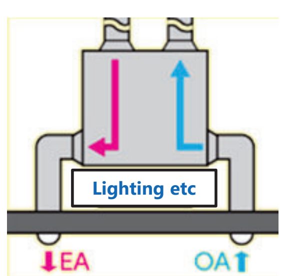
Duct direction change

When ventilation equipment is installed in the ceiling, other products (lighting, air conditioner) may be installed on the route of the ventilation duct.





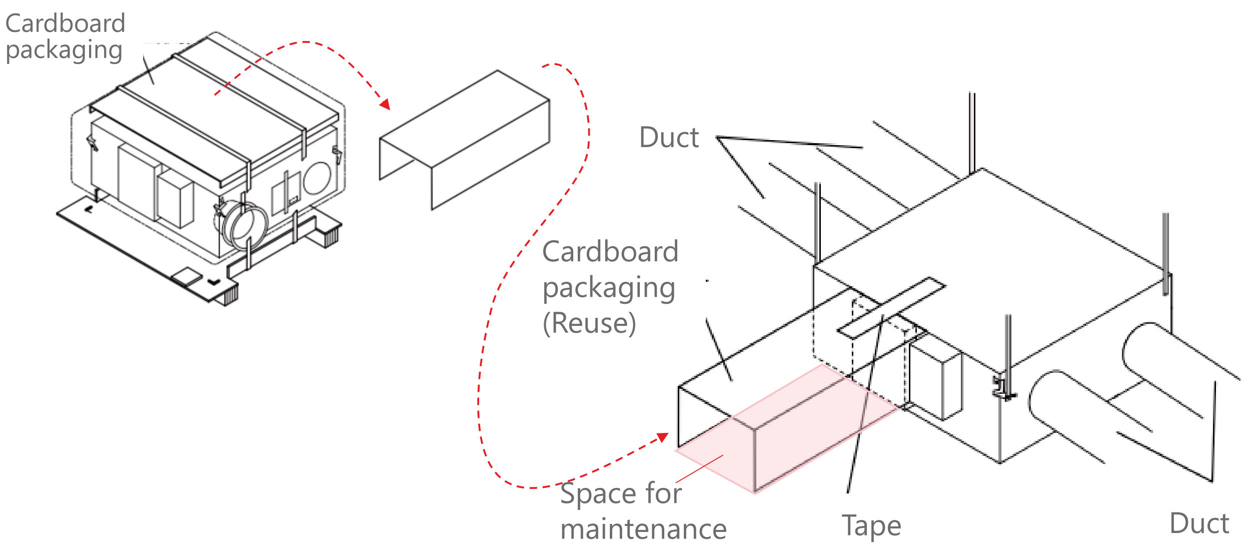
The **duct direction of OA and EA can be changed** from the product



Avoid installations where the ducts would be blocked by lighting or air conditioning units.

Keep the maintenance space using cardboard (Reuse)

When ventilation equipment is installed in the ceiling, **the space for maintenance may be unintentionally blocked by installation of ducts or other equipment.**



The cardboard packaging of the product can be used as a jig for securing maintenance space during construction (Reuse)

Gas Transfer

7. Transmission Rate of Various Gases and Maximum Workplace Concentration Levels

Measurement Conditions	Gas	Air Volume Ratio Q_{SA}/Q_{RA}	Exhaust Air Concentration C_{RA} (ppm)	Supply Air Concentration C_{SA} (ppm)	Transmission Rate (%)	Max. Workplace Concentrations* (ppm)
Measurement method • Chemical analysis with colorimetric method for H_2SO_4 • Ultrasonic method with gas concentration device for CO, SF_6 • Infrared method with gas concentration device for CO_2 • Gas chromatography for others The fans are positioned at the air supply/exhaust suction positions of the element Measurement conditions: 24°C, 85% RH * OA density for CO_2 is 500 ppm.	Hydrogen fluoride	1.0	36	<0.5	~ 0	2
	Hydrogen chloride	1.0	42	<0.5	~ 0	
	Nitric acid	1.0	20	<0.5	~ 0	
	Sulfuric acid (H_2SO_4)	1.0	2.6 mg/m³	~ 0 mg/m³	~ 0	5
	Trichlene	1.0	85	1.36	1.6	25
	Acetone	1.0	5	0.04	0.8	500
	Xylene	1.0	313	<5.0	<1.6	50
	Isopropyl alcohol	1.0	3,000	<25	<0.8	200
	Methanol	1.0	41	0.49	1.2	200
	Ethanol	1.0	35	0.49	1.4	
	Ethyl acetate alcohol	1.0	25	0.28	1.1	200
	Ammonia	1.0	290	7.25	2.5	
	Hydrogen sulfide	1.0	15	0.24	1.6	5
	Carbon monoxide (CO)	1.0	71.2	0.43	0.6	
	Carbon dioxide (CO_2)	1.0	37,800	600	0.3	
	Formaldehyde	1.0	32	0.3	0.9	
	Sulfur nexafluoride	1.0	116	0.8	0.7	
	Toluene	1.0	6.1	0.1	1.7	50

*Refered from the announcement No.369 of Ministry of Health, Labour and Welfare on 1st October 2004.

Humid recover etc

(2).Energy Recovery Calculation (Winter Example); LGH-100RVX-E

Supply Air	Lossnay ERV	Sensible HRV	General Fan
D.B. (°C)	16	16	0
A.H. (g/kg)	5.2	1.9	1.9
R.H. (%)	46	17	50
Enthalpy (kJ/kg)	29.2	21	4.7
Recovered heat (kW)	8.2	5.5	0
OA load (kW)	3.1	5.8	11.3
OA load ratio (%)	27	51	100

Exhaust Air

Temp. efficiency: 80%
Enthalpy eff. (Heating): 72.5%
Ventilation rate : 1,000m3/h

Indoor Unit of Air-Conditioner

Indoor Air

D.B.	20°C
A.H.	7.3(g/kg)DA
R.H.	50%
Enthalpy	38.5(kJ/kg)DA

Outdoor Air

D.B.	0°C
A.H.	1.9(g/kg)DA
R.H.	50%
Enthalpy	4.7(kJ/kg)DA

Humid recover etc

(1).Energy Recovery Calculation (Summer Example); LGH-100RVX-E

Supply Air	Lossnay ERV	General Fan
D.B. (°C)	**27.4**	33.4
A.H. (g/kg)	13.5	22.2
R.H. (%)	59	68
Enthalpy (kJ/kg)	61.9	90.5
Recovered heat (kW)	**9.5**	**0**
OA load (kW)	**3.9**	**13.4**
OA load ratio (%)	**29**	**100**

Exhaust Air

Temp. efficiency: 71.5%
Enthalpy eff. (cooling): 71.0%
Ventilation rate : 1,000m3/h

Calculation example
27.4℃
=33.4℃- (33.4℃-25℃) × 71.5%

Air-Conditioner

Indoor Air

D.B.	**25°C**
A.H.	9.9(g/kg)DA
R.H.	**50%**
Enthalpy	50.2(kJ/kg)DA

Outdoor Air

D.B.	**33.4°C**
A.H.	**22.2(g/kg)DA**
R.H.	**68%**
Enthalpy	90.5(kJ/kg)DA

Filters

Optional Filter lineup

Standard filter
PZ- RF8-E

(This filter is originally equipped in the Lossnay)
- Optional parts as replacement
- Washable & cleanable
- Clean once a year or every 3,000 hrs

- Filtration specifications
  EN779(2012): G3
  ISO 16890: Coarse 35%

High efficiency filter
PZ- RFM-E

- Optional parts
- Disposable
- Replace once a year or every 3,000 hrs

- Filtration specifications
  EN779(2012): M6
  ISO 16890: ePM10 75%

Advanced High efficiency filter
PZ- RFP2-E(New)

- Optional parts
- Disposable
- Replace when clogging.
  *For detail refer to next page.

- Filtration specifications
  ASHRAE 52.2-2017: MERV16
  ISO 16890: ePM1 75%,
  ePM2.5 80%,
  ePM10 95%
  GB/T14295-2008: YG class, 99.7%
  (Collecting efficiency for particles that are 0.5μm or larger at rated airflow)

*Filtration specifications are results of tests conducted by third-party and are not guaranteed values.

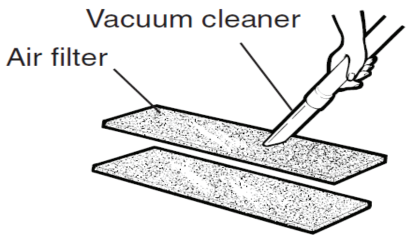
Maintenance

Standard-Filter and Core Maintenance

STEP 1. Freq. Once a year/ Every 3,000 hr

-Use a vacuum cleaner to remove dusts on the surface.
-To remove persistent dirt, wash with mild solution of detergent and warm water (Under 40 °C).

CAUTION
-Refrain from washing the filters with water over 40 °C and scrubbing them.
-Do not expose them to flame when drying.

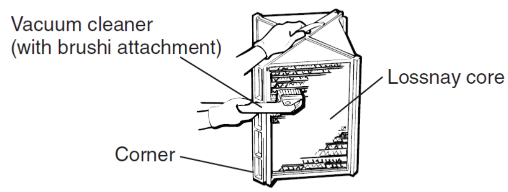


STEP 2. Freq. Once every 2 yrs/ Every 6,000 hr

-Use a vacuum cleaner and a soft brush to remove dusts and dirt on the surface of the Lossnay cores.

CAUTION
-Refrain from using a hard nozzle of the vacuum cleaner. It may damage the surfaces of the Lossnay cores.
-Lossnay cores should not be washed in water.

Do NOT wash in water.



TOWARDS SMART VENTILATION

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Performance assessment framework for smart ventilation systems

Hilde Breesch (KU Leuven, Belgium)

KU LEUVEN · UNIVERSITEIT GENT · Universiteit Antwerpen · TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY · Buildwise

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Starting point

- Smart ventilation system (AIVC)
  - Able to continually adjust itself to provide IAQ while minimizing energy use, discomfort, noise
  - Responsive to e.g. occupancy, outdoor thermal and air quality
  - Can provide info about e.g. IAQ, energy use, need for maintenance

↕

- Current practice in design of ventilation systems
  - Driven by minimum requirements of individual indicators
  - In mid-sized buildings: very conservative and inefficient
  - Existing methods dependent on brainpower of engineer

TOWARDS SMART VENTILATION

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Aim and goals

- **Aim** = determine performance-based framework for smart ventilation design driven by optimisation during whole life-cycle
- **Specific goals**
  - Define performance **sub-indicators** for **indirect metrics**
  - Aggregate all sub-indicators into **1 general economic performance indicator**
  - **Automate and optimise** aerolic **lay-out** ventilation design
  - **improve and optimise positioning of connections** to outdoor and indoor
- **Focus**: new + renovated mid-sized buildings (Q > 1000 m^3/h)
  - Multi-family residential
  - Schools
  - Offices
  - Care facilities (elderly homes)

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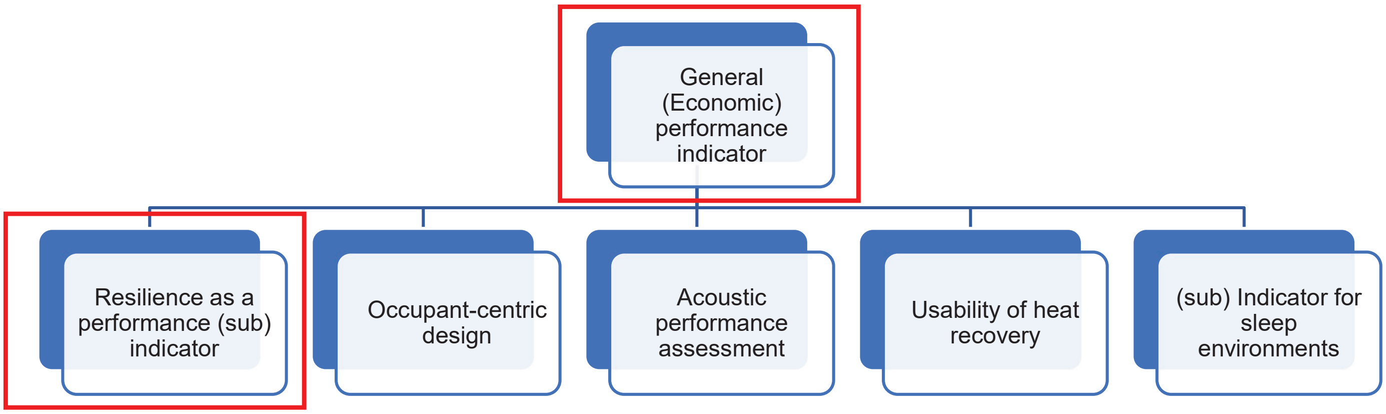
Research method

- Performance assessment



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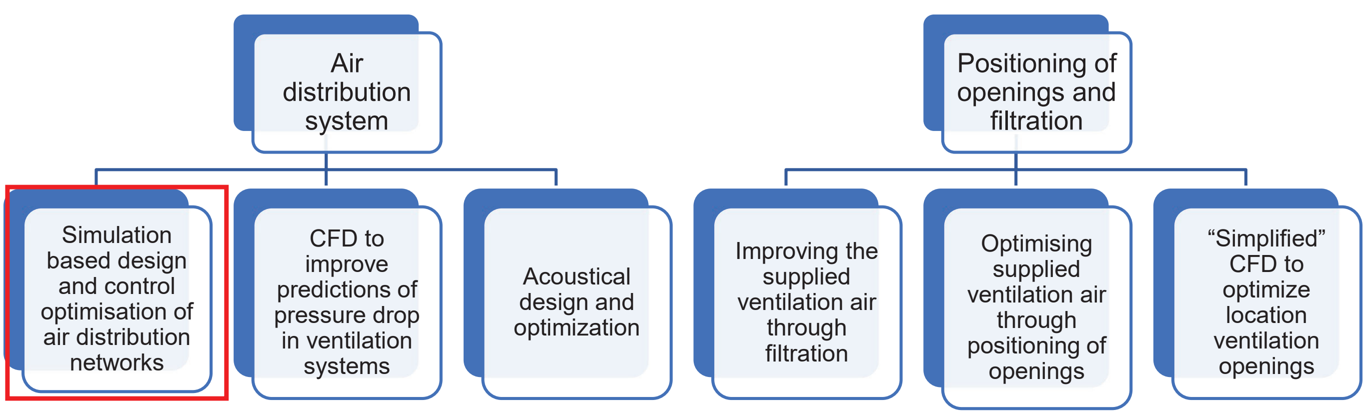
Research method

- Optimisation of system design



TOWARDS SMART VENTILATION

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Overview

- Introduction
- Performance assesment framework
  - General performance indicator (Cony and Laverge, Ghent University)
  - Resilience
- Optimisation of system design
  - Principle
  - Case study
- Conclusions

TOWARDS SMART VENTILATION

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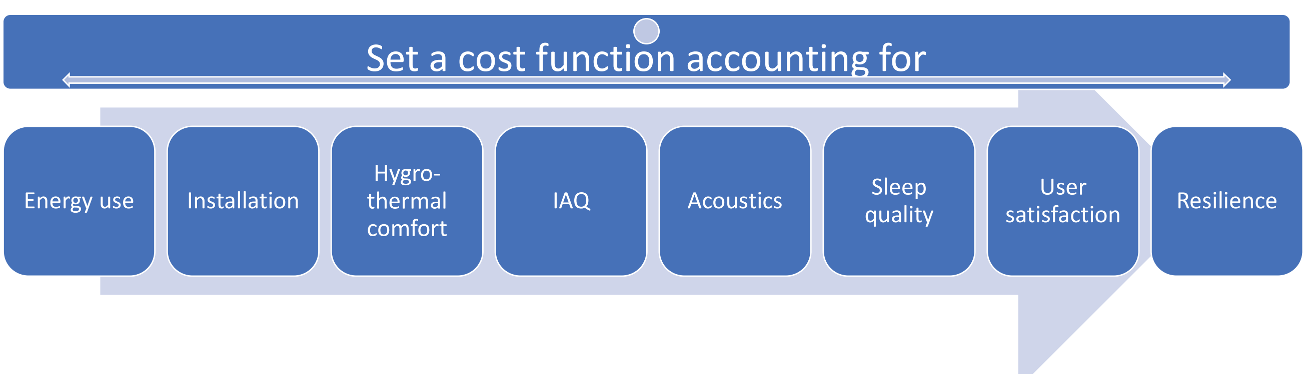
Performance assessment framework



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Performance assessment framework

- Material
- Maintenance
- Operational
- Installation

Hard costs

- Health
- Productivity loss
- Learning disturbance

Soft costs

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Hygro-thermal comfort

Hygro-thermal comfort cost

- Hours of thermal discomfort can be calculated from initial simulation
- 2nd simulation with ideal setpoint T° and infinite hot/cold power

→ $Hygrothermal\ comfort\ cost\ = \Delta E_{need} X\ PPD$

  - ΔE_{need}: extra energy need during discomfort hours (electrical cost)
  - PPD: Percentage of person disatisfied

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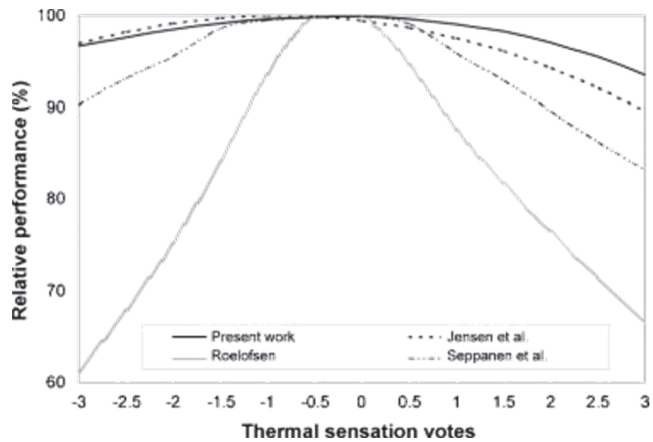
User satisfaction

User satisfaction cost

- Cost= productivity loss*productivity



Lan, Li, Pawel Wargocki, and Zhiwei Lian. 2011.

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Disability Adjusted Life Year (DALY) = Metric of harm

Planemad CC BY-SA 3.0

Rationale:

Mortality does not give a complete picture of the burden of disease borne by individuals in different populations. The overall burden of disease is assessed using the disability-adjusted life year (DALY), a time-based measure that combines years of life lost due to premature mortality (YLLs) and years of life lost due to time lived in states of less than full health, or years of healthy life lost due to disability (YLDs). One DALY represents the loss of the equivalent of one year of full health. Using DALYs, the burden of diseases that cause premature death but little disability (such as drowning or measles) can be compared to that of diseases that do not cause death but do cause disability (such as cataract causing blindness).

Definition:

One DALY represents the loss of the equivalent of one year of full health.

DALYs for a disease or health condition are the sum of the years of life lost to due to premature mortality (YLLs) and the years lived with a disability (YLDs) due to prevalent cases of the disease or health condition in a population.

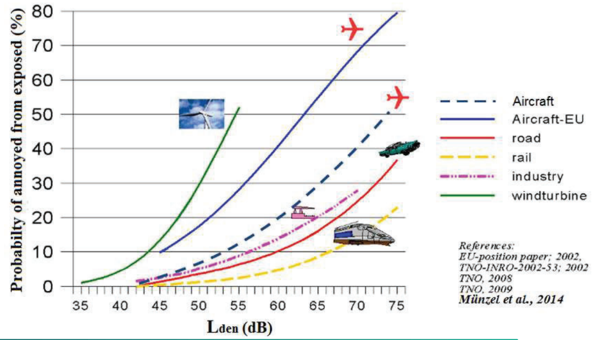
https://www.who.int/data/gho/indicator-metadata-registry/imr-details/158

World Health Organisation, “WHO methods and data sources for global burden of disease estimates 2000-2019.” 2020.

Acoustics

Acoustical cost

- $Noise_{Cost} = DALY_{noise} \times DALY\ cost \quad + Productivity\ loss$
- $DALY\ cost_i = life\ year\ cost + Productivity\ cost + health\ cost$
- $DALY_{noise}$ creation:
  - Diseases induced
  - Life impact of disease
  - Probability of disease occurrence **due to acoustic disturbance**
- Productivity loss estimation :
  - % of people Highly Annoyed by noise disturbance
  - % of productivity decrease



Indoor Air Quality

IAQ cost

Pollutant	Health cost (€)
Benzene	46 000
Trichloroethylene	70 971
Radon	25 526
PM	10 402
CO	1 085

- $IAQ_{Cost} = \sum_i^p DALY_i \times DALY\ cost_i + SBS_{cost}$
  - DALY : Disability adjusted life years lost
  - SBS: sick building syndrome
- $DALY\ cost_i = life\ year\ cost + Productivity\ cost + health\ cost_i$
- $SBS_{cost} = productivity\ cost \times \left(POPS2 \times productivity\ decrease + POPS \times \frac{productivity\ decrease}{2}\right) \times \frac{2}{5}$
  - POPS and POPS2: Percentage Of People with (SBS) 1 (POPS) or 2 (POPS2) Symptoms (from 1 to 3 days a week)
  - POPS and POPS2 : questionary input metrics but calculation formula exists (from indoor air pollution and indoor environmental indexes)

TOWARDS SMART V≋NTILATION

FLANDERS INNOVATION & ENTREPRENEURSHIP

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Overview

- Introduction
- Performance assesment framework
  - General performance indicator
  - Resilience (Al-Assaad and Breesch, KU Leuven)
- Optimisation of system design
  - Optimisation method
  - Case study
- Conclusions

TOWARDS SMART V≋NTILATION

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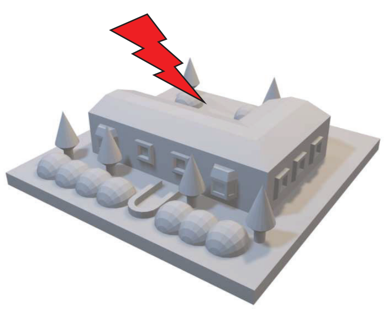
Resilience: why does it matter?

Expected indoor/outdoor conditions

Thermal comfort
Good breathable air quality
Energy efficient



Unexpected disruptive events

Building shifts drastically from its **IAQ design conditions**

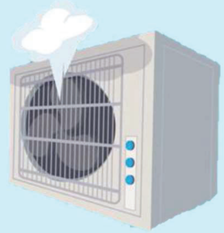
(-) Accumulation of pollutants

(-) Acute exposure

Resilience: how to assess?

1. Identify disruptive events

Mechanical disruptions



Partial or complete disruption in the operation of the ventilation system (e.g., fan failure, power outages, fouling filters)

Internal disruptions

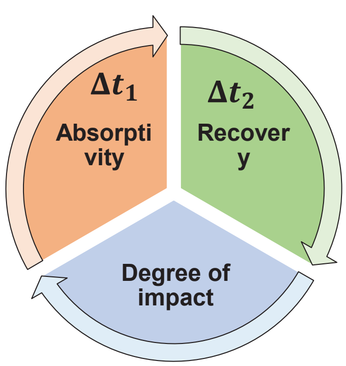
Occurs inside the space due to excessive indoor pollution event (e.g.,excess occupants beyond capacity of AHU)

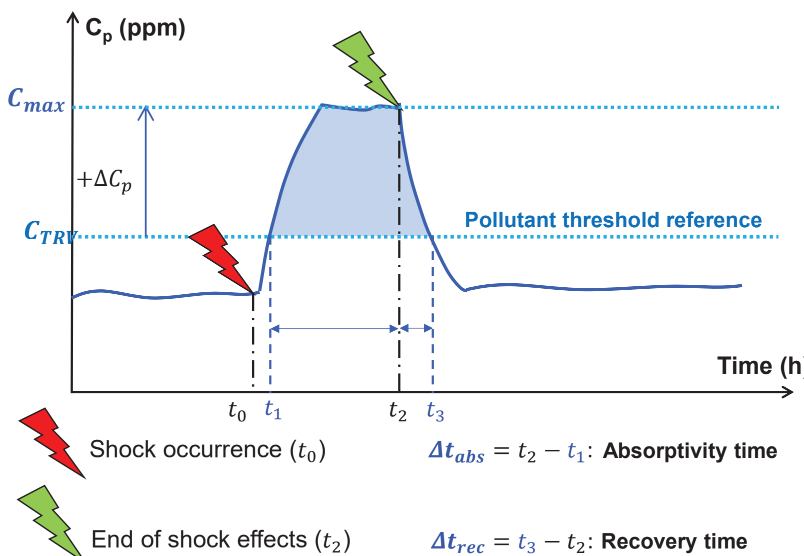
External disruptions

Occurs outside the building envelope due to excessive outdoor pollution (e.g., outdoor fire, traffic jams)

Resilience: how to assess?

2. Quantify the aspects of resilience





$\Delta t_{abs} = t_2 - t_1$: **Absorptivity time**

$\Delta t_{rec} = t_3 - t_2$: **Recovery time**

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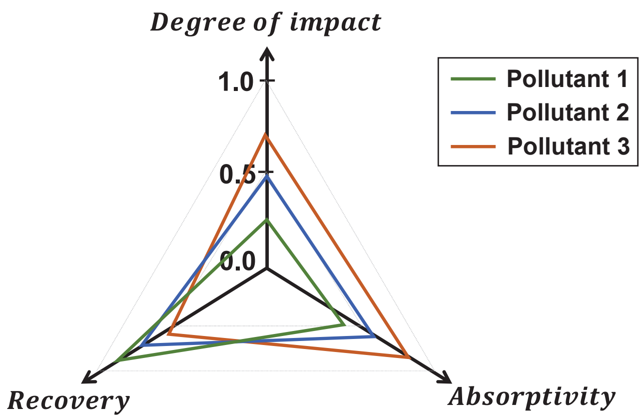
Resilience: how to assess?

3. Resilience score (RS)



TOWARDS SMART VENTILATION

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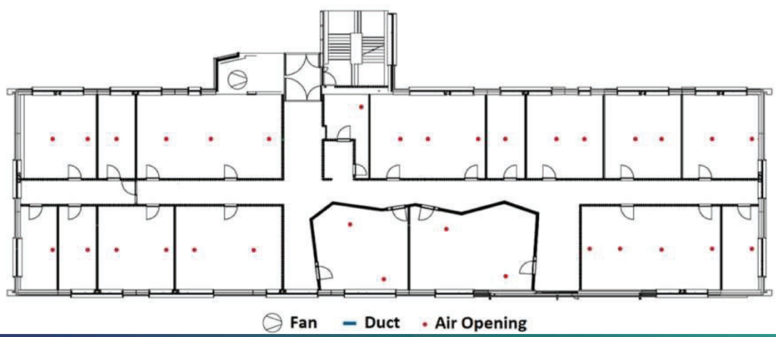
Overview

- Introduction
- Performance assesment framework
  - General performance indicator
  - Resilience
- Optimisation of system design (Jorens, Kabbara and Verhaert, UAntwerpen) & (Cony and Laverge, Ghent University)
  - Optimisation method
  - Case study
- Conclusions

Optimization problem: objective

For a random floorplan: find ductwork configuration (= layout + sizing) with minimum life-cycle cost

minimize ('soft' costs & 'hard' costs)



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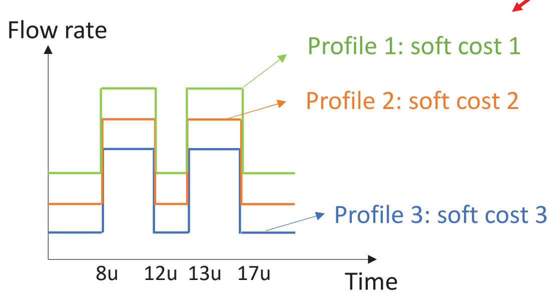
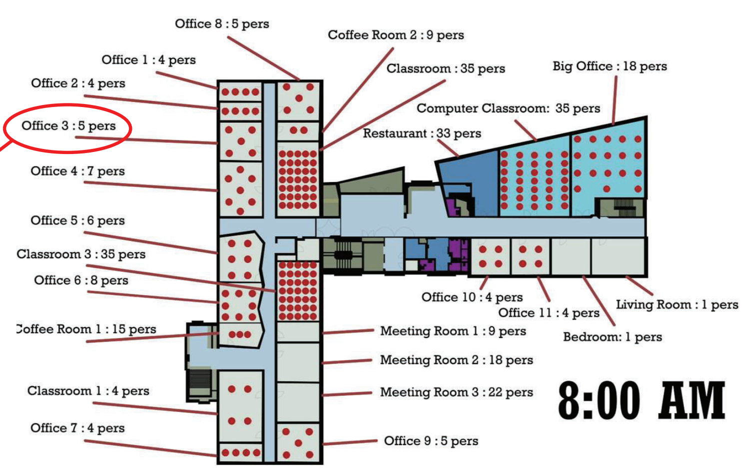
Input optimization method

- Floorplan
- Input profiles

  → based on demand profiles/room





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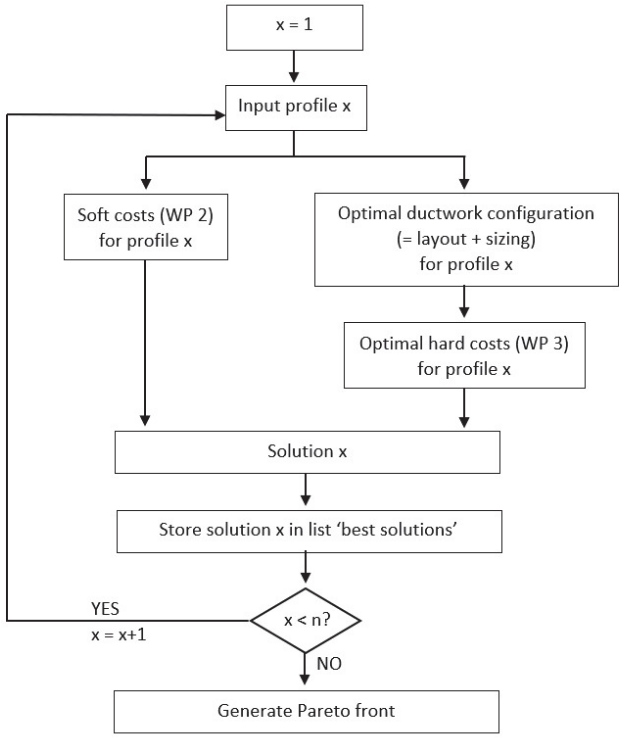
Optimization method



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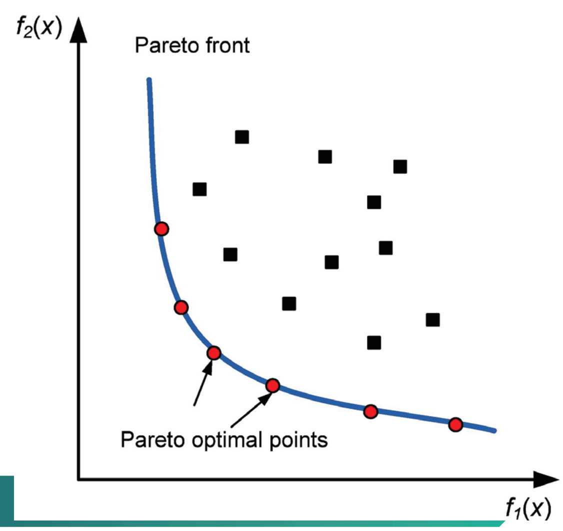
Output optimisation algorithm

Soft costs and hard costs: not the same order of magnitude

- **Pareto front** instead of 1 optimized solution:
  user can select solution according to preference



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Case study: University of Antwerp: Building Z

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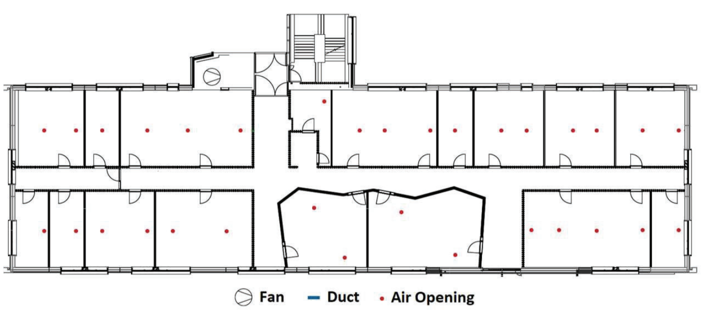
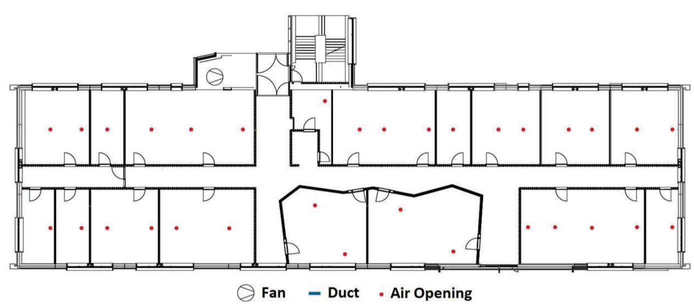
Case study

Potential design method



Existing design



Optimized design

Total hard costs: 15% lower

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Overview

- Introduction
- Performance assesment framework
  - General performance indicator
  - Resilience
- Optimisation of system design
  - Principle
  - Case study
- Conclusions

TOWARDS SMART VENTILATION

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Conclusions

- Need for design guideance for smart ventilation systems
- Performance assessment framework for smart ventilation defined
- System optimisation design method developed

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Various building types

- **Offices** → Original formulation
- **Residential buildings** → Productivity cost replaced by extra energy (electical Wh) cost to reach minimum productivity loss
- **Retirement house** → $$Retirement\ house_{Cost} = \frac{Residential_{cost} \times N_{retired} + Office_{cost} \times N_{workers}}{N_{retired} + N_{workers}}$$
- **Hotels** → $$Hotel_{Cost} = \frac{Residential_{cost} \times N_{customers} + Office_{cost} \times N_{workers}}{N_{customers} + N_{workers}}$$
- **Schools** → $$School_{Cost} = \frac{Student_{cost} \times N_{students} + Office_{cost} \times N_{workers}}{N_{students} + N_{workers}}$$
  → $Student_{cost}$: Actually encountering difficulties to estimate learning disturbance cost

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Sleep quality cost

Assumptions

- Many factors influence sleep quality
- Litterature may have divergent opinions
- Sleep quality is hard to quantify from environmental parameters only

→ Improving sleep quality only from ventilation related parameters is complex

→ Detection of bad environment for sleep quality is possible

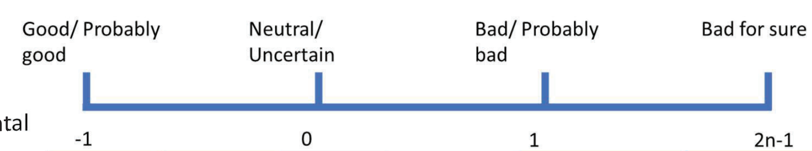
all bad conditions gathered → probability of sleep disturbance is 1

$$Sleep\ quality = \frac{1}{K_{tot}} \sum_1^n \frac{k_i w_i}{n}$$

Sq ≤ 0 → good

0 < Sq ≤ 1 → probably bad

Sq ≥ 1 → bad for sure



	Coefficient	Good (-1)	Neutral (0)	Probably bad (1)	Bad (2n-1=3)
T (°C)	0,0447		17-28	<17 or >28	
H° (%)	0,0447		40-60	<40 or >60	
CO2 (ppm)	0,0351		750-1150	1150-2600	2600
Noise (dB)	0,0319			35	

From assessment to health cost

- Translation, from sleep disturbance issue to DALY
  - Equivalent of DALY lost per issue
  - Probability of issue with & without sleep disturbance
  - Cost induced/issue

FACULTY OF ENGINEERING AND ARCHITECTURE

DEPARTMENT OF ARCHITECTURE AND URBAN PLANNING
BUILDING PHYSICS, CONSTRUCTION AND SERVICES RESEARCH GROUP

EFFECT OF INDOOR TEMPERATURE DIFFERENCES AND ZONING ON THE PERFORMANCE OF ENERGY EFFICIENT VENTILATION STRATEGIES FOR DOMESTIC BUILDINGS *(Josue Borrajo Bastero)*

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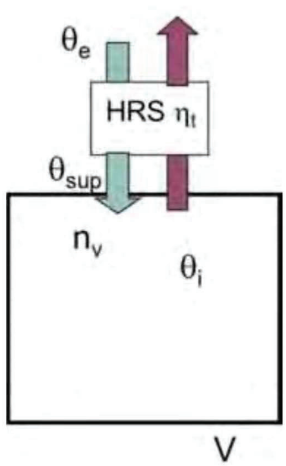
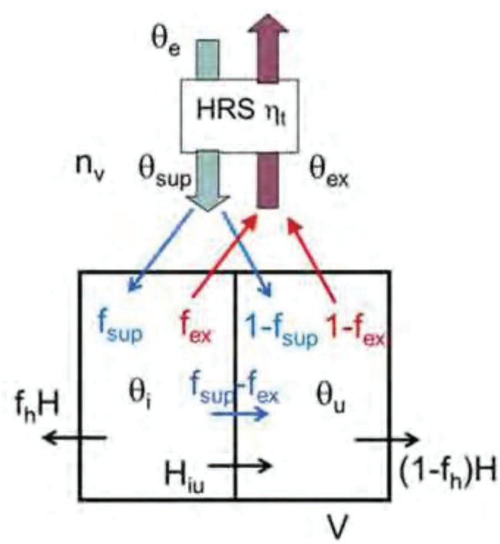
ZONING AND HRV





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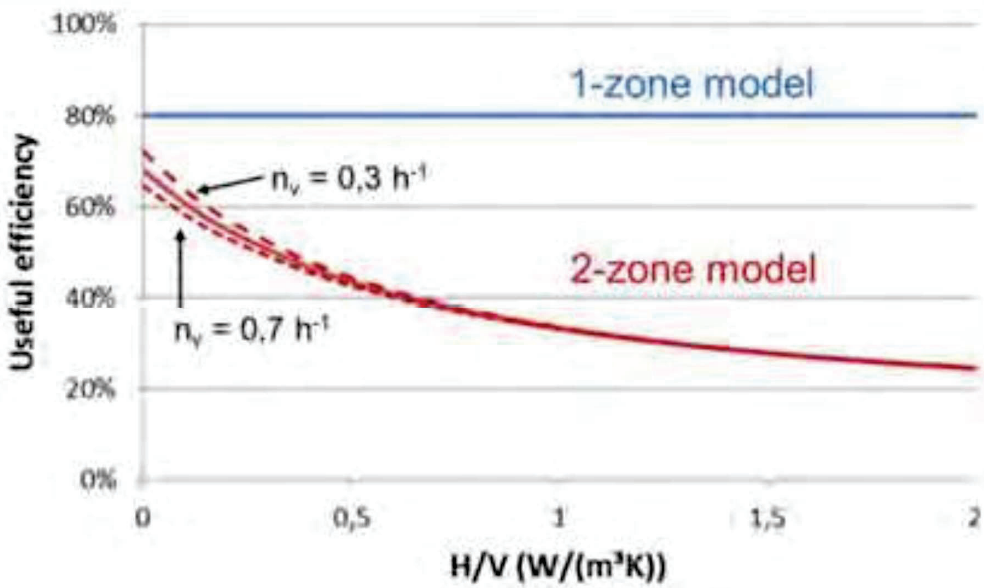
ZONING AND HRV: EXPECTED EFFECT



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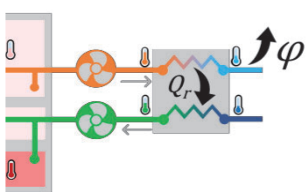
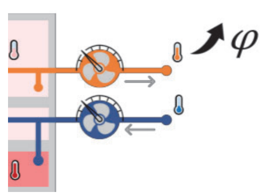
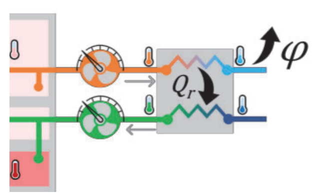
‘ENERGY EFFICIENT’ VENTILATION







- **Heat exchanger(s)**
Part of the heat can be recovered.

- **Demand controlled ventilation**
Reduced aiflows -> Less conditioned air is released to the atmosphere

- **Demand controlled ventilation**
- **Heat exchanger(s)**

$$\downarrow \varphi \Rightarrow \downarrow Q$$

Q = Annual heating demand
φ = Annual ventilation heat losses
Q_r = Recovered heat

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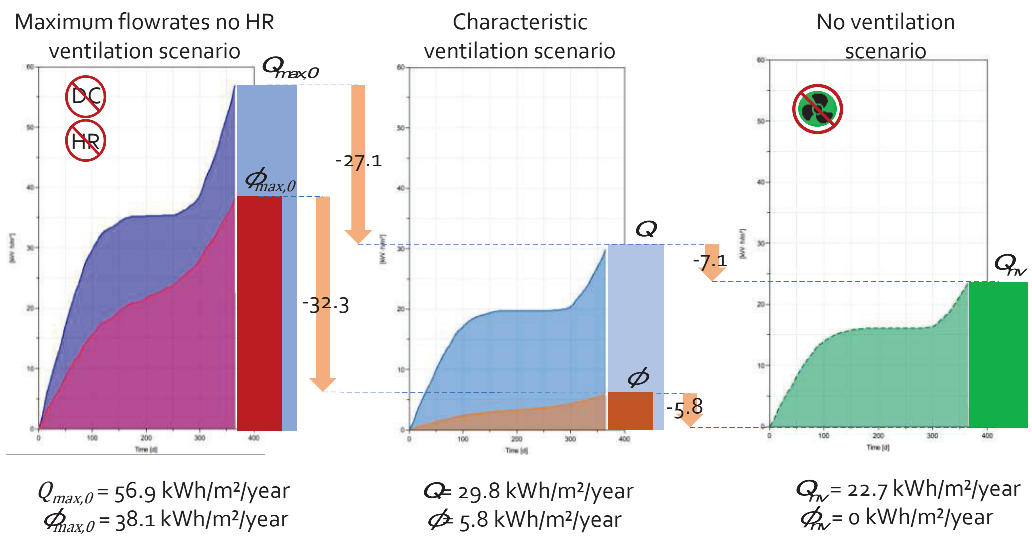
GENERIC ASSESSMENT METHOD



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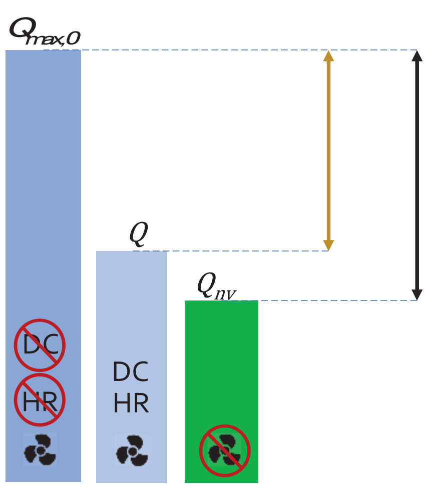
INDICATOR/METRIC



$$(Q_{max,0} - Q) / (Q_{max,0} - Q_{nv})$$

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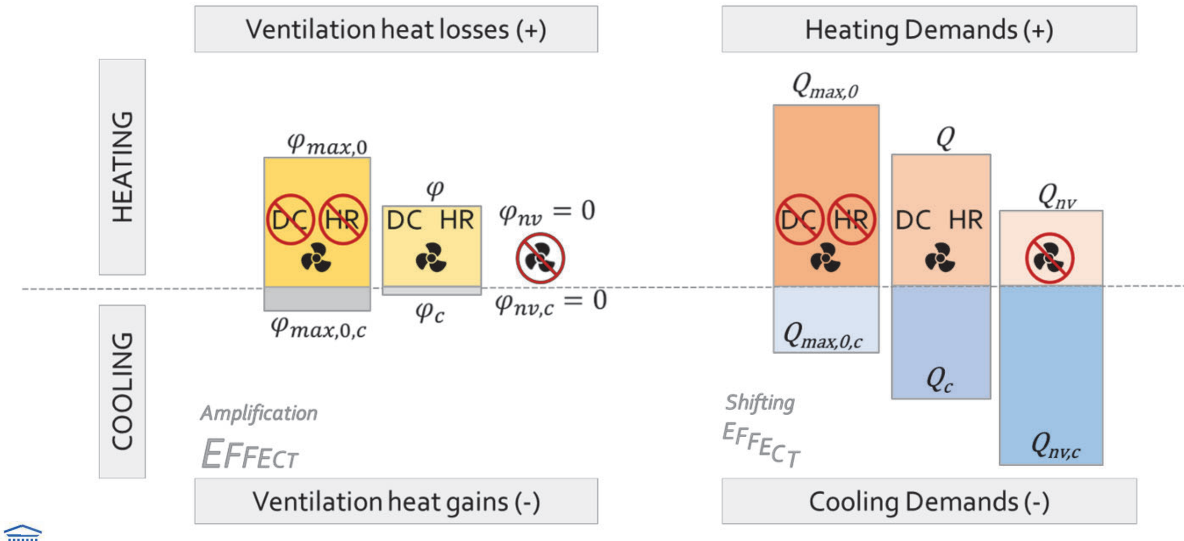
EFFECT COOLING



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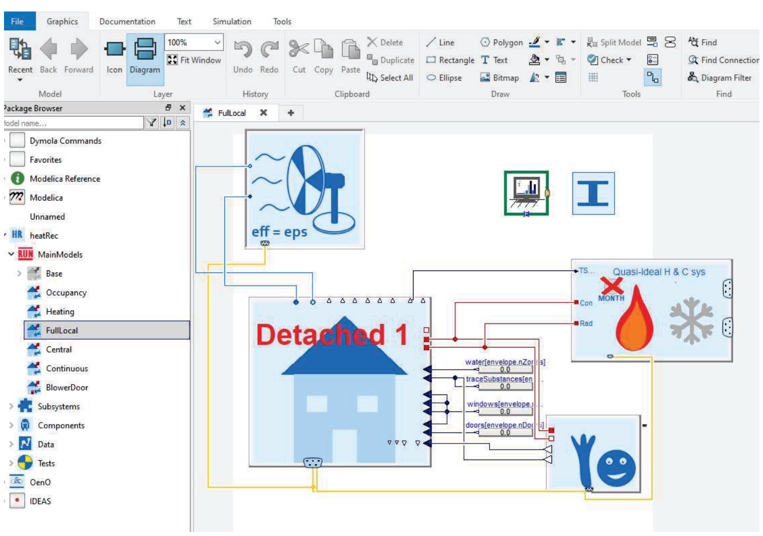
MODELING



Modelica: modelling language

Dymola: Commercial software

Libraries used:

- **MSL** 4.0.0
- **IDEAS** 2.1.0 (modified version)
- **OenO**: Library developed in a previous project

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VARIATIONS

Dwellings (6)

Detached house (BE) | Terraced house (NL) | Semi Detached house (IE) | Apartment (NL) 2 versions | Big detached house (IE)

Insulation Level (2)

(U-values: ~0.35 W/m²/K) 2 ACH50 **New construction**

U-values: ~0.15 W/m²/K 0.6 ACH50 **Passive house**

Weather (4)

Occupation Profiles (2) *StROBe*

- 2 full time workers

- 1 full time worker
- 1 adult at home
- 1 teenager
- 1 kid

Total combinations:
6x2x2x4 = 96

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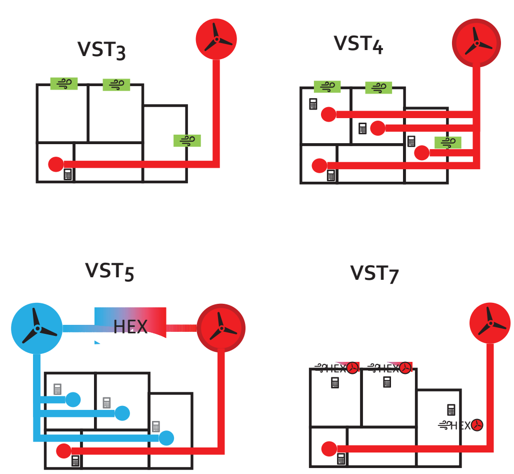
VENTILATION SYSTEMS

Ventilation systems (16)			
ID	VST	Heat recovery	DC/CAV
3a	VST3	✗	DC
3b	VST3	✗	DC
3c	VST3	✗	DC
3d	VST3	✗	DC
4a	VST4	✗	DC
5a_c	VST5	✓	CAV
5b_c	VST5	✓	CAV
5c_c	VST5	✓	CAV
5d	VST5	✓	DC
5e	VST5	✓	DC
5f	VST5	✓	DC
5g	VST5	✓	DC
7a_c	VST7	✓	CAV
7b_c	VST7	✓	CAV
7c_c	VST7	✓	CAV
7d	VST7	✓	DC

* DC = Demand Controlled ventilation
CAV = Constant Air Volume



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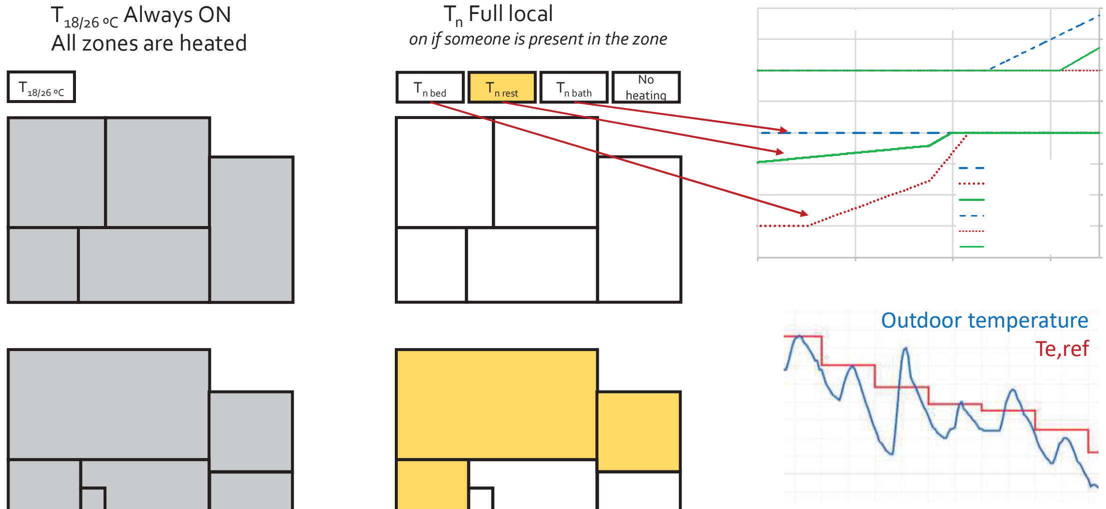
HEATING AND ZONING

$T_{18/26\,°C}$ Always ON
All zones are heated

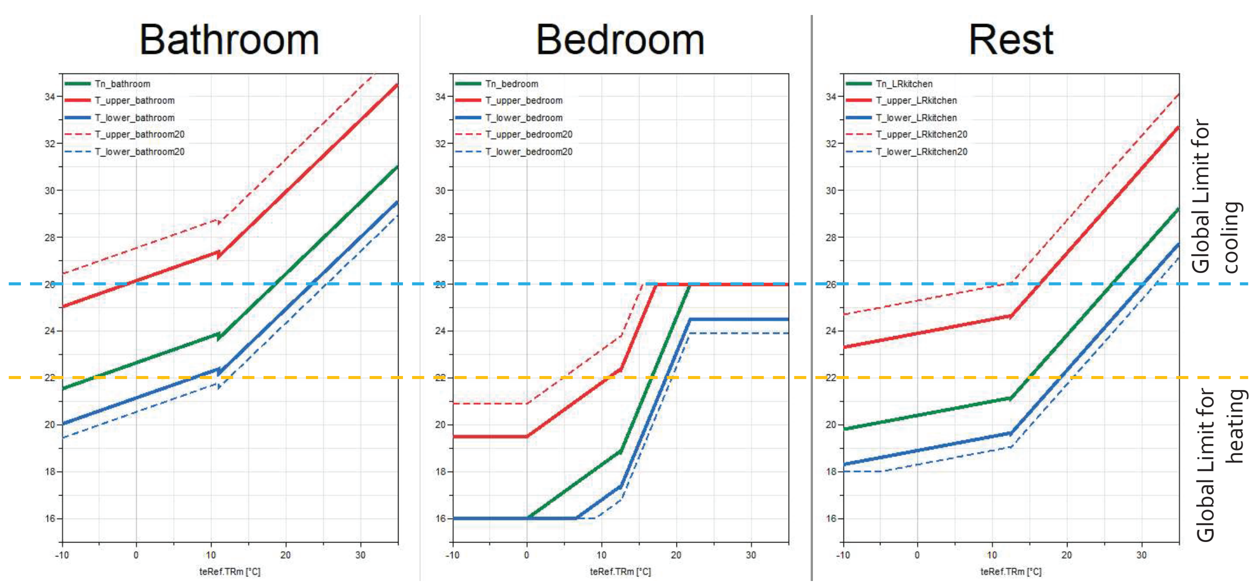
T_n Full local
on if someone is present in the zone



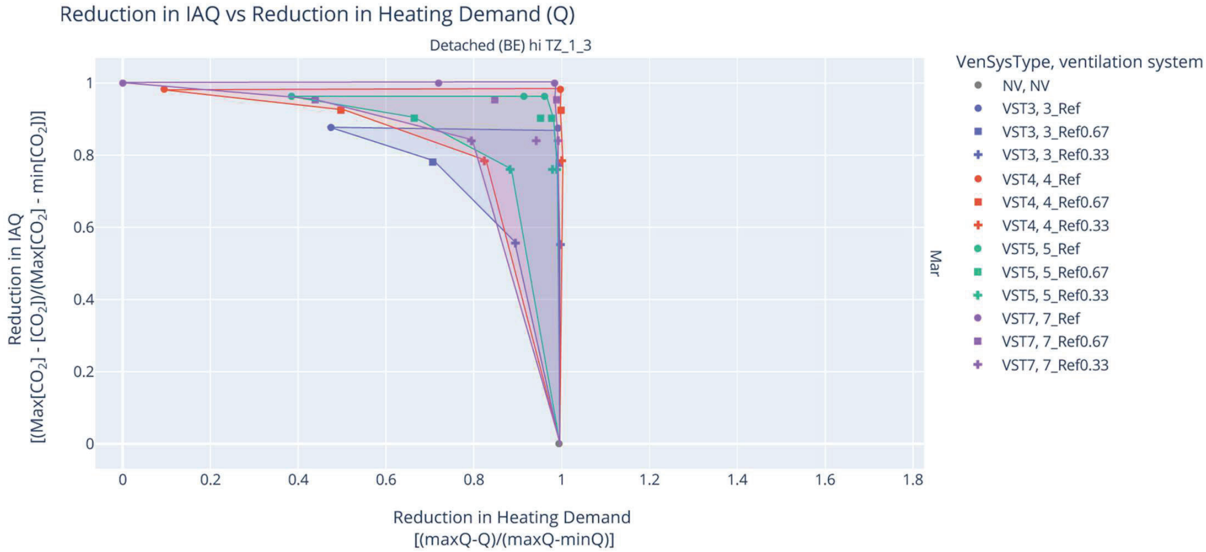
$$T_{e,ref} = \frac{(T_{today} + 0.8T_{today-1} + 0.4T_{today-2} + 0.2T_{today-3})}{2.4}$$

Total combinations: BC x vent. x heating modes x scenarios → 6x2x2x4x16x2x(2+1/16) = 6336 simulations

HEATING AND ZONING



RESULTS



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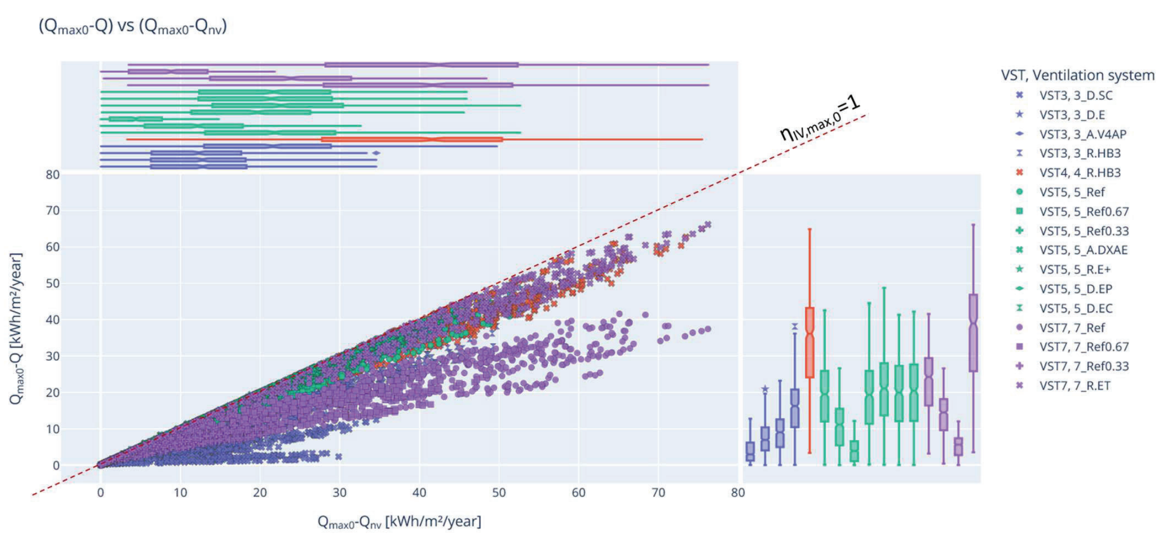
RESULTS



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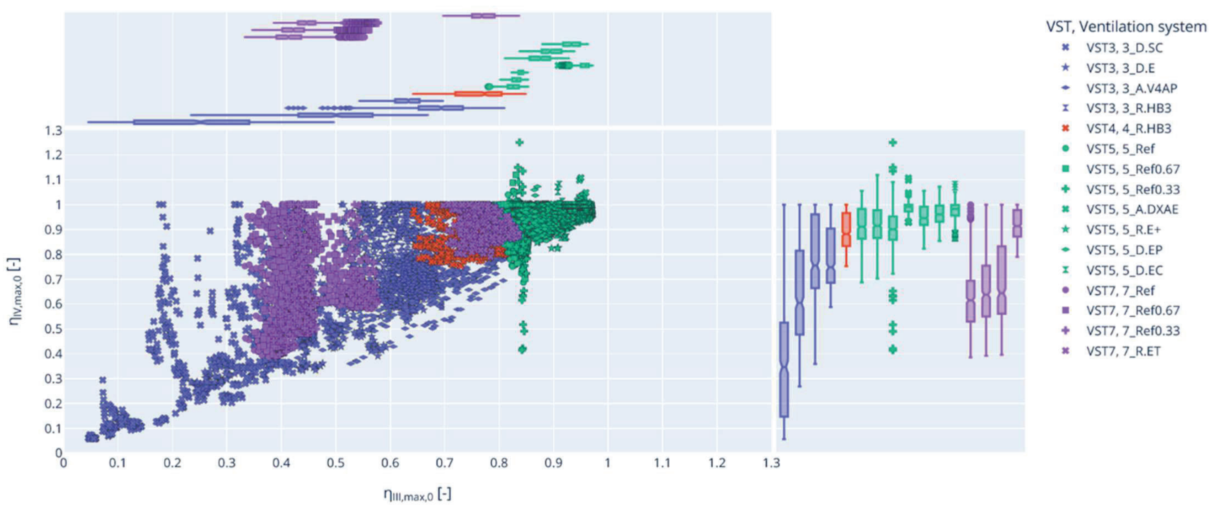
HEALTH VS ENERGY



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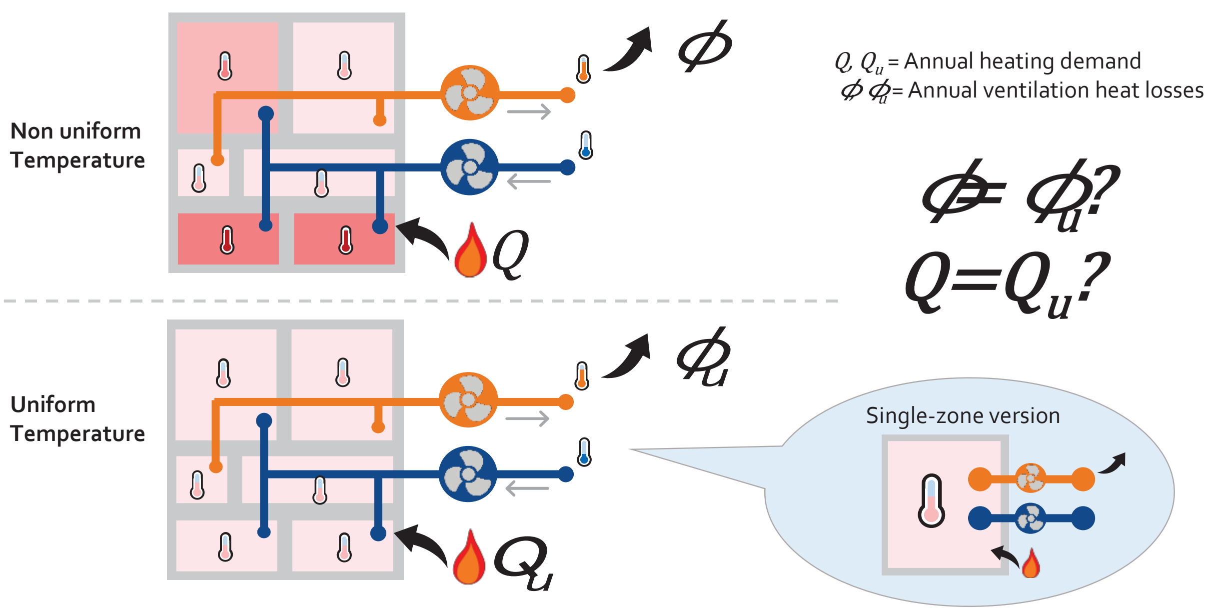
EFFECT OF ASSUMING UNIFORM T



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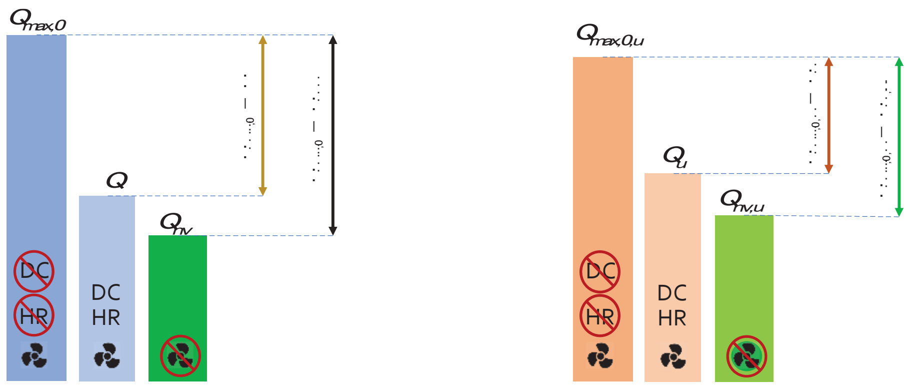
EFFECT OF ASSUMING UNIFORM T



$$\frac{\eta_{IV,max,0}}{\eta_{IV,max,0,u}} = \frac{\frac{Q_{max,0} - Q}{Q_{max,0} - Q_{nv}}}{\frac{Q_{max,0,u} - Q_u}{Q_{max,0,u} - Q_{nv,u}}}$$

> 1 The non-uniform temperatures scenario has a better energy performance.

< 1 The uniform temperatures scenario has a better energy performance.

6 simulations involved

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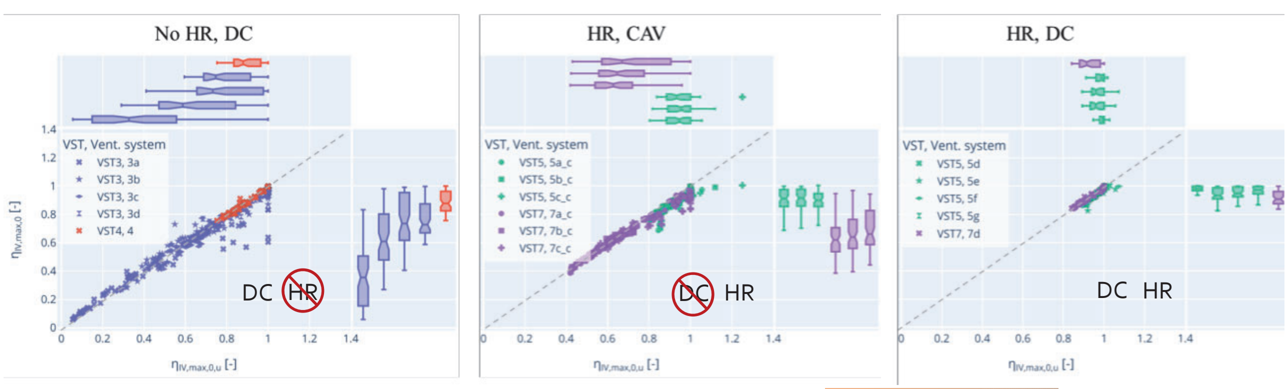
EFFECT OF ASSUMING UNIFORM T



- The energy performances are similar, but uniform temperatures show a slightly better energy performance (differences in performance around 5 %).
- VST3 have the lowest energy performance.

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Proposal to promote airtightness in non-residential buildings in Japan

May 19, 2023

Taisei Corporation
Kiyoshi Hiwatashi

This content is under study by the study group "Proposal for the Realization and Dissemination of a System for Airtightness in Non-residential Buildings Toward Carbon Neutrality" in the Consortium for Building Research and Development.

The Situation of Airtightness in Non-Residential Buildings in Overseas Countries

- Around 2000, the U.S. and the U.K. began to establish measurement and evaluation standards for airtightness in non-residential buildings.
- Since then, airtightness of non-residential buildings and accumulation of airtightness data have been progressing.

	Evaluation codes	Target building	Measurement Standard
U.S.A	ASHRAE 90.1-2016	Other than low-rise residential	ASTME779-10
	Washington State, Seattle Code	Buildings with more than 4 floors	
	USACE	large Build.	ASTME779-10, ASTME1827
U.K	ATTMA TSL2	Office	ATTMA TSL2
	ATTMA TSL2	Warehouse	ATTMA TSL2
DE	Passivhaus	All buildings	ISO9972, EN13829
UAE	Abu Dhabi Building Code (IECC)	Commercial	ASTME779-10, ASTME1827
JPN	No Codes Values are reference values	Tight	No Standards
		Average	
		Loose	

The Situation of Airtightness in Non-Residential Buildings in Japan

- In Japan, airtightness of high-rise buildings was measured in the 1980s, and reference values for airtightness were presented.
- However, no progress has been made since then.

	Evaluation codes	Target building	Measurement Standard
U.S.A	ASHRAE 90.1-2016	Other than low-rise residential	ASTME779-10
	Washington State, Seattle Code	Buildings with more than 4 floors	
	USACE	large Build.	ASTME779-10, ASTME1827
U.K	ATTMA TSL2	Office	ATTMA TSL2
	ATTMA TSL2	Warehouse	ATTMA TSL2
DE	Passivhaus	All buildings	ISO9972, EN13829
UAE	Abu Dhabi Building Code (IECC)	Commercial	ASTME779-10, ASTME1827
JPN	No Codes Values are reference values	Tight	No Standards
		Average	
		Loose	

- To change this situation and promote air tightness in non-residential buildings, the following proposals are made.

1 Proposal to create a network utilizing current airtightness testing businesses for residential buildings

2 Proposal to establish measurement and evaluation standards with reference to the U.S. and the U.K. standards

3 Proposal for training content

4 Proposal for setting airtightness performance requirements

5 Proposal to approach the Climate Citizens' Assembly

6 Recognition of a sense of speed in the proposed schedule for the start of the system's operation

1 Proposal to create a network utilizing current airtightness testing businesses for residential buildings

■IBECs(Institute for Built Environment and Carbon Neutral for SDGs)

・In Japan, IBECs is an association that provides training, testing, and certification for airtightness testing for residential buildings.

・IBECs is an organization affiliated with the Ministry of Land, Infrastructure, Transport and Tourism.

■Qualification method

・Business operators are registered after training and passing the "JIS A 2201 Airtightness performance test method for houses using a blower" course.

■ Registered Business Office

・About 1100 business offices are registered nationwide. (as of April 2023).

Questionnaire survey and community networking

■ Questionnaire survey

・We will conduct a questionnaire survey of these offices to see if they are also interested in airtightness measurement of non-residential buildings.

■Community networking

・We will also encourage the creation of a community network.

・The objective is to have each region conduct a study session on airtightness testing methods and airtightness installation for non-residential buildings.

・And, the objective is to have them take on the role of spreading the information to the local residents.

■Proposal for expensive test equipment

・In addition, since airtightness testing equipment is very expensive, for large buildings, it is necessary to consider a system in which multiple businesses in a region can take measurements together.

2 Proposal to establish measurement and evaluation standards with reference to the U.S. and the the U.K. standards

Measurement Standards in the U.S.

・In the U.S., ASTM standards have been developed for a variety of airtightness-related content.
・The 16 standards listed in the table below cover the areas of field and laboratory airtightness test methods, materials, and commissioning.

Fields			Standard number
Airtightness	Airtightness Testing Methods at Building Sites	1	ASTM E779-19
		2	ASTM E1827-22
		3	ASTM E3158-18
		4	ASTM E783-02(2018)
	Identification Methods for Leakage Points at Building Sites	5	ASTM E1186-22
	Fittings Laboratory Test Method	6	ASTM E283/E283M-19
		7	ASTM E1424-22
		8	ASTM E2319-22
		9	ASTM E1680-16(2022)
		10	ASTM D8052/ D8052M-22
	Test Specimen fabrication method	11	ASTM E2357-18
	Test Method (Material)	12	ASTM E2178-21a
	Calibration of air volume	13	ASTM E1258-88(2018)
Material	Specifications	14	ASTM E1677-19
Commissioning	Procedure	15	ASTM E2813-18
		16	ASTM E2947-21a

Measurement Standards in the U.K.

Standards in the U.K. were developed by ATTMA.
(The Air Tightness Testing & Measurement Association)

The standard is based on ISO 9972 and is classified into 4 categories according to the complexity of the building, as shown in the table below.

There are no standards except for airtightness testing standards in ATTMA.

	Standard No.	Classification
1	TSL1	Simple Building
2	TSL2	Nom-Simple Building
3	TSL3	Complex Building
4	TSL4	Passivhaus &Low Energy Building

Measurement Standards in Japan

- In Japan, there are no standards for airtightness testing of non-residential buildings at present.
- JIS A2201 is a modified version of ISO 9972 for Japanese residential buildings.
- JIS A1516 is a laboratory airtightness test method for fittings.
- JIS B9330 is the standard for calibration methods for general fan airflow.

	Standard No.	Field
1	JIS A 2201:2017	Airtightness Testing Methods at Building Sites
2	JIS A 1516:1998	Fittings Laboratory Airtightness Test Method
3	JIS B 9330:2000	Calibration of air volume

Proposal for development of measurement standards

- In Japan, there is a need to establish measurement and evaluation standards as soon as possible.

- In order to respond quickly, it is acceptable to initially introduce foreign standards basically as they are.

- Modifications will be made as necessary.

- A candidate for a standard would be ATTM, which is simpler and explains specific procedures.

- ATTMA is based on ISO 9972, which is the same as JIS A 2201.

- The ATTMA evaluation standards are for each building type.

Proposal for development of measurement standards

- In Japan, there is currently no accumulated data, so the same evaluation standards should be adopted as in the U.S.

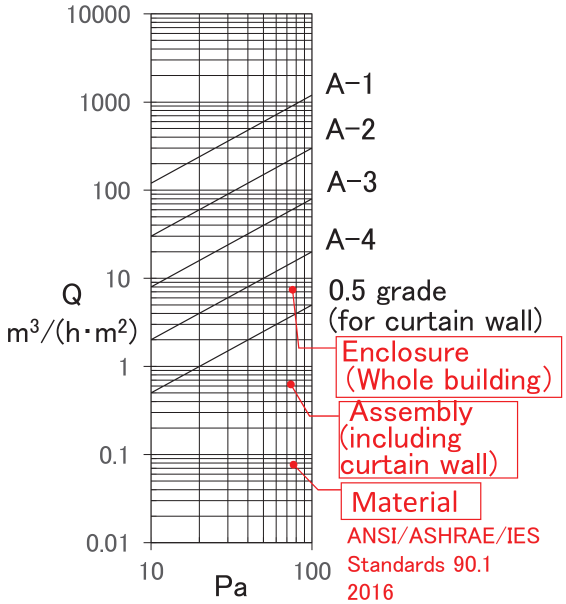
- The standards for materials and commissioning should be supplemented with those of ASTM.

- The set pressure should be set from 50 Pa to 75 Pa in a stepwise manner, taking into consideration the number of test equipment required.

- The USACE 2012 wind-unaffected method should be adopted.

- For the purpose of dissemination, a pattern in which the ventilation openings are not closed should be adopted as the basis in order to reduce labor and cost.

Airtightness class for fittings



Japanese fittings standards JIS A 1516 and ANCI/ASHRAE/IES standards for airtightness performance are compared.

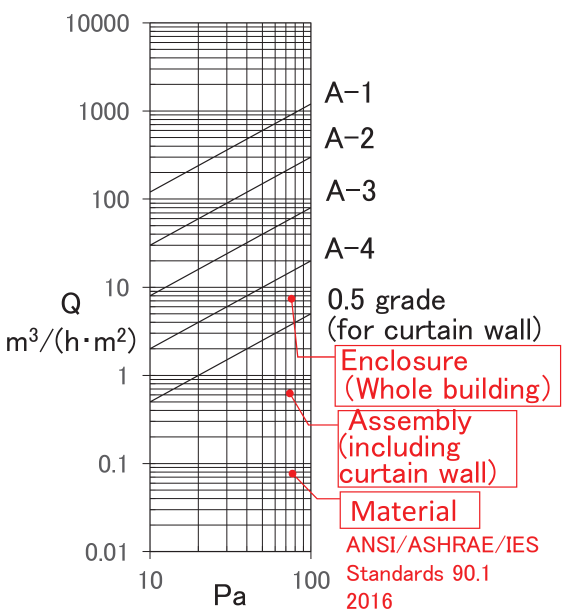
Japanese standards are classified as A-1 to A-4.

The standards are A-2 or lower for general buildings and A-3 for soundproofing, thermal insulation, and dustproofing buildings.

There is also 0.5 grade for curtain wall.

However, there are no standards for airtightness of materials and no standards for airtightness of the exterior envelope of non-residential buildings.

Airtightness class for fittings



The ANCI/ASHRAE/IES standards are stratified into three categories.

The standards for those assemblies have higher airtightness performance than the Japanese standards for fittings and curtain wall.

It is considered necessary to reconsider the Japanese standards for fittings and curtain wall.

3 Proposal for training content

Training Course in Japan

■Japan

・In Japan, IBECS conducts airtightness testing courses.

・This course is targeted at residential buildings, and there is no course for non-residential buildings.

Course Length – 3 hours
Classroom learning , Certification Examination and Registration – ¥28,050(About $200)

Training Course in the U.S.

■In the case of ABAA
(Air Barbour Association of America)
In the U.S., the case of the ABAA is mentioned as an example.

The ABAA has 3 types of training courses

(1) Whole Building Airtightness Technician Program
(Blower Door Technician Training)
(2) Auditor Courses (Field Auditor Training)
(3) Installer Course

Whole Building Airtightness Technician Program

・Whole Building Airtightness Technician Program is Comprehensive training program covering ASTM, CGSB, ISO Standards and USACE test methods.

Course Length: 5 Days
Conceptual Learning: 2Days
Hands-on Training: 2Days
Performing a Test: 1Day

Training Course Fees:
Members – $2,500.00 (About ¥340,000)
Non-Members – $2,850.00 (About ¥380,000)

Auditor Courses (Field Auditor Training)

■The role of the Field Auditor

The role of the Field Auditor is performing quality assurance audits of air barrier assemblies on new commercial and institutional construction projects during installation.

Course Length: 2.5 Days

Total Fees

(Training Course Fees, Certification Exam Certification Registration)

Members – $1245.00（About ¥170,000)

Non-Members – $1445.00(About ¥195,000)

Installer Courses

■Installer Courses (2 Courses)

(1) Self-Adhered & Fluid Applied Installer Training Course

(2) Spray Polyurethane Foam & Self-Adhered Installer Training Course

Course Length: 2.5 Days

Total Fees

(Training Course Fees, Certification Exam Certification Registration)

Members – $1445.00 (About ¥195,000)

Non-Members – $1945.00 (¥About 260,000)

Training Course in the U.K.

■The Case of ATTMA in the U.K.

ATTMA in the U.K. also has training courses for air tightness testers at each level, similar to ABAA.

Proposal for training courses in Japan

・Pre-planning for airtightness testing is important for non-residential buildings because they are larger and more complex than residential buildings.
⇒Therefore, it is important to have a training course that includes more detailed pre-planning methods and practical skills.

・Training on installation methods and supervisors is also necessary.

・In order to respond quickly, it is proposed that the content of training courses in the U.S. and the U.K., which have a proven track record, be introduced directly to Japan at first.

Proposal for training courses in Japan

- In order to increase the number of qualified personnel, subsidies for acquisition of qualifications are also proposed.

- In addition, subsidies for the purchase of expensive testing equipment are also proposed.

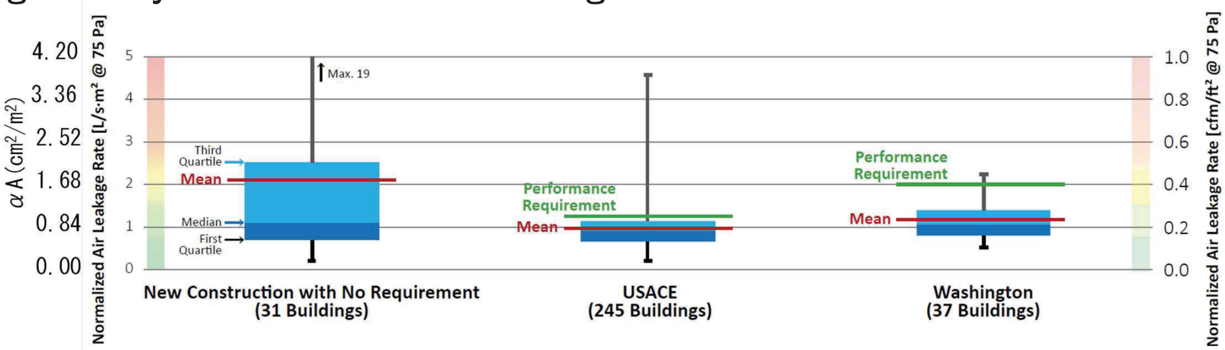
4 Proposal for setting airtightness performance requirements

Survey Results in the U.S.

In the study, new buildings in different jurisdictions with mandatory air tightness requirements were compared to new buildings without air tightness testing requirements.

The results showed that buildings built with the intent to meet the performance requirements for air tightness achieved the target values.

New buildings built without performance requirements were generally shown to be less airtight.



Distribution of test results for each set of buildings in different juisdictions

This figure was quoted from "Illustrated Guide Achieving Airtightness " published by BC Housing, Canada.

https://www.bchousing.org/research-centre/library/residential-design-construction-guides/illustrated-guide-achieving-airtight

Proposal for setting airtightness performance requirements

In Japan, the actual situation of airtightness performance has not yet been investigated.

It is important to accumulate airtightness performance data and set the required performance.

The number of non-residential airtightness testing companies will be increased and the understanding of the public will be deepened in order to accumulate data.

5. Proposal to approach the Climate Citizens' Assembly

Outline of the Climate Citizens' Assembly

Climate Citizens' Assemblies were held at the national political level in France and the U.K. in 2019–20.

This attempt is also spreading to local governments.

In Japan, the first one was held in Sapporo in 2020.

Recently, Musashino City and Tokorozawa City have also hosted the conference, and many local governments are planning to do so in the future.

Members are randomly selected from the general public and are gathered in proportions that represent a microcosm of society.

Outline of the Climate Citizens' Assembly

The number of members ranges from a few dozen to about 150.

Citizens spend weeks or months receiving information from various experts, deliberating, and making recommendations to the national and local governments.

The national and local governments will make use of the recommendations in their policies.

Questionnaires on visions of future life

- At Climate Assembly Sapporo 2020, participants were asked to complete a questionnaire regarding their visions for their future lives.

- An analysis was conducted on the results of the questionnaire, using the strength of support and the scattering of opinions as indicators.

- "Improvement of residential thermal insulation" and "Spread of energy-efficient buildings" were strongly supported, and there was little scattering in opinions.

Questionnaires on visions of future life

・However, awareness of airtightness is lower than that of thermal insulation.
→It is important to raise awareness of airtightness improvement

・It is important that a network of air tightness measurement companies in each region create a system to disseminate information to the public.

6 Recognition of a sense of speed in the proposed schedule for the start of the system's operation

Sense of schedule to be operational in 2030

- This is a proposed schedule for a target of having the system operational by 2030.
- We realize that it is a very tight schedule.
- It is necessary to start operation as soon as possible at a realistic speed.

		2023	2024	2025	2026	2027	2028	2029	2030
1	Examination of measurement standards								
2	Training of measurement experts								
3	Promotion of airtightness testing equipment								
4	Grasping the actual airtightness performance								
5	Acquisition of information on airtightness construction methods								
6	Training of construction engineers								
7	Consideration and establishment of assessment standards								
8	Dissemination to citizens' meetings								
9	Starting operation of the system (Step 1)								

Thank you for your attention.

PLEIAQ

Trends in building and ductwork airtightness in different countries

WORKSHOP "TOWARDS HIGH QUALITY, LOW-CARBON VENTILATION IN AIRTIGHT BUILDINGS"

MAY 19TH 2023

VALÉRIE LEPRINCE
CEREMA

NOLWENN HUREL
PLEIAQ/INIVE

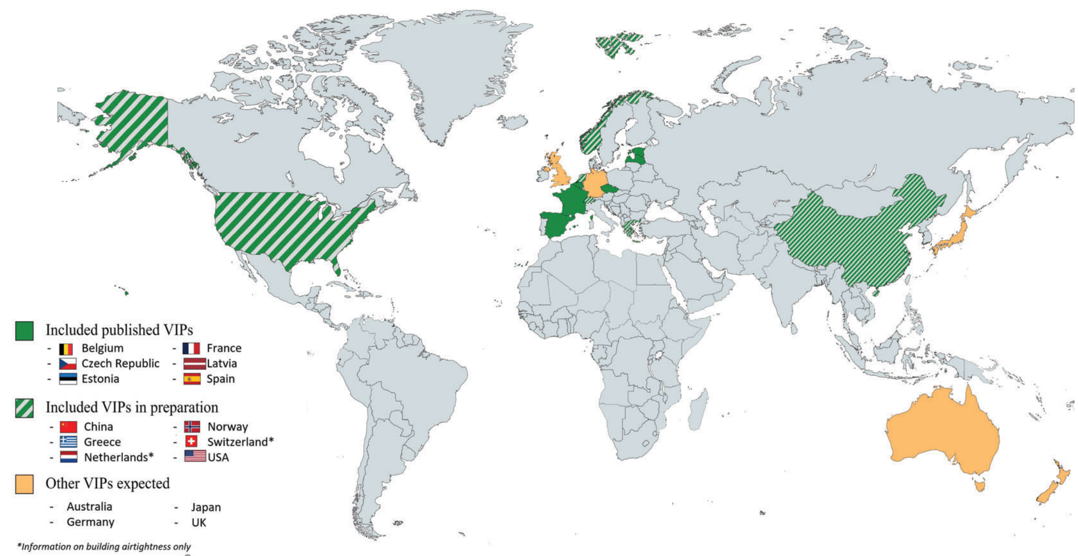
- Context : AIVC VIPs
- Building airtightness
- Ductwork airtightness

VIP series on Building & Ductwork Airtightness

Series of Ventilation Information Papers (VIP) published by the AIVC

- Title: *“Building and ductwork airtightness - National trends and requirements”*
- Authors found in various countries via the TightVent Airtightness Associations Committee (**TAAC**) and the **AIVC** board members
- Template prepared: **similar structure** for all papers
- Already **7 published papers**:
  - Estonia (VIP 45.1)
  - Spain (VIP 45.2)
  - Czech Republic (VIP 45.3)
  - Belgium (VIP 45.4)
  - Latvia (VIP 45.5)
  - France (VIP 45.6)
  - Greece (VIP 45.7)
- Available on the **AIVC website**: https://www.aivc.org/collection-keys/vip
- Overview summary in preparation

Countries included in this overview (12)



Context : AIVC VIPs

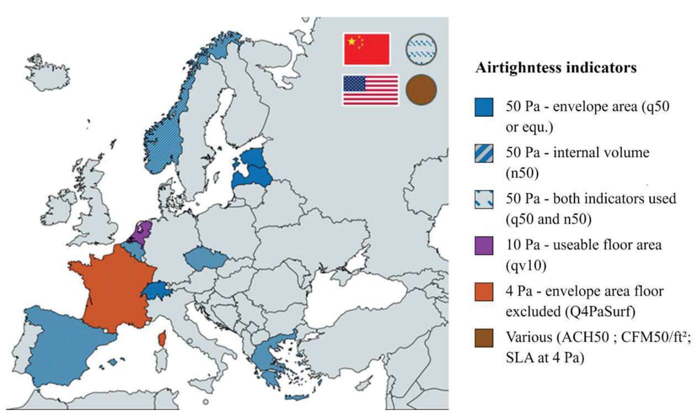
Building airtightness

Ductwork airtightness

Envelope airtightness indicators

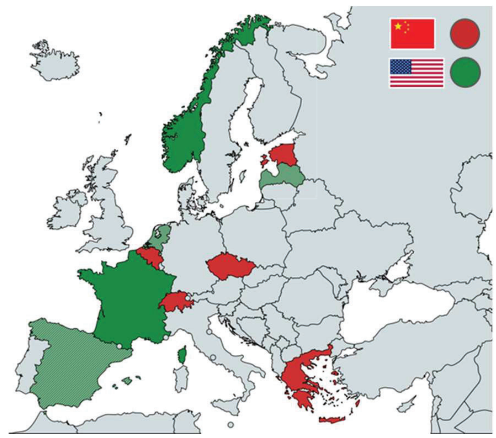
Flowrate at pressure :	Devided by :		
	Envelope area	Building volume	-
50 Pa	q_{50} (m³/(h.m²))	n_{50} (h⁻¹)	
10 Pa			q_{v10} (m³/h)
4 Pa	$q_{4PaSurf}$ (m³/(h.m²))		

- BE: Average of p^+ and p^- ; external dim.
- FR: Floor excluded from the envelope area
- LV: n_{50} also sometimes used
- NL: q_{v10} sometimes divided by the floor area
  n_{50} and ACH50 also used
- USA: various indicators: ACH50 ; CFM50/ft²; Specific Leakage Area (-) at 4 Pa



Mandatory envelope airtightness requirements

Mandatory requirements?					
NO	YES				
	Country	Mandatory for:	Values: Indic. (unit)	Values: Max. values	Mandatory justification ?
	FR	Residential buildings	$q_{4PaSurf}$ ($m^3/(h.m^2)$)	• 0.6 for single-family • 1 for multi-family	YES, by test or certified quality management approach
	LV	Residential houses, homes for the elderly, hospitals, kindergartens, and public buildings	q_{50} ($m^3/(h.m^2)$)	• 3,0 for natural vent. • 2,0 for mech. vent • 1,5 for heat recov. • 4,0 for industrial build.	NO
	NL	All buildings ?	q_{v10} (L/s)	• 200 up to 500 m^3, pro rata above • Stricter in EPC: about 0,6 $/m^2$ of floor	NO
	NO	All buildings	n_{50} (h^{-1})	• 1.5 for all buildings • target of 0.6 for dwellings	YES
	ES	Residential build. > 120 m^2, with mandatory controlled mech. or hybrid vent. system	n_{50} (h^{-1})	• 6 if Vol//Env. Area <2 • 3 if Vol//Env. Area >4 • Interpolation in between	YES, by test or calculation with a formula: $n_{50} = 0.629 \frac{C_0 \times A_0 + C_h \times A_h}{V_{int}}$
	US	Residential buildings in some states that have adopted the IECC energy codes	ACH50	• 3 nationally • 5 in few locations with very mild climates	YES, by test (sampling allowed for muti-family)



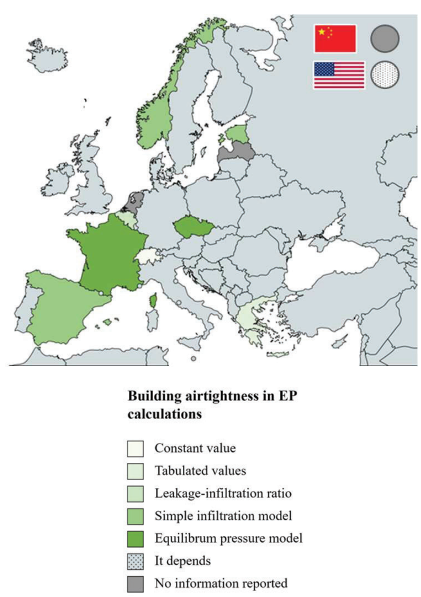
Building airtightness in Energy Performance Calculations

Level of accuracy and complexity

Type of model	Country	Details	Default values: Used?	Default values: Values	Default values: Comments
Constant value (per building surface)	CH	Not a variable: fixed additional outside air volume flow of 0.15 $m^3/(h.m^2)$ (net floor area reference) regardless of the quality of the envelope (not possible to use test values)			
Tabulated values	GR	Fixed tabulated air infiltration rates (m^3/h) given for different types of windows and doors; for chimneys and ventilation boxes (not possible to use test values)			
Leakage-infiltration ratio	BE	$v_{inf} = 0.04 * v_{50} * A_T$	YES	**VERY penalizing** v_{50}: 12 $m^3/(h{\cdot}m^2)$ for heating; 0 for cooling	**Test** not officially mandatory but **necessary** for the EP calculation
Simple infiltration model (SIM)	EE	$q_{inf} = q_{50}.A/X$ A: area of the building envelope (m^2) X: factor depending on the **number of storeys** (ranging from 15 to 35)	YES	Penalizing q_{50} ($m^3/(h.m^2)$): - detached house: 4 (6 for minor renovation) - other buildings : 2,5 (4)	Other possibilites: - Use 1.5 $m^3/(h{\cdot}m^2)$ to be justified by test later - Use of a calculated "declared air leakage rate"
	NO	Common case: $n_{inf} = n_{50}.0{,}07$ but depends **on number of facade exposed** and **degree of exposure to wind**	NO	-	Requirements can be used prior to the test
	ES	Fixed infiltration rate estimated from n_{50} with hypotheses (wind speed of 2,8 m/s, Cp values per façade, n=0,67; etc.)	YES	Calculation of n_{50} by a formula: $n_{50} = 0.629 \frac{C_0.A_0 + C_h.A_h}{V_{int}}$	-
Equilibrum pressure model	CZ	Method 1 of the standard EN 16798-7, with an hourly time step (pressure calculated by a mass balance equation)	NO	-	Common practice: use recommended n_{50} values at level I according to ČSN 73 0540-2
	FR		YES	Non-residential: $Q_{4PaSurf}$: 1.7 or 3 $m^3/(h{\cdot}m^2)$ depend. on the building use	No default values for residential buildings: minimum requirements to be justified

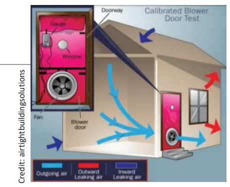
US: it depends on the states, most jurisdictions use a prescriptive approach and do not model energy use (IECC: SIM; dynamic infiltration rat; California: SIM; fixed infiltration rate)

LV,NL, CN: no information reported on the model



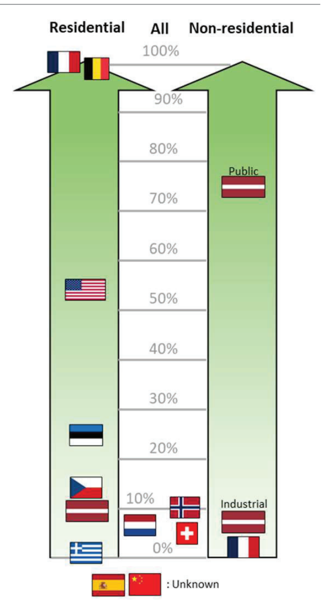
Building airtightness test protocol

Country	National qualification for testers				National guidelines		
	Existing?	Mandatory?	Name	Number or %	Existing?	Name (year)	Specificities
BE	YES (Fl.)	YES ?	By BCCA and SKH	150 – 190 (Fl.)	YES	STS-P 71-3 (2014), mandatory only in Fl.	Tests in p^+ and p^- (or correction if not possible)
CN	NO	-	-	-	YES	T/CECS 704 (2020)	Tracer gaz method allowed
CZ	YES	NO	A.BD_CZ (mandatory for members)	15 (30-35%)	YES	annex of TNI 73 0330	Method for testing multi-family build.
						New Green Savings (NGS) guidelines	For buildings in this energy performance programme
EE	NO	NO	-	-	NO	-	-
FR	YES	YES	Qualibat	842	YES	FD P50-784	Application guide of EN ISO 9972
GR	YES	NO	Seminars by Aerosteganotita	10	NO	-	-
LV	NO	NO	Some qualified with Retrotec, FliB, ATTMA	11	NO	In accordance with LVS EN 9972:2016	
NL	NO	NO	Some qualified by SKH	10-15%	YES	NEN 2686	Tests in p^+ and p^-
NO	NO	NO	-	-	YES	There are simplified methods in use not complying entirely with ISO 9972	
ES	NO	NO	Trainings by manufacturers	?	NO	In accordance with UNE-EN ISO 9972:2019	
CH	NO	NO	qualified with FLIB	2 (~2%)	YES	Minergie airtightness guideline (RiLuMi)	for building and test preparation (test in accordance with EN ISO 9972)
US	YES	NO ?	energy auditor certification (ABNSI/BPI-1100-T-2014) by BPI	?	YES	Standard ASTM E779	for multipoint measurements
						Standard ASTM E1827	for single point measurements (50 Pa)
						More commonly used: ANSI/RESNET 380 or blower door manufacturer's instructions (more simple than ASTM standards)	



Building airtightness tests performed

Country	Residential buildings	Non-residential buildings	Public database		
			Existing?	In charge:	% of tests
BE	New: alm. 100%	-	YES	Flanders: VEKA	100%
	deep retrofit: ~ 25%			quality frameworks like BCCA	All from this QF
CN	unknown	-	NO	-	-
CZ	<15%	-	YES	A.BD_CZ	~ 3%
EE	~ 25%	-	NO	-	-
FR	100%	very few	YES	Qualibat (since 2007)	100%
GR	very very few	-	YES	Aerosteganotita	?
LV	5-15%	public: 70-80%	NO	-	-
		industrial: 5-10%			
NL	5-10%		NO	Some data gathered (Retrotec's rCloud, SKH scheme, Uni. of Twente)	
NO	~ 10%		NO	-	-
ES	Unknown		NO	One-time effort: 400 cases (INFILES Project)	
CH	~ 5%		NO	survey of Minergie	
US	>50% (depends on the states)	-	NO	Old one from LBNL (150 000 entries)	



Guidelines to build airtight

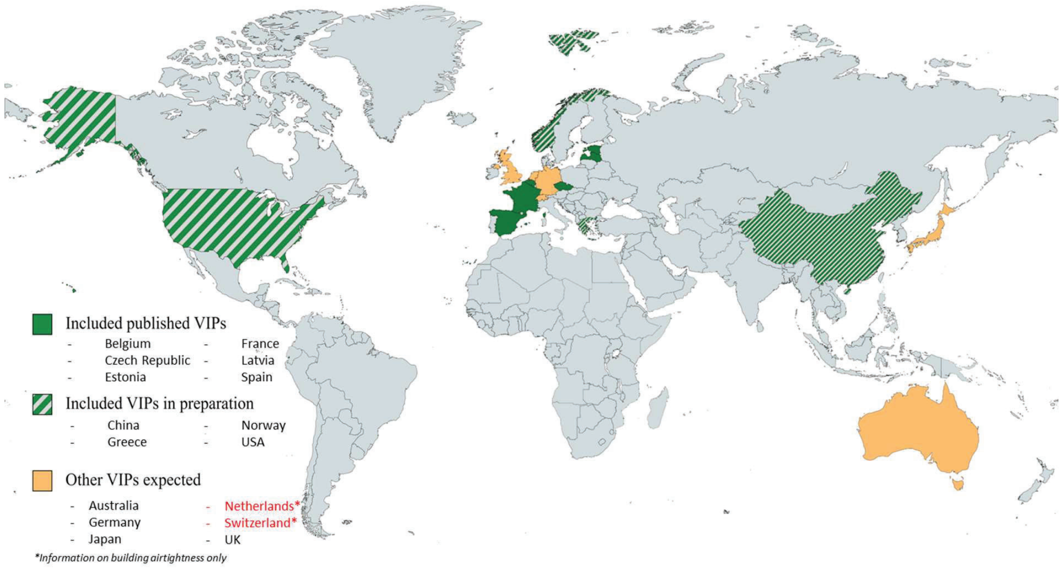
Country	Guidelines to build airtight		
	Existing?	Name	Details/Comments
BE	YES	Technical Guidance on building airtightness (by Buildwise)	Technical Information Note : recommended principles for constructing airtight buildings
CN	YES	Guideline T/CECS 826 (2021)	applies to the design, construction, and acceptance of airtight materials for building construction
CZ	YES	Standard ČSN 74 6077	recommends several technical solutions for an airtight design of the window-to-wall interface
EE	In prep.		Estonian national standard under development
FR	YES	Carnets Mininfil (2010)	Design and implementation guide for designers, craftsmen and construction companies
GR	NO	-	-
LV	NO	-	-
NL	NO	-	Some manufacturers of building provide guideline
NO	NO	-	Airtightness issues are important in the Norwegian building research details database
ES	YES	Basic Document for the Energy Saving in Buildings (DB HE1)	Construction solutions and workmanship of the building envelope for good airtightness
		UNE 8529:2016	Joints and discontinuities on the thermal envelope
CH	YES	SIA 180, SIA 4001,...	Standards that relate to specific components (roof, wall, window....)
		RiLuMi for Minergie	
US	YES	Guidelines in many individual programs, usually in the form of checklists. Examples : ENERGY STAR Qualified Homes, Version 3 (Rev. 04), Inspection Checklists for National Program Requirements ; IECC Air Barrier and Insulation Inspection Checklist ; BPI Technical Standards for Certified Shell Specialists.	

Context : AIVC VIPs

Building airtightness (12 countries)

Ductwork airtightness (10 countries)

10 countries included (not NL and CH)



Ductwork airtightness indicators

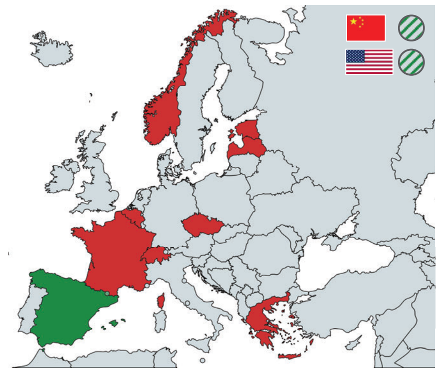
- **European countries**: f ($m^3/(s.m^2)$)
  Flowrate divided by the ductwork area
  Use of airtightness classes →
- **USA**: CFM25/ft²
  Flowrate at 25 Pa divided by the floor area
- **China:** Q ($m^3/(h.m^2)$)
  Flowrate divided by the ductwork area (pressure not defined)

Airtightness classes		Air leakage limit (fmax) according to the test pressure (p_t) [$m^3.s^{-1}.m^{-2}$]
Previous name	**New name**	
	ATC 7	Not classified
	ATC 6	$0{,}0675 \times p_t^{0{,}65} \times 10^{-3}$
A	ATC 5	$0{,}027 \times p_t^{0{,}65} \times 10^{-3}$
B	ATC 4	$0{,}009 \times p_t^{0{,}65} \times 10^{-3}$
C	ATC 3	$0{,}003 \times p_t^{0{,}65} \times 10^{-3}$
D	ATC 2	$0{,}001 \times p_t^{0{,}65} \times 10^{-3}$
	ATC 1	$0{,}00033 \times p_t^{0{,}65} \times 10^{-3}$

Mandatory ductwork airtightness requirements

Mandatory requirements?					
NO	YES				
	Country	Mandatory for:	Values: Indic. (unit)	Values: Max. values	Mandatory justification ?
	ES	New and retrofitted buildings		Class B	YES (by test since 2007 - UNE-EN 12599) but in practice: not always tested)
	CN	All buildings	Q (m³/h)	See Table	NO
	US	Some cases / States	CFM25 (CFM)	ENERGY STAR & IECC: Max (8 /100 ft²; 80) California & ASHRAE 62.2: 6% of total system airflow North Carolina: 6 /100 ft² Kentucky: 12 /100 ft² ; …	NO

Design pressure	Permitted air leakage rate m³/(m²·h): Rect. metal duct	Permitted air leakage rate m³/(m²·h): Round metal duct
≤ 500 Pa	≤ 0.1056$P^{0.65}$	≤ 0.0528$P^{0.65}$
500 -1500 Pa	≤ 0.0352$P^{0.65}$	≤ 0.0176$P^{0.65}$
≥ 1500 Pa	≤ 0.0117$P^{0.65}$	≤ 0.0117$P^{0.65}$



Mandatory ductwork airtightness requirements?

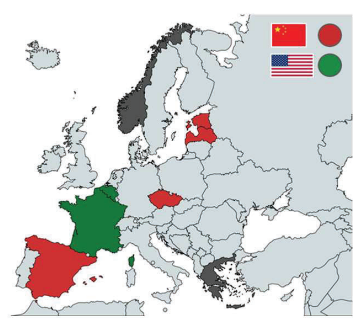
- No
- Yes (in at least some cases) - no mandatory justification
- Yes (in at least some cases) - mandatory justification

Ductwork airtightness in Energy Performance Calculations

Country	Details	Default values: Used?	Default values: Values	Default values: Comments
BE	non-residential: NO residential: can be valorised through a reduction in the factor m (valorising the execution quality of the vent. system)	-		
FR	The ductwork airtightness influences the total air change rate of the internal volume (included in the calculation of the ventilation flow rate)	YES	2.5 Class A	Any other class used in the EP calculation has to be justified
USA (Califo.)	A multizone air flow and thermal model is used to calculate the impacts of duct leakage as a reference that other compliance software must match	YES (CA)	15% prior to 2013; 5% since 2013 (introduction of duct perf. Requirements in 2013)	No information on other states

CN, CZ, EE, ES, LV: Not included in the EP calculation

GR, NO: No information provided



Ductwork airtightness in EP calculation ?

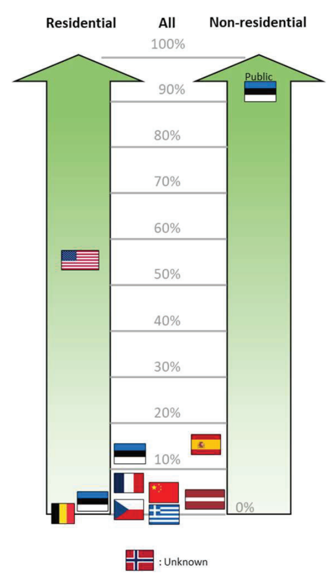
- Yes (in at least some cases)
- No
- No information provided

Ductwork airtightness test protocol

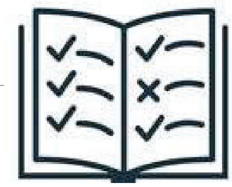
Country	National qualification for testers			National guidelines		
	Existing?	Mandatory?	Name	Existing?	Name (year)	Specificities
BE	NO	NO	-	NO	-	-
CN	NO	NO	-	N/A	-	-
CZ	NO	NO	(2 accredited laboratories to test products)	NO	-	-
EE	NO	NO	-	NO	-	-
FR	YES		Qualibat (133 testers)	YES	FD E 51-767 (Tests have to comply with EN 12237, EN 1507, EN 13403 and EN 12599)	- sampling rules for multi-family dwellings - rules to select a sample of houses among a group of houses, and a sample of ductworks for buildings than include more than 5 fans. - requirements regarding the preparation of the ductwork - reference pressure difference of the test depending of the type on building - corrections that shall be applied for particular situations
GR	N/A	N/A	-	N/A	-	-
LV	NO	NO	-	NO	-	-
NO	NO	NO	-	NO	-	-
ES	NO	NO	Usually: technicians who install the system also test it	NO	-	-
US	YES	NO	BPI (BPI 2017 ANSI/BPI-1200-S-2017) and RESNET	YES	For residential: - More commonly used for residential: ANSI/RESNET 380 - More advanced test methods in ASTM Standard (ASTM E1554) - In California (and ref. in ASHRAE 62.2): California Building Energy Efficiency Standards, Residential Appendix RA3.1 (CEC 2019) For non-residential: also fixed-pressure duct testing methods	

Ductwork airtightness tests performed

Country	Residential buildings	Non-residential buildings	Public database		
			Existing?	In charge:	% of tests
BE	< 1%	-	No	(not public: VEKA in Flanders)	limited
CN	Very few		NO	-	-
CZ	Very limited for special installations		NO		
EE	Few (usually no test)	Public: almost 100%	YES	Estonian building registry	100% ?
	10-15%				
FR	Few (1323 tests in 2020)		YES	Cerema	100%
GR	Close to 0%		NO		
LV	Very few		NO	-	-
NO	N/A		NO	-	-
ES	Rather low		NO	-	
US	>50% (depends on the states)	-	NO	Old one from LBNL (150 000 entries)	



Guidelines to build airtight ductwork



Country	Guidelines to build airtight ductwork		
	Existing?	Name	Details/Comments
BE	NO	-	-
CN	YES	Standard GB 50738-2011 and JGJ 141-2017	Stipulated: material selection, production, installation and inspection, etc.
CZ	NO	-	Every producer provides his product with installation description
EE	YES	RKAS guideline	
FR	YES	DTU 68.3 (national standard)	Rules for design and installation of ventilation systems in buildings. Widely required by building owner for insurance purposes
GR	N/A	-	-
LV	N/A	-	-
NO	N/A	-	-
ES	NO	-	-
US	YES	California: California building standards include thorough instructions for duct and envelope sealing Many organizations provide training for testing and sealing ductwork: - US DOE Building America: BSC information on duct sealing for all climates - Energy Star duct sealing guidance for homeowners - SMACNA HVAC Duct Construction Standards - Metal and Flexible - ACCA Quality Installation Specification	

Thank you for your attention

And thank you to the VIP authors:

- BE: Liesje Van Gelder (BCCA), Maarten De Strycker (BCCA), Christophe Delmotte (Buildwise), Arnold Janssens (Ugent)
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- ET: Targo Kalamees, Jaanus Hallik, Alo Mikola (Tallinn University of Technology)
- FR: Bassam Moujalled, Adeline Mélois (Cerema, LOCIE)
- GR: Theodoros Sotirios Tountas (F.U.V.)
- LV: Andrejs Nitijevskis (IRBEST Ltd), Latvia Vladislavs Keviss (IRBEST Ltd), Nolwenn Hurel (PLEIAQ)
- NL: Frans Dam, Rob Dam (Retrotec EU)
- NO: Tormod Aurlien (NMBU)
- US: Iain Walker (LBNL), Steve Emmerich (NIST)

Airtightness Testing of Large Buildings

Iain Walker
Scientist
Building Technology & Urban Systems Division

Why are we testing?

- To meet building regulation for air tightness requirements
  - To limit air flows that
    - Increase energy use
    - Lead to moisture issues and other building failures
    - Prevent proper HVAC operation, e.g., maintaining building pressurization
  - To assess construction quality and identify flaws during construction process
- Typical metrics:
  - Air flow at fixed pressure m^3/h (cfm or L/s) at 50 Pa or 75 Pa
  - Normalized by surface area: $m^3/h/m^2$ (cfm/ft^2) at 50 or 75 Pa
- Examples: CO0
  - ASHRAE 90.1 in US: 0.40 cfm/ft^2 at 75 Pa (7 $m^3/h/m^2$)
  - International Green Construction Code: 0.25 cfm/ft^2 at 75 Pa (4 $m^3/h/m^2$)

スライド 2

CO0 Formatting issue: this bullet does not fit on screen for me
Collin Olson, 2023-05-08T19:17:26.859

Large Building Testing Issues

- Pressure uniformity
  - Resistance of interior air flow paths
  - Wind and stack effects
- Moving enough air
  - Need a lot of fans or one really big one
  - Safety issues – noise, slamming doors, high air speeds, opening fire doors
  - Power (independent circuits, generators or battery capacity)
- What about occupants? Can we only test when empty?
- Operation of other air moving systems and general building control
  - Building HVAC system
  - Building zones

Background – Current Test Methods

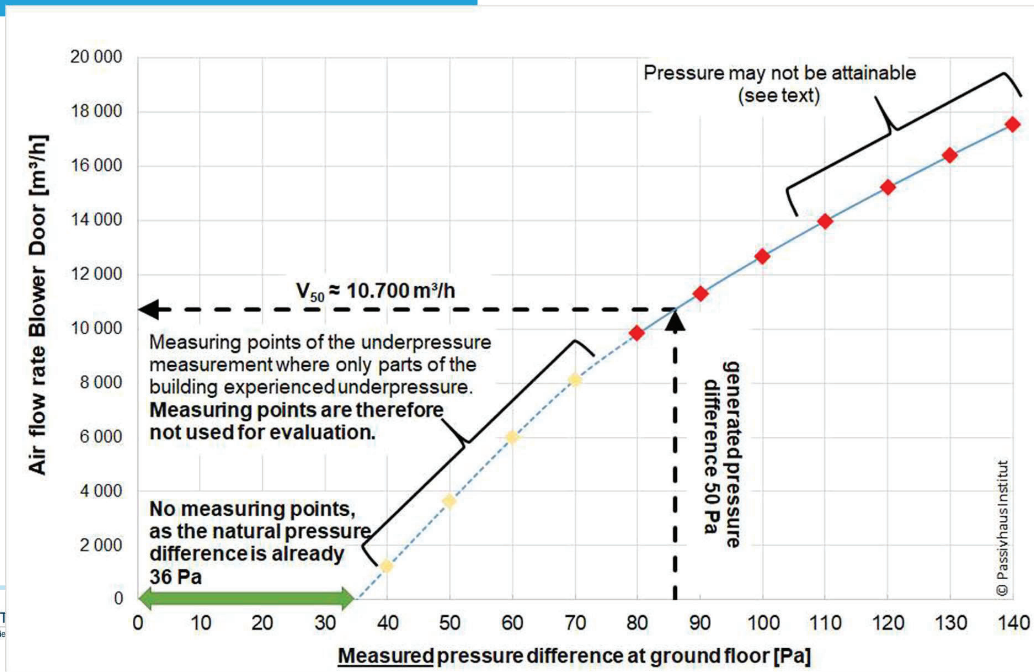
- ISO 9972 & EN 13829
  - has requirement for <10% pressure difference variation
  - Lowest measuring point > 5 times natural pressures: this gets unfeasibly high
  - Multipoint testing at several induced envelope pressures
- ASTM E779
  - "Single Zone" if internal pressure differences < 5% of inside to outside pressure difference
  - Limits height x temperature difference to 200 mK
  - Multipoint testing at several induced envelope pressures
- ASTM E3158 Standard Test Method for Measuring the Air Leakage Rate of a Large or Multizone Building
  - Instructions for building preparation
  - Pressure uniformity if internal openings > 2m^2 and flow less than 2800 L/s.
  - Multipoint testing at several induced envelope pressures + single point testing (50 or 75 Pa)
  - Internal pressure differences <10% of induced envelope pressure
- PassivHaus Guideline:
  - Considers deviating from standard test procedures:
  - Changing measurement pressures so that they all have the same sign: either the whole building is pressurized or the whole building is depressurized (Not very satisfactory because different parts of the building are at different pressures and traditional analysis assumptions are invalid?)

CO0

スライド 4

CO0 Maybe not, granted, but modeling suggests this is a good rule
Collin Olson, 2023-05-08T19:25:24.886

Example from PassivHaus Guideline



Ideas for large/tall building testing

- Use many fans at different locations
- Measure pressure differences at multiple locations
- Wait for favorable weather: small temperature differences and not windy
- Test when unoccupied for window/door/HVAC control
- Need data automation: multiple air flow and pressure location measurements need to be combined

Tall Building Example – Three towers in Austria

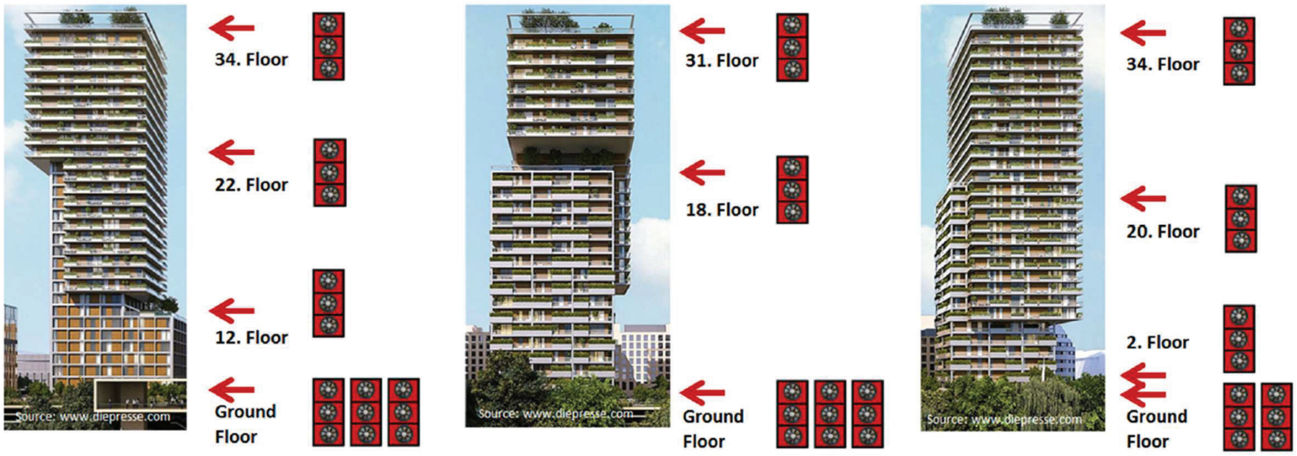
Tall Building Example – Three towers in Austria

	Tower 3	Tower 2	Tower 1
Floors →	36 floors + + 2 basement	32 floors + 2 basement	35 floors + 2 basement
h →	125 m	108 m	115 m
V →	76.844 m³	68.779 m³	71.280 m³
A_E →	15.652 m²	17.933 m²	16.079 m²

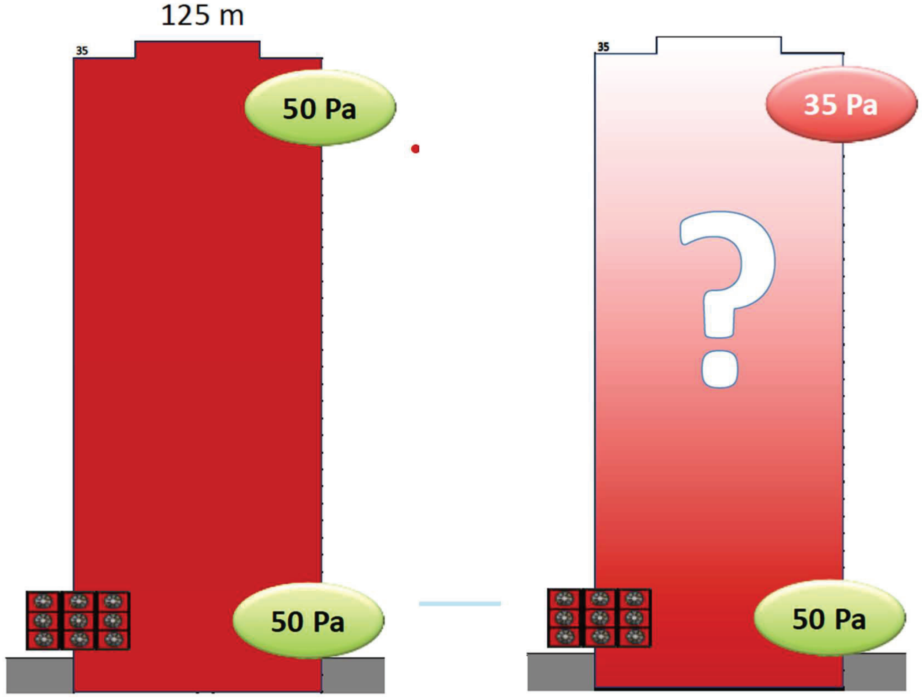
Where to install fans?

Estimate that 18 fans will be needed
120,000 m^3/h

Example fan locations



Uniform Pressure Difference?

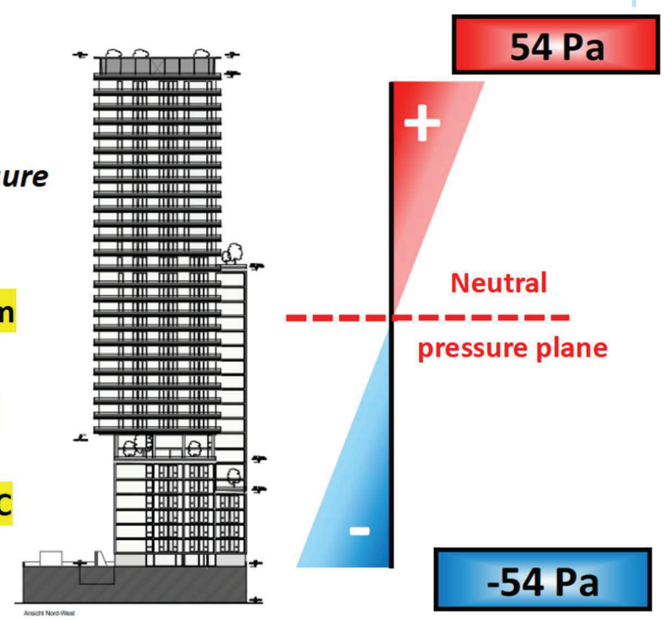


Stack Effect – a significant challenge

Tower 3, Test in Feb. 2021

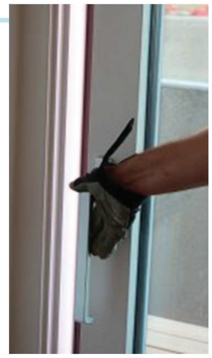
Estimation of *natural building pressure* some weeks BEFORE the test

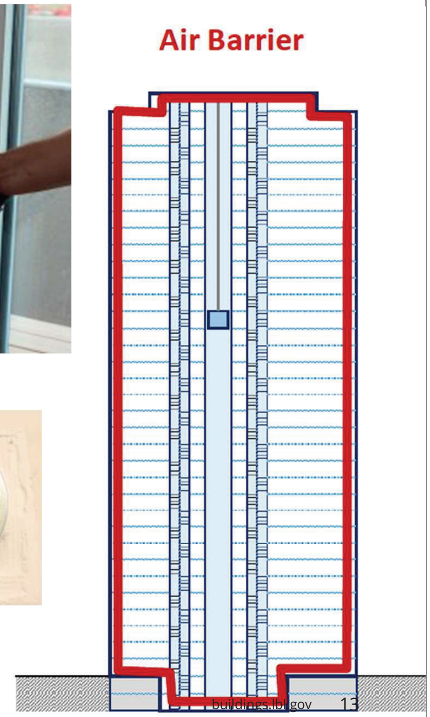
- building height **125 m**
- inside temperature **20°C**
- outside temperature **-1,5°C**



Building Preparation

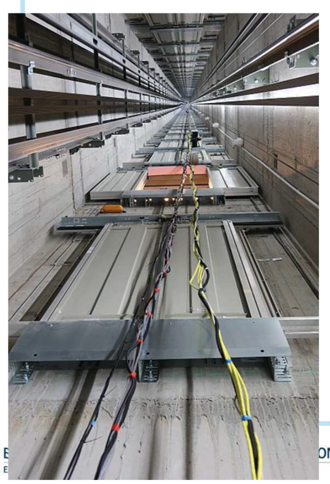
- Close all exterior doors and windows
- Fill all drains for sinks, showers, toilets
- Dampers in ventilation system
- Dampers in ducts for fire control
- Open all interior doors
  - 1200 wedges!

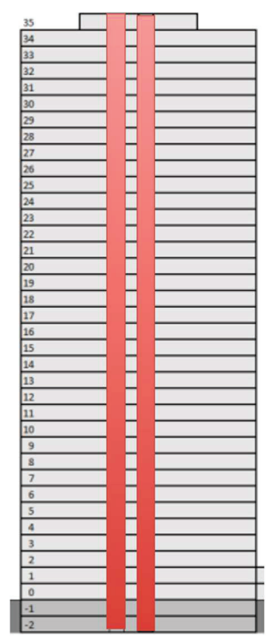




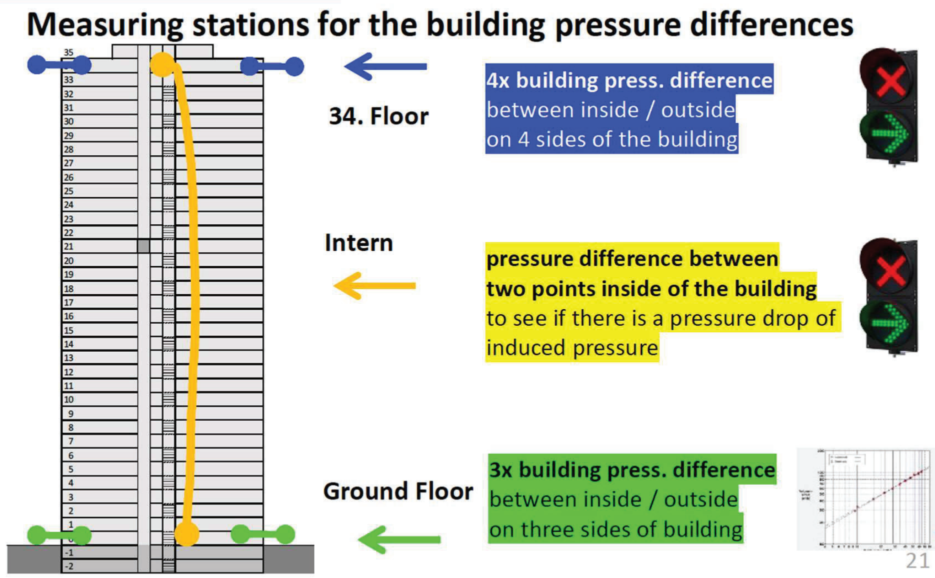
Internal air flow paths

- Stairs – narrow and only 2 or 3 doors/flo
- Lift Shaft – fall protection + other safety





Measure pressures at multiple locations

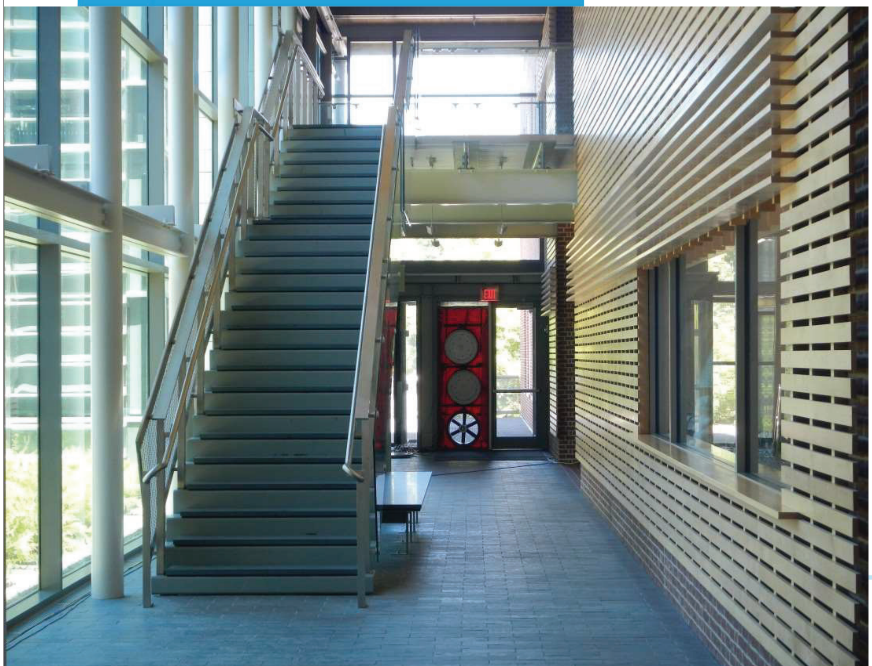


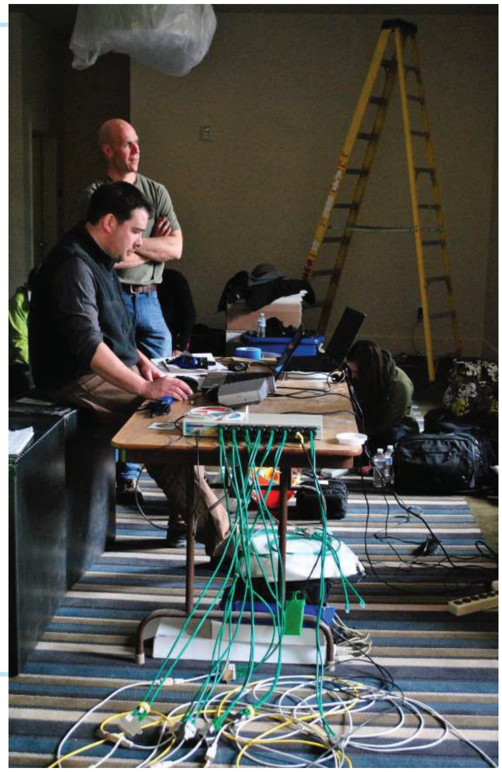
What sort of results do we get?

Table 2: Results of the Airtightness Measurements

	Tower 3	Tower 2	Tower 1
q_{50} depressurization	52,700 m³/h	75,970 m³/h	69,937 m³/h
q_{50} pressurization	66,800 m³/h	75,760 m³/h	69,222 m³/h
q_{50} average	**59,750 m³/h**	**75,865 m³/h**	**69,580 m³/h**
n_{50} air change rate	**0.78 h^{-1}**	**1.10 h^{-1}**	**0.98 h^{-1}**
q_{E50} air permeability	3.8 m³/hm²	4.2 m³/hm²	4.3m³/hm²

Example #2 ASHRAE RP 1478

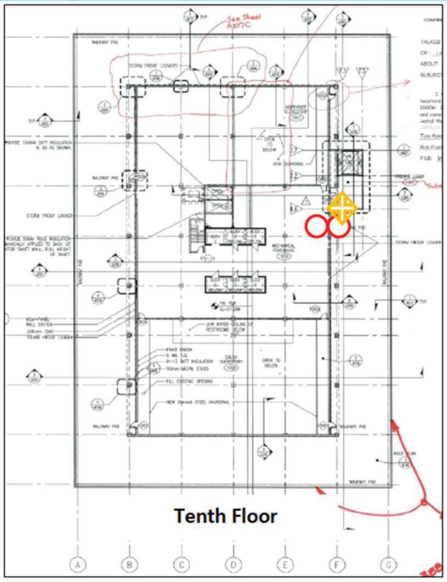


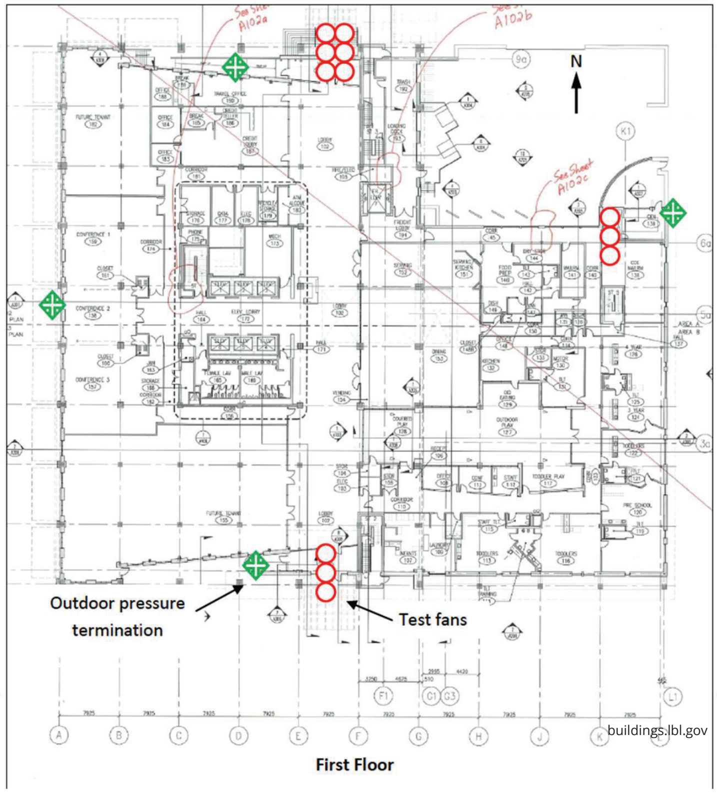


Building Types

- 16 buildings
- 4 to 14 stories
- 7,000 to 24,000 m^2
- Offices, university buildings, public buildings, food and retail
- Use modified ASTM E779 using multiple fans

Building Complexity a Major Challenge

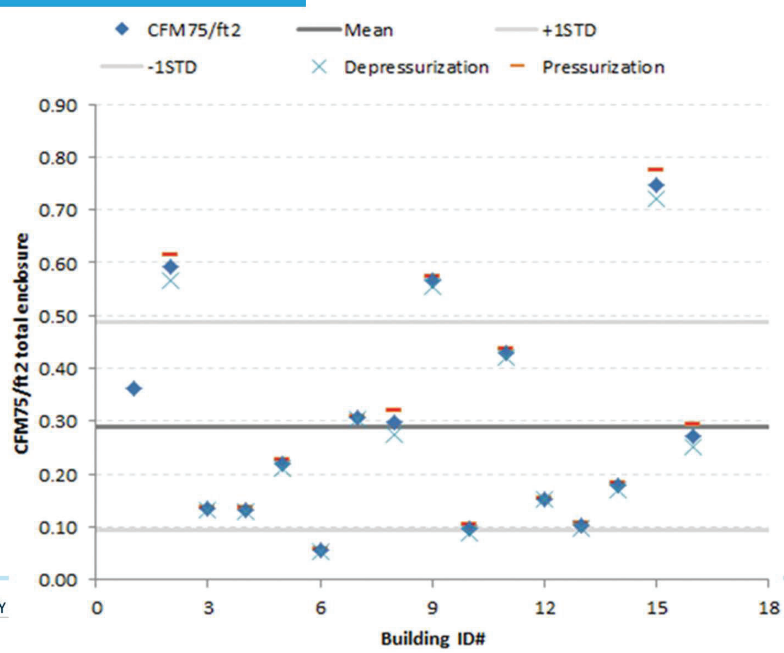




- One building was also pressurized and depressurized using the building HVAC system. How easy is it to control the HVAC system?
- Measuring surface area for normalization not obvious: 2-15% difference between testing team and independent 3rd party
- Enclosure pressures measured on upper floors need not be included in the baseline or test point calculations because they have little effect on the average and significantly increase wind noise
- Questions about what is inside/outside the pressure boundary; e.g., what to do about mechanical rooms?
- Sealing HVAC system openings is very important and attention must be paid to HVAC system dampers – particularly gravity dampers that can open and close at different test pressures.

CO0	Title needed Collin Olson, 2023-05-08T19:31:19.278
CO1	I can talk about that one. We had an interesting event which caused the building to reach + 160 Pa. Collin Olson, 2023-05-08T19:32:04.528
CO2	Uniform INDUCED pressures is ensured if pressure differences measured internally stay near zero. Collin Olson, 2023-05-08T19:33:16.420

Lots of building to building variability



Recommendations

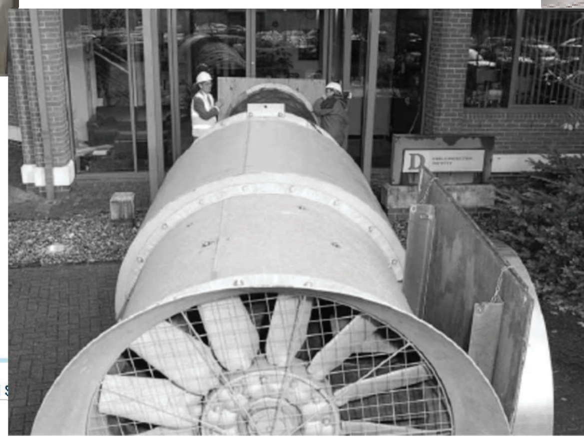
- General
  - Use multiple fans and pressure measurement locations
  - Whole building needs to be positive or negative pressure
  - Test both pressurization and depressurization
  - Need careful envelope and HVAC system preparation
- Austria three towers:
  - A temperature difference from 8 K-10 K should not be exceeded for buildings with a height of up to 125 meters - this corresponds to 1000 mK to 1250 mK. NOTE: ASTM E 779 has a limit of 200 mK
  - While testing, the wind speed should be equal or below 3 on the Beaufort scale.

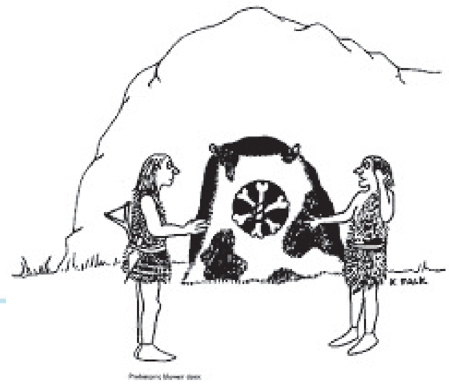
Thanks to…

Stephanie Rolfsmeier, Emanuel Mairinger, Johannes Neubig, Thomas Gayer. 2022. Measuring airtightness of 100-meter high-rise buildings (lessons Learned). Proc. AIVC Conference 2022.

Terry Brennan, Gary Nelson, Wagdy Anis and Collin Olson. 2013. ASHRAE 1478: Measuring Airtightness of Mid- and High-Rise Non-Residential Buildings

Comments and Questions





Contact info: iswalker@lbl.gov

BUILDING TECHNOLOGY & URBAN S
Energy Technologies Area

Measurement for Exterior Wall Airtightness of High-Rise Buildings Using Stack Effect/Individual Air Conditioning and Outdoor Air Entering through Entrance Doors

19 May 2023

Yuichi Takemasa, Kajima Technical Research Institute
Shin Hayakawa, Hayakawa Building Environment Laboratory

KaTRI KAJIMA TECHNICAL RESEARCH INSTITUTE

Contents of Presentation

1. Backgrounds and objectives
2. Simple test method of airtightness using buoyancy caused by the stack effect in a high-rise building
3. Guideline for amount of air leakage at exterior walls made by Architectural Institute of Japan (AIJ)
4. Method to measure the airtightness of the exterior walls using individual air-conditioning systems
5. Measurements in a high-rise building for outdoor air volumes and heating loads through entrance doors in the winter
6. Conclusions

1. Backgrounds and objectives

Backgrounds and Objectives (1)

- A simple test method of airtightness that uses buoyancy caused by stack effect in a high-rise building was developed in 1980s in Japan.
- When doors are opened near the ground floor or the rooftop, it is the same as pressurizing or depressurizing the building with a blower.
- The amount of airflow in and out of an open door or window at this time corresponds to the amount of air supplied and exhausted by the blower.
- Based on these results, the equations for the inflow and outflow volumes at the exterior wall can be formulated to estimate the airtightness of the exterior walls.
- Through the activities of Technical Committee of AIJ, we calculated the amount of air leakage at the exterior walls of 3 model buildings (low-rise, middle-rise, and high-rise buildings) and developed equations that can manually calculate air infiltration rates.

Backgrounds and Objectives (2)

- We also developed a method to measure the airtightness of the exterior walls on a reference floor using individual air-conditioning systems for each floor, which began to be widely used in 2000s.
- This method is introduced and measurement results are discussed in this presentation.
- We also report measurement results for outdoor air volumes entering through entrance doors and resulting heating loads in a high-rise building in winter, considering large impacts of stack effect.

2. Simple test method of airtightness using buoyancy caused by the stack effect in a high-rise building

Test Method of Airtightness using Buoyancy by Stack Effect

Developed new method to measure wall airtightness using stack effect

- Generate 3 equations for 3 conditions by changing the opening status of doors/windows on top and ground floors.
- Airtightness of exterior walls on top floor (αA_R), standard floors (αA_T), and ground floor (αA_G) are calculated by solving the 3 equations. Here, αA stands for "equivalent opening area (cm^2/m^2)".
- Airtightness of exterior walls for 3 buildings were measured.

$$Q_i = (\alpha A)_G \sqrt{2g\gamma_o|\Delta P_G|} + \sum_{j=2}^{M-1} (\alpha A)_{T\text{-}j}\sqrt{2g\gamma_o|\Delta P_j|}$$

$$Q_o = \sum_{j=M}^{N} (\alpha A)_{T\text{-}j}\sqrt{2g\gamma_i|\Delta P_j|} + (\alpha A)_R\sqrt{2g\gamma_i|\Delta P_R|}$$

Since the values in the root mark, denoted by K_G, K_j, and K_R can be obtained as measurement results, and $Q_i = Q_o$ can be assumed, the above-mentioned equations will be

$$K_G\,(\alpha A)_G + \sum_{j=2}^{N} K_j\,(\alpha A)_{T\text{-}j} - K_R\,(\alpha A)_R = 0 \qquad (1)$$

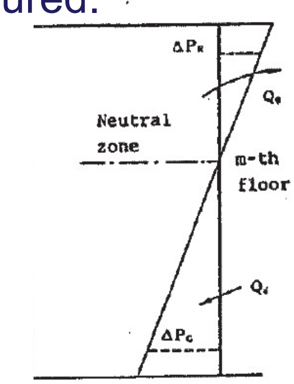


FIG. 2—Ordinary state.

Outline of Building A

- Middle-rise Office building of 9 floors with RC structure.

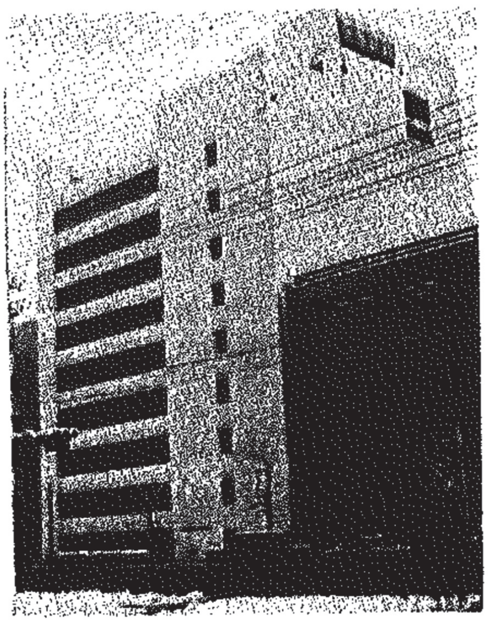


FIG. 5—*External appearance (Building A).*

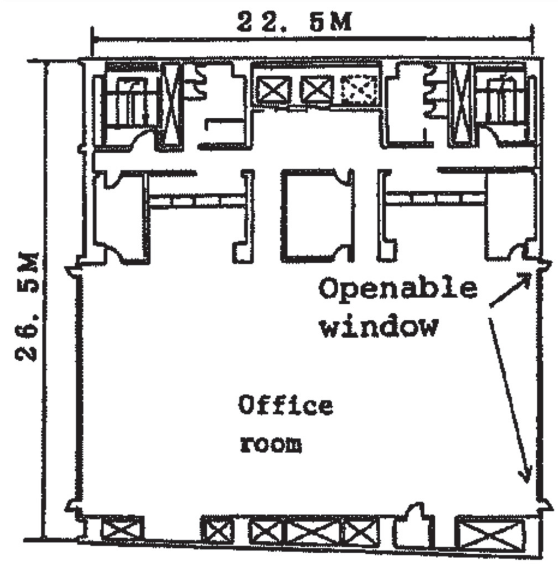


FIG. 6—*Plan of typical floor.*

Measurement Results for Building A

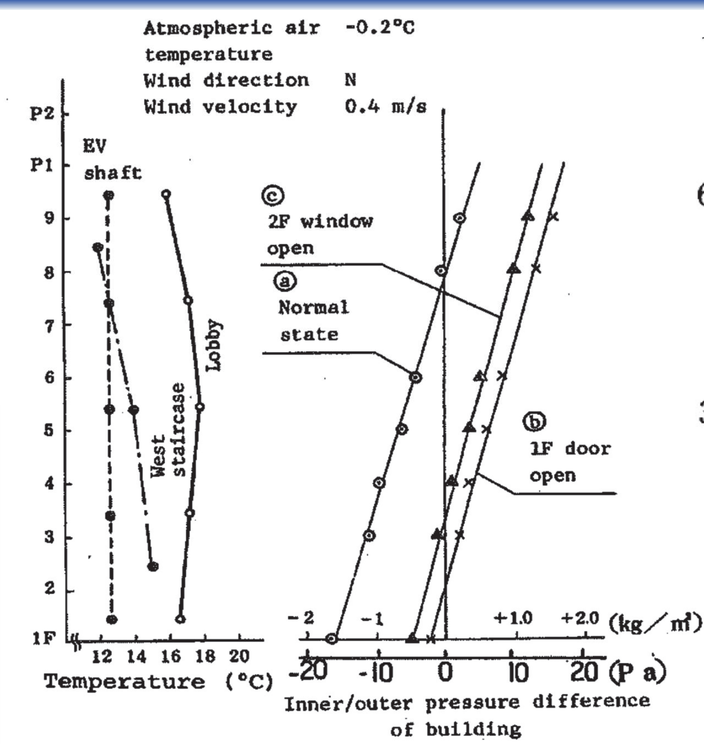


FIG. 7—*Measured results.*

$$6.37(\alpha A)_G + 20.20(\alpha A)_T - 3.66(\alpha A)_R = 0 \quad \cdots\cdots (4)$$

$$32.30(\alpha A)_T - 6.53(\alpha A)_R = 2.33 \quad \cdots\cdots (5)$$

$$3.26(\alpha A)_G - 21.64(\alpha A)_T - 6.09(\alpha A)_R = -1.83 \quad \cdots\cdots (6)$$

- αA_T can be calculated by these equations.

Process of Calculating Airtightness of Building A

TABLE 1—*Process of calculating coefficient K of Eq 4.*

Floor No.	Height*1 (m)	ΔP*2 (kg/m²)	γ*3 (kg/m³)	$Sign(\Delta P)\sqrt{2g\gamma\lvert\Delta P\rvert}$ *4	K
R	31.6	(0.56)*5		3.662	K_R=3.66
9	28.2	0.32	1.222	2.771	
8	24.8	0.05		1.097	
7	21.4	(-0.14)		-1.884	
6	18.0	-0.33		-2.891	K_T=-20.20
5	14.6	-0.53	1.293	-3.667	
4	11.2	-0.88		-4.725	
3	7.8	-1.03		-5.113	
2	4.4	(-1.32)		-5.788	
1	1.0	-1.6		-6.368	K_G=-6.37

*1 Height from the ground level to 1 m above the floor
*2 External wall pressure difference (inside vs. outside)
*3 Specific weight of air When ΔP>0: Indoor air (15.7°C)
When ΔP<0: Outside air (0.1°C)
*4 Sign (ΔP) = (1, ΔP>0)
(-1, ΔP<0)
*5 Figure in parentheses shows estimated value and others are measured values.

Outline of Building B

- High-rise office building of 17 floors with steel structure and precast concrete curtain walls.

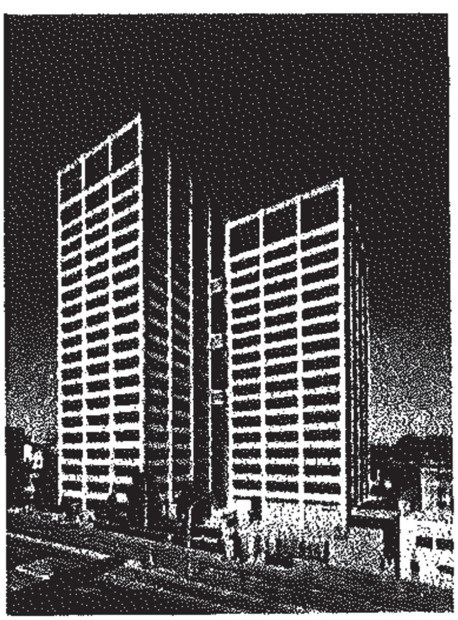


FIG. 8—*External appearance (the building on the right).*

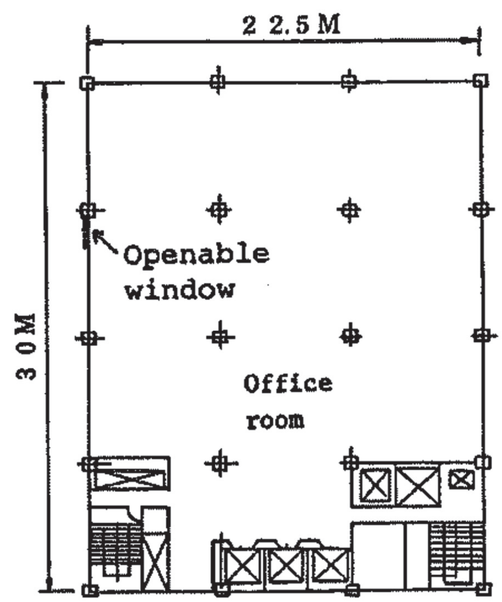


FIG. 9—*Typical floor of Building B.*

Measurement Results for Building B

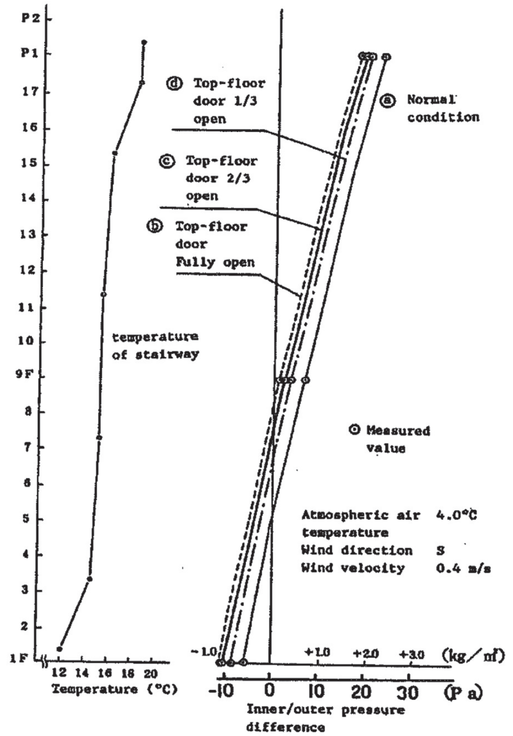


FIG. 10—*Measured result of Building B.*

$$5.27(\alpha A)_G - 12.24(\alpha A)_T = 4.00 \cdots\cdots (7)$$

$$5.07(\alpha A)_G - 19.66(\alpha A)_T = 2.82 \cdots\cdots (8)$$

$$4.69(\alpha A)_G - 28.26(\alpha A)_T = 1.85 \cdots\cdots (9)$$

- αA_T can be calculated by these equations.

Outline of Building C

- Super-high-rise office building of 55 floors with steel structure and metal curtain walls.

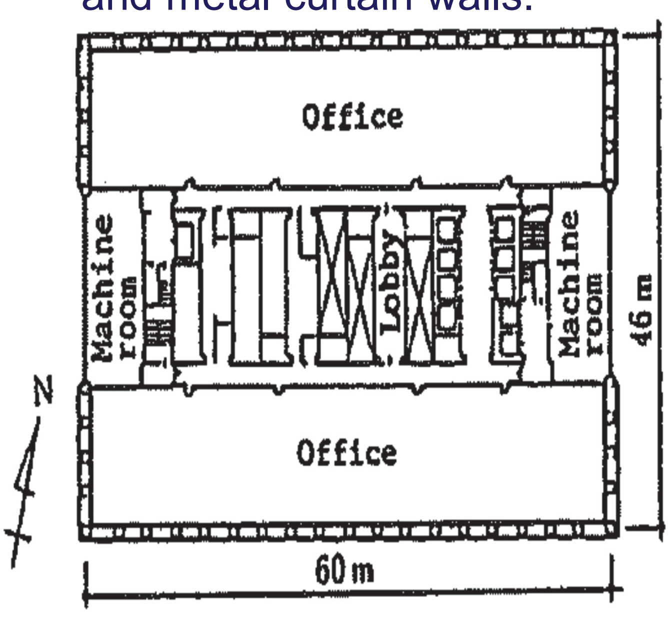


FIG. 11—*Plan of typical floor of Building C.*

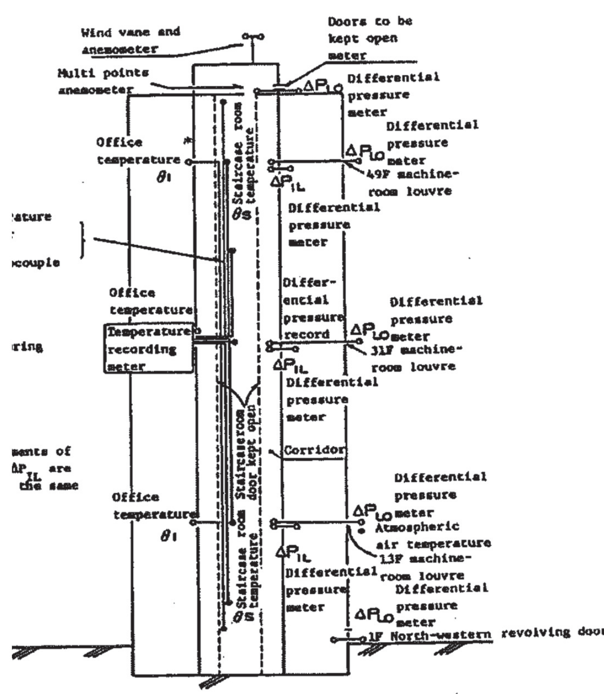


FIG. 12—*Measuring instrument layout diagram of Building C.*

Measurement Results for Building C

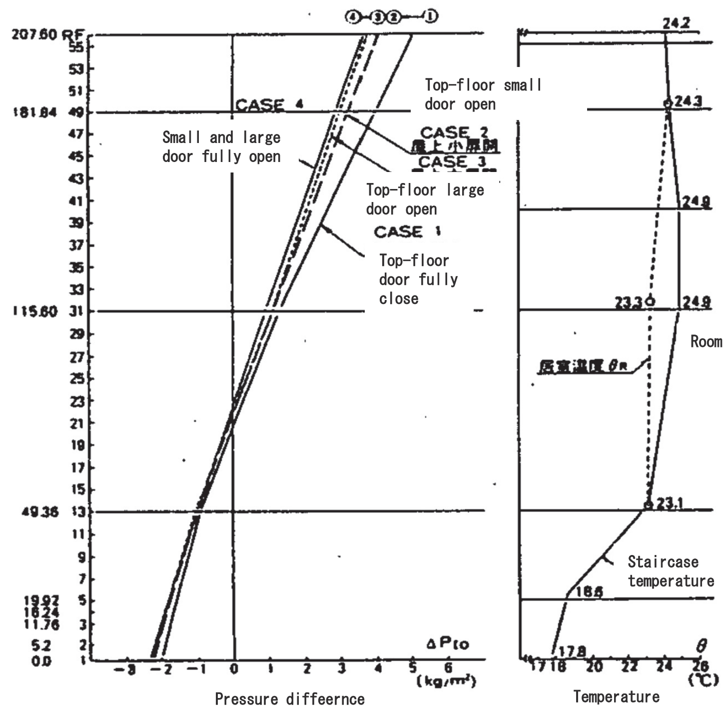


FIG.-21 Pressure fluctuations due to top-floor entrance/exit door kept open

CASE 2 より

$$14.55(\alpha A)_C - 127.16(\alpha A)_T - 9.75(\alpha A)_R = 13.22 \quad \cdots\cdots(12)$$

CASE 3 より

$$14.57(\alpha A)_C - 118.91(\alpha A)_T - 9.36(\alpha A)_R = 15.63 \quad \cdots\cdots(13)$$

CASE 4 より

$$14.77(\alpha A)_C - 107.59(\alpha A)_T - 9.16(\alpha A)_R = 18.54 \quad \cdots\cdots(14)$$

- αA_T can be calculated by these equations.

Measurement Results for Airtightness of Exterior Walls

- Based on the measurements, airtightness of exterior walls are summarized as below.

Measured Airtightness of Exterior Walls

Building type	Equivalent Opening Area	
8 Floors, RC Structure, Aluminum Sash, Sliding Window	0.5㎠／㎡	Tight
RC Structure, 9 Floors, Steel Sash, Fixed Window	0.8㎠／㎡	Tight
Steel Structure, 55 Floors, Metal Curtain Wall, Fixed Window	1.5㎠／㎡	Average
Steel Structure, 17 Floors, Precast Concrete, Steel Sash, Fixed Window	2.8㎠／㎡	Loose

Categories of Airtightness of Exterior Walls

- Based on the measurements, airtightness of exterior walls are categorized as below.

Categories of Airtightness of Exterior Walls

Cast-in-place RC	·· ··· ··· Tight 、Average
Metal Curtain Wall	··· ··· ··· Average 、Loose
Precast Concrete Curtain Wall	··· Loose

Tight: Around 0.5 cm_2/m_2 or smaller

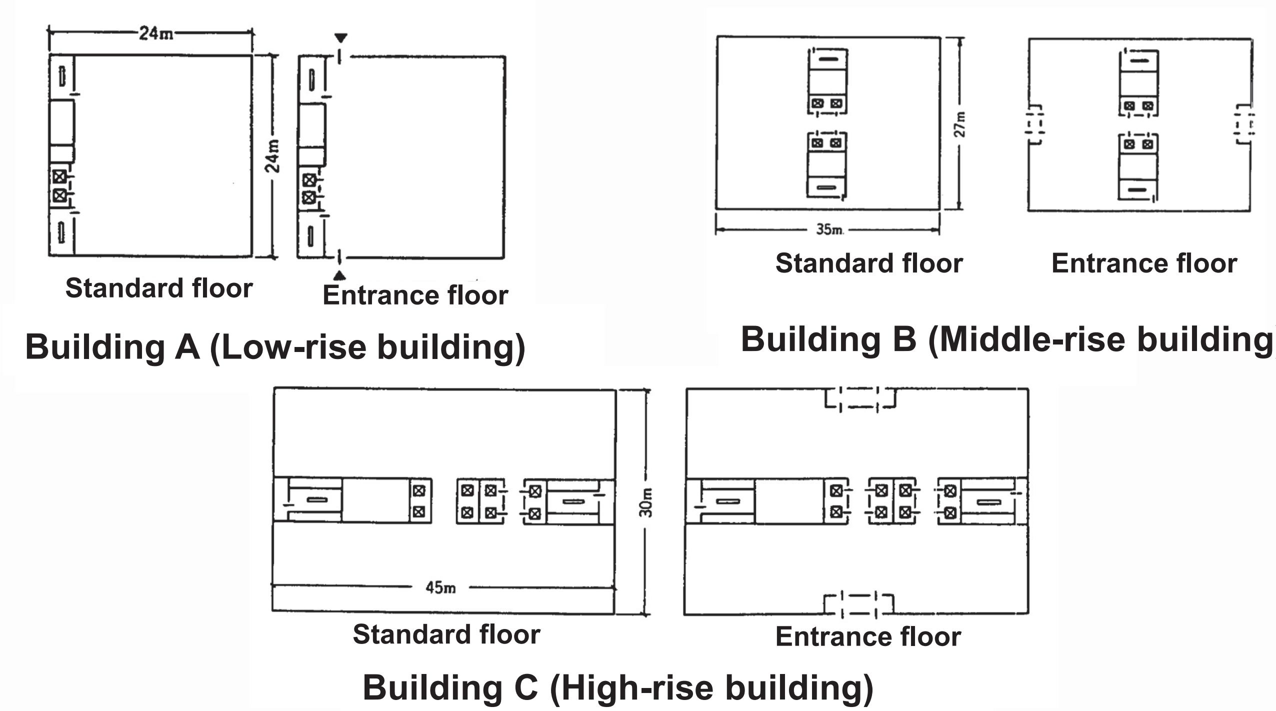
Average: Around 1.0 cm_2/m_2

Loose: Around 2.0 cm_2/m_2 or larger

3. Guideline for amount of air leakage at exterior walls made by Architectural Institute of Japan (AIJ)

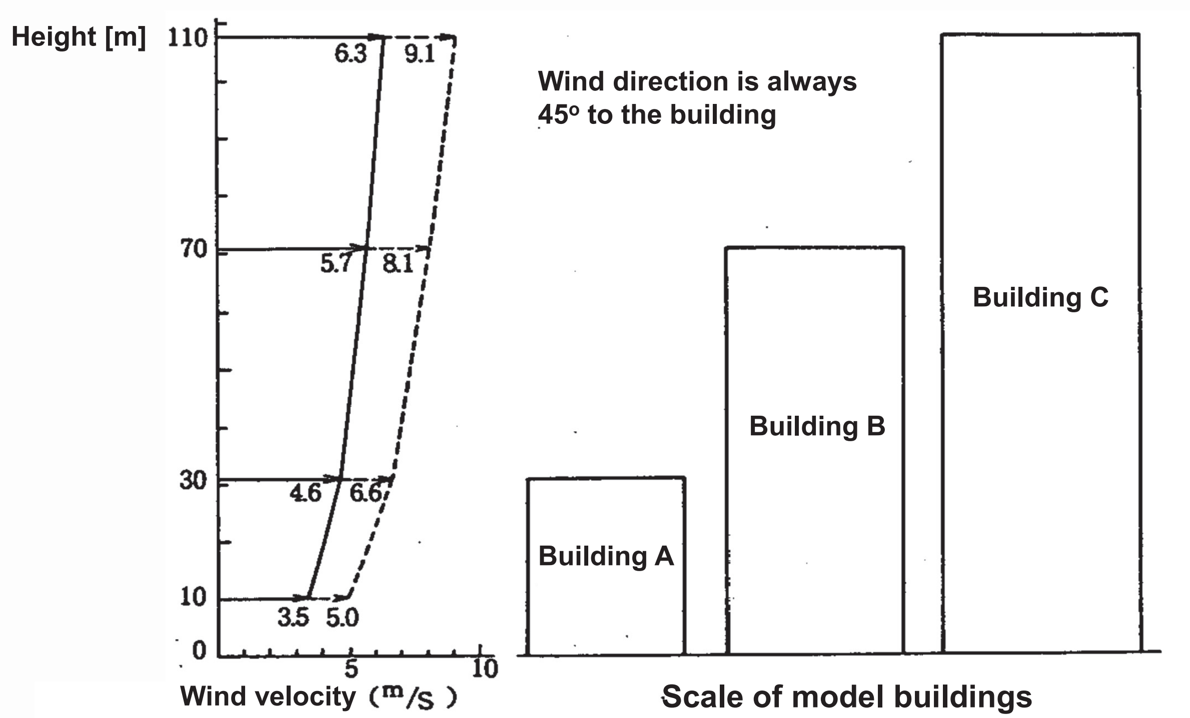
Plans for Model Buildings A, B and C

Calculated amount of air leakage at exterior walls for 3 model buildings



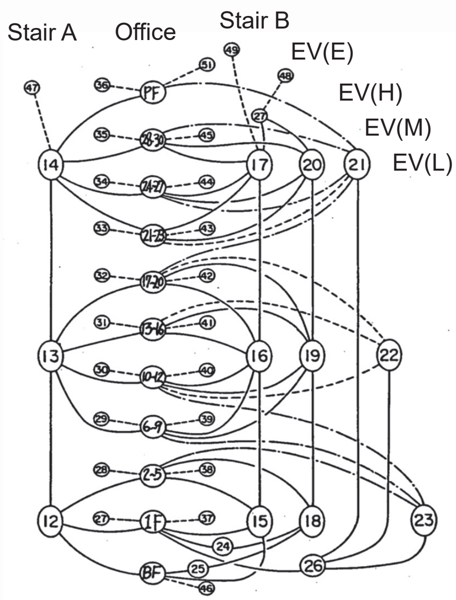
Wind Velocity Setting for Simulations

- Vertical wind profile was assumed for 3 model buildings.

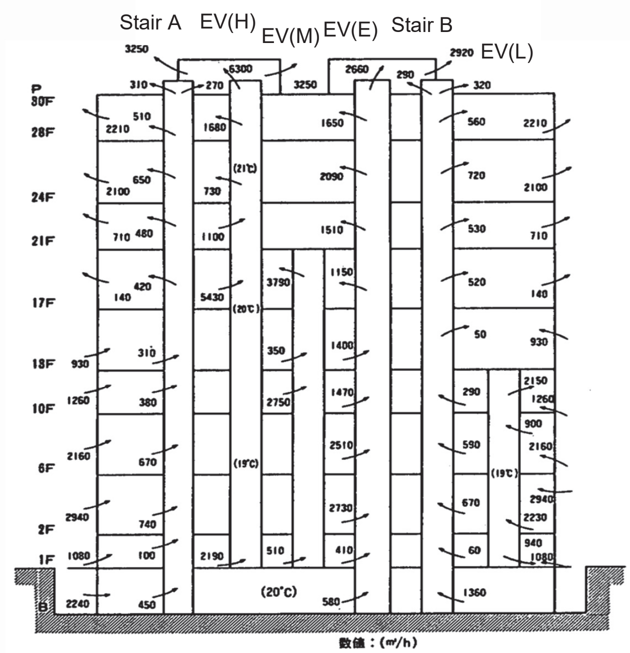


Airflow Network Model for Building C

- Air leakage at exterior walls are calculated using airflow network model.



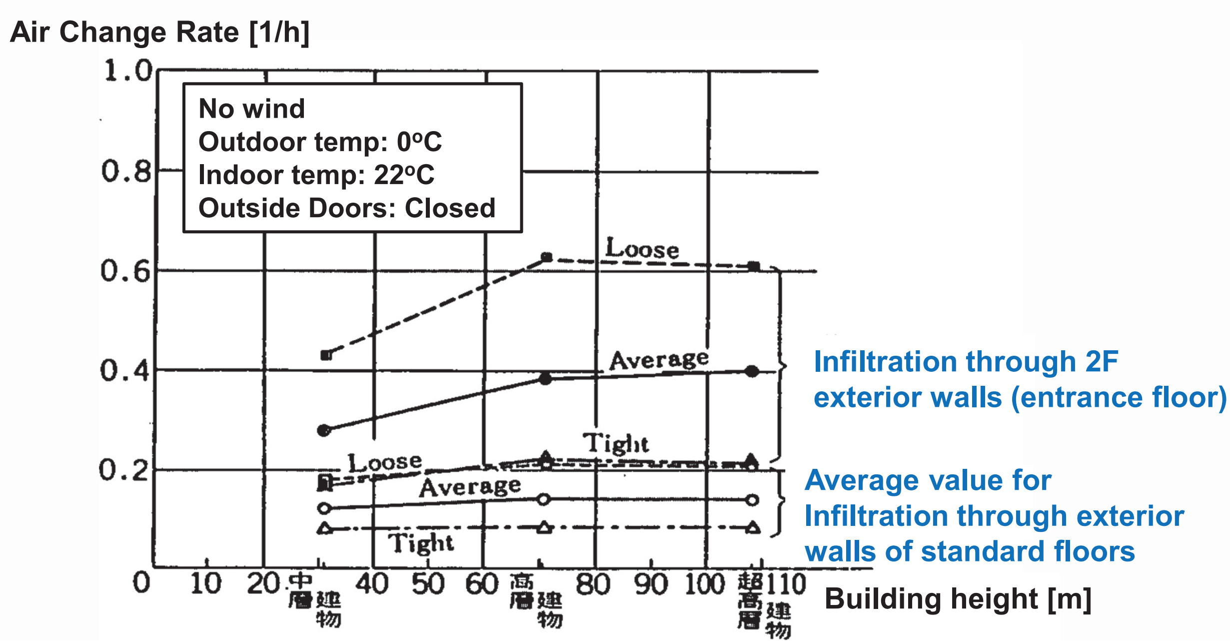
Airflow network model for Building C



Calculated results of air movement in Building C when there is no wind

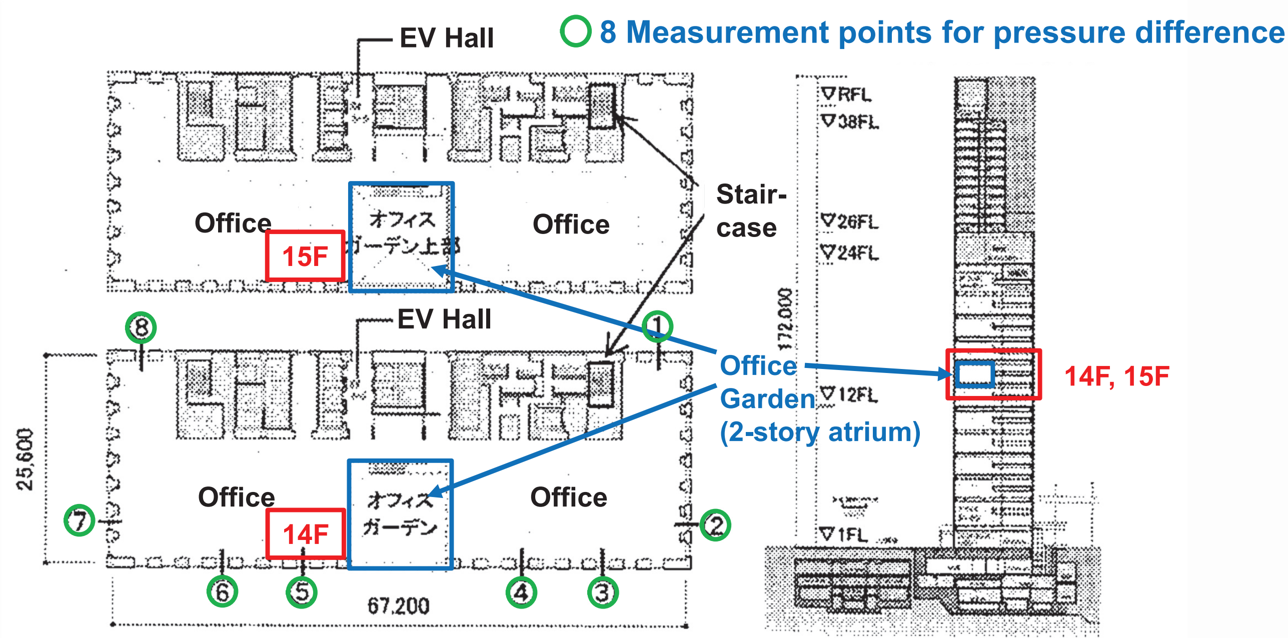
Air Change Rate by Infiltration through Exterior Walls of Standard Floors

- Infiltration through exterior walls for standard floors was evaluated by simulation.
- Results were summarized as Guideline for Calculating Cooling/Heating Loads of Society of Heating, Air-conditioning and Sanitary Engineers of Japan (SHASE).



4. Method to measure the airtightness of the exterior walls using individual air-conditioning systems

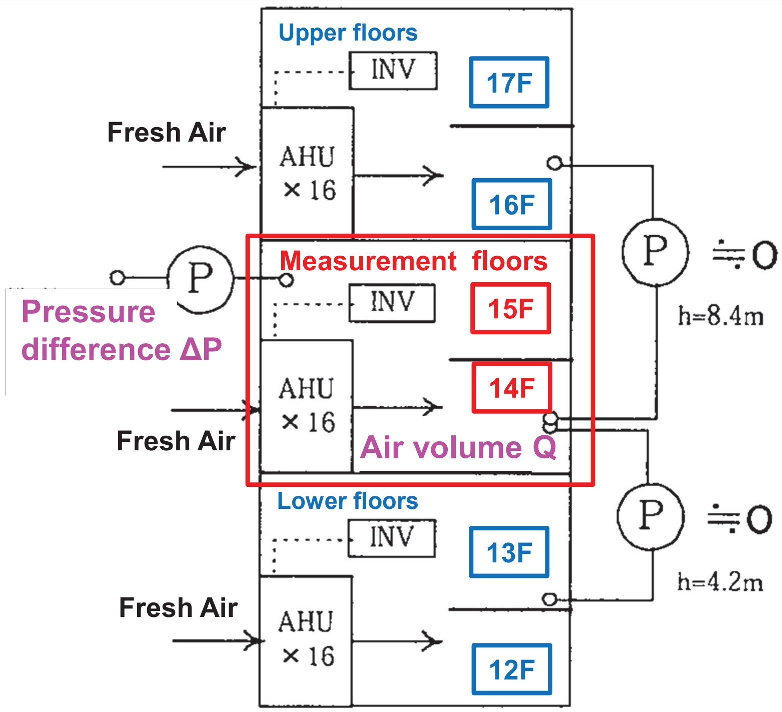
Outline of Measured High-rise Building



Plan of the standard floors (2 stories)

Section of the building

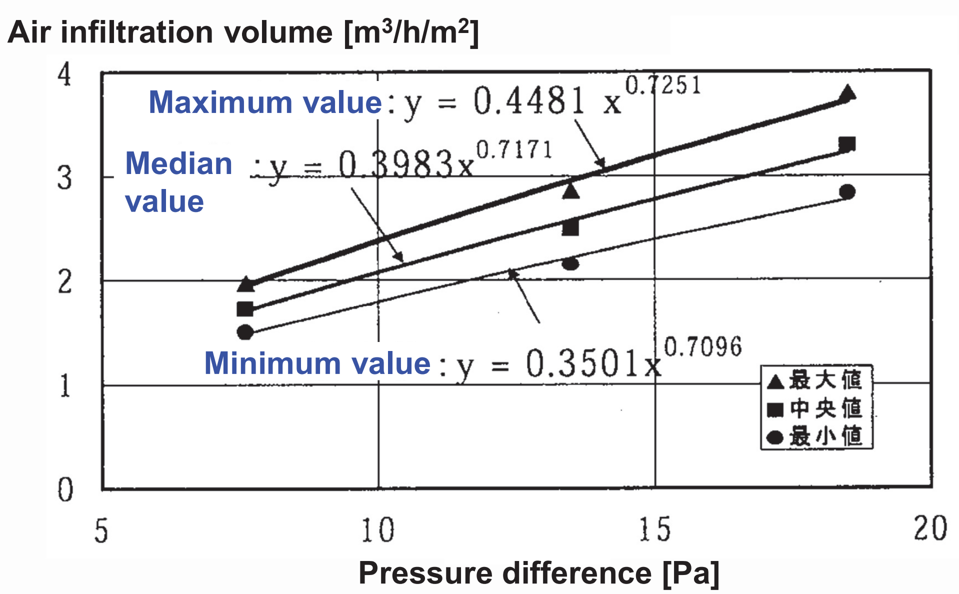
Outline of Pressurization System



- Pressurized air volume Q and pressure difference ΔP were measured by changing Q by controlling AHUs.
- Pressure difference between measurement floors and upper/lower floors were controlled to be nearly zero.

Pressure Difference vs. Air Infiltration Volume

- Pressure difference vs. air infiltration volume was clarified by this measurement.
- The results are equivalent to the airtightness of exterior walls of 1.25 to 1.67 cm^2/m^2 (“Average”).

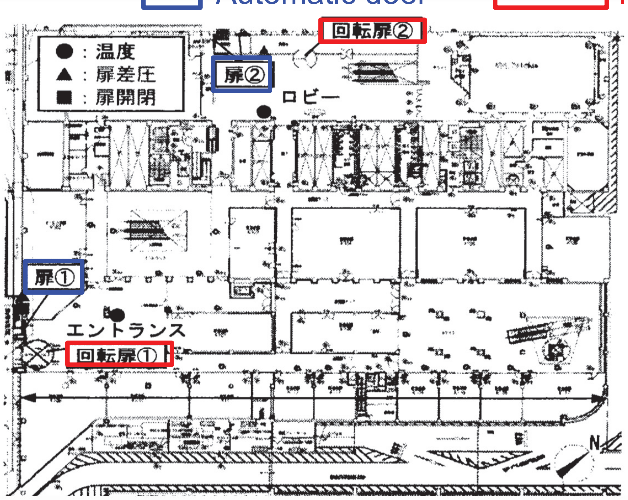


5. Measurements in a high-rise building for outdoor air volumes and heating loads through entrance doors in the winter

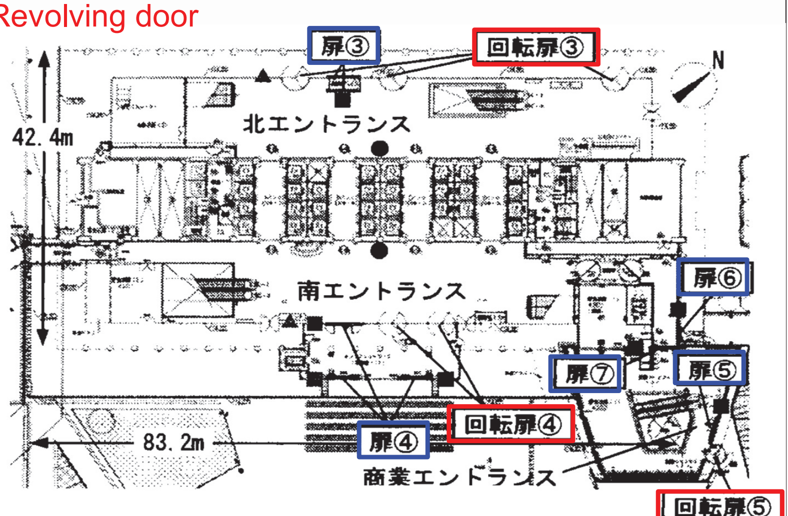
Outline of the Measurement

- Outdoor air volumes and heating loads through entrance doors were measured in a high-rise building in the winter (37 stories and 147m high).
- We compare the case when both automatic and revolving doors were normally operated and the case when opening doors were always used.
- Opening status of doors, pressure differences at entrance doors were measured.

Automatic door　Revolving door

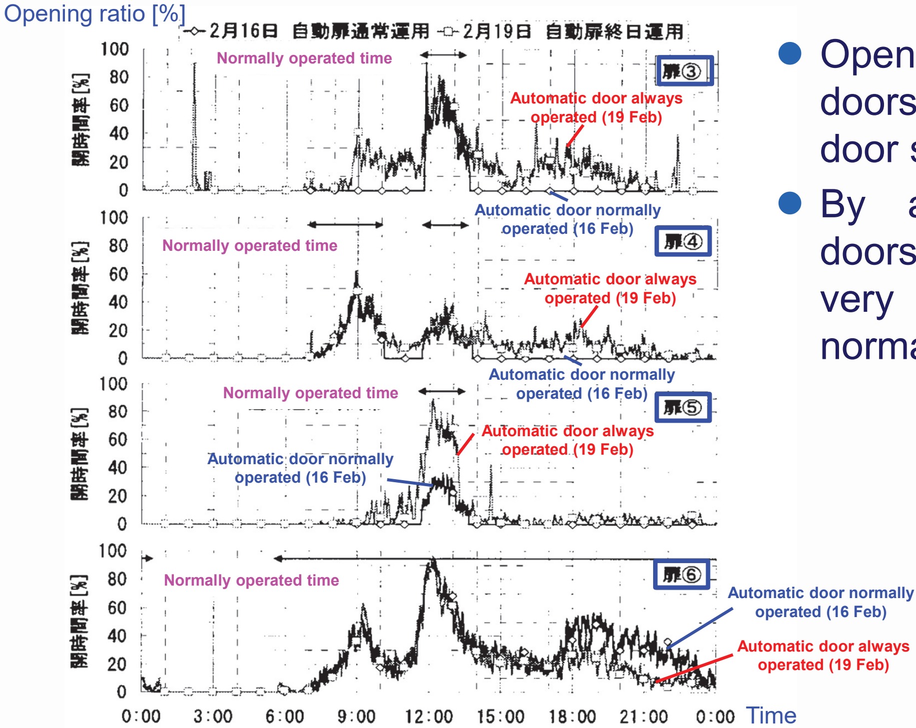


1F Plan



2F Plan

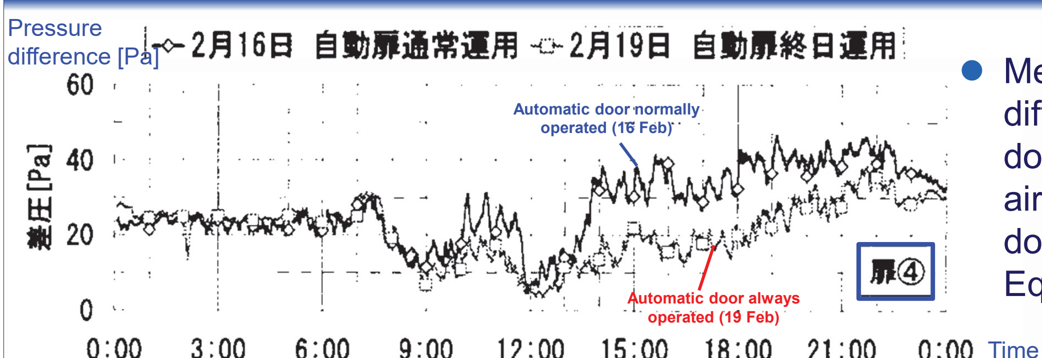
Measured Results for Opening Ratios for Entrance Doors



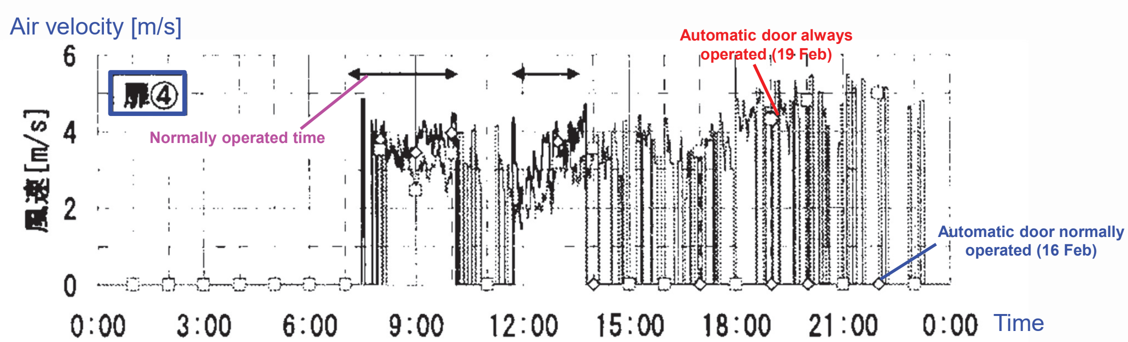
Measured Opening Ratio for Entrance Doors

- Opening ratios for entrance doors were measured using door sensors.
- By always using automatic doors, opening ratios became very large compared to the normally operated case.

Measured Pressure Difference and Air Velocity at Entrance Doors



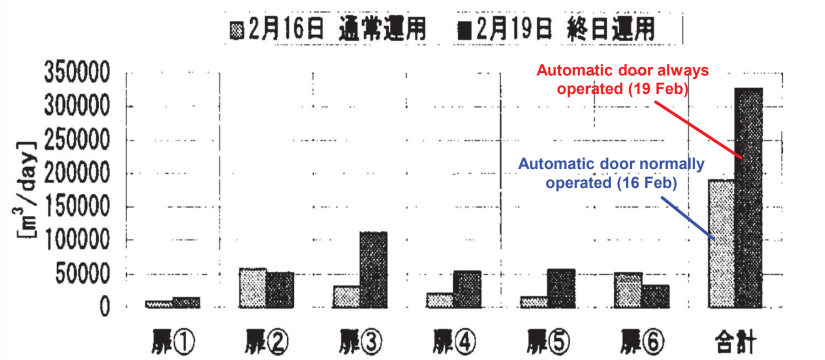
Measured Pressure Difference at Entrance Door No. 4



Estimated Air Velocity at Entrance Door No. 4

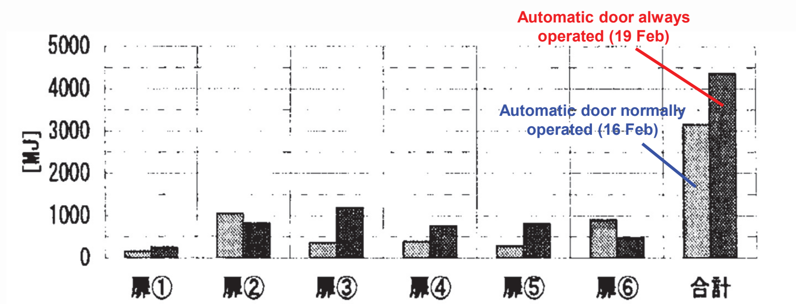
- Measured pressure difference at entrance doors can be converted to air velocity at the entrance doors using Bernoulli Equation.

Accumulated Daily Outdoor Air Volume & Heating Load through Entrance Doors



Accumulated daily outdoor air volume through entrance doors

- Accumulated outdoor air volume through entrance doors became large when automatic doors were used for a long time.



Accumulated daily heating load through entrance doors

- Accumulated heating loads became also large when automatic doors were used for a long time.
- Revolving doors are effective to reduce heating loads in the winter.

6. Conclusions

Conclusions

- A measurement method of airtightness that uses buoyancy caused by stack effect in a high-rise building was introduced.
- Based on the measurements, airtightness of different types of exterior walls were analyzed and categorized.
- We calculated the amount of air leakage at the exterior walls of 3 model buildings (low-rise, middle-rise and high-rise buildings). Results were summarized as Guideline for Calculating Cooling/Heating Loads of SHASE.
- Another method to measure the airtightness of exterior walls using individual air-conditioning systems for each floor was also introduced and measurement results were discussed.
- Considering the large impacts of stack effect, measurement results for outdoor air volumes entering through entrance doors and resulting heating loads in a high-rise building in the winter were also discussed.
- Air volume infiltrated through entrance doors in high-rise buildings is very large especially in winter and it's important to make the lower part of the building airtight to reduce heating loads caused by air entering through entrance doors.

References (1)

1. HAYAKAWA, S. and S. TOGARI. 1990. "Simple Test Method for Evaluating Exterior Wall Airtightness of Tall Office Buildings" Air Change Rate and Airtightness in Buildings (STP: 1067), American Society of Testing and Materials (ASTM), 231-245.
2. HAYAKAWA, S. and S. TOGARI. 1988. "Study on the Stack Effect of Tall Office Buildings (Part 1) Pressure Distribution in Tall Buildings Caused by the Stack Effect and Solutions of Troublesome Problems" Journal of Architecture Planning, Architectural Institute of Japan (AIJ),Vol. 387, pp.42-52 (In Japanese).
3. HAYAKAWA, S. and S. TOGARI. 1989. "Study on the Stack Effect of Tall Office Buildings (Part 2) Airtightness of Main Doors and Exterior Walls" Journal of Architecture Planning, Architectural Institute of Japan (AIJ),Vol. 402, pp.9-18 (In Japanese).
4. HAYAKAWA, S. and S. TOGARI. 1990. "Study on the Stack Effect of Tall Office Buildings (Part 3) The Evaluation of Infiltration Air Rates Caused by Stack Effect and Wind for Tall Buildings" Journal of Architecture Planning, Architectural Institute of Japan (AIJ),Vol. 407, pp.47-56 (In Japanese).

References (2)

5. MIURA, K., M. HIRAOKA, and Y. TAKEMASA. 2003. “A Study of Air-Conditioning System utilizing Natural Ventilation by Wind Pressure in a High-rise Building (Part 2) Measurement of Airtightness of Exterior Walls before Completing Construction” Proceedings of Annual Meeting of Architectural Institute of Japan (AIJ), 2003, pp.1097-1098 (In Japanese).
6. TAKEMASA, Y., M. KATOH, Y. TAKAHASHI, and Y. USHIKI. 2011. “Field Measurement of Stack Effect in a High-rise Building with Revolving Doors (Part 1) Outline of the Measurement and Thermal Environment at the Entrance” Proceedings of Annual Meeting of Architectural Institute of Japan (AIJ), 2011, pp.735-736 (In Japanese).
7. KATOH, M. and Y. TAKEMASA, Y. TAKAHASHI, and Y. USHIKI. 2011 “Field Measurement of Stack Effect in a High-rise Building with Revolving Doors (Part 2) Usage and Pressure Difference of Doors and Estimation of Air Infiltration Rate and Heat Loss” Proceedings of Annual Meeting of Architectural Institute of Japan (AIJ), 2011, pp.737-738 (In Japanese).

Thank you for your attention!

Airtightness of large buildings in Japan

current situation and a proposal for the future

Takashi Hasegawa & Haruki Hasegawa
Eikan Shoji
t-hasegawa@eikan.co.jp

Introduction

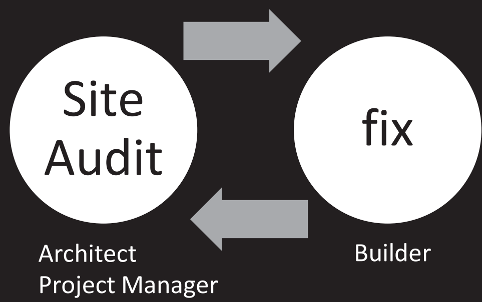
MEIKEN LAMWOOD Corp. Head Office

MEIKEN LAMWOOD Corp. Head Office
AIJ (Architectural Institute of Japan)
Annual Architectural Design Commendation 2022

Reasons of the commendation

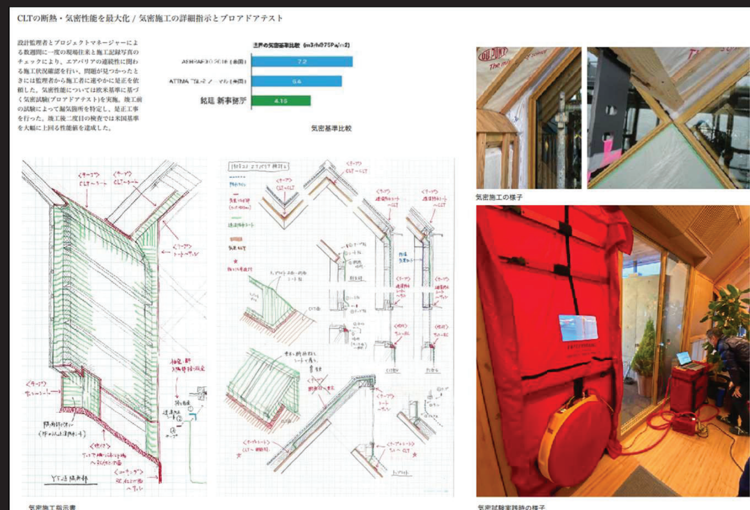
- Shows the company’s core competency using CLT material abundantly.
- Deeply thought both in beauty and function
- Highly airtight and the way to achieve the level

The process might be future model



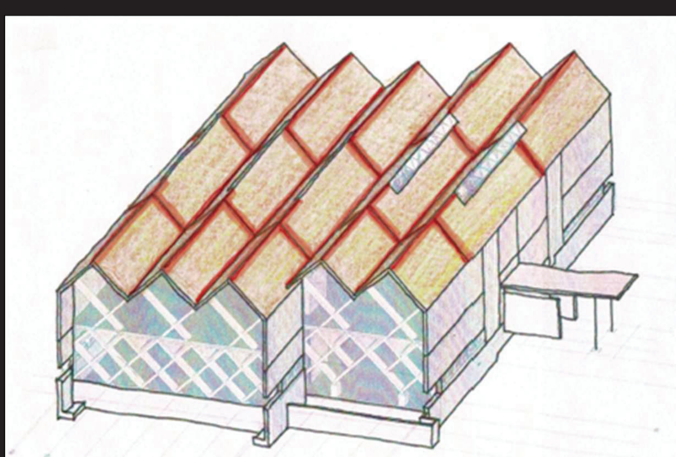
Pen check & Audit

Test


CLTの断熱・気密性能を最大化 / 気密施工の詳細指示とブロアドアテスト

設計監理者とプロジェクトマネージャーによる数週間に一度の現場往来と施工記録写真のチェックにより、エアバリアの連続性に関わる施工状況確認を行い、問題が見つかったときには監理者から施工者に速やかに是正を依頼した。気密性能については欧米基準に基づく気密試験(ブロアドアテスト)を実施。施工前の試験によって漏気箇所を特定し、是正工事を行った。施工後二度目の検査では米国基準を大幅に上回る性能値を達成した。

Our role



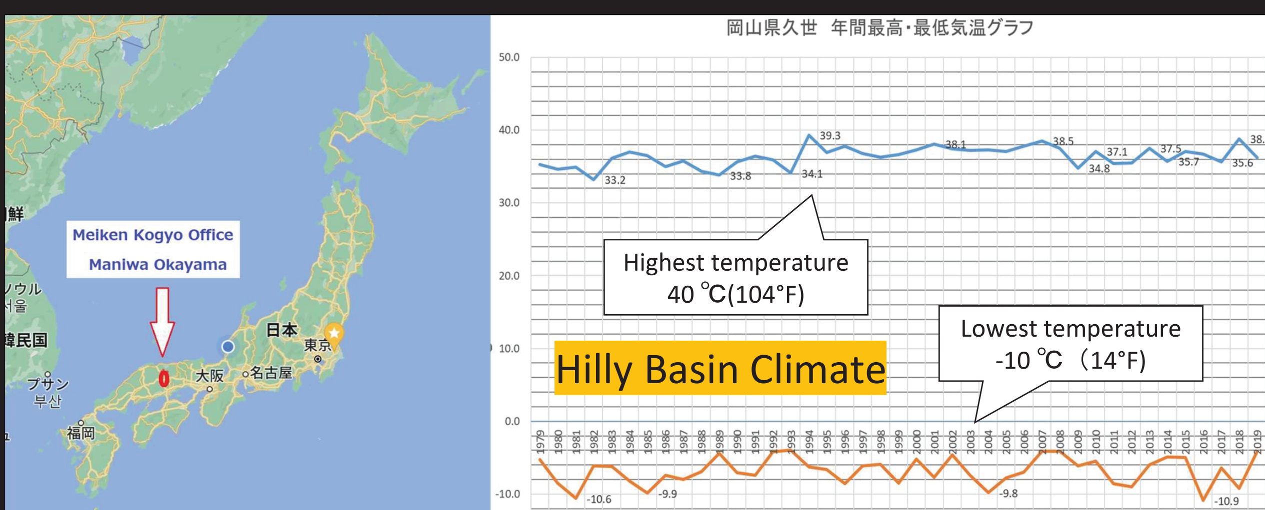
Continuous Air Barrier
main theme of Building Commissioning

Blower Door Test, twice

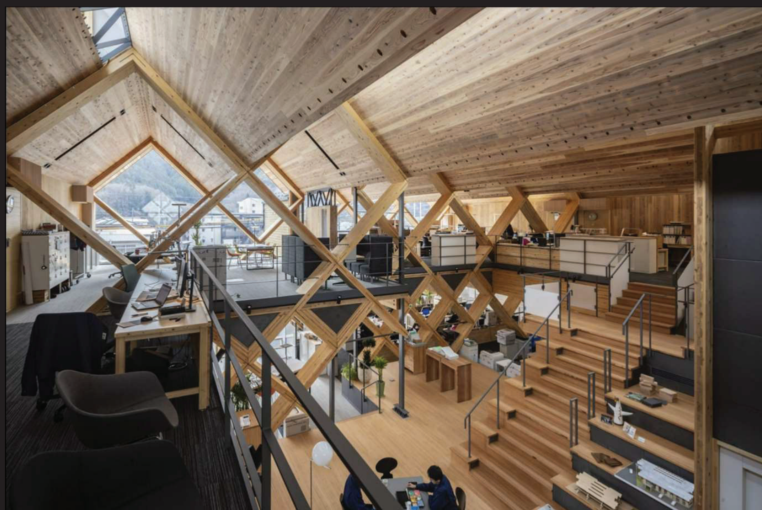
Location and comportments

Meiken Lamwood Corporation Head Office

Location and climate

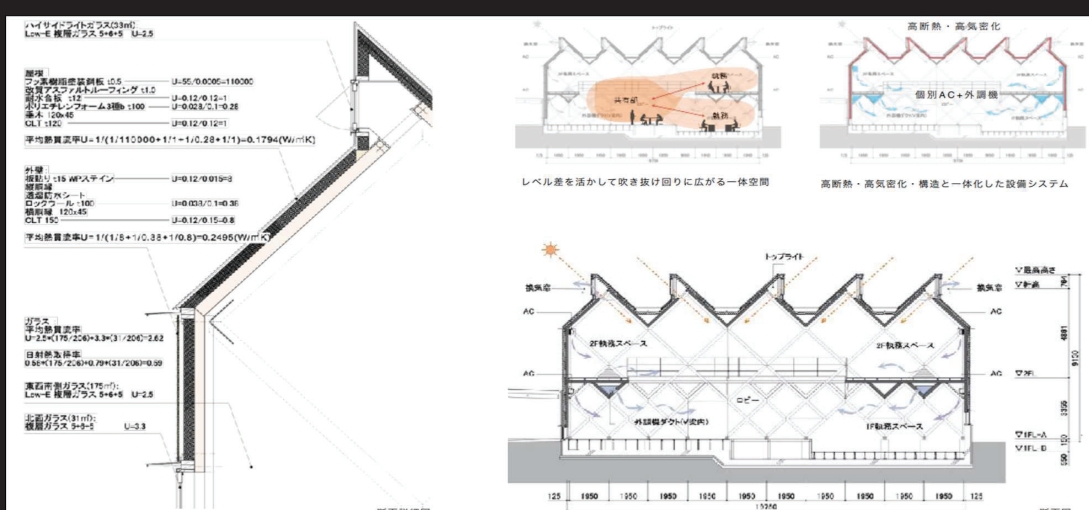


Basic information



- 2-story building forming one large space
- Total floor area: 1,000 m²
- Enclosure area: 2,235 m²
- Volume: 5,428.4 m³ (roughly)

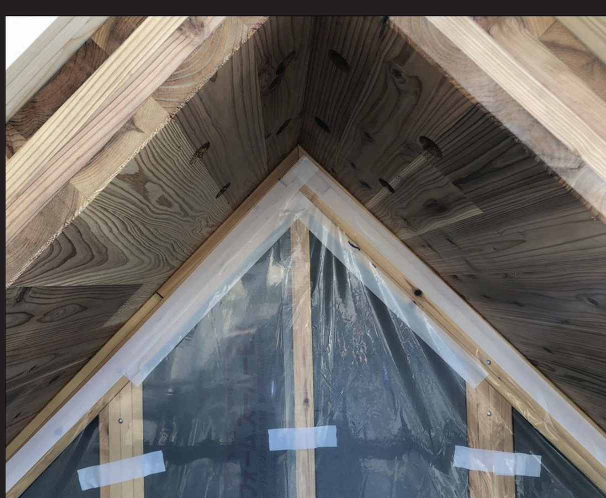
Specification: Roof, Wall, and Base No word "Air Barrier" nor "Continuity"

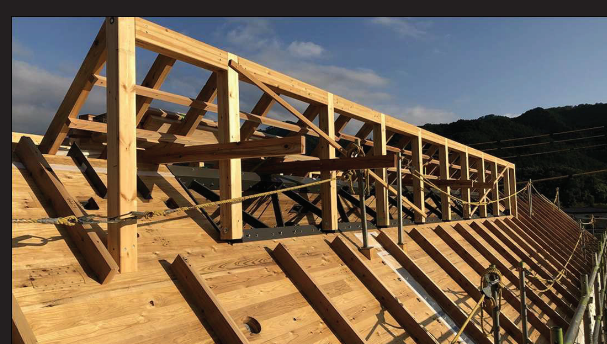


But air barrier materials were well arranged

Tyvek sheet is AB Product

Structure of exterior (vacant insulation)





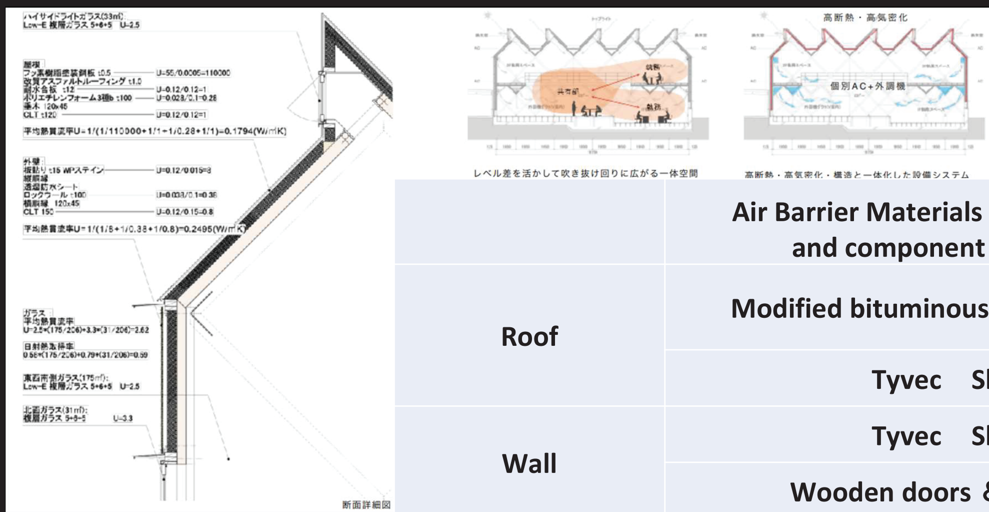
Process to improve air tightness

What was done in this project

Three checks for continuous air barrier

① 2019 May. : Air barrier materials were checked
② 2019 Aug. : Pen check started
③ 2019 Oct. : Intermediate inspection

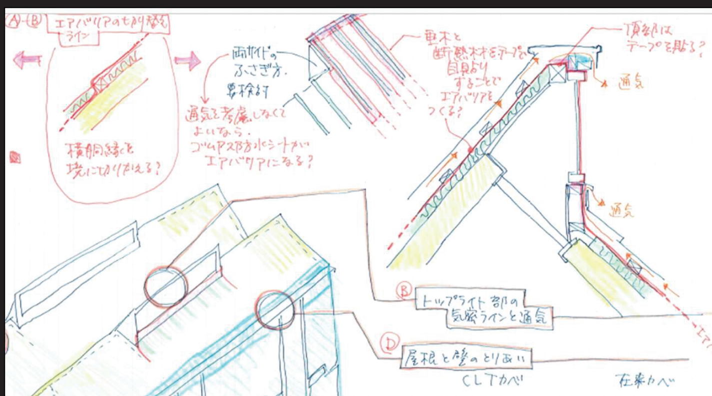
①Material check (2019 May)

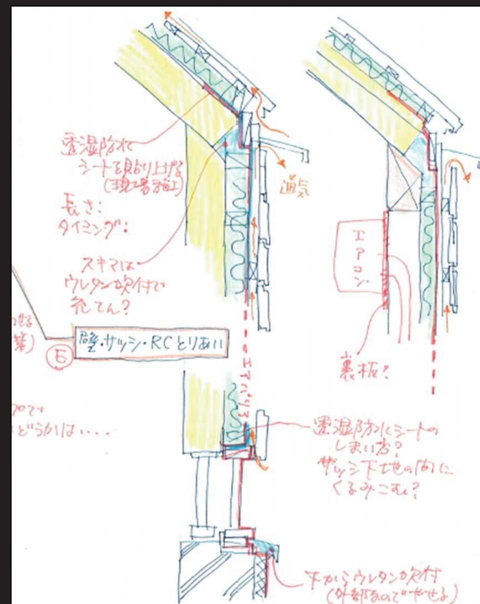


	Air Barrier Materials ,Products, and component
Roof	Modified bituminous roof membrane
	Tyvec　Sheet
Wall	Tyvec　Sheet
	Wooden doors ＆Windows
Base	Cast-in-place concrete

②Pen check (2019 Aug.～) By Architect & Project Manager

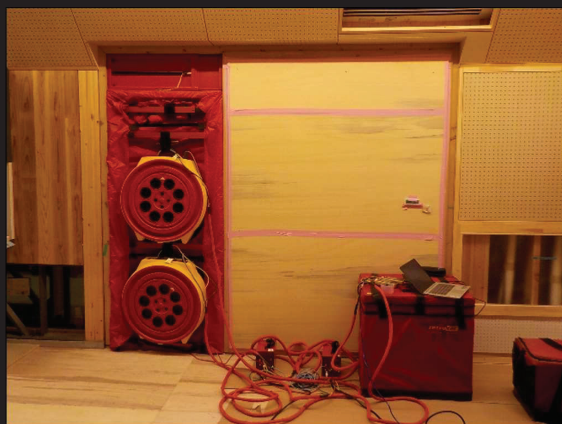
②Pen check (2019 Aug.~)





③Intermediate inspection (2019 Oct.)

1st test (2019 Dec.)

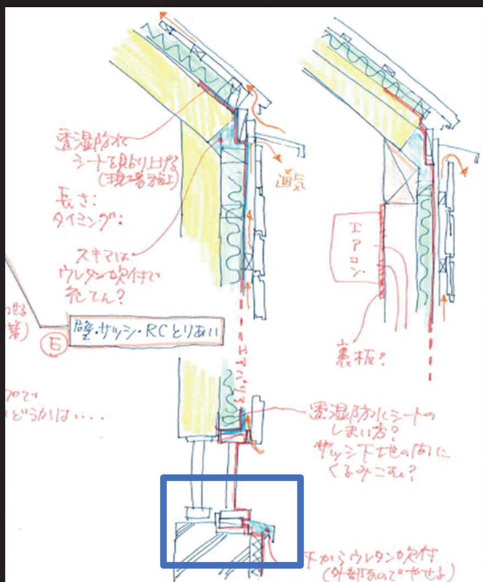


- Measured air tightness:
  5.15 ($m^3/h@75Pa/m^2$)
- Goal : ASHRAE 90.1 requirement
  7.2 ($m^3/h@75Pa/m^2$) or less

⇒PASS

Leakage was found

Leakage was found



Red lines are Air

There was discontinuity
Eyes and hands enable to reach
Another solution preferable

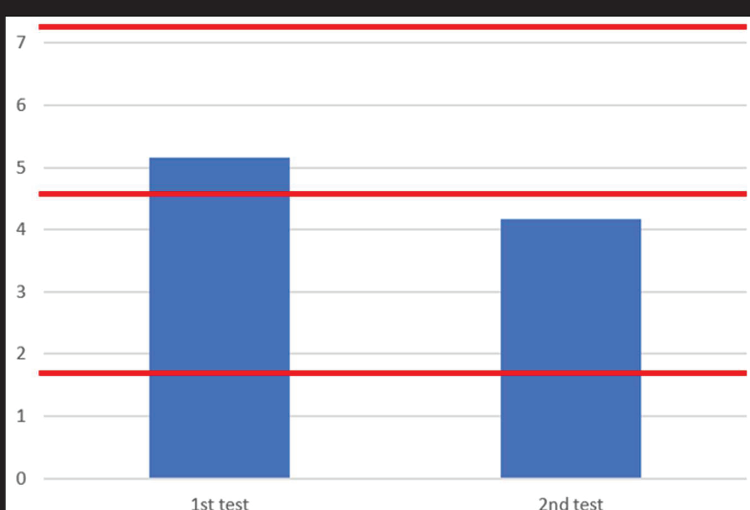
2nd test (2020 Feb.)

- 1st test:
  5.15 ($m^3/h@75Pa/m^2$)
- 2nd test:
  4.16 ($m^3/h@75Pa/m^2$)

⇒19.2% improved

Result

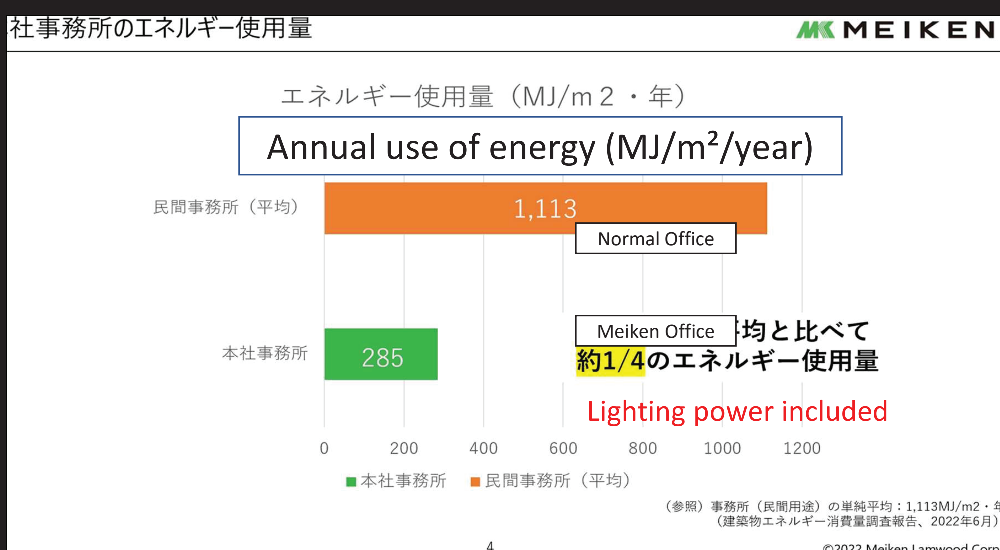
Consideration: standards



- ASHRAE 90.1:
  7.2 $m^3/h/m^2$ 75Pa
- USACE Protocol
  4.572$m^3/h/m^2$ 75Pa
  (0.25CFM/ft^2 0.3in)
- Passive house
  1.78$m^3/h/m^2$ 75Pa
  (0.6ACH50)

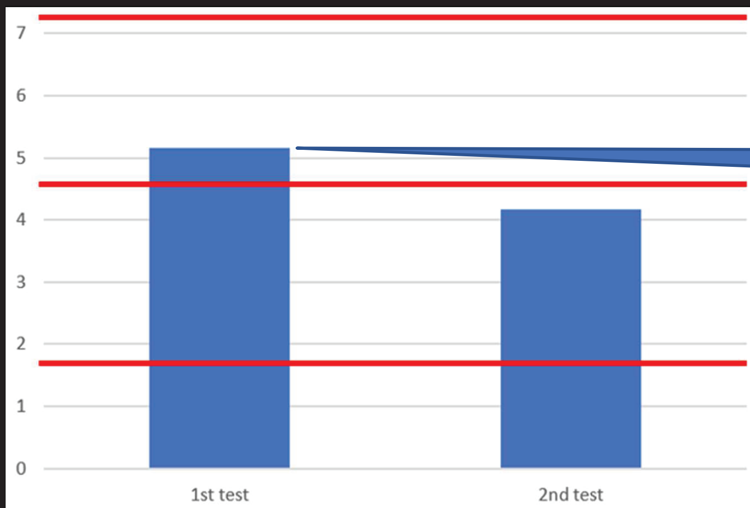
Meiken Lamwood report

Meiken Lamwood report



Steps and improvement

Without pen-check



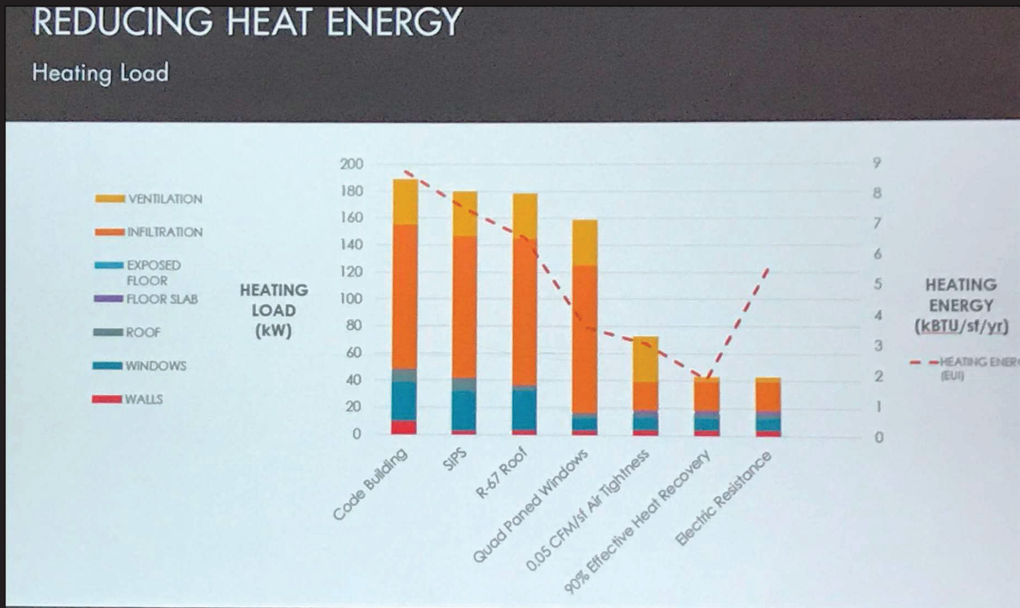
Without additional sealant

Possible?

- ASHRAE 90.1:
  7.2 m³/h/m²
- USACE Protocol
  4.572m³/h/m² (0.25CFM/ft²)
- Passivhaus
  1.78m³/h/m² (0.6ACH50)

Consideration

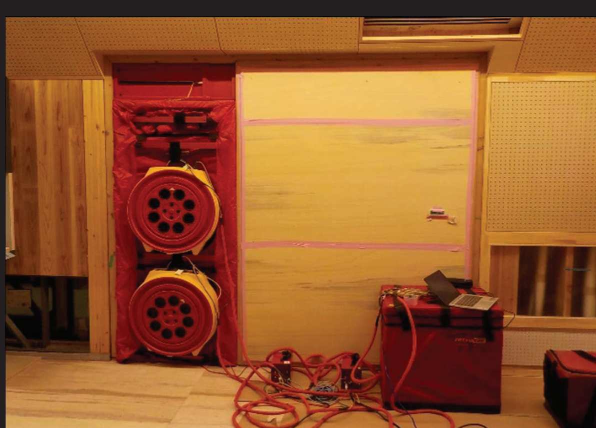
Importance of airtightness / reducing heat load



Greenbuild2017

By
Rocky Mountain Institute

Blower door test / Air tightness test in Japan

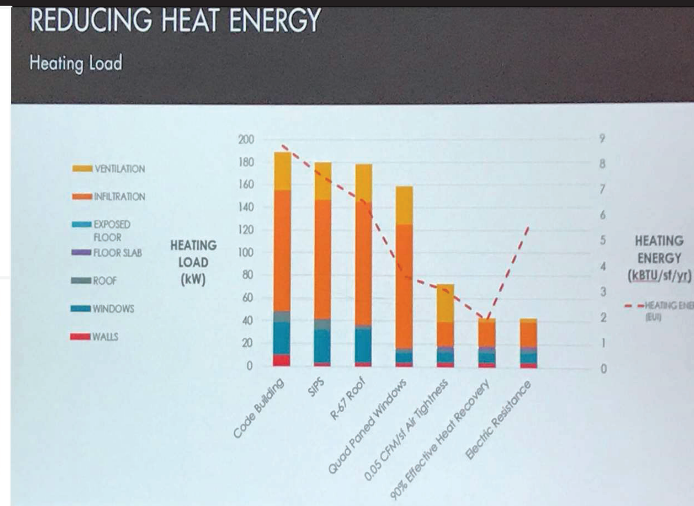


- Commercial buildings: hardly
- Residential buildings: possibly

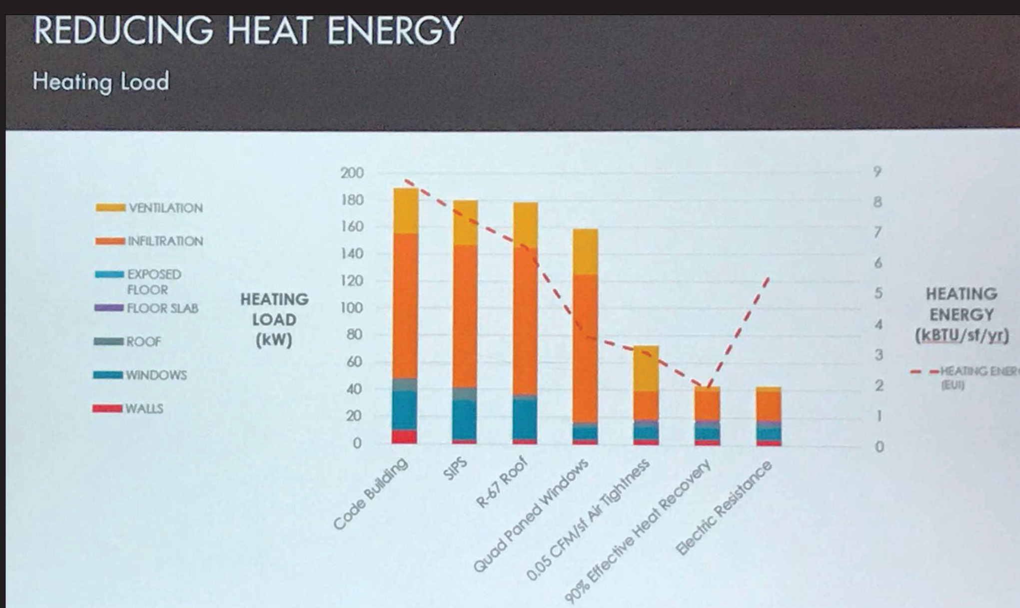
2 coincidences

On the way to build a zero energy building, among the approaches with latest technologies, reducing air leakage which is old school, worked best.

Greenbuild 2017 では、「建築単体」の日々の改良に関わる多様な取り組み事例が紹介された。最新技術を導入したグリーンビル事例では、ZEB 実現に最も大きな効果をもたらしたのは気密性の確保（すきまからの熱損失防止）というきわめて古典的な手法だったという報告があった。ロングライフビルに関しては、歴史様式建築の



Article of BELCA NEWS Jan. 2018



Greenbuild2017

By Rocky Mountain Institute

Rocky Mountain Institute Innovation Center

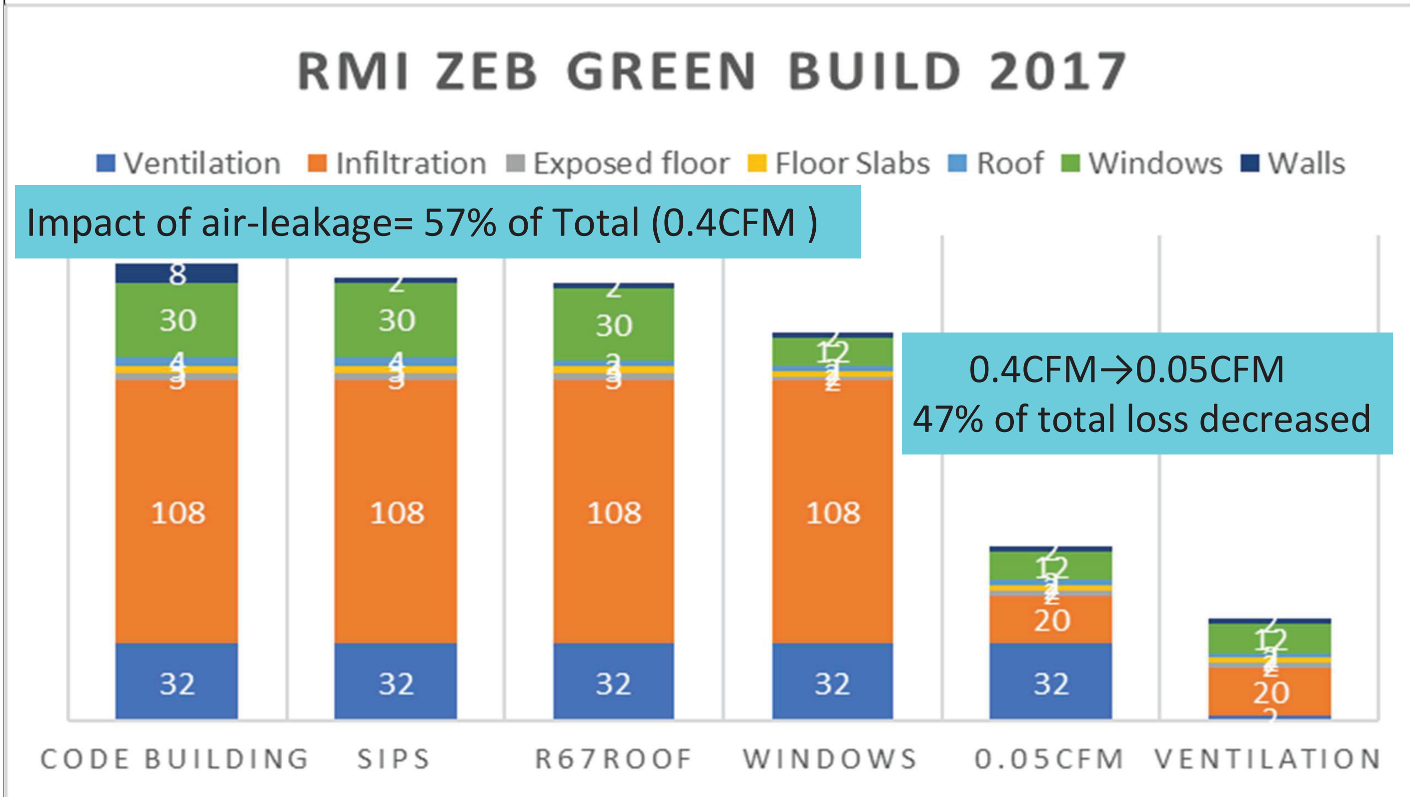
Tim Griffith

RMI's new headquarters in Basalt, Colo.

It seems cold.

Rocky Mountain Institute Innovation Center

- Built in 2016
- Colorado
- LEED Platinum certified
- Passive House Certified
- PHIUS+ Source Net Zero Project and meets Architecture 2030 goals
- Very airtight (0.36 ACH)



Past experience

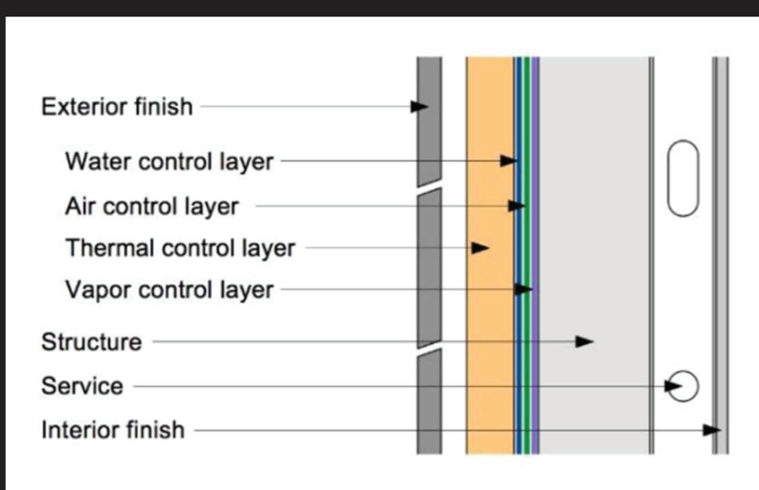
ALL Passed, but half failed Code requirement without pencheck

Building	Structure	No of Floor	Size m2	CMH/㎠2 @75Pa	CFM @75Pa	Without Pen-Check
Meiken	W	2	1,000	4.16	0.231	Fail
Office	S	4	6,460	5.06	0.281	Fail
Office	S	4	2,392	4.46	0.248	Passed
Office	S	4	2,655	5.003	0.278	Passed
Office	S	4	2,567	5.00	0.278	Passed
Training Accomodation	S	3	2,000	3.21	0.178	Fail
Office	-	-	3,600	6.21	0.345	Fail
Church	RC	2	1,188		0.000	Passed

Value	These passed USACE requirement, 0.25 cfm/sf 0.3 IW
Fail	These would not have passed ASHRAE requirement, but for Pen-check

Japanese engineers think BECx is difficult and special?

What is Building Enclosure?



- Water barrier (water control layer)
- Air barrier (air control layer)
- Vapor barrier (vapor control layer)
- Thermal barrier (thermal control layer)

BE is consist of 4 barriers, which have order J. Lstiburek

Inportance	Barrier	Principle
1	Water	Gravity
2	Air	Contiuity
3	Vapor	Vapor Pressure
4	Thermal	Enough Amount

Order of occurence

Beginning	Barrier	Age
1	Water	Ancient
2	Thermal	1930's
3	Sheet Polyethylene Air & Vapor	1950's
4	Air	1980's

Air barrier made BECx possible

Building Practice Note No. 54

The Difference Between a Vapour Barrier and an Air Barrier

by R.L. Quirouette 1985

- ASHRAE 90.1

Building: 7.2 $m^3/h/m^2$ at 75Pa

Assembly: 0.72 $m^3/h/m^2$ at 75Pa

Material: 0.072 $m^3/h/m^2$ at 75Pa

BECx: Building Enclosure Commissioning

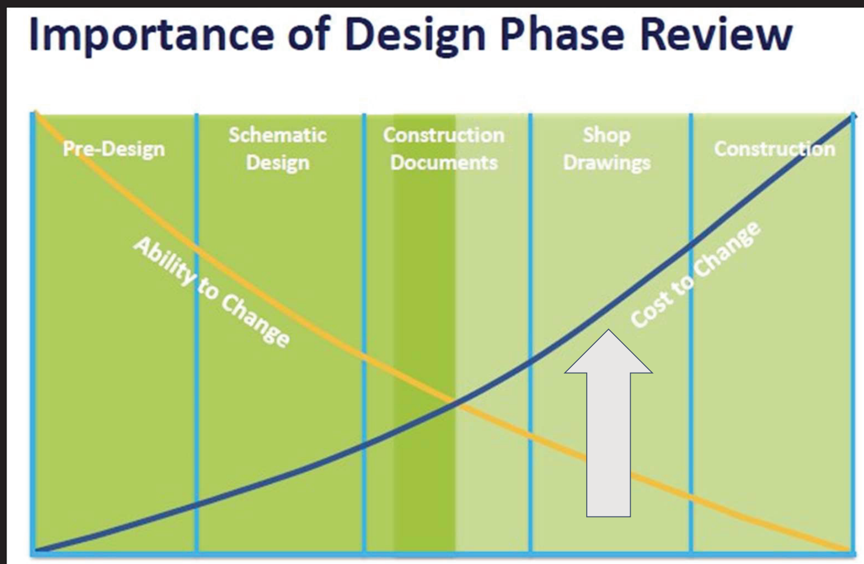
Points for improvement

Meiken Lamwood

Points to improve airtightness from BECx view

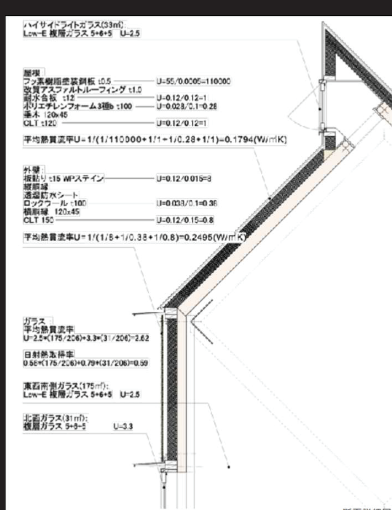
① Start earlier
② Recognize what and where Air Barrier is
③ Check if new material is air barrier
④ Air barrier Plan at schematic design

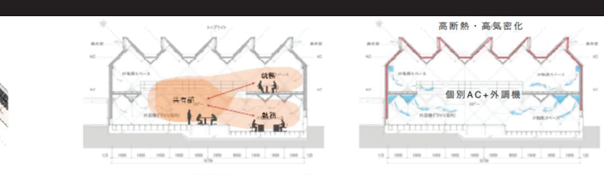
① Start earlier



By Mr. Brian Neely

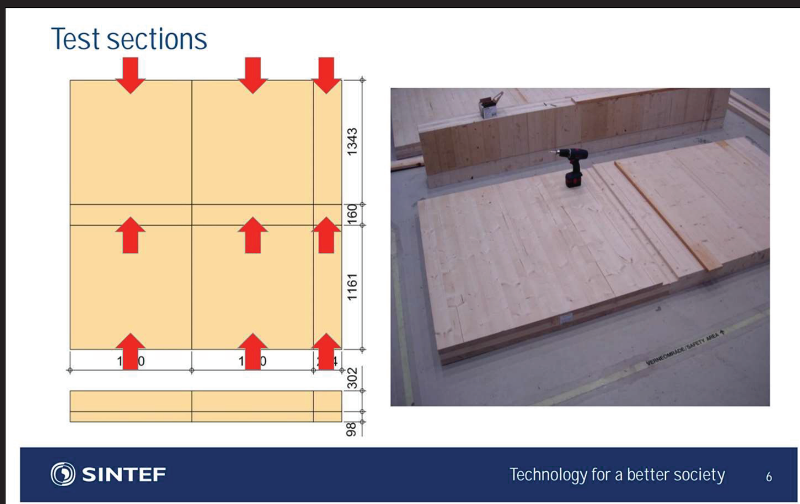
② Recognize Air Barrier





	Air Barrier Material ＆ Product
Roof	Modified bituminous roof membrane
	Tyvec Sheet
Wall	Tyvec Sheet
	Wooden doors ＆Windows
Base	Cast-in-place concrete

③ Check if new material is air barrier

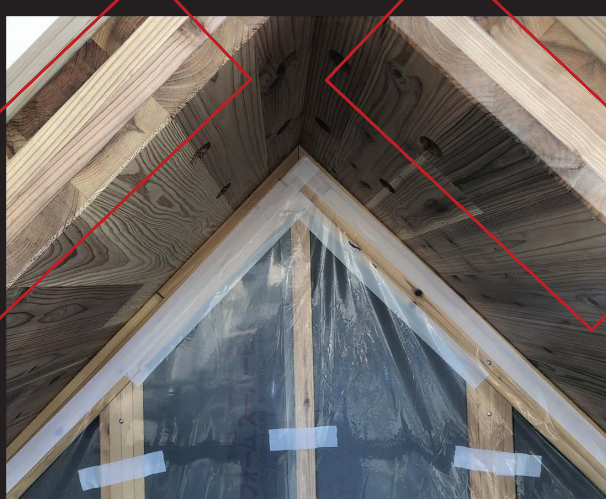


- CLT is NOT air barrier material, while plywood is.
- Test has to be done
- ASHRAE 90.1 requirement

  Material

  0.072 $m^3/h/m^2$ at 75Pa

Upper Air Leakage



Air leaks from CLT itself

Moisture content greatly affect air leakage

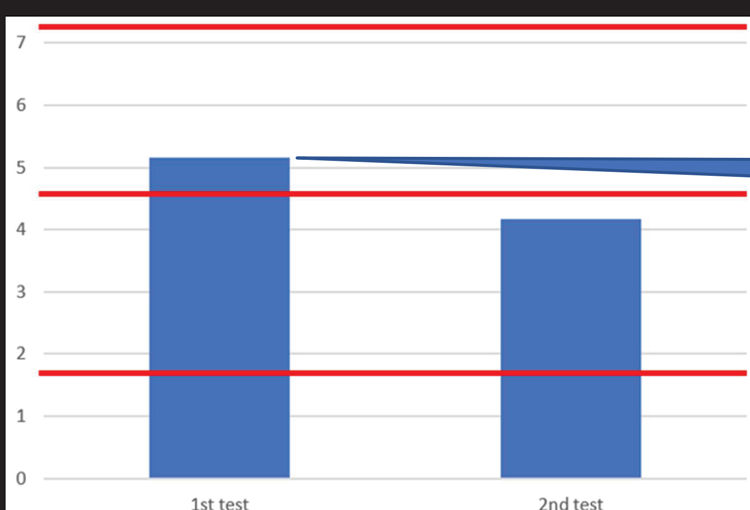
④ Air barrier plan at schematic design

ARCHITECTURE

A-001	ABBREVIATIONS, REFERENCE SYMBOLS, AND GENERAL NOTES
A-002	INTERIOR WALL DETAILS
A-003	INTERIOR WALL TYPES
A-004	INTERIOR WALL TYPES
A-005	UL WALL TYPES
A-101.1	FIRST FLOOR PLAN - NOTATIONS
A-101.2	FIRST FLOOR PLAN - DIMENSIONS
A-111	FIRST FLOOR REFLECTED CEILING PLAN
A-121	ROOF PLAN
A-131	AIR BARRIER PLAN
A-132	AIR BARRIER DETAILS
A-201	NORTH AND SOUTH ELEVATIONS
A-202	EAST AND WEST ELEVATIONS
A-301	BUILDING SECTIONS
A-302	BUILDING SECTIONS
A-311	WALL SECTIONS

Potential to improve

Without pen-check



- ASHRAE 90.1:
  7.2 m³/h/m²

Without 1st test

- USACE Protocol
  4.572m³/h/m² (0.25CFM/ft²)

Possible?

- Passive House
  1.78m³/h/m² (0.6ACH50)

Conclusion and proposal

Proposal: Let’s start study air barrier

AB is a new concept,
architectural term having clear criteria,
which is different from what we Japanese imagine.

Free Text : BSC, ABAA, NIBS, IECC, and etc.

Proposal: Let’s start study air barrier

- First step: pen-check
- You will see the importance if you try it
- The word “Importance” means that you might find large or long enough gaps to be astonished with and laugh, not tiny holes
- It is not difficult to pass CODE requirement.

Proposal: Let’s start study air barrier

- Home Page | buildingscience.com

- The Air Barrier Association of America (ABAA) | Home

Thank you!

Reference

Meiken Lamwood website
https://www.meikenkogyo.com/works/1084/

AIJ Annual Architectural Design Commendation 2022
https://www.aij.or.jp/jpn/design/2022/data/5_award_004.pdf

RMI Innovation Center Year 1 Insights, Results, and Lessons Learned Current as of February , 2017
https://rmi.org/our-work/buildings/scaling-zero-net-carbon/rmi-innovation-center/

Ayako Omura [1 ロングライフビルと LEED　2018
ー Built Environment のサステナビリティ向上をあらためて考える]

SINTEF [Air leakage thorough cross laminated timber (CLT) constructions]

Air leakages through cross laminated timber (CLT) constructions - SINTEF

RÉPUBLIQUE FRANÇAISE
Liberté Égalité Fraternité

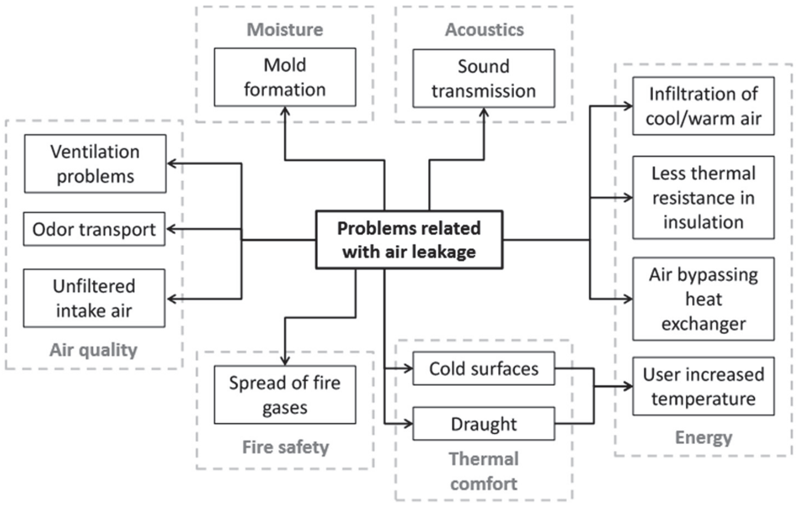
Cerema
CLIMAT & TERRITOIRES DE DEMAIN

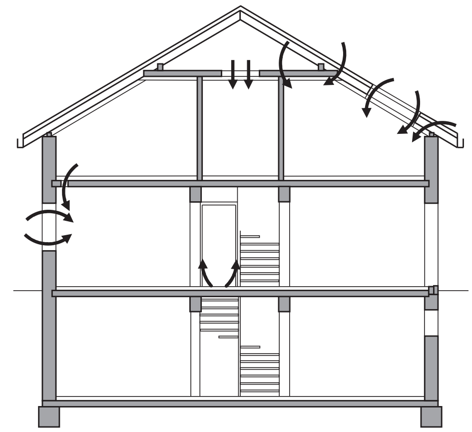
ISO 9972: AN OVERVIEW OF DIFFICULTIES WITH THE CURRENT STANDARD

AIVC Workshop, Tokyo (JP) – 19.05.2023

Benedikt Kölsch, Valérie Leprince & Adeline Mélois

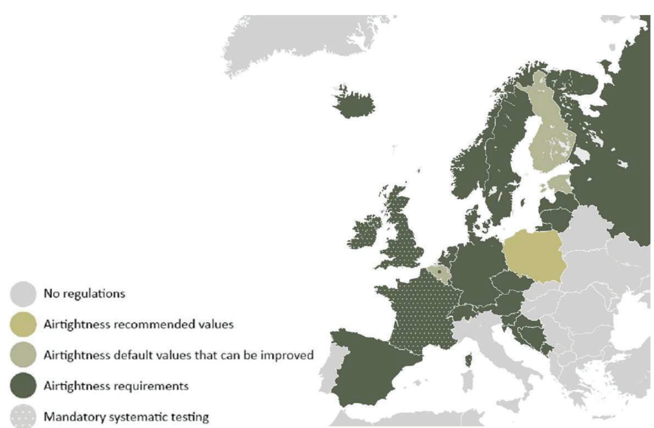
IMPORTANCE OF AIRTIGHTNESS





AIRTIGHTNESS REGULATIONS IN EUROPE

- Increasing number of tests performed in Europe
- Testing → important part in national energy regulations
- Test is used for :
  - **Measuring air leakage** in buildings to fulfill energy performance standards
  - **Comparing relative airtightness** of buildings
  - **Determining reduction** or air permeability after implementation of improvements



Poza-Casado et al. (2020)

ISO 9972: FAN PRESURIZATION METHOD

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN ISO 9972

September 2015

ICS: 91.120.10

Supersedes EN 13829:2000

English Version

Thermal performance of buildings —
Determination of air permeability of buildings —
Fan presurization method
(ISO 9972:2015)

Performance thermique des bâtiments —
Détermination de la perméabilité à l'air des bâtiments —
Méthode de pressurisation par ventilateur
(ISO 9972:2015)

Wärmetechnisches Verhalten von Gebäuden —
Bestimmung der Luftdurchlässigkeit von Gebäuden —
Differenzdruckverfahren
(ISO 9972:2015)

ISO 9972: FAN PRESURIZATION METHOD

- Describes measurement procedure and calculation methods for determining airtightness
- To obtain comparable and credible results, it needs to be
  - ➢ Reliable and valid for different kinds of buildings
  - ➢ Reproducible under challenging environmental conditions
  - ➢ Consistant with other standards
- Recent scientific works + more experience in field testing → **need to improve ISO 9972!**

WORKING GROUP ON ISO 9972

Collection of data and knowledge from experts in the field

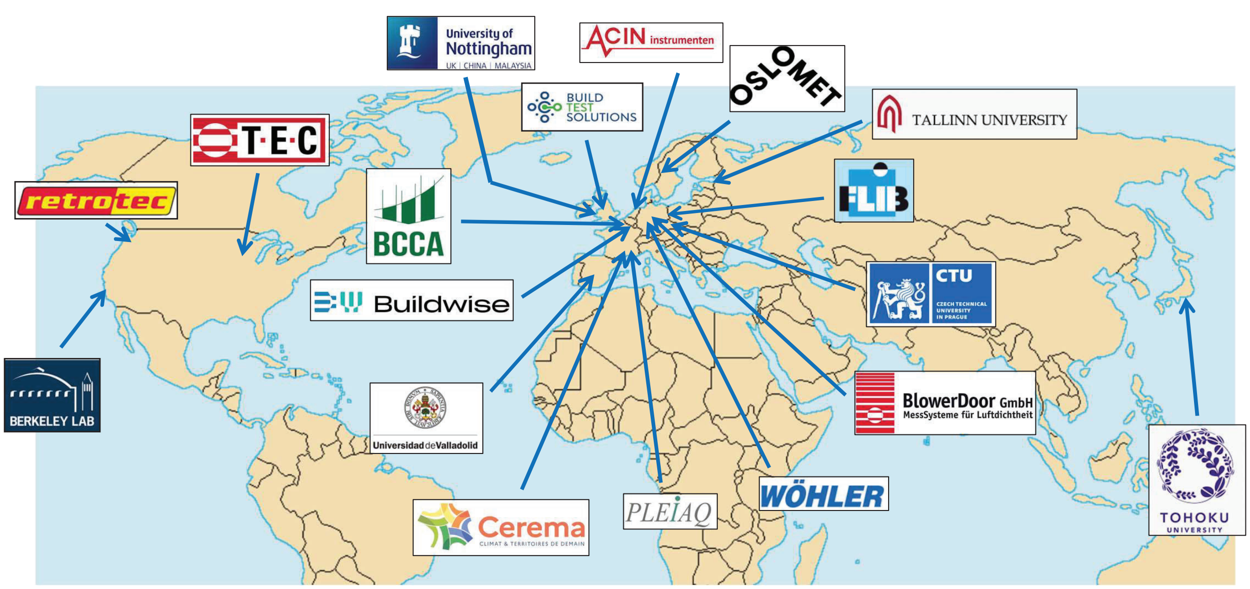
Provision of a proposal for revision of ISO 9972, that

- allows performing tests even under **challenging conditions**
- is a more **reliable** calculation procedure + improved uncertainty estimation
- Is **consistent** with other standards

Collecting a comprehensive **list of relevant issues** with survey among experts

No formal revision → **provision of best knowledge** for official revision process in ISO/TC 163/SC 1 technical committee

WORKING GROUP AFFILIATIONS



REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **reliability**

= result's consistency over time
+
reproducibility

- Building preparation
- Wind speed and temperature measurements
- Placement of external pressure taps
- Duration of pressure/airflow measurements
- Induced pressure differences
- Type of regression

REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **reliability**

- **Building preparation**
- Wind speed and temperature measurements
- Placement of external pressure taps
- Duration of pressure/airflow measurements
- Induced pressure differences
- Type of regression

- How intentional openings should be sealed, closed, or left open during tests
- Influences final results *
- ➢ Avoid ambiguities in the standard

Work has not started yet

* Rolfsmeier et al. (2011), Leprince & Carrié (2014)

REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **reliability**

- Building preparation
- **Wind speed and temperature measurements**
- Placement of external pressure taps
- Duration of pressure/airflow measurements
- Induced pressure differences
- Type of regression

Unclear information on where and how (or if) to measure wind speed and ambient temperatures

ISO 9972

➢ Recommendations are given for temperature and wind measurements *

Proposal finished

* Novák (2019)

REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **reliability**

- Building preparation
- Wind speed and temperature measurements
- **Placement of external pressure taps**
- Duration of pressure/airflow measurements
- Induced pressure differences
- Type of regression

REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **reliability**

ISO 9972

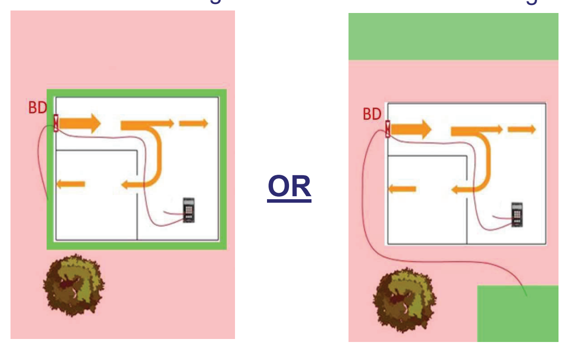
- **Placement of external pressure taps**

  Location of pressure taps used as reference for every pressure measurement → location not clearly stated

  ➢ Especially for zero-flow pressure measurements, clarification if taps should be placed *

Next to the building

Further away from the building



Pressure difference across envelope

Equilibrium internal pressure

Work has started - more research needed

* Delmotte (2021), Hurel & Leprince (2021)

REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **reliability**

- Building preparation
- Wind speed and temperature measurements
- Placement of external pressure taps
- **Duration of pressure/airflow measurements**
- Induced pressure differences
- Type of regression

- Averaging test results makes readings more reliable in presence of wind

  ➢ Recommend extending the duration to 60 s, recording 1 data point per second *

Work on proposal has started

* Prignon et al. (2021), Hurel & Leprince (2021)

REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **reliability**

- Building preparation
- Wind speed and temperature measurements
- Placement of external pressure taps
- Duration of pressure/airflow measurements
- **Induced pressure differences**
- Type of regression

- Number and level of pressure differences may influence test reproducibility
- ➢ Adding option of single-point test? *

Work has not started yet

* Hurel & Leprince (2021)

REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **reliability**

- Building preparation
- Wind speed and temperature measurements
- Placement of external pressure taps
- Duration of pressure/airflow measurements
- Induced pressure differences
- **Type of regression**

REASONS BEHIND A NECESSARY REVISION

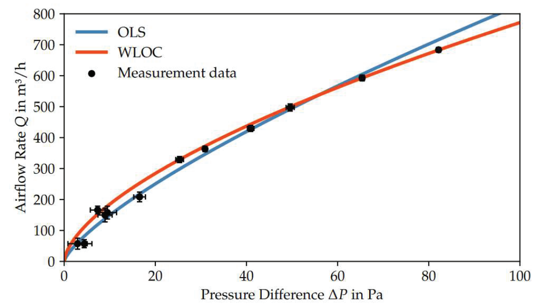
Limitations on measurement **reliability**

- **Type of regression**

ISO 9972

Least square regression shall be used to determine airflow coefficient *C* and pressure exponent *n*

- ➢ Weighted line of organic correlation **(WLOC)** uses standard uncertainty at each pressure/flow data point as a weight + optimizes in x and y-direction
- ➢ **Improves predictability** of airflows and **reduces variability** in *C* and *n* *



Work on proposal has started

* Delmotte (2017), Prignon et al. (2018), Kölsch & Walker (2020)

REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **validity**

= determination of the value intended to be measured

- Airflow corrections
- Calculation of building volume and area
- Limits on zero-flow pressure measurements
- Knowledge of uncertainty
  - Errors due to measurement instruments, measurement protocol and analysis
  - Errors arising from physical model assumptions

REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **validity**

- **Airflow corrections**
- Calculation of building volume and area
- Limits on zero-flow pressure measurements
- Knowledge of uncertainty
  - Errors due to measurement instruments, measurement protocol and analysis
  - Errors arising from physical model assumptions

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REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **validity**

- **Airflow corrections**

ISO 9972

Airflows must be corrected to standard conditions of temperatures/pressures → tests can be compared

- Simplifications assume:
  - barometric pressure negligible,
  - blower door calibrated close to reference conditions
  - *n* close to 0.5 *

$$q_{\text{env}} = q_{\text{m}} \left(\frac{\rho_{\text{int}}}{\rho_{\text{e}}} \right) \approx q_{\text{m}} \left(\frac{T_{\text{e}}}{T_{\text{int}}} \right)$$

$$C_{\text{L}} = C_{\text{env}} \left(\frac{\rho_{\text{e}}}{\rho_0} \right)^{1-n} \approx C_{\text{env}} \left(\frac{T_0}{T_{\text{e}}} \right)^{1-n}$$

* Walker et al. (1998)

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REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **validity**

- **Airflow corrections**

ISO 9972

Airflows must be corrected to standard conditions of temperatures/pressures → tests can be compared

➢ Giving modern computing equipment → **simplification not necessary anymore** *

$$q_{env} = q_m \left(\frac{\rho_{int}}{\rho_e}\right) \approx q_m \left(\frac{T_e}{T_{int}}\right)$$

$$C_L = C_{env} \left(\frac{\rho_e}{\rho_0}\right)^{1-n} \approx C_{env} \left(\frac{T_0}{T_e}\right)^{1-n}$$

Work on proposal has started

* Carrié (2014)

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REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **validity**

- Airflow corrections
- **Calculation of building volume and area**
- Limits on zero-flow pressure measurements
- Knowledge of uncertainty
  - Errors due to measurement instruments, measurement protocol and analysis
  - Errors arising from physical model assumptions

- Every country has different measures for building volume/area → difficult to compare

➢ Common standardized method to compare results could be convenient

Work has started - more research needed

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REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **validity**

- Airflow corrections
- Calculation of building volume and area
- **Limits on zero-flow pressure measurements**
- Knowledge of uncertainty
  - Errors due to measurement instruments, measurement protocol and analysis
  - Errors arising from physical model assumptions

REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **validity**

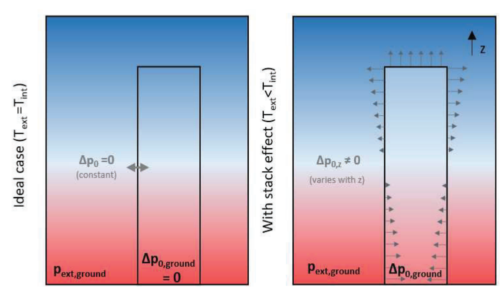
- **Limits on zero-flow pressure measurements**

ISO 9972

ΔP_0 = Pressure difference between inside and outside when building is not artificially pressurised

If **ΔP_0 > 5 Pa → test not valid!**

- This constraint shall limit influence of wind and temperatures on uncertainty – leak distribution has influence as well *



* Carrié et al. (2022), Mèlois (2020)

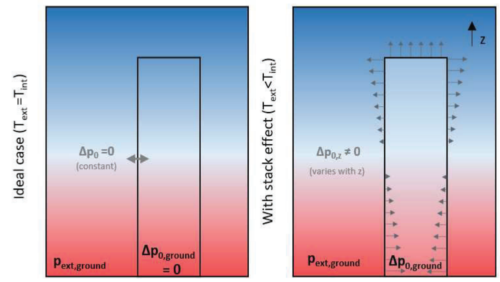
REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **validity**

- **Limits on zero-flow pressure measurements**

ISO 9972 If **ΔP_0 > 5 Pa → test not valid!**

  - This constraint **excludes testing of high-rise buildings** from being tested according to the standard *
  - Possible solution: only recommend that **ΔP_0 < 5 Pa** + **include ΔP_0** (+ maybe variability) **in uncertainty calculation**



Work on proposal has started

* Peper & Schnieders (2019), Rolfsmeier et al. (2022)

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REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **validity**

- Airflow corrections
- Calculation of building volume and area
- Limits on zero-flow pressure measurements
- **Knowledge of uncertainty**
  - Errors due to measurement instruments, measurement protocol and analysis
  - Errors arising from physical model assumptions

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REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **validity**

- **Knowledge of uncertainty**
  - ➢ Errors due to measurement instruments, measurement protocol and analysis
  - Errors of measurement devices given as maximum permissible measurement error (**MPME**) → used as influence parameter in uncertainty calculation
  - Inclusion of uncertainties from **building preparation**, **reference values** or **sampling**

Proposal finished

Work has not started yet

REASONS BEHIND A NECESSARY REVISION

Limitations on measurement **validity**

- **Knowledge of uncertainty**
  - ➢ Errors arising from physical model assumptions

ISO 9972

Assumes that airflow rate through all leaks can be approximated as flow through a single opening *
→ **Power law**

$$q_{pr} = C_L (\Delta p_r)^n$$

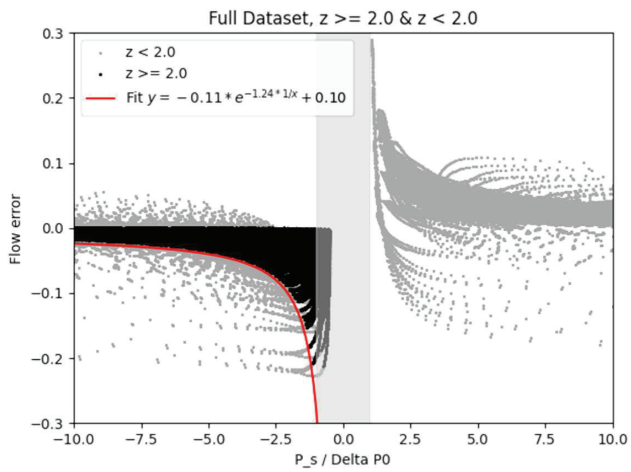
- Model error increases for high wind speed and stack effect
- More work necessary to understand and quantify errors

Work has started - more research needed

* Delmotte (2021), Carrié (2022)

REASONS BEHIND A NECESSARY REVISION

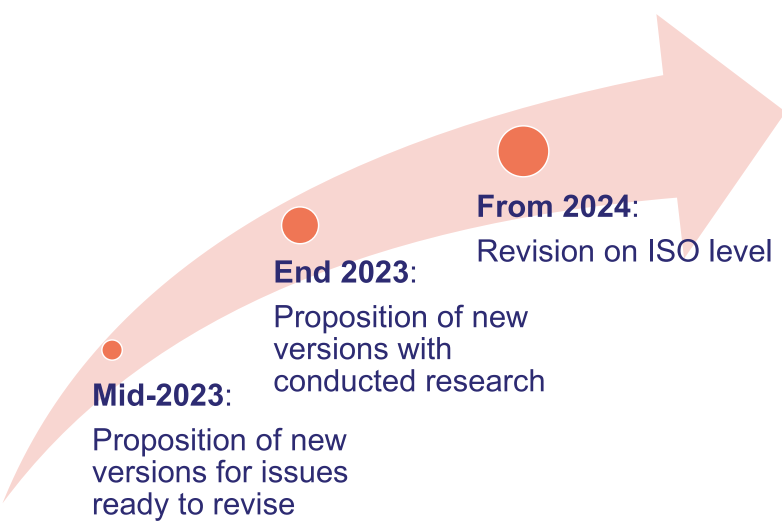
Limitations on measurement **validity**



$$q_{pr} = C_L (\Delta p_r)^n$$

Work has started - more research needed

OUTLOOK



Thank you!

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REFERENCES

Carrié, F. R. (2014). Temperature and pressure corrections for power-law coefficients of airflow through ventilation system components and leaks. *Proceedings of the 35th AIVC Conference*.

Carrié, F. R., Olson, C., & Nelson, G. (2022). Characterizing model errors due to flow-pressure formulation and zero-flow pressure correction in building pressurization tests in steady windy anisothermal conditions. *Energy and Buildings*, *270*, 112283. https://doi.org/10.1016/j.enbuild.2022.112283

Delmotte, C. (2017). Airtightness of Buildings – Considerations regarding the Zero-Flow Pressure and the Weighted Line of Organic Correlation. *Proceedings of the 38th AIVC Conference*.

Delmotte, C. (2021). Airtightness of buildings – Assessment of leakage-infiltration ratio and systematic measurement error due to steady wind and stack effect. *Energy and Buildings*, *241*, 110969. https://doi.org/10.1016/j.enbuild.2021.110969

Hurel, N., & Leprince, V. (2021). Impact of wind on the airtightness test results. *AIVC Ventilation Information Paper No 41*.

Kölsch, B., & Walker, I. S. (2020). Improving air leakage prediction of buildings using the fan pressurization method with the Weighted Line of Organic Correlation. *Building and Environment*, *181*, 107157. https://doi.org/10.1016/j.buildenv.2020.107157

Leprince, V., & Carrié, F. R. (2014). Comparison of building preparation rules for airtightness testing in 11 European countries. *Proceedings of the 35th AIVC Conference*.

Mélois, A. (2020). *Impact of the wind during a building airleakage measurement* [Doctoral Thesis]. ENTPE.

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REFERENCES

Novák, J. (2019). Implementation of the EN ISO 9972 standard into the Czech Republic. *Proceedings of the 11th International BUILDAIR-Symposium*.

Peper, S., & Schnieders, J. (2019). *Airtightness Measurement of High-Rise Buildings*. Passive House Institute.

Poza-Casado, I., Cardoso, V. E. M., Almeida, R. M. S. F., Meiss, A., Ramos, N. M. M., & Padilla-Marcos, M. Á. (2020). Residential buildings airtightness frameworks: A review on the main databases and setups in Europe and North America. *Building and Environment*, *183*, 107221. https://doi.org/10.1016/j.buildenv.2020.107221

Prignon, M., Dawans, A., & Van Moeseke, G. (2018). Uncertainties in airtightness measurements: Regression methods and pressure sequences. *Proceedings of the 39th AIVC Conference*.

Prignon, M., Dawans, A., & Van Moeseke, G. (2021). Quantification of uncertainty in zero-flow pressure approximation. *International Journal of Ventilation*, *20*(3–4), 248–257. https://doi.org/10.1080/14733315.2020.1777020

Rolfsmeier, S., Vogel, K., & Bolender, T. (2011). Ringversuche zu Luftdurchlässigkeitsmessungen vom Fachverband Luftdichtheit im Bauwesen e.V. *Proceedings of the 6th International BUILDAIR-Symposium*.

Rolfsmeier, S., Mairinger, E., Neubig, J., & Gayer, T. (2022). Measuring airtightness of 100-meter high-rise buildings (lessons learned). *Proceedings of the 42nd AIVC Conference*.

Walker, I. S., Wilson, D. J., & Sherman, M. H. (1998). A comparison of the power law to quadratic formulations for air infiltration calculations. *Energy and Buildings*, *27*(3), 293–299. https://doi.org/10.1016/S0378-7788(97)00047-9

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PLEIAQ

Durability of building airtightness

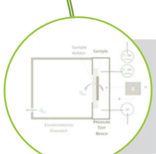
WORKSHOP "TOWARDS HIGH QUALITY, LOW-CARBON VENTILATION IN AIRTIGHT BUILDINGS"

MAY 19TH 2023

VALÉRIE LEPRINCE
CEREMA

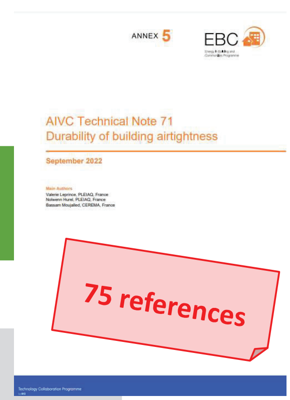
NOLWENN HUREL
PLEIAQ/INIVE

- Field studies in real buildings



- Experiments in a controlled environment

- Implementation conditions impact


ANNEX 5 EBC

AIVC Technical Note 71
Durability of building airtightness

September 2022

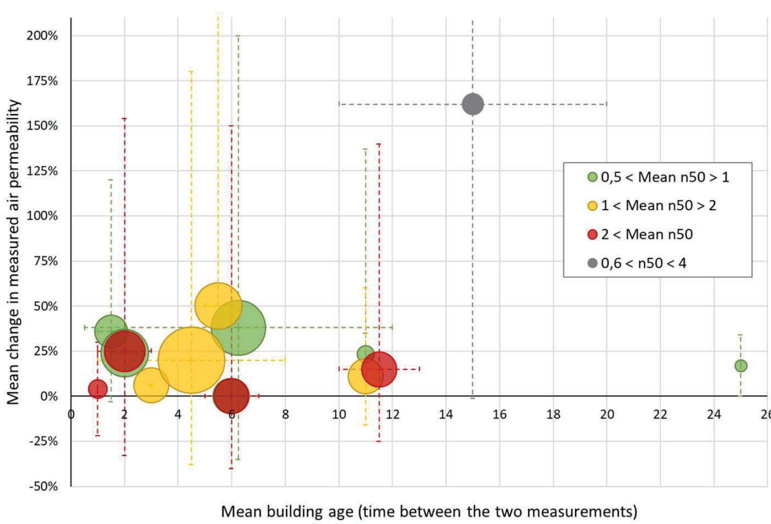
75 references

Review of on-site studies testing buildings airtightness durability

Country	Sample size	Year of cons-truction	Age (years)	Mean air permeability n_{50}	Main material	Air permeability evolution	Reference
Belgium	15 new houses	2010	1-2	0.6 ACH	Concrete blocks	Max: +120% Mean: +36% Min: -3%	(Bracke et al., 2016)
	41 new houses	2007 - 2019	0.5-12	0.94 ACH	? (low-energy houses)	Max : +200% Mean : +38% Min : -35%	(Verbeke and Audenaert, 2020)
Canada	17 new houses	1985	3 / then 11	1.5 ACH	Wood	Max: - / +60% Mean: +6% / +11% Min: - / -16%	(Proskiw, 1998)
Czech Republic	4 new houses	2007	11 (or tested regularly between 3 and 11)	0.57 ACH	Wood	Houses A&B : +35% House C: +137% House D: +103%	(Novák, 2018)
France	30 new houses	2009	5-6	1.8 ACH	Concrete blocks	Max: - Mean: +50% Min: -	(ADEME, 2016)
	61 new houses	2009 - 2016	1-8	1.38 ACH	Hollow brick (36) ; Concrete blocs (19); Wood (6)	Max: +180% Mean: +20% Min: -38%	(Moujalled et al., 2021)
Germany	2 new houses	1990	25	0.6 ACH	Concrete blocks	1st house: 0% 2nd house +34%	(Feist et al., 2016)
	17 new houses	?	1.4-10.5	0.42 ACH	Wood (9); Composite (4); Concrete (2) solid (2)	« almost always within the measuring accuracy"	(Peper et al., 2017)
	31 new houses	2000	2	0.37 ACH	? (passive houses)	Mean : +24%	(Erhorn-Kluttig et al., 2009)
Sweden	6 new houses	1990	10-20	0.6-4 ACH	Wood	Max: +580% Mean: +162% Min: -1%%	(Hansén and Ylmén, 2012)
UK	23 new houses	2007	1-3	4 ACH	Wood and concrete blocks	Max: +154% Mean: +25% Min: -33%	(Philips et al., 2011)
	5 new houses	2005	1	5 ACH	Concrete blocks	Max +30% Mean:+4% Min: -22%	(Jez Wingfield et al., 2008)
US	17 new houses	2001-2003	10-13	6 ACH	Wood	Max: +140% Mean: +15% Min: -25%	(Chan et al., 2015)
	17 refurbished houses	2007-2008	5-7	10 ACH	Wood	Max: +150% Mean: 0% Min: -40%	

14 studies from 8 countries

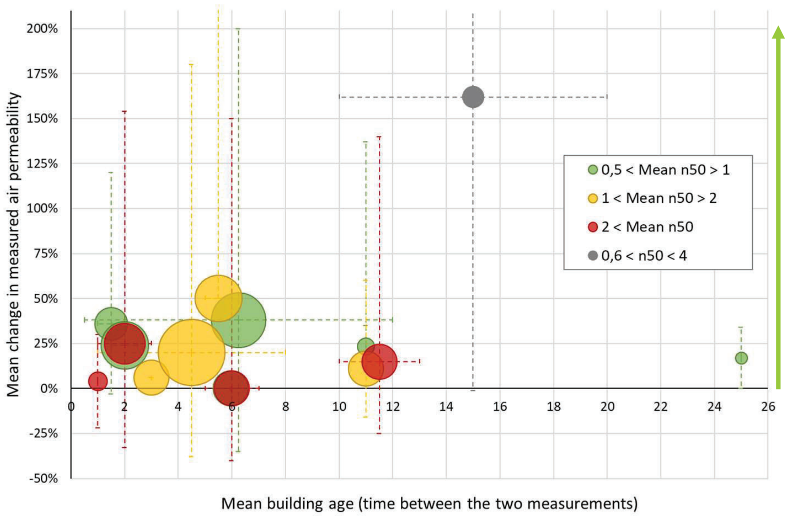
Review of on-site studies testing buildings airtightness durability



Airtightness is **not robust**

→ Significant **changes in air permeability with time** are observed for at least part of the tested houses in all studies except one study (Peper et al., 2017).

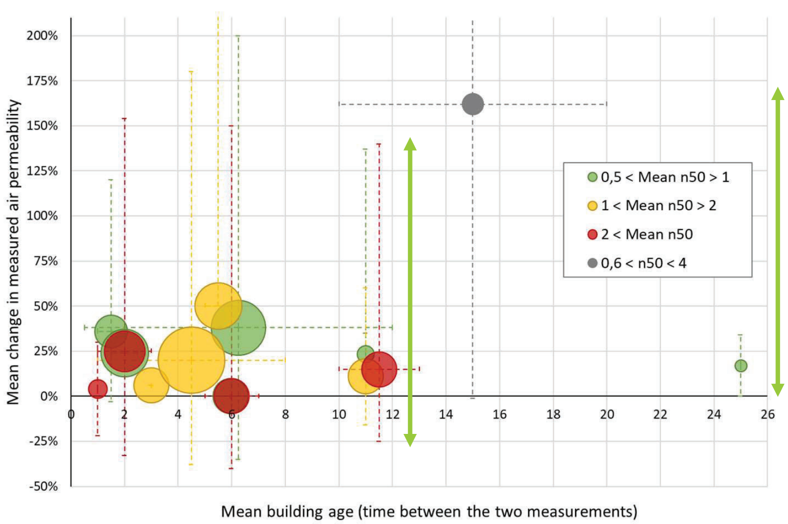
Review of on-site studies testing buildings airtightness durability



Airtightness tends to **deteriorate after completion**

→ The **mean change in air permeability is positive for all studies**. The average of all mean changes weighted by the sample size gives an increase of **24%**.

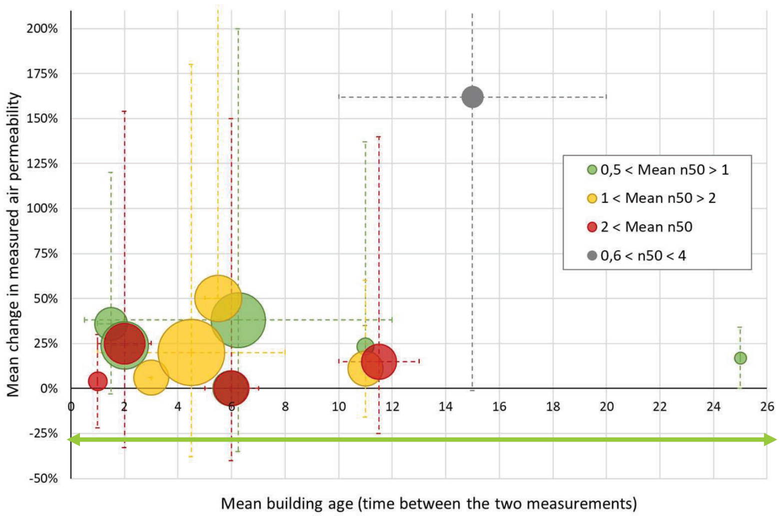
Review of on-site studies testing buildings airtightness durability



Changes in airtightness are **highly variable**

→ For each study **results differ considerably between the tested houses**, with almost always at least one presenting an improved airtightness (by up to 40%) and almost always at least one presenting a very deteriorated airtightness (by up to 580%).

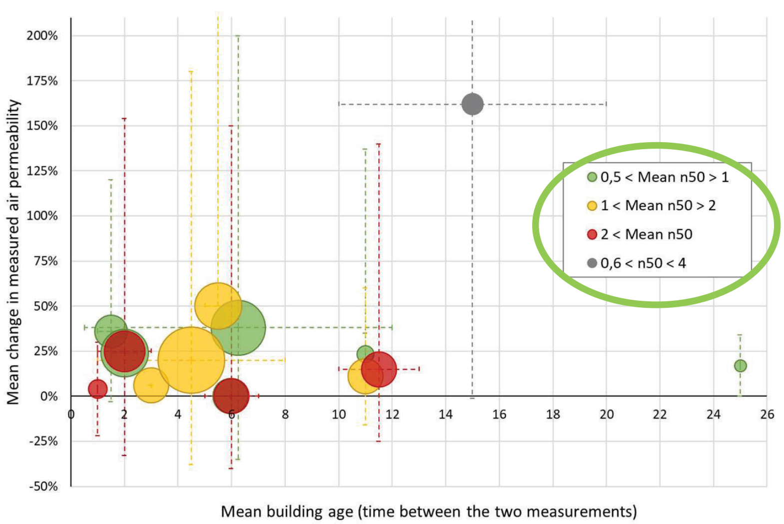
Review of on-site studies testing buildings airtightness durability



Changes in airtightness occur **quickly after construction**

→ The mean change in measured air permeability does not seem to clearly increase with the building age, which would mean that **changes occur mostly within the first (1 or 2) year(s)** of the building use. This is suggested in the study with the largest sample size (Moujalled et al., 2021) and confirmed by a study with buildings tested regularly where air permeability increased mainly in the first years (Novák, 2018).

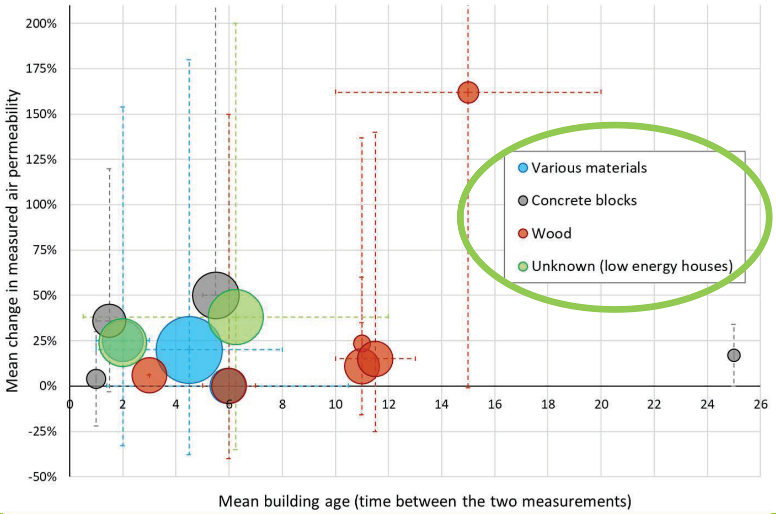
Review of on-site studies testing buildings airtightness durability



Changes in airtightness in absolute terms seem **correlated to the initial air permeability level**

→ The mean change in measured air permeability are given in percentage and there is no clear difference between the three levels of initial air permeability so **changes in absolute terms are bigger for initially more permeable buildings**.

Review of on-site studies testing buildings airtightness durability

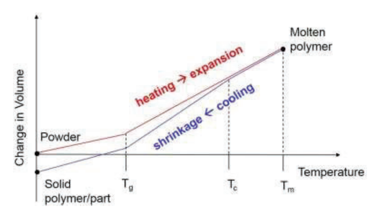


Changes in airtightness **does not seem to strongly depend on the main construction material**

→ Both **wooden and concrete** constructions were sometimes found to have a durable airtightness and other times a strongly deteriorated airtightness.

Key factors for airtightness change over time

Possible factors of airtightness DECREASE over time:



- **Building's natural "movements":**
  - Heating houses for the first time;
  - Shrinkage of mastic
  - Structure movements and packing

- **External interventions:**
  - Drilling hole into the envelope, unless it is done with concern on the air barrier system protection (Novák, 2018).
  - Installation of cables or ductwork after the completion of the building (for example to rooftop solar panels) (Verbeke and Audenaert, 2020).

Key factors for airtightness change over time

Possible factors of airtightness DECREASE over time :

- **Specific building materials and construction types**:
  - **Uncertain impact of the number of storeys**: 2-storey houses seem to deteriorate more than 1-storey ones (Moujalled et al., 2021) but houses generally become leakier than flats (Philips et al., 2011)
  - **Air barriers made of plasterboard seem to deteriorate in average more than air barriers made of polyethylene membrane** (Proskiw, 1998) (Johnston and Lowe, 2006)) (ADEME, 2016)
  - **Air barriers made with membranes can also, however, potentially strongly deteriorate**: timber frame dwellings showed the largest change in airtightness when compared to plastered masonry (Philips et al., 2011), especially in case of exposed wood frame roofs (Moujalled et al., 2021)
- **Poor workmanship**
- **Unsuitable implementation conditions**

Key factors for airtightness change over time

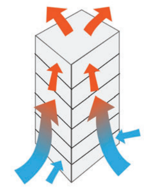
Possible factors of airtightness IMPROVMENT over time :

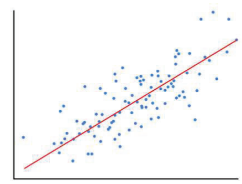
- **The settlement**: the installation of carpets and floor finishes after the original test, the presence of plugs in electrical sockets
- **Wood expansion with humidity** (Durabilit'air 1)
- The **user reducing the air inlets** to decrease the heating load (Ramos et al., 2013)

Uncertainties in airtightness testing

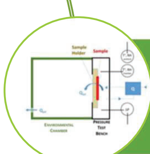
Part of the difference between tests results may not be due to the airtightness change with time but **due to test uncertainty**. Deviations in airtightness testing are due to:

- Variations in the testing protocol (including building preparation and testing equipment installation)
- Wind and thermal draft impact;
- Measurement device uncertainty;
- Seasonal variation of airtightness;
- Regression model.





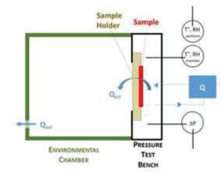
Field studies in real buildings



Experiments in a controlled environment

Implementation conditions impact

Loads on the air barrier and equivalent artificial ageing



- **Various load types:**
  - Pressure load (mechanical ageing): fatigue tests

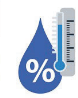
$$P_{wind} = \tfrac{1}{2}.\ \rho.\ Cp.v^2$$

Table 1 Fatigue test representing typical UK service loads in 50-year exposure period

	Number of cycles	Percentage of design pressure
Apply sequence five times	1	90
	960	40
	60	60
	240	50
	5	80
	14	70
Finish with	1	100

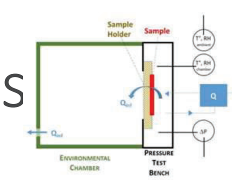
  - Thermal & humidity loads (physical ageing)
    - High temperature & RH are effective in artificial ageing of polymers, of which many adhesives consist
    - The estimation of these thermal and humidity loads is however difficult

Artificial aging at 65 °C / 80 % r.F. in days	Natural aging following ASTM D3611-89 in years	Natural aging following SATAS in years
21	10,5	3
40	20	5,7
80	40	11,4
120	60	17,1



  - Outdoor weathering loads (irradiation and wetting)
    - Some sealing products as building joints can also be used on the **outdoor side** of the wall. Durability tests should include in this case **ultraviolet (and possibly infrared) irradiation as well as wetting tests**.
    - Tapes intended for indoor vapor-barrier application can be affected by solar radiation or wetting **during the transportation, storage or construction period**.

Review of ageing tests for airtightness durability assessment



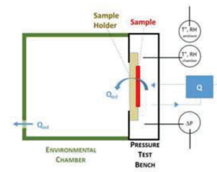
- **Artificial ageing for INDOOR air barrier components/systems**

13 studies from 8 countries

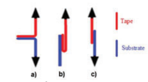
- **Ageing of OUTDOOR sealing products**

→ Less critical but can also impact the building airtightness durability

Key points for laboratory airtightness durability assessment

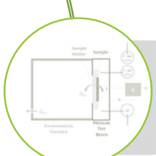


- **The airtightness durability depends on many factors and further research are needed to better define each impact:**
  Product manufacturer; compatibility problems between products; implementation conditions; type of loads



- **Importance of testing the durability of wall assemblies rather than products alone**
  Mechanical resistance tests (peel, shear, …) of products alone seem not relevant for the wall assembly durability assessment
- **All load types should be included in the protocol**
  Different impact of the various constraints (extreme temperature, humidity or pressure) depending on the air barrier type
- **Necessity to test simultaneous loads**
  More representative of reality and necessary
- **General standardised procedure is missing**
- **The ageing strategy has to be consistent with real solicitation of product**

Field studies in real buildings



Experiments in a controlled environment

Implementation conditions impact

Workmanship

4 main issues identified:

- **Workmanship quality and reproducibility**
  - The application of minor technical solutions and educational sessions allowed to reduce the specific air leakage rate by 27% on 14 houses (Colijn et al., 2017)
  - (Böhm et al., 2021) : large differences in airtightness performance for identical types of houses → the most important parameter influencing the resulting airtightness values was the **control of the implementation of individual building details during the construction of a building.**
- **Last minute corrections** (J. Wingfield et al., 2008)
  - **secondary sealing** may have benefits in the short-term to pass the airtightness test but is **prone to degradation** over a relatively short time

Workmanship

4 main issues identified:

- **Airtightness tests reproducibility and repeatability** (Bracke et al., 2016):
  - **Reproducibility:** with special attention to airtightness : variance coefficient of 12% on 15 buildings (VS 28% with no special attention to airtightness in (Laverge et al., 2014))
  - **Repeatability:** 2 houses tested up to 10 times a day, on respectively 7 and 6 different days → standard deviation of respectively 1.1% and 2.7% and a maximum variation within the same day of respectively 3.5% and 7.7%
  - **small preparation details** such as locking doors can be determining for passing the test for passive houses (necessity of having the same operator testing all houses when studying airtightness durability)

Workmanship

4 main issues identified:

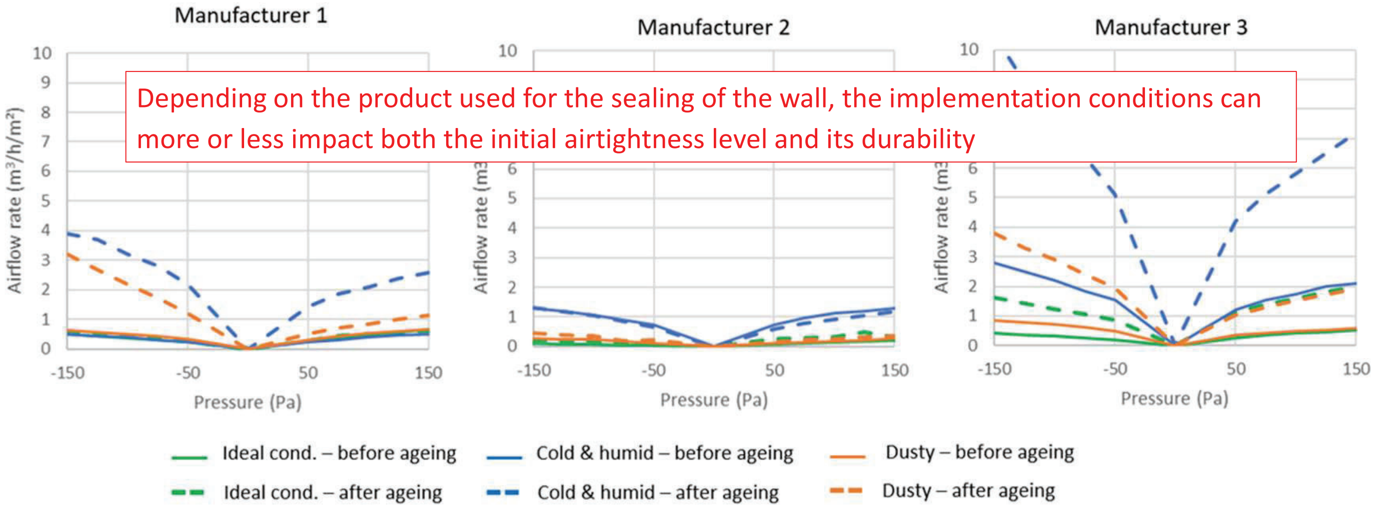
- **Compatibility of products with implementation conditions**
  - (Fufa et al., 2018): importance of the **surface condition** for the adhesion performance with the necessity of **a good adequation between the intended and actual tape use**, and a **special treatment of the substrate** when required
  - (Van Linden and Van Den Bossche, 2020) : tested **18 sealing materials** → faulty workmanship has a significantly greater impact on the material performance than artificial ageing
  - (Nečasová et al., 2017): building joints submitted to **external environment** → *"in most tested cases, diversion from the above-given steps resulted in failure of the sealed joint"*

Temperature, humidity and dust conditions

Main study: (Antonsson and Emanuelsson, 2018)

- **Durability of 3 airtightness systems** (≠ manufacturers) tested with air permeability measurements before and after artificial ageing for 3 implementation conditions:
  - **Ideal conditions**: normal indoor laboratory climate
  - **Cold and humid environment**: about 5°C and 90-95% RH on both sides of the wall
  - **Dusty conditions**: artificial dust (made of crushed concrete sieved to a grain size of max. 0.063 mm, gypsum and wood sawdust) sprayed against the plastic foil
- The **artificial ageing** was done through heat treatment with 7 days under a temperature of 60°C for system 1 and 3 and 70°C for system 2 and a RH of 50%. The authors estimate that it is the equivalent of respectively 25 and 50 years of natural ageing.

Temperature, humidity and dust conditions



Depending on the product used for the sealing of the wall, the implementation conditions can more or less impact both the initial airtightness level and its durability

Aerosol transmission route of respiratory pathogens and their mitigation strategies

U Yanagi, Prof. DPH, PhD

School of Architectural, Kogakuin University, Japan

Topics

- Transmission route of infectious respiratory pathogens
- Physical and biological characteristics of SASR-CoV-2 in the air
- Primary engineering mitigation strategies for respiratory infections
  - Ventilation
  - Filtration
  - GUV（Germicidal Ultraviolet）

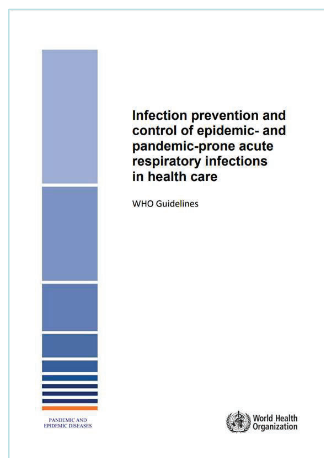
Transmission route of infectious respiratory pathogens

Traditional definition of transmission route

The mode of transmission of respiratory infections have been classified as contact, droplet, and airborne.

The World Health Organization (WHO) defines respiratory aerosols with a particle size of >5 μm as droplets and dried respiratory aerosols with a particle size ≤ 5 μm as droplet nuclei (i.e., residue of dried respiratory aerosols). Droplet and airborne infections are defined by droplet transmission and droplet nucleus transmission, respectively.

WHO Guidelines. Infection prevention and control of epidemic-and pandemic-prone acute respiratory infections in health care. 2014



The recommended distance to avoid infection varies from 1 m per WHO and in parts of Europe, to 1.5 m in Australia, to 2 m in the USA, Canada and the UK.

Randall K., et al. How did we get here: what are droplets and aerosols and how far do they go? A historical perspective on the transmission of respiratory infectious diseases. Interface Focus ***11****: 20210049. https://doi.org/10.1098/rsfs.2021.0049*

Classifying droplet infection and airborne infection with 5 μm as the threshold diameter is a dualistic medical dogma that has not been proven by direct measurements.

Greenhalgh T, et al. Ten scientific reasons in support of airborne transmission of SARS-CoV-2. *Lancet* 2021;397:1603-5. doi:10.1016/S0140-6736(21)00869-2.

William Wells was the first person to rigorously study the size of spray-borne droplets vs. airborne aerosols. In the 1930s, he conceptualized a dichotomy of spray-borne droplets (≳100 μm) that reach the ground before they dry, vs. aerosols (≲100 μm) that dry before they reach the ground (thus referred to as "droplet nuclei").

Jose L. Jimenez et al. What were the historical reasons for the resistance to recognizing airborne transmission during the COVID-19 pandemic? *Indoor Air*. 2022;32:e13070. https://doi.org/10.1111/ina.13070

In fact, ≳5 μm of SARS-CoV-2 has been detected in the air.

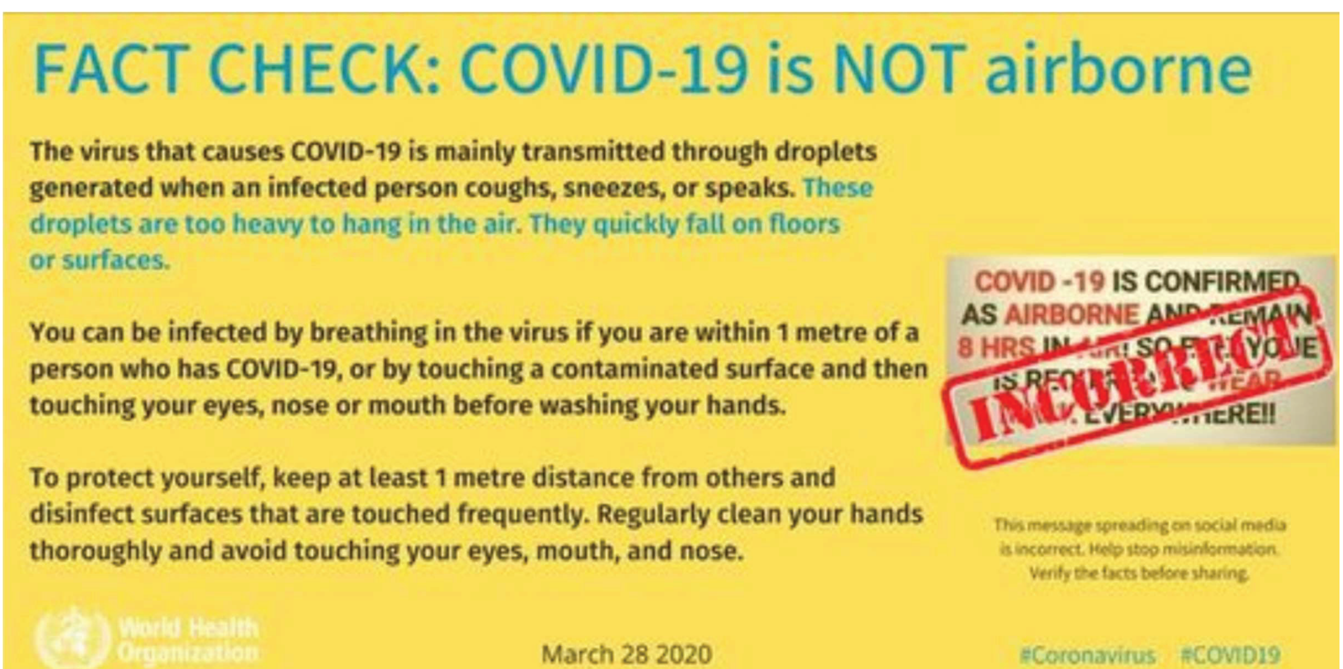
Table 1 Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) detections in the air of hospital rooms of infected patient.

Patient	Day of illness	Symptoms reported on day of air sampling	Clinical Ct value[a]	Airborne SARS-CoV-2 concentrations (RNA copies m^{-3} air)	Aerosol particle size	Samplers used
1	9	Cough, nausea, dyspnea	33.22	ND	>4 μm	NIOSH
				ND	1–4 μm	
				ND	<1 μm	
				ND	-	SKC filters
2	5	Cough, dyspnea	18.45	2,000	>4 μm	NIOSH
				1,384	1–4 μm	
				ND	<1 μm	
3	5	Asymptomatic[b]	20.11	927	>4 μm	NIOSH
				916	1–4 μm	
				ND	<1 μm	

ND none detected.
[a]PCR cycle threshold value from patient's clinical sample.
[b]Patient reported fever, cough, and sore throat until the day before the sampling. Patient reported no symptoms on the day of sampling, however was observed to be coughing during sampling.

Chia PY, et al. Detection of air and surface contamination by SARS-CoV-2 in hospital rooms of infected patients. *NatureCommunications* (2020) 11:2800 https://doi.org/10.1038/s41467-020-16670-2

The WHO emphatically declared on March 28, 2020, that SARS-CoV-2 was not airborne



Transmission of SARS-CoV-2: implications for infection prevention precautions

Scientific brief

9 July 2020

World Health Organization

This document is an update to the scientific brief published on 29 March 2020 entitled "Modes of transmission of virus causing COVID-19: implications for infection prevention and control (IPC) precaution recommendations" and includes new scientific evidence available on transmission of SARS-CoV-2, the virus that causes COVID-19.

Overview

Outside of medical facilities, some outbreak reports related to indoor crowded spaces *(40)* have suggested the possibility of aerosol transmission, combined with droplet transmission, for example, during choir practice *(7)*, in restaurants *(41)* or in fitness classes.*(42)* In these events, short-range aerosol transmission, particularly in specific indoor locations, such as crowded and inadequately ventilated spaces over a prolonged period of time with infected persons cannot be ruled out. However, the detailed investigations of these clusters suggest that droplet and fomite transmission could also explain human-to-human transmission within these clusters. Further, the close contact environments of these clusters may have facilitated transmission from a small number of cases to many other people (e.g., superspreading event), especially if hand hygiene was not performed and masks were not used when physical distancing was not maintained.*(43)*

Fomite transmission

Respiratory secretions or droplets expelled by infected individuals can contaminate surfaces and objects, creating fomites

Another person can then contract the virus when infectious particles that pass through the air are inhaled at short range (this is often called short-range aerosol or short-range airborne transmission) or if infectious particles come into direct contact with the eyes, nose, or mouth (droplet transmission).

World Health Organization

Health Topics | Countries | Newsroom | Emergencies | Data | About WHO

Home / Newsroom / Questions and answers / Coronavirus disease (COVID-19): How is it transmitted?

Coronavirus disease (COVID-19): How is it transmitted?

23 December 2021 | Q&A

The English version was updated on 23 December 2021.

العربية | 中文 | Français | Русский | Español

WHO TEAM

WHO Headquarters (HQ)

How does COVID-19 spread between people?

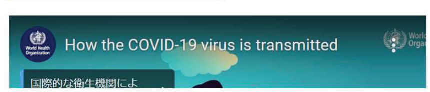
We know that the disease is caused by the SARS-CoV-2 virus, which spreads between people in several different ways.

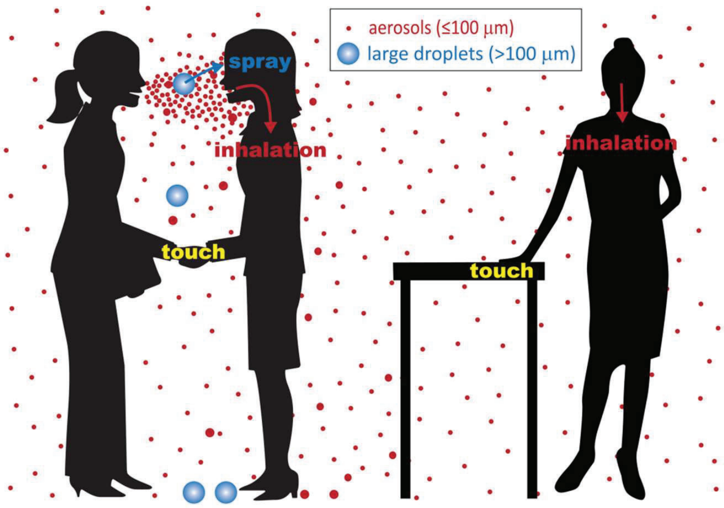
- Current evidence suggests that the virus spreads mainly between people who are in close contact with each other, for example at a conversational distance. The virus can spread from an infected person's mouth or nose in small liquid particles when they cough, sneeze, speak, sing or breathe. Another person can then contract the virus when infectious particles that pass through the air are inhaled at short range (this is often called short-range aerosol or short-range airborne transmission) or if infectious particles come into direct contact with the eyes, nose, or mouth (droplet transmission).
- The virus can also spread in poorly ventilated and/or crowded indoor settings, where people tend to

Related

Transmission of SARS-CoV-2: implications for infection prevention precautions

Access the publication





Traditional definitions of "airborne" and "droplet" transmission have been shown to be misleading, and revised definitions of transmission routes are more closely aligned with the actual mechanisms by which pathogens are transferred from one person to another (Marr and Tang 2021). These revised routes are (1) inhalation of aerosols, (2) spray of large droplets, and (3) touching a contaminated surface

Source: Marr LC, Tang JW. A paradigm shift to align transmission routes with mechanisms. Clin Infect Dis 2021; 73 (10): 1747-1749. https://doi.org/10.1093/cid/ciab722

Source: ASHRAE Positions on Infectious Aerosols.
Approved by the ASHRAE Board of Directors October 13, 2022
Expires October 13, 2025

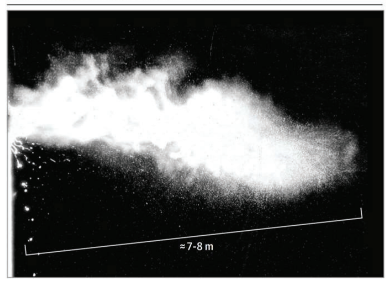
Physical and biological characteristics of SASR-CoV-2 in the air

※**Aerosol** A suspension of solid or liquid particles in a gas. The term aerosol includes both the particles and the suspending gas, which is usually air. Particle size ranges from 0.002 to more than 100 µm. (currently a generation definition: 0.001 - 100 µm)
(William C. Hinds. Aerosol Technology, Second Edition, 1999)

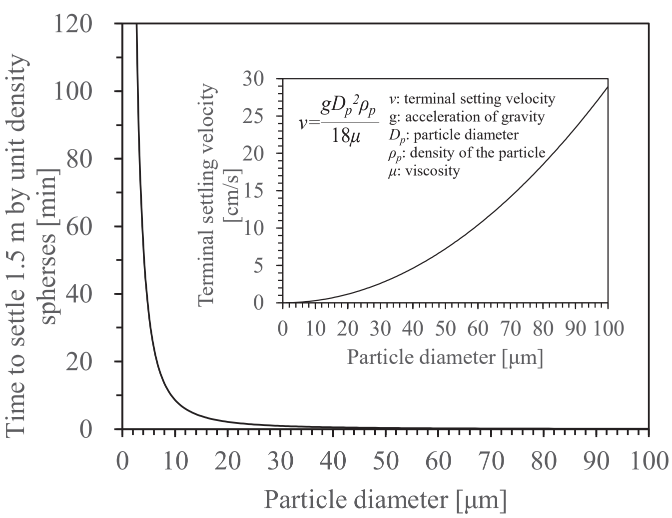
※**Bioaerosol** is an aerosol comprising particles of biological origin or activity which may affect living things through infectivity, allergenicity, toxicity, pharmacological or other processes. Particle sizes may range from aerodynamic diameter of circa 0.5 to 100 µm.
(Christopher MW. and Christopher SC. Bioaerosols handbook. Lewis publishers. 1995

※Since SARS-CoV-2 is released from the mouth with the air, so it is in the state of aerosols in environment

Figure. Multiphase Turbulent Gas Cloud From a Human Sneeze



← Source
Turbulent Gas Clouds and Respiratory Pathogen Emissions Potential Implications for Reducing Transmission of COVID-19. *JAMA*.2020;323(18):1837-1838. https://doi.org/10.1001/jama.2020.4756



It turns out that particles ≤10 µm are suspended in still air for a longer time (1 µm for 14.4 hours; 5 µm for 35 minutes; and 10 µm for 9 minutes).
Field measurement results show the highest and average velocities in occupant spaces are 0.4 m/s and 0.1 m/s, respectively 0.1-0.4 m/s（10～40cm/s）. Therefore, aerosol particle ≤10 µm are easily transported over a long-range (even up to the inlet air) in the indoor airflow during the operation of air-conditioning and/or ventilation equipment.

Hayashi M, Yanagi U, Azuma K, Kagi N, Ogata M, Morimoto S, et al. Measures against COVID-19 concerning Summer Indoor Environment in Japan. *Jpn Archit Rev*. 3(4):423–434, 2020. https://doi.org/10.1002/2475-8876.12183

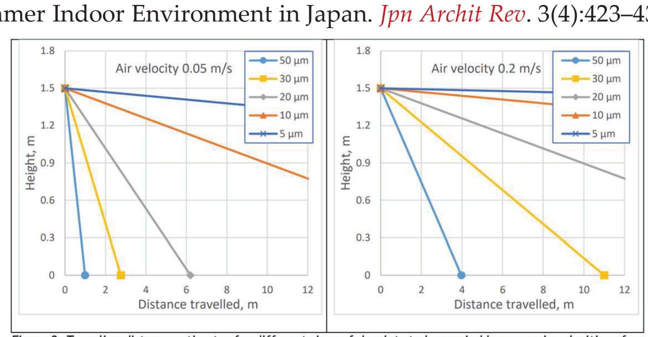
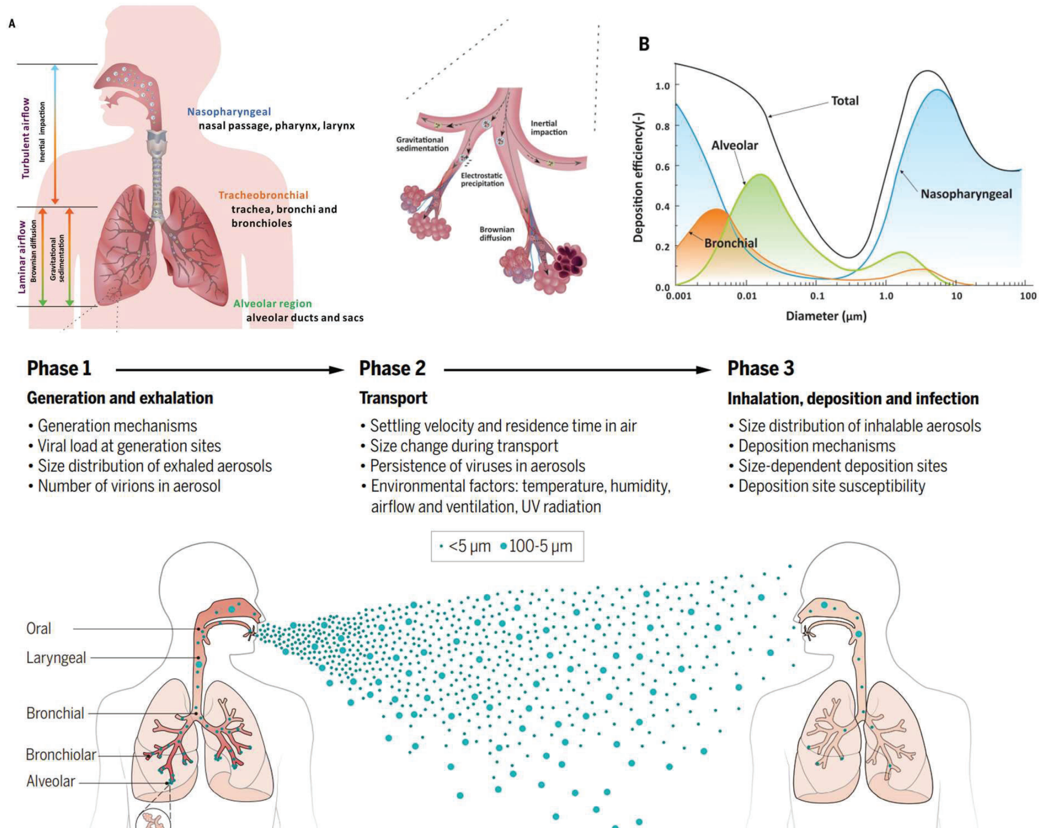


Figure 2. Traveling distance estimates for different sizes of droplets to be carried by room air velocities of 0.05 and 0.2 m/s before settling 1.5 m under the influence of gravity. The travelled distance accounts for movement after the initial jet has relaxed and is calculated with the equilibrium diameter of completely desiccated respiratory droplets (µm values in the figure refer to equilibrium diameters). With turbulence distance travelled is less, but settling time is longer.

REHVA COVID-19 guidance document, Ver 4.1, How to operate HVAC and other building service systems to prevent the spread of the coronavirus (SARS-CoV-2) disease (COVID-19) in workplaces, 20210415.

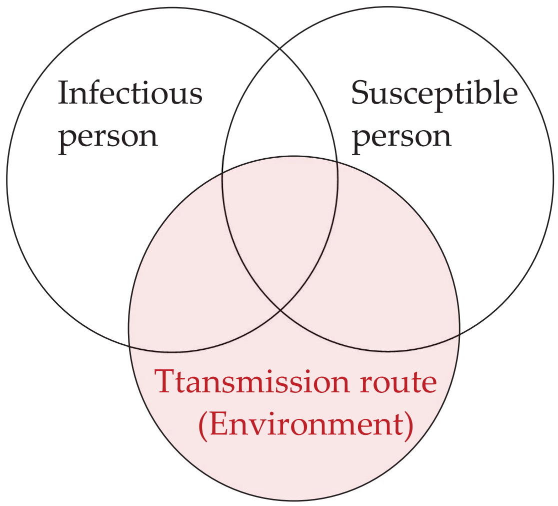


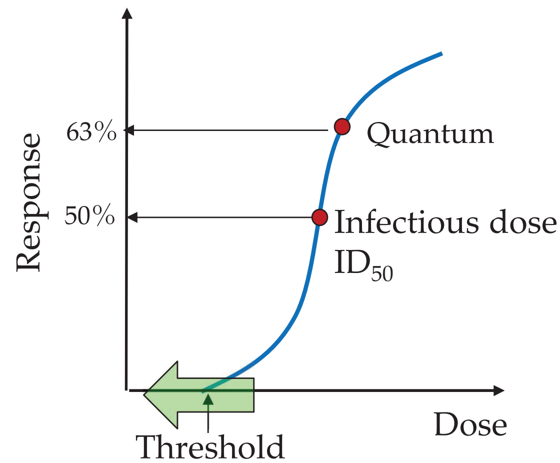
particle shrinkage: 25–50% of initial diameter

Fig. 1. Airborne transmission of respiratory viruses. Phases involved in the airborne transmission of virus-laden aerosols include (i) generation and exhalation; (ii) transport; and (iii) inhalation, deposition, and infection. Each phase is influenced by a combination of aerodynamic, anatomical, and environmental factors. (The sizes of virus-containing aerosols are not to scale.)

Source: Wang CC, et al. Airborne transmission of respiratory viruses, *Science* 373, 981 (2021). https://doi.org/10.1126/science.abd9149

Primary engineering mitigation strategies for respiratory infections





Three elements; infectious agent, host and environment

Mitigation strategies for respiratory infections by transmission route

Contact (direct, indirect)

- Hand hygiene
- Surfaces cleaning

In my presentation, <100μm particles classified to aerosol; aerosols contain droplets;
>100μm particles classified to droplets.
In the medical field, particles <5μm are called droplet nuclear.

Droplet, >100μm

- Avoid the 3Cs
- Wear a mask
- Ensure social distancing

>100μm; terminal settling velocity >0.3m/s
It only takes about 5 seconds for the lease to fall from a height of 1.5 meter to the floor.
Indoor airflow velocity 0.1m/s : estimate traveling distance
100μm: 0.5m; 50μm: 2m; 10μm: 52m; 5μm:324m

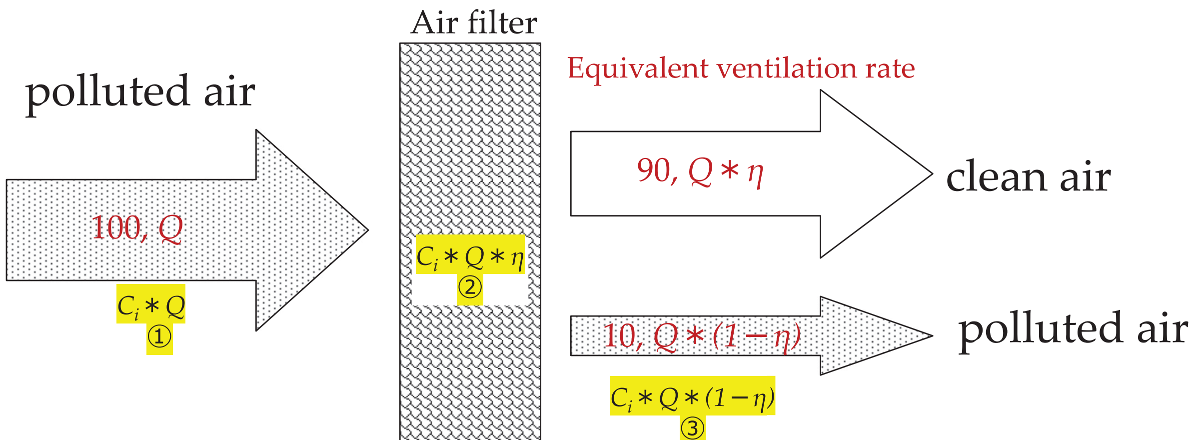
Aerosol, < 100μm

- Behavior change（avoid 3Cs、wear a mask）
- Ventilation
- Air purification（central system air filtration, local air filtration）
- GUV

Ventilation

Equivalent ventilation rate (air changes)

In case of the collection efficiency of the air filter is 90%

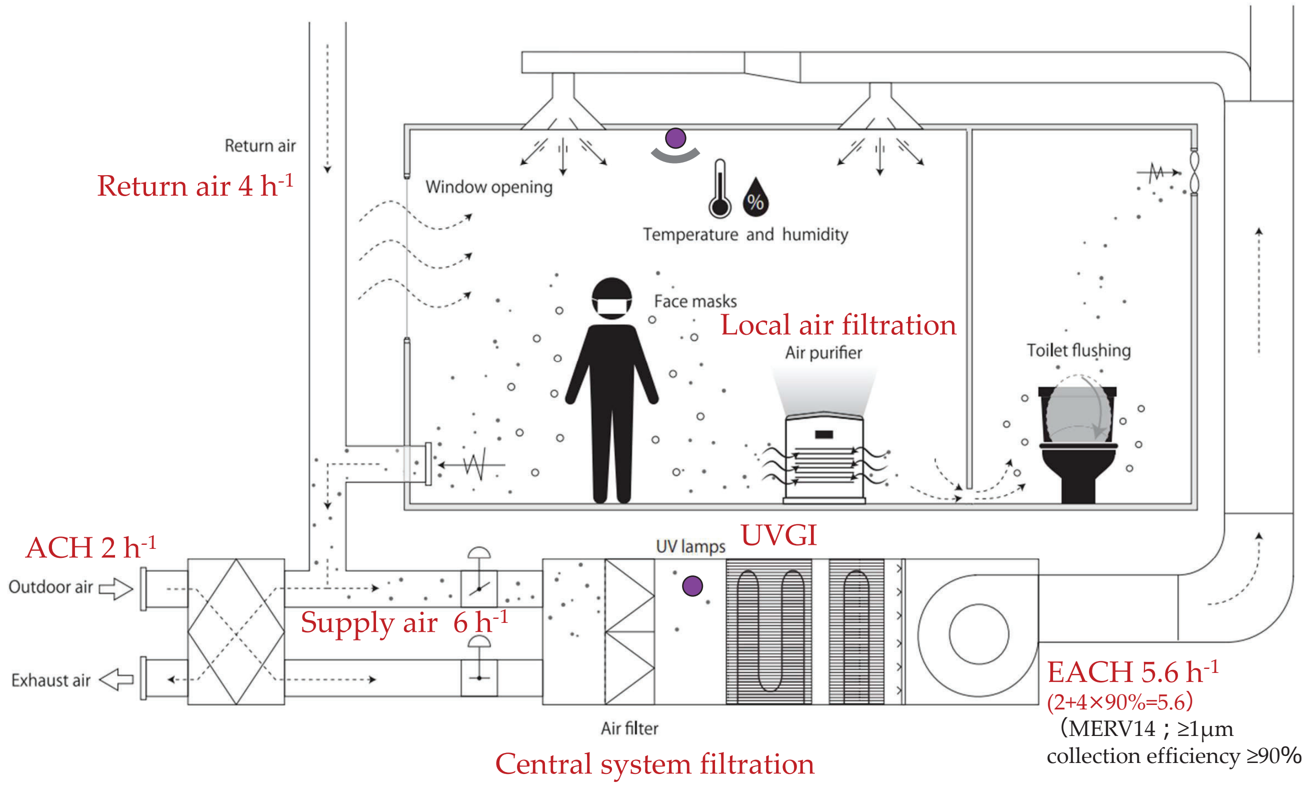


Mass balance: $C_i * Q - C_i * Q * \eta = C_i * Q * (1 - \eta)$

C: concentration, viruses/m^3; Q: ventilation rate, m^3/h

Central air conditioning system

Joseph G. Allen; Andrew M. Ibrahim. Indoor Air Changes and Potential Implications for SARS-CoV-2 Transmission. JAMA May 25, 2021 Volume 325, Number 20



Takashi Kurabuchi, U Yanagi, Masayuki Ogata, Masayuki Otsuka, Naoki Kagi, Yoshihide Yamamoto, Motoya Hayashi, Shinichi Tanabe, 2021. Operation of air-conditioning and sanitary equipment for SARS-CoV-2 infectious disease control. Japan Architectural Review. 4(4): 608–620.2021. https://doi.org/10.1002/2475-8876.12238

Azuma et al. Environmental Health and Preventive Medicine (2020) 25:66
https://doi.org/10.1186/s12199-020-00904-2

Environmental Health and Preventive Medicine

REVIEW ARTICLE Open Access

Environmental factors involved in SARS-CoV-2 transmission: effect and role of indoor environmental quality in the strategy for COVID-19 infection control

Kenichi Azuma[1*], U Yanagi[2], Naoki Kagi[3], Hoon Kim[4], Masayuki Ogata[5] and Motoya Hayashi[6]

$$P_I = \frac{C}{S} = 1 - e^{-\frac{Iqpt}{Q}}$$

P_I = probability of infection (-)
C = the number of infection cases (p)
S = number of susceptible individuals (p)
I = number of infector individuals
p = pulmonary ventilation rate of a person (m^3/hr)
q = quanta generation rate (1/hr)
t = exposure time (hr)
Q = room ventilation rate with clean air (m^3/hr)

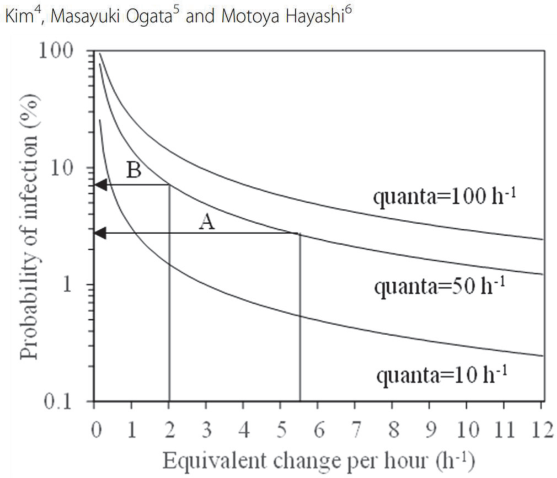


Figure 2. Probability of infection vs. equivalent change per hour
Conditions: I = 1 person; p = 0.48 m^3/hr; t = 8 hours; floor aera = 500 m^2; room volume =1,300 m_3

Ventilation rate for mitigating aerosol transmission

In the early 20th century, Billings proposed, and ASHRAE's predecessor society ASHVE recommended, outdoor airflow rates of 30 cfm/person (14.2 L/s-person) (51 m^3/h-person) based on considerations of infection prevention (Janssen. 1999)

systematic reviews of research on the quantitative relationship between risk of infection and ventilation rate have concluded that sufficient data to specify minimum ventilation rates for infection control does not exist (Li et al. 2007).

WHO recommended minimum outdoor airflow rates of 10 L/s-person (21.2 cfm/person) (36 m^3 /h-person) for nonhealthcare facilities and 60 L/s-person (127 cfm/person) (216 m^3 /h-person) for most spaces in health care facilities (WHO 2021).

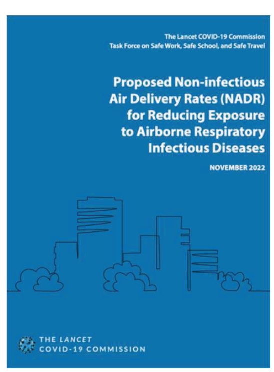
Source: ASHRAE Positions on Infectious Aerosols.
Approved by the ASHRAE Board of Directors October 13, 2022
Expires October 13, 2025

TABLE 1.
Proposed Non-infectious Air Delivery Rates (NADR) for Reducing Exposure to Airborne Respiratory Diseases; The Lancet COVID-19 Commission Task Force on Safe School, Safe Work, and Safe Travel

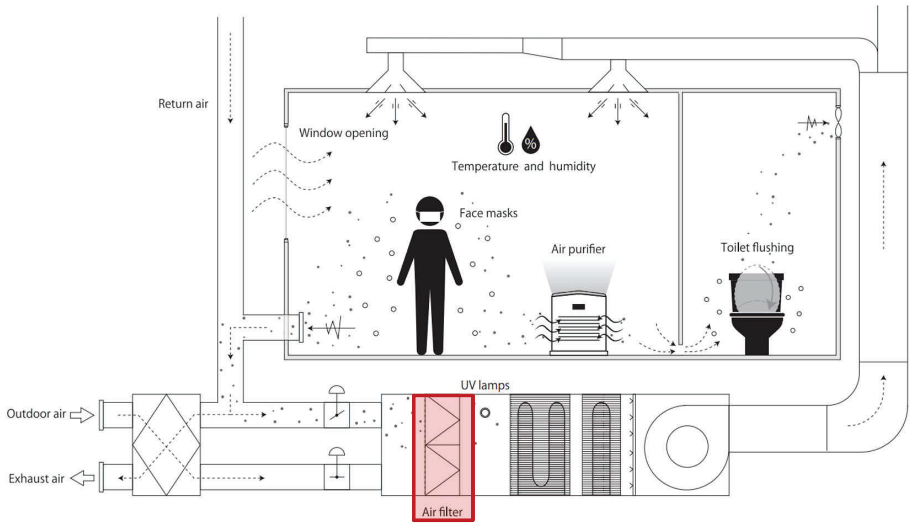
	Volumetric flow rate per volume	Volumetric flow rate per person		Volumetric flow rate per floor area	
	ACHe	cfm/person	L/s/person	cfm/ft²	L/s/m²
Good	4	21	36 m³/h · person 10	0.75 + ASHRAE minimum outdoor air ventilation	3.8 + ASHRAE minimum outdoor air ventilation
Better	6	30	50 m³/h · person 14	1.0 + ASHRAE minimum outdoor air ventilation	5.1 + ASHRAE minimum outdoor air ventilation
Best	>6	>30	>14	>1.0 + ASHRAE minimum outdoor air ventilation	>5.1 + ASHRAE minimum outdoor air ventilation

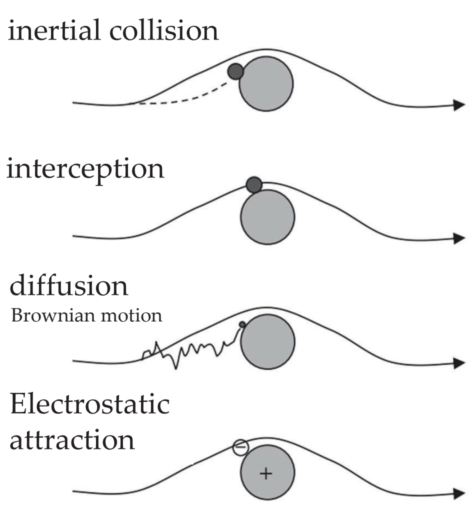
LANCET COVID-19 COMMISSION TASK FORCE ON SAFE WORK, SAFE SCHOOL, AND SAFE TRAVEL. NOVEMBER 2022.

https://static1.squarespace.com/static/5ef3652ab722df11fcb2ba5d/t/637740d40f35a9699a7fb05f/1668759764821/Lancet+Covid+Commission+TF+Report+Nov+2022.pdf



Filtration





An air filter collects suspended particles near the filter media by mechanisms such as inertial collision, interception, diffusion, and electrostatic attraction. Besides this, there is also a gravitational sedimentation

Minimum Efficiency Reporting Values(MERVs) and Filter Efficiencies by Particle Size

MERV	0.3-1.0 µm	1.0-3.0 µm	3.0-10 µm	Colorimetric method
1	n/a	n/a	E3<20	-
2	n/a	n/a	E3<20	-
3	n/a	n/a	E3<20	-
4	n/a	n/a	E3<20	-
5	n/a	n/a	20≦E3	-
6	n/a	n/a	35≦E3	-
7	n/a	n/a	50≦E3	40
8	n/a	$20 \leqq E_2$	70≦E3	40
9	n/a	$35 \leqq E_2$	75≦E3	50
10	n/a	$50 \leqq E_2$	80≦E3	50
11	$20 \leqq E_1$	$65 \leqq E_2$	85≦E3	60
12	$35 \leqq E_1$	$80 \leqq E_2$	90≦E3	75
13	$50 \leqq E_1$	$85 \leqq E_2$	90≦E3	90
14	$75 \leqq E_1$	$90 \leqq E_2$	95≦E3	95
15	$85 \leqq E_1$	$90 \leqq E_2$	95≦E3	98
16	$95 \leqq E_1$	$95 \leqq E_2$	95≦E3	-

n/a: not available,
Source: ASHRAE Standard 52.2-2017.

Takashi Kurabuchi, U Yanagi, Masayuki Ogata, Masayuki Otsuka, Naoki Kagi, Yoshihide Yamamoto, Motoya Hayashi, Shinichi Tanabe, 2021. Operation of air-conditioning and sanitary equipment for SARS-CoV-2 infectious disease control. *Japan Architectural Review*. 4(4): 608–620.2021. https://doi.org/10.1002/2475-8876.12238

SARS-CoV-2: measurement result 1

<1μm ND
1-4μm 1384 RNA copies/m^3 (40%)
>4μm 2000 RNA copies/m^3 (60%)

When using a MERV12 filter
＝40%×80%＋60%×90%
＝86%

When using a MERV13 filter
＝40%×85%＋60%×90%
＝88%

SARS-CoV-2: measurement result 2

<1μm ND
1-4μm 916 RNA copies/m^3 (50%)
>4μm 927 RNA copies/m^3 (50%)

When using a MERV12 filter
＝50%×90%＋50%×95%
＝85%

When using a MERV13 filter
＝50%×85%＋50%×95%
＝88%

Source: Chia PY, et al. Detection of air and surface contamination by SARS-CoV-2 in hospital rooms of infected patients. *Nature Communications* (2020) 11:2800https://doi.org/10.1038/s41467-020-16670-2

GUV（Germicidal Ultraviolet）

Microbial response to GUV exposure can be modeled as a single stage exponential decay or a two-stage exponential decay, and the response may include a shoulder.
Figure 5.1 illustrates the complete microbial decay curve.

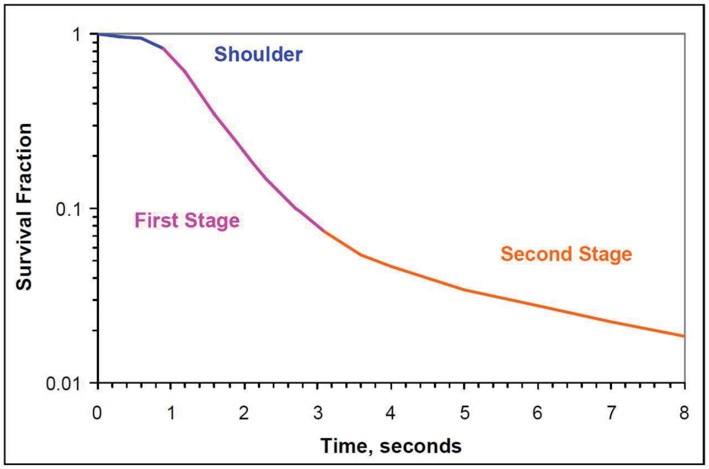


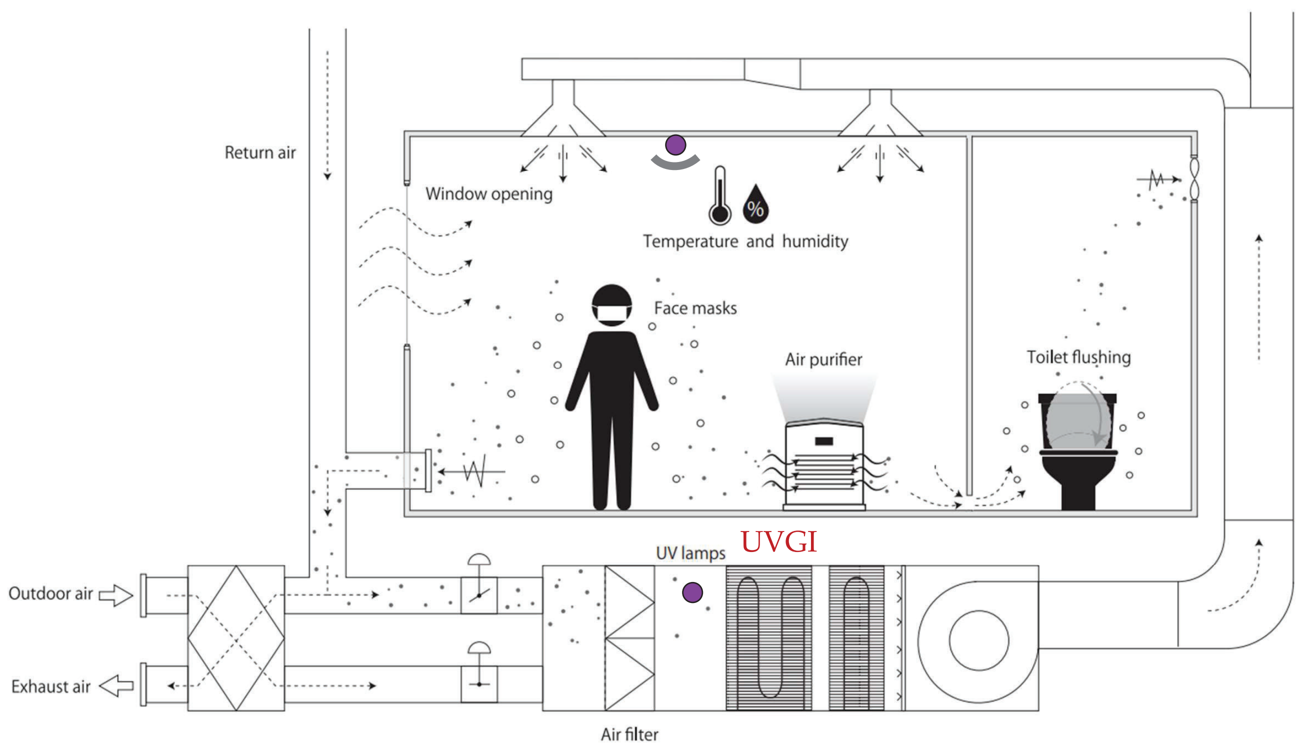
Figure 5.1: Two-stage Decay Curve with Shoulder for *Staphylococcus aureus*. Based on data from Sharp (1939).

Kowalski WJ, 2001. Design and Optimization of UVGI Air Disinfection Systems. A Thesis in Architectural Engineering. The Pennsylvania State University The Graduate School College of Engineering

$$S_t = e^{-kIt}$$

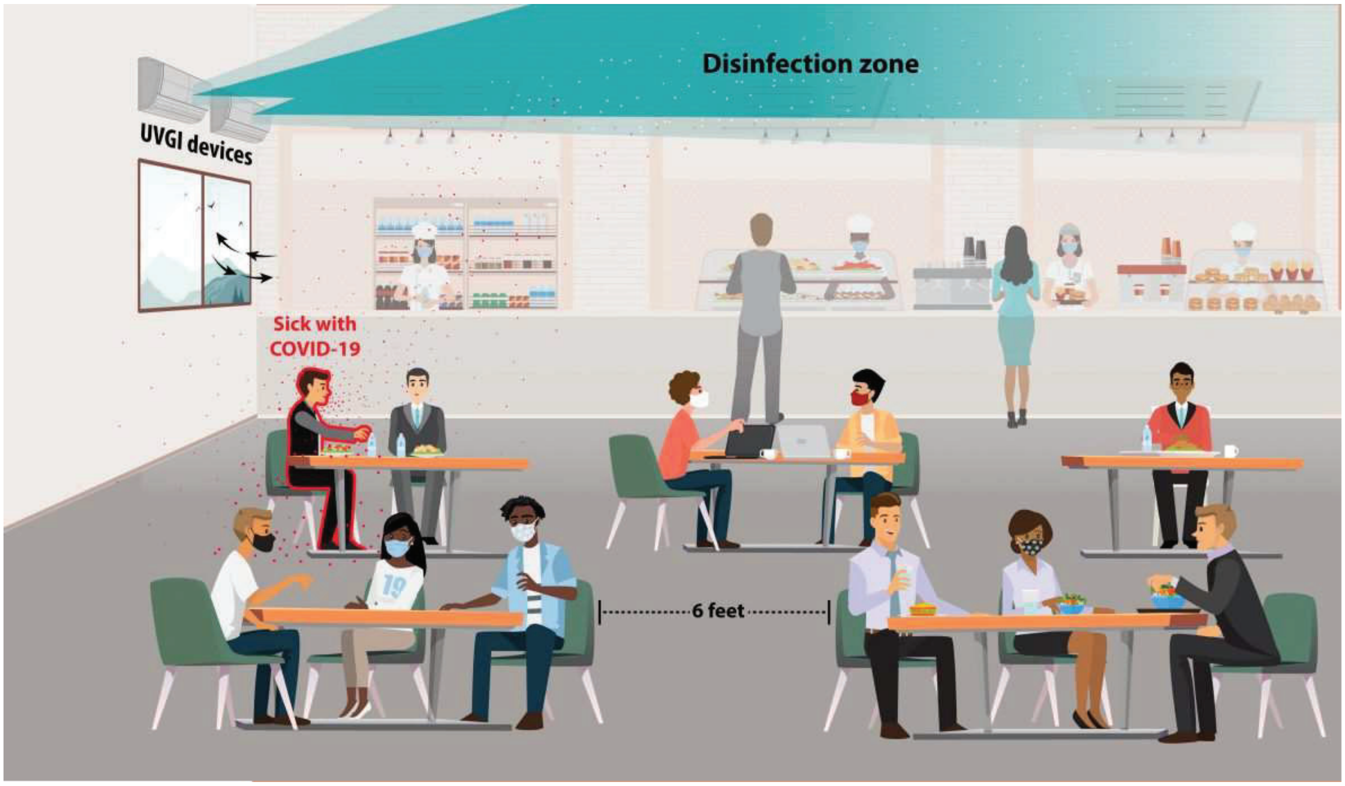
S_t : surviving fraction of initial microbial population (−)
k : standard rate constant (cm²/μW-s)
I : intensity of UVGI irradiation (μW/cm²)
t : time of exposure (s)

Central air conditioning system



Takashi Kurabuchi, U Yanagi, Masayuki Ogata, Masayuki Otsuka, Naoki Kagi, Yoshihide Yamamoto, Motoya Hayashi, Shinichi Tanabe, 2021. Operation of air-conditioning and sanitary equipment for SARS-CoV-2 infectious disease control. *Japan Architectural Review*. 4(4): 608–620.2021. https://doi.org/10.1002/2475-8876.12238

Upper-Room GUV



Source
https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation/uvgi.html

VIEWPOINT

Airborne Spread of SARS-CoV-2 and a Potential Role for Air Disinfection

Edward A. Nardell, MD
Brigham and Women's Hospital, Division of Global Health Equity, Harvard Medical School, Boston, Massachusetts.

Ruvandhi R. Nathavitharana, MD, MPH
Beth Israel Deaconess Medical Center, Division of Infectious Diseases, Harvard Medical School, Boston, Massachusetts.

Supplemental content

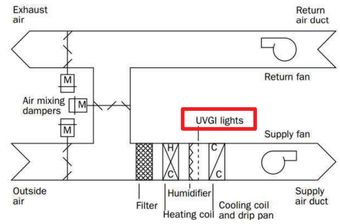
An April 2, 2020, expert consultation from the National Academies of Sciences, Engineering, and Medicine to the White House Office of Science and Technology Policy concluded that available studies are consistent with the potential aerosol spread of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), not only through coughing and sneezing, but by normal breathing.[1] This response to a White House request for a rapid review of the literature likely contributed to the recommendation from the US Centers for Disease Control and Prevention (CDC) that healthy persons wear nonmedical face coverings, when in public, to reduce virus spread from undiagnosed infectious cases.

Although clear evidence of person-to-person airborne transmission of SARS-CoV-2 has not been published, an airborne component of transmission is likely based on other respiratory viruses such as SARS, Middle East respiratory syndrome, and influenza. While air sampling for SARS-CoV-2, in a clinical setting, has demonstrated detectable viral RNA, the extent of transmis-ing costs when intake air must be heated or cooled and dehumidified. Portable room air cleaners may be a potential solution, but depending on room volume, their specified clean air delivery rates generally add too few equivalent air changes per hour to provide adequate protection against airborne infection. In contrast, commercially available upper-room GUV air disinfection (with an effective rate of air mixing) has been shown, in clinical settings, to reduce airborne tuberculosis transmission by 80%, equivalent to adding 24 room air changes per hour.[3]

In resource-limited settings, where air disinfection depends on natural ventilation, upper-room GUV may be increasingly important as windows are closed due to use of ductless air conditioners in response to global warming and severe outdoor air pollution. In resource-rich settings, upper-room GUV can be retrofitted into most areas with sufficient ceiling height. GUV technology is effective against viruses that have been tested, including influenza and SARS-CoV-1.[4,5]

JAMA July 14, 2020 Volume 324, Number 2

Effect of ultraviolet germicidal lights installed in office ventilation systems on workers' health and wellbeing: double-blind multiple crossover trial



Dick Menzies, Julia Popa, James A Hanley, Thomas Rand, Donald K Milton

Summary

Background Workers in modern office buildings frequently have unexplained work-related symptoms or combinations of symptoms. We assessed whether ultraviolet germicidal irradiation (UVGI) of drip pans and cooling coils within ventilation systems of office buildings would reduce microbial contamination, and thus occupants' work-related symptoms.

Methods We undertook a double blind, multiple crossover trial of 771 participants. In office buildings in Montreal, Canada, UVGI was alternately off for 12 weeks, then turned on for 4 weeks. We did this three times with UVGI on and three times with it off, for 48 consecutive weeks. Primary outcomes of self-reported work-related symptoms, and secondary outcomes of endotoxin and viable microbial concentrations in air and on surfaces, and other environmental covariates were measured six times.

Introduction

The office or office-like indoor environment is now the workplace for more than 70% of the work force in North America and western Europe.[1,2] Most of these people work in buildings with sealed exterior shells, in which highly automated heating, ventilation, and air conditioning systems, run by only one or two operators, control the indoor environment.[3] Many reports have documented health problems related to this work environment;[2–4] their resolution could result in health benefits for as many as 15 million workers, and economic benefits of $5–75 billion per year, in the USA alone.[2]

Most occurrences of illnesses in workers in these buildings, which are termed non-specific building-related illnesses[3] or symptoms[2], remain unexplained,[2,3] but evidence suggests that microbial contamination of building air-conditioning systems plays a part. Cross-sectional studies have consistently detected increased

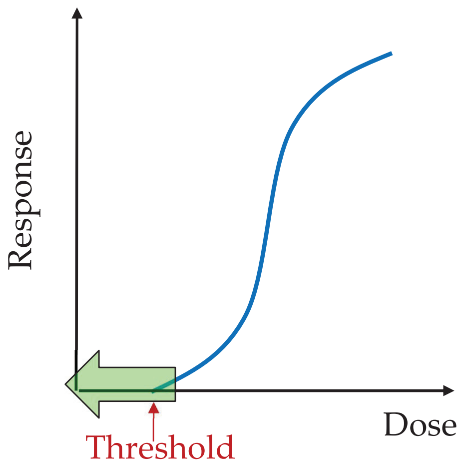
Table 7
The impact of UV radiation on coronaviruses.

UV type	Virus	UV irradiance	Distance	Time	Log reduction	Reference
UV-C (254 nm)	CCoV	7.1 μW/cm²	1 m	72 h	4.8	Pratelli (2008)
UV LED (267 nm)	HCoV-OC43	6–7 mJ/cm²	No data	60 s	3	Gerchman et al. (2020)
UV LED (297 nm)	HCoV-OC43	32 mJ/cm²	No data	60 s	3	Gerchman et al. (2020)
UV LED (286 nm)	HCoV-OC43	13 mJ/cm²	No data	90 s	3	Gerchman et al. (2020)
UV-C (254 nm)	MERS-CoV	–	1.22 m	5 min	5.91	Bedell et al. (2016)
UV-C (254 nm)	MERS-CoV	0.2 J/cm²	No data		>3.8	Eickmann et al. (2018)
UV-C (254 nm)	MERS-CoV	0.05 J/cm²	No data		2.9	Eickmann et al. (2018)
UV-A (365 nm)	SARS-CoV-1	2133 μW/cm²	3 cm	15 min	0	Darnell et al. (2004)
UV-C (254 nm)	SARS-CoV-1	134 μW/cm²	No data	15 min	5.3	Kariwa et al. (2006)
UV-C (254 nm)	SARS-CoV-1	134 μW/cm²	No data	60 min	6.3	Kariwa et al. (2006)
UV-C (254 nm)	SARS-CoV-1	4016 μW/cm²	3 cm	6 min	4 (below detection limit)	Darnell et al. (2004)
UV-C (260 nm)	SARS-CoV-1 (strain P9)	>90 μW/cm²	80 cm	60 min	6	Duan et al. (2003)
UV-A (365 nm)	SARS-CoV-2	540 mW/cm²	3 cm	9 min	1	Heilingloh et al. (2020)
UV-C (222 nm)	SARS-CoV-2	0.1 mW/cm²	24 cm	10 s	0.94	Kitagawa et al. (2020)
UV-C (222 nm)	SARS-CoV-2	0.1 mW/cm²	24 cm	30 s	2.51	Kitagawa et al. (2020)
UV-C (222 nm)	SARS-CoV-2	0.1 mW/cm²	24 cm	60 s	2.51	Kitagawa et al. (2020)
UV-C (222 nm)	SARS-CoV-2	0.1 mW/cm²	24 cm	300 s	2.51	Kitagawa et al. (2020)
UV-C (254 nm)	SARS-CoV-2	1940 mW/cm²	3 cm	9 min	Complete virus inactivation	Heilingloh et al. (2020)
UV-C (254 nm)	SARS-CoV-2	3.7 mJ/cm²	220 mm	–	3	Bianco et al. (2020)
UV-C (254 nm)	SARS-CoV-2	0.849 mW/cm²	No data	0.8 s	Reduced below a detectable level	Storm et al. (2020)
PX-UV	SARS-CoV-2	–	1 m	1 min	3.53	Simmons et al. (2020)
PX-UV	SARS-CoV-2	–	1 m	2 min	>4.52	Simmons et al. (2020)
PX-UV	SARS-CoV-2	–	1 m	5 min	>4.12	Simmons et al. (2020)
DUV LED	SARS-CoV-2	3.75 mJ/cm²	20 mm	1 s	0.9	Inagaki et al. (2020)
DUV LED	SARS-CoV-2	37.5 mJ/cm²	20 mm	10 s	3.1	Inagaki et al. (2020)
DUV LED	SARS-CoV-2	225 mJ/cm²	20 mm	60 s	>3.3	Inagaki et al. (2020)

CCoV — canine coronavirus, HCoV-OC43 — human coronavirus OC43, MERS-CoV — Middle Eastern respiratory syndrome coronavirus, SARS-CoV-1 — severe acute respiratory syndrome coronavirus 1, SARS-CoV-2 — severe acute respiratory syndrome coronavirus 2, PX-UV — pulsed-xenon ultraviolet light, UV LED — UV light-emitting diodes, DUV LED — deep ultraviolet light-emitting diode.

Source
Science of the Total Environment 770 (2021) 145260.
https://doi.org/10.1016/j.scitotenv.2021.145260

Summary



Dose-response relationship

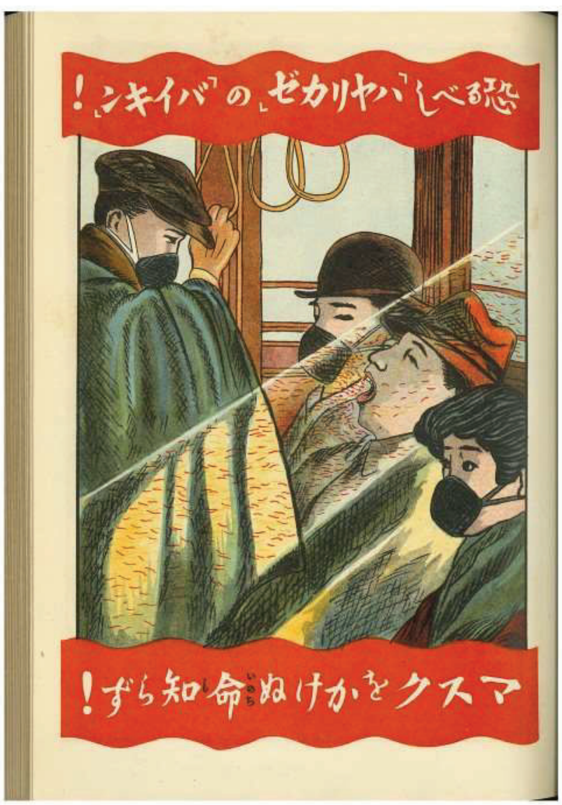
The main engineering mitigation strategies for respiratory infections is to control exposure load below the threshold, that is lowering the concentration of viable virus indoors.

1) Dilution by ventilation. Increasing the air dilution rate also means can shorten exposure time to the viruses.

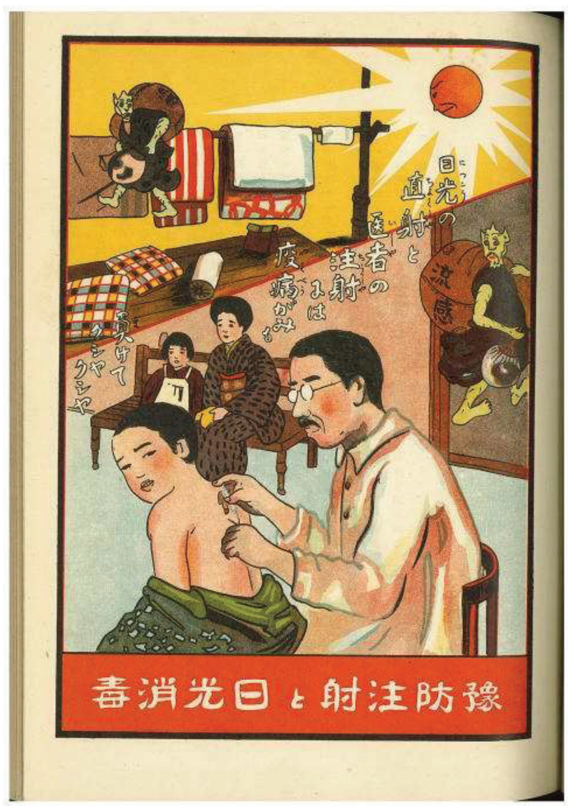
2) Removal by filtration and/or increase equivalent air changes per hour.

3) Sterilization by UV rays (GUV).

Mask: air filtration



Sunlight: UV sterilization



「Influenza」Japanese government (March, 1922)

Thank you for your attention !

AIVC workshop Tokyo
19 May 2023

Countermeasures against Indoor Aerosol Infection in Japan

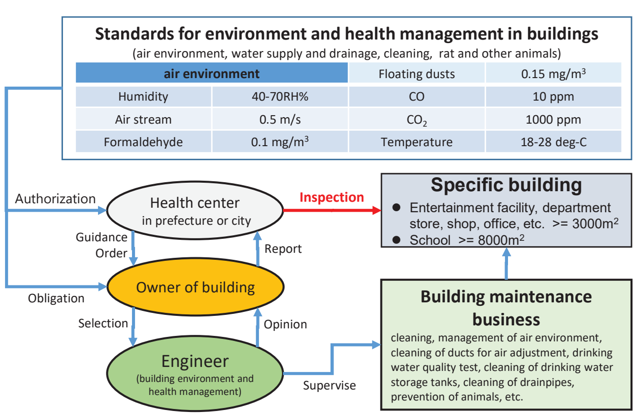
Motoya Hayashi
Laboratory of Environmental Space Design
Faculty of Engineering, Hokkaido University

Contents

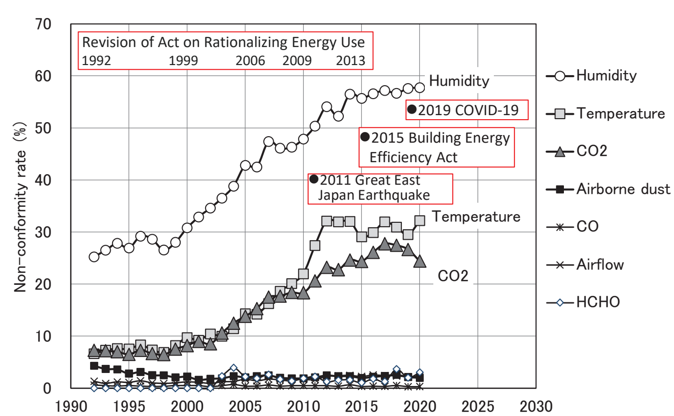
1.Introduction

The law for environmental health in buildings (LEHB) in 1970

- It was believed that sick building syndrome could be prevented by LEHB in the 1970s.
- The recent studies showed that the rate of sick building syndrome in offices is not low.
- One of the factors in the nonconformity rates of indoor air environment is thought to be energy saving in buildings since the 1990s.



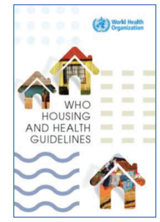
System based on the law for environmental health in buildings (LEHB)

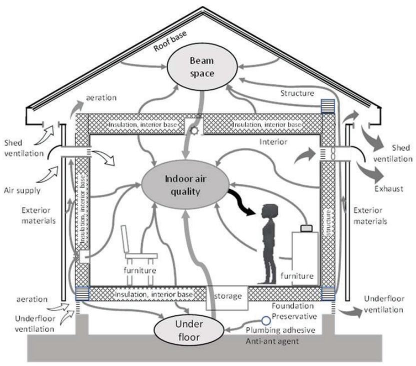


Non-conformity rate of indoor air environment

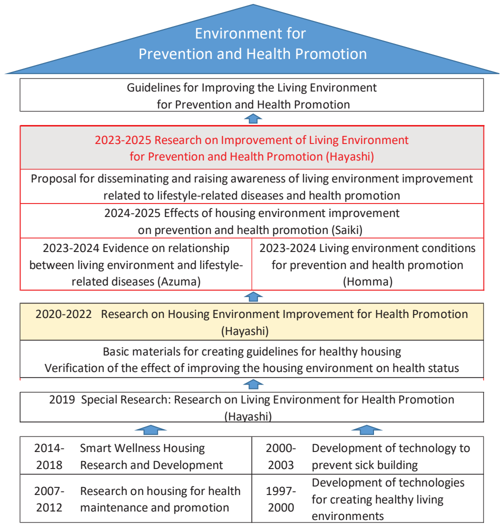
Health risks in Japanese houses caused by adaptation to new living style in cold and hot seasons

- Japanese houses based on wooden axis structure are suitable to to Japanese hot humid summer.
- Low insulation and much air leak caused low indoor temperature in winter and chemical pollution through the year .
- Housing improvement is necessary for healthy and sustainable living in today's high aged and carbon neutral society.

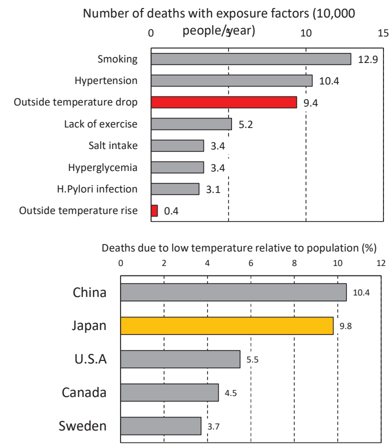




Sick house mechanism in Japanese houses



Project on Improvement of Houses for Health



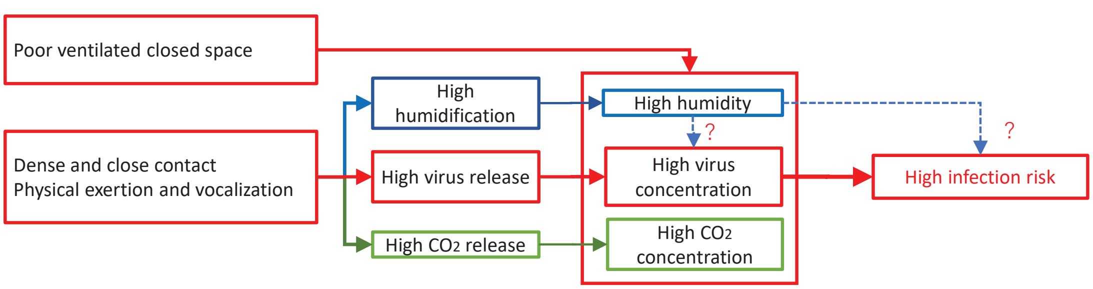
Influence of environments upon health

2. Countermeasures against COVID-19 in indoor spaces by the Japanese government

① The first analysis on indoor environment in COVID-19 cluster cases (MHLW Cluster Control Team, 27 February 2020)

The first analysis on the influences of indoor environment upon indoor infection

- Initial infection clusters occurred in a houseboat, a sport gym, a hospital and a temporary venue in Snow Festival.
- In all cases ventilation was poor and humidity was high.
- When people gather and have a lot of activity, they release vapor, CO_2 and virus.
- Poor ventilation leads to high humidity, the high concentrations of CO_2 and virus.
- Density and physical activities make the volume of virus release and suction larger.
- Influence of humidity upon virus inactivation and infection was unknown.



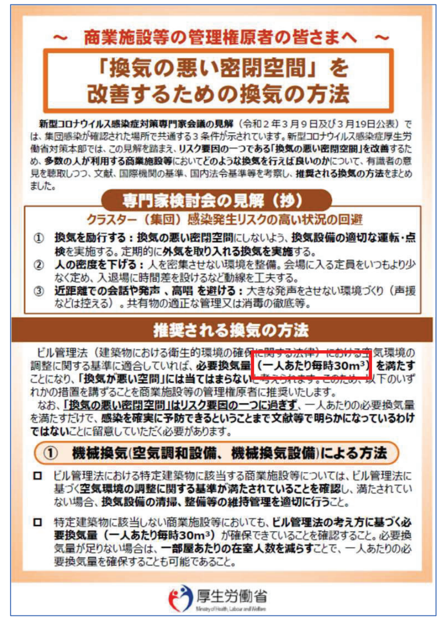
Analysis on Indoor environment and cluster infection

② Effective Ventilation Methods in "Closed and Poorly-Ventilated Indoor Spaces" in Commercial Facilities, etc. (MHLW,30 March 2020)

Three conditions of COVID-19 outbreaks

- The expert meeting against COVID-19, showed three conditions common in the spaces where outbreaks occurred (9 and 19 March 2020) .
- The emergency head-quarters of MHLW showed recommended ventilation methods "closed and poorly-ventilated spaces" in commercial facilities many people use.

3 conditions of COVID-19 outbreak



Effective Ventilation Methods in "Closed and Poorly-Ventilated Indoor Spaces" in Commercial Facilities, etc.

Ventilation methods in "closed and poorly-ventilated spaces"

As for mechanical ventilation systems

- The required ventilation rates in the Act on Maintenance of Sanitation in Buildings (30 m^3 per hour per person) should be assured.
- If the ventilation rates are lower, the number of persons in the space should be reduced.

As for opening windows

- Ventilation times should be twice or more per hour (opening a window wide for several minutes once or more per half an hour).
- If two or more windows are in a space, windows facing each other should be open to make an air current.

③ Measures against COVID-19 Concerning Summer Indoor Environment in Japan (NIPH, May 2020)

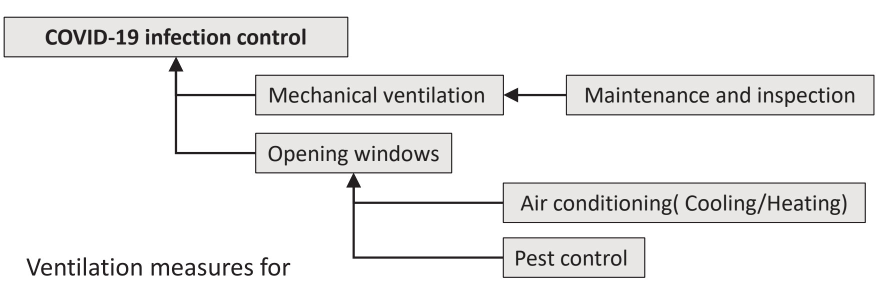
Motoya Hayashi, U Yanagi, Kenichi Azuma, Naoki Kagi, Masayuki Ogata, Shoichi Morimoto, Hirofumi Hayama, Taro Mori, Koki Kikuta, Shin-ichi Tanabe, Takashi Kurabuchi, Hiromi Yamada, Kenichi Kobayashi, Hoon Kim and Noriko Kaihara

[In every indoor space]

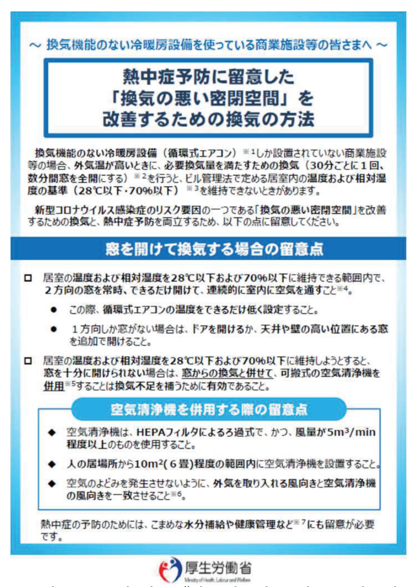
- In summer, air-conditioning is essential for good health, such as heat stroke prevention.
- General air-conditioners do not function as ventilators.
- When windows are open, it is necessary to prevent animal or insect pests from coming in.

[In case an air-conditioner and a ventilation system are equipped]

- The designed ventilation rates should always be gained by the inspection and maintenance of the equipment.



Ventilation measures for summer air-conditioning



Ventilation Methods in "Closed and Poorly-Ventilated Indoor Spaces" In summer, for heat stroke prevention

④ Effective Ventilation Methods in “Closed and Poorly-Ventilated Indoor Spaces” in Winter (MHLW, 27 November 2020)

Effective ventilation and the prevention of the negative influence of low indoor temperature on health.

- ✓ Continuous window opening, heating and adequate temperature and humidify (18 ℃ or higher and 40% or higher.)
- ✓ CO_2 monitor (under 1000 ppm) and air cleaners (HEPA filter, 5 m^3 /min/10 m^2)

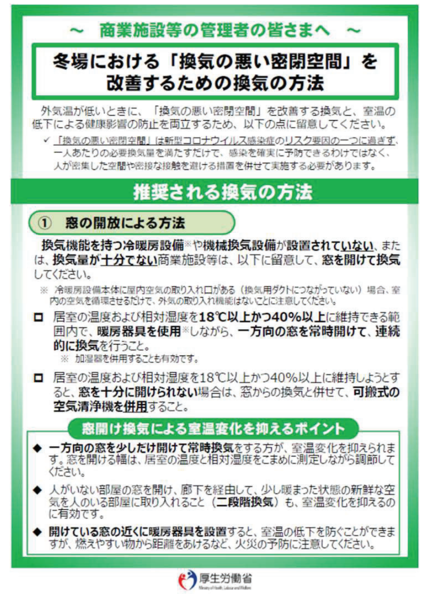
Ventilation using two sides opening | Ventilation using one side opening | Ventilation using one side opening and useless spaces

Season	Indoor condition*	Continuously opening	Contemporary opening	Ventilation methods and the characteristics
Cooling season	≦28°C (≦RH70%)	Two side Small opening	Two side Large opening	• Ventilation rates change with outside wind speed and direction. • Ventilation rates will be larger with two sides opening. • Opening area has to be controlled according to weather conditions (wind, rain, snow, etc.).
Mild season	18～28°C (RH40 ～70%)	Two sides Large opening		
Heating season	18°C≦ RH40%≦	One side Small opening	One side Large opening	• Ventilation rates change with the temperature difference between inside and outside. • Ventilation rates will be steady with one side opening and steady indoor temperature. • Supply air has to be heated using a heater near an opening and/or using the next space.

* Temperature and humidity have to be controlled according to people's physical condition.

Window opening methods in cooling season, heating season and mild season

Jpn Archit Rev | October 2021 | vol. 4 | no. 4 | 608–620


～ 商業施設等の管理者の皆さまへ ～

冬場における「換気の悪い密閉空間」を改善するための換気の方法

外気温が低いときに、「換気の悪い密閉空間」を改善する換気と、室温の低下による健康影響の防止を両立するため、以下の点に留意してください。

✓「換気の悪い密閉空間」は新型コロナウイルス感染症のリスク要因の一つに過ぎず、一人あたりの必要換気量を満たすだけで、感染を確実に予防できるわけではなく、人が密集した空間や密接な接触を避ける措置を併せて実施する必要があります。

推奨される換気の方法

① 窓の開放による方法

換気機能を持つ冷暖房設備※や機械換気設備が設置されていない、または、換気量が十分でない商業施設等は、以下に留意して、窓を開けて換気してください。

※ 冷暖房設備本体に屋内空気の取り入れ口がある（換気用ダクトにつながっていない）場合、室内の空気を循環させるだけで、外気の取り入れ機能はないことに注意してください。

□ 居室の温度および相対湿度を18℃以上かつ40%以上に維持できる範囲内で、暖房器具を使用※しながら、一方向の窓を常時開けて、連続的に換気を行うこと。
※ 加湿器を併用することも有効です。

□ 居室の温度および相対湿度を18℃以上かつ40%以上に維持しようとすると、窓を十分に開けられない場合は、窓からの換気と併せて、可搬式の空気清浄機を併用すること。

窓開け換気による室温変化を抑えるポイント

◆ 一方向の窓を少しだけ開けて常時換気をする方が、室温変化を抑えられます。窓を開ける幅は、居室の温度と相対湿度をこまめに測定しながら調節してください。

◆ 人がいない部屋の窓を開け、廊下を経由して、少し暖まった状態の新鮮な空気を人のいる部屋に取り入れること（二段階換気）も、室温変化を抑えるのに有効です。

◆ 開けている窓の近くに暖房器具を設置すると、室温の低下を防ぐことができますが、燃えやすい物から距離をあけるなど、火災の予防に注意してください。

厚生労働省

Ventilation Methods in “Closed and Poorly-Ventilated Indoor Spaces” In winter

⑤ Opinion by Advisory Board on COVID-19 Control (MHLW,30 July 2020)

Three conditions of COVID-19 outbreaks

- At the first stage of the COVID-19 pandemic, its infection route was assumed to be through “droplets containing virus” and “contact with virus”.
- However, **in Japan, around the time when the basic policies toward COVID-19 were adopted in February 2020**, other infection routes were pointed out and the measures were taken.
- Recently “**micro-droplet infection**” has been recognized in the world. However, while walking outside, shopping or dining at a shop or a restaurant where infection control measures are taken, or commuting on well-ventilated trains, the possibility of “micro-droplet infection” is assumed to be weak.

⑥ Infection Routes of SARS-CoV-2 (National Institute of Infectious Diseases (NID), 28 March 2022)

A person becomes infected with SARS-CoV-2 through the exposure of an aerosol containing infectious virus emitted from the nose or mouth of an infected person.

The main three infection routes are:

i. breathing in an aerosol containing virus floating in the air (**aerosol infection**)
ii. the attachment of droplets containing the virus on bare mucous membranes such as mouths, noses, or eyes (**droplet infection**)
iii. fingers touching bare mucous membranes after touching droplets containing virus or touching the surface of things with virus (**contact infection**)

⑧ Effective Ventilation Methods in an Emergent Proposal (Subcommittee on Novel Coronavirus Disease Control,14 July 2022)

① To prevent **Aerosol Infection** ＋② **Droplet Infection** **in necessary**

① Measures to prevent Aerosol Infection

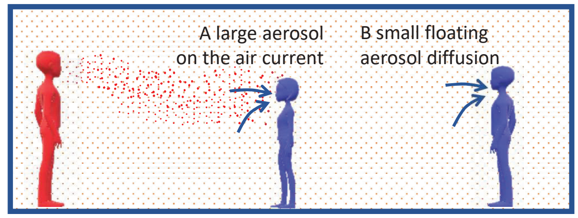
The relationship between infectiousness and the particle size of aerosol has not been clear, so the following **A and B** is desirable

A. Prevent infection caused by large aerosol on air current

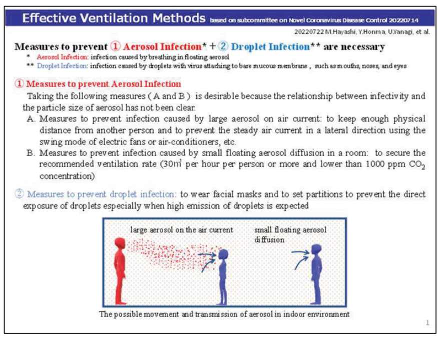
⇒ Physical distance, Prevent the steady air current.

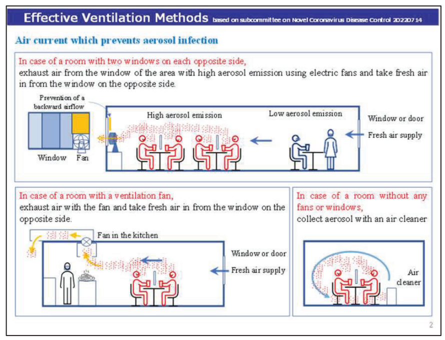
B. Prevent infection caused by small floating aerosol diffusion

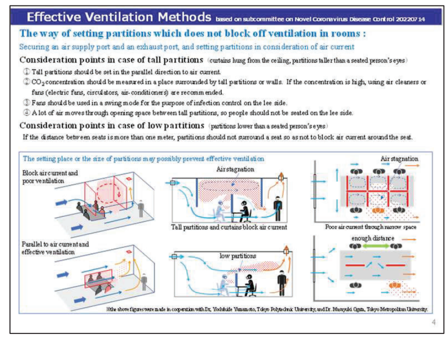
⇒ Ventilation rate 30 m^3/h person, CO_2 under 1000ppm.



The possible movement and transmission of aerosol in indoor environment

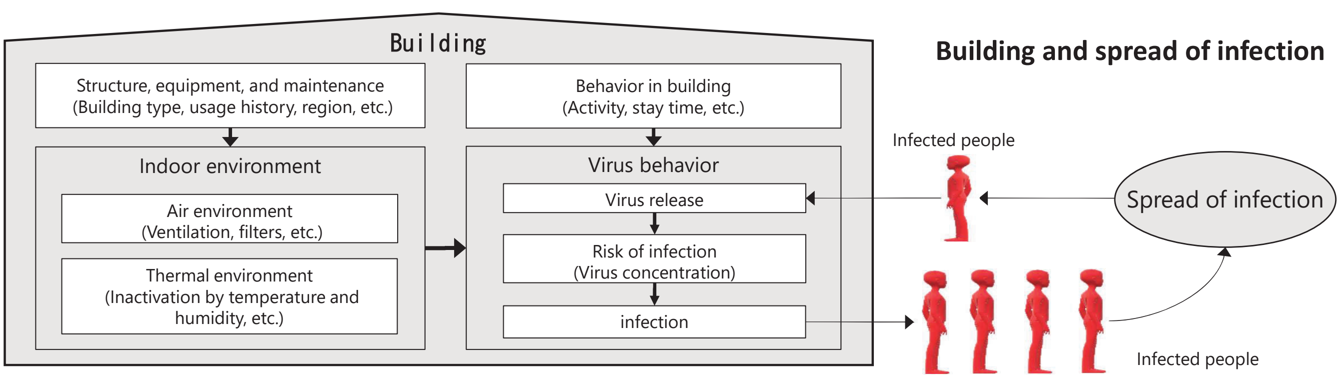






Atmosphere 2023, 14, 150. https://doi.org/10.3390/atmos14010150

3.Investigations on the building environment of COVID-19 outbreak cases



Building and spread of infection

Infection mechanisms in buildings

1. Infectious and medical effects of viruses
2. Effects of Indoor Environment and Effects of Infection Control
3. Virus infectiousness, countermeasure effect, and scale of damage

"Research on risk assessment of emerging and re-emerging infectious diseases and implementing crisis management functions"

Health and Labor Sciences Research Grant.

I. Infection mechanism and countermeasure effect in the indoor environment

II. Investigations on building environments of COVID-19 outbreak cases

Exhibition halls, restaurants with music and entertainment, offices, call centers, hospitals, facilities for the elderly, ice arenas, etc.

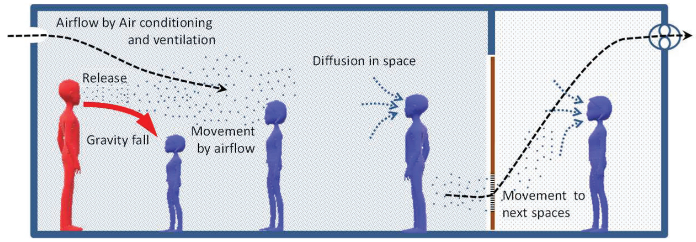
Ⅱ. Investigations on building environments of COVID-19 outbreak cases

Motoya Hayashi, Hirofumi Hayama, Mori taro ,Koki Kikuta, Yoshinori Honma, Naoki Kagi, U Yanagi, Asako Hasegawa, Sayaka Murata, Kenichi Kobayashi, Michiko Bando Hoon Kim Isao, Noriko Kaihara, Novel Coronavirus Infection Control Headquarters, Cluster Control Team, National Institute of Infectious Diseases, Local governments, public health centers, facility officials, related organizations, companies

Basics of ventilation measures to prevent

A. Infection caused by large aerosol on air current

B. Infection caused by small floating aerosol diffusion



Movement of floating droplet (aerosol) in building

Consideration of countermeasures

- Investigation on the influences of ventilation properties upon the cluster infection.
- Improvement proposals (usage restriction, emergency response, repair, etc.)

Measurement of indoor air environment

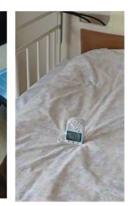
- Air conditioning and ventilation system
- Operation and maintenance
- Airflow rates and pressure difference between rooms
- CO_2 concentrations monitoring data
- Experiments on aerosol movement using tracers(aerosol, smoke, CO_2)



① Wards for uninfected patients in hospitals

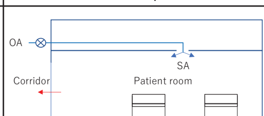
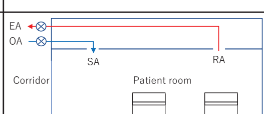
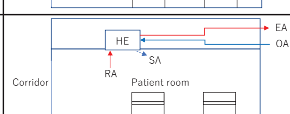
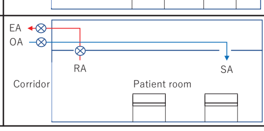
- 8 hospitals were investigated, from Hokkaido to Kyushu .
- The age after construction was form 10 to over 30 years.
- Poor ventilation was recognized in 4 hospitals, caused by the aging of the equipment, energy and cost saving.


CO_2 generation by dry ice



CO_2 concentration meter

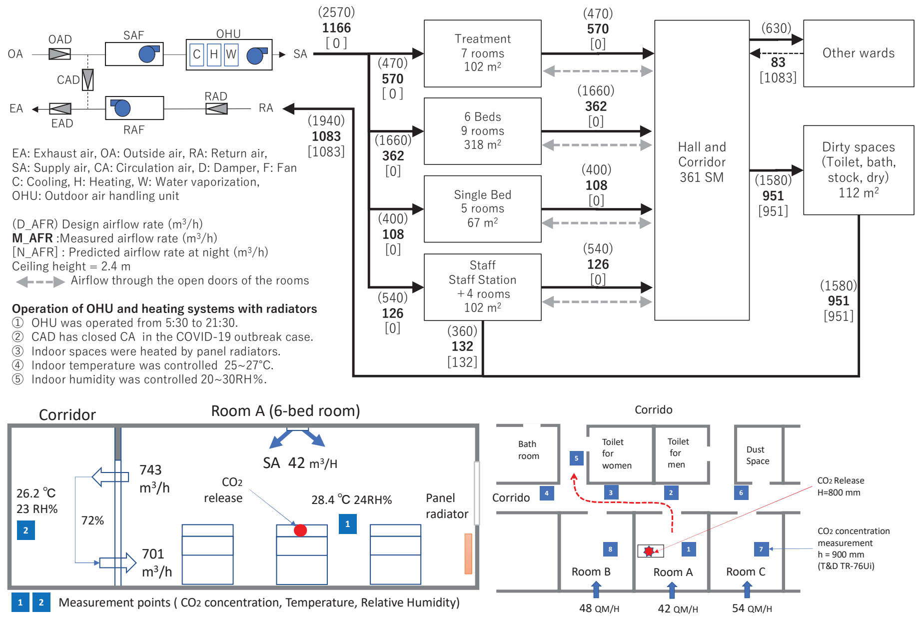
Pressure gauge

Hospital	Number of infected people	Ventilation of patient room	Ventilation properties and the operation of air conditioning and ventilation system
A	Approx.300 in heating season		i. NHF* was used for a week in a treatment room where ventilation rate was 10% of the design value. ii. The ventilation rate of the ward reduced to 30% of the design value. iii. Outside air supply stopped at night to keep indoor temperature. iv. Air supply rates were 4-31% of the design value in patient rooms. v. Aerosol flowed from patient rooms to corridors, especially when the door was opened.
B	Approx.50 in cooling season		i. NHF* was used in patient rooms. ii. Air supply rates were close to the design value, but exhaust rates were about 50% of design value. iii. Air supply stopped for about 3 minutes every 30 minutes to save electricity cost. iv. Aerosol flowed from patient rooms to corridors especially when air supply stopped.
C	Approx.150 in heating season		i. NHF* was used in patient rooms. ii. Supply rates and exhaust rates were about 50% of the capacity of heat exchange unites, in patient rooms.
D	Approx.10		i. NHF* weas used in patient rooms. ii. Supply rates and exhaust rates were about 50% of the design values, in patient rooms.

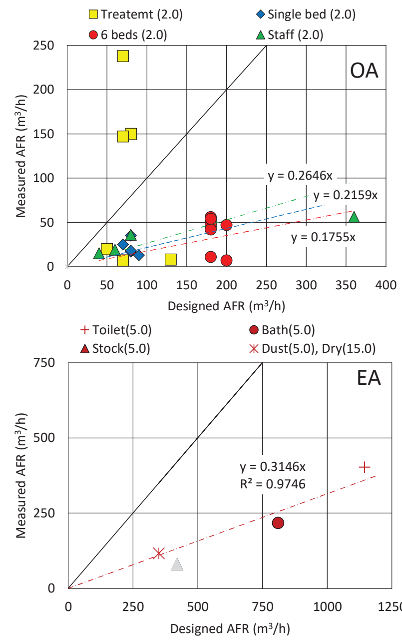
＊ NHF(nasal high flow): high oxygen concentration and humidity is sent continuously from a tube attached to the nose

Hospital A

- Ventilation and airflow in the ward where a cluster occurred in winter.



Ventilation rates and airflow by tracer gas, etc.

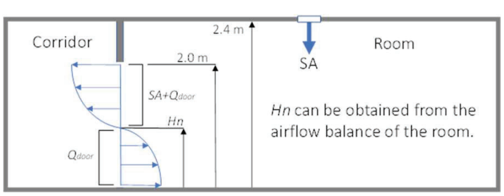


Measured airflow rates and the design value

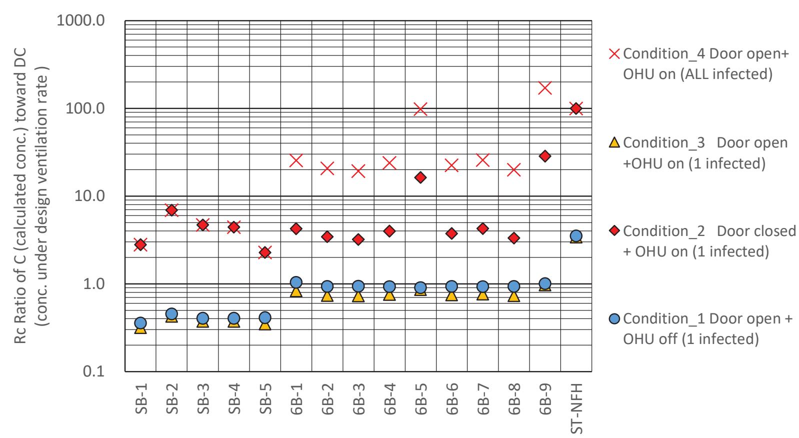
Hospital A

- The ventilation rates were calculated in rooms of the ward using measured data on ventilation and indoor environment.
- The expiratory concentrations from the infected were calculated and compared with the concentrations when the ventilation rates meet to the design values.
- The ratio of the expiratory concentrations toward those under the design ventilation rates, were 0.3 – 7 in Single bedroom (SB-1~6), 0.3 – 170 in 6 bed-room (6b-1~9) and 3.4-100 in treatment room (ST-NFH).

- NHF was initially used in poorly ventilated (10% of the design value) treatment room.
- During the outbreak, large numbers of patients used 6 bed-rooms.
- **The possibility of Aerosol infection** could not be denied in poor ventilated rooms in the ward.



Calculation of ventilation rates in heated patient rooms using measured data on ventilation, etc.



Predicted ratios of the expiratory concentrations from the infected, toward those when the ventilation rates meet to the design values

MHLW Notice "About ventilation equipment when treating new coronavirus infection" 7 April 2021

Health Crisis Report
according to the investigation results
(30 March 2021)

Administrative liaison by MHLW
"About ventilation equipment when treating new coronavirus infection" (7 April 2021)

- The Japanese government has already noticed that adequate ventilation should be provided in the treatment of patients infected or possibly infected with COVID-19.
- The recent investigation showed the influence of the poor ventilation upon the outbreaks in hospitals.
- The following ventilation measures are proposed here.

① Inspection (the measurement of ventilation rate, etc.)
② Cleaning and repair of ventilation equipment, etc.
③ Temporary measures until the improvement of ventilation system (opening windows ,etc.)

Cluster infection in hospitals

In-room infection

Out-of-room infection

Poor ventilation (OA, EA)
①Duct shedding (construction, renovation, earthquake, etc.)
②Narrowing of ducts (dust in exhaust, etc.)
③Damper close (earthquake, mechanical vibration, etc.)
④Ventilation stop for energy-saving, cost-saving and keeping indoor air environment

Poor airflow and air pressure
①Opening door of patient room
②Loss of supply/exhaust balance

Inspection of air conditioning and ventilation equipment
①Confirmation of ventilation (air volume, airflow direction measurement)
②Optimization of air conditioning and ventilation (continuous operation)
③Cleaning filters, fans, etc.

First aid
①Window opening ventilation
②Air Purifier
③Temporary ventilation equipment (exhaust system, etc.)
④Temporary partitions (seats, etc.) Consideration for opening and closing room doors

Cleaning and renewal of air conditioning and ventilation equipment, renewal of buildings

Cluster infection due to poor ventilation and countermeasures

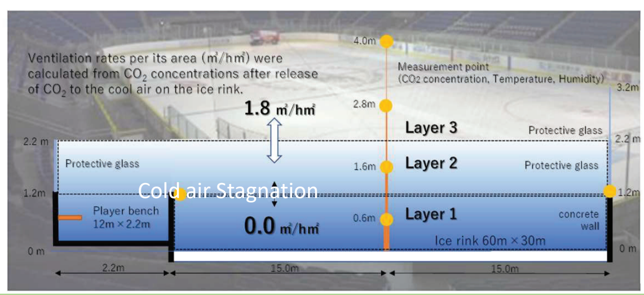
② Ice arenas for ice hockey

- Large infection-clusters occurred in two ice arenas in Hokkaido.

National High School Selection Ice Hockey Tournament

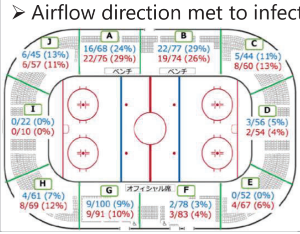
Investigation
- Contact and droplet infection in practices and tournaments.
- Possibility of aerosol infection due to ice arena-specific behavior (heavy physical exertion) and ventilation properties (stagnation of cold air) .

Measures to prevent aerosol infection among players
- ✓ Remove perimeter panel to improve ventilation on ice rink
- ✓ Set fans to reduce aerosol concentration around players' benches
- ✓ Set CO2 concentration monitor to check ventilation efficiency

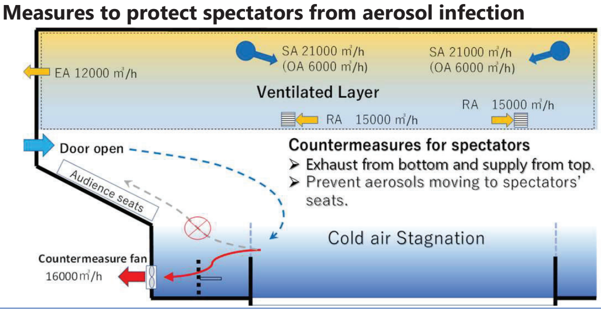


Asia League Ice Hockey Tournament

Investigation
- Many players released virus with heavy physical exertion on ice rink.
- Aerosol moved to spectators with air conditioning airflow.
- Airflow direction met to infection ratios at each seat area.



Measures to protect spectators from aerosol infection

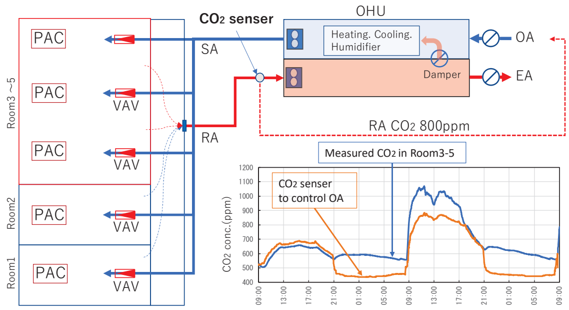


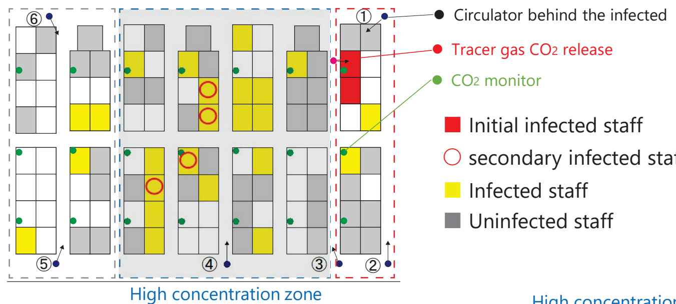
③ Office spaces used as call centers

- Infection-clusters occurred in many office spaces used as call centers.

Investigation

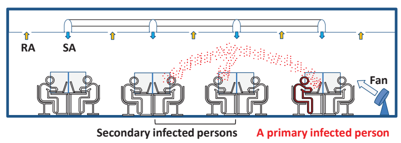
➢ Possibility of aerosol infection due to
telephone call staff's continuous talking at desk with 3 side partition to prevent droplet infection,
guidance stuff's access to desks and talking with telephone staff in high concentration space,
poor ventilation caused by malfunction of ventilation system with a CO_2 sensor,
high concentration zone by steady air current of a circulator behind infected staff.

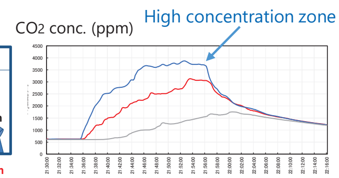




Measures to prevent aerosol infection

- ✓ Repair CO_2 sensors and ventilation control
- ✓ Removal of circulators and Installation of air purifiers
- ✓ Reduction of staff density





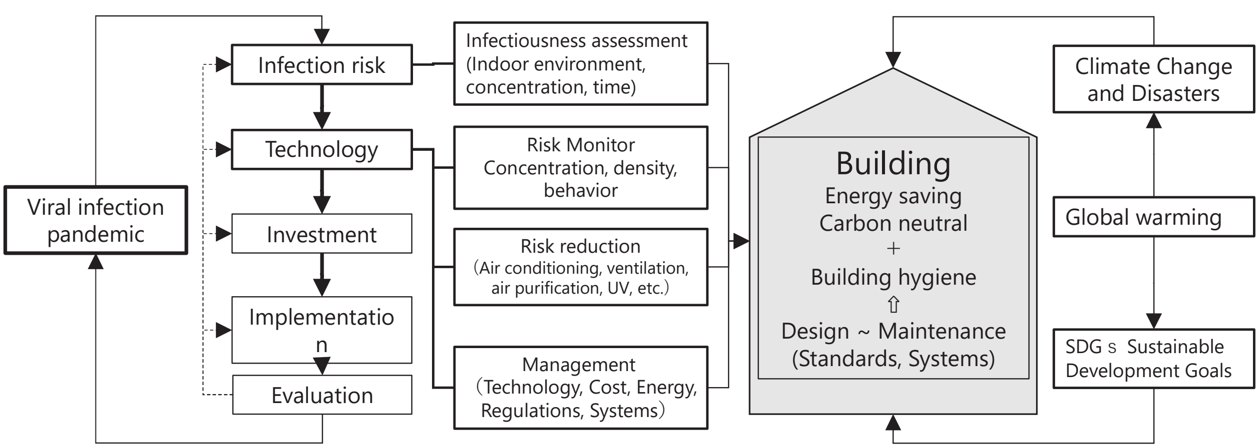
4. Infection control and Energy Conservation in Buildings for Post-COVID-19

"Committee on Air Conditioning, Ventilation in the Post-COVID-19" by Institute for Built Environment and Carbon Neutral for SDGs

Global warming influences upon public health now and in future.

➢ Global warming increases the risk of emerging and re-emerging infectious diseases by the change of ecosystem and the thaw of permafrost.

➢ Effective solution sets for both infection control and warming control is an emergent task in architecture as well as other fields.



Research and developments for energy saving and health in building under the age of viral infection pandemic and global warming

Conclusion

- In large buildings, poor air environment has increased since the 1990s.
- In houses, poor air environment influenced upon the health of the residents before.

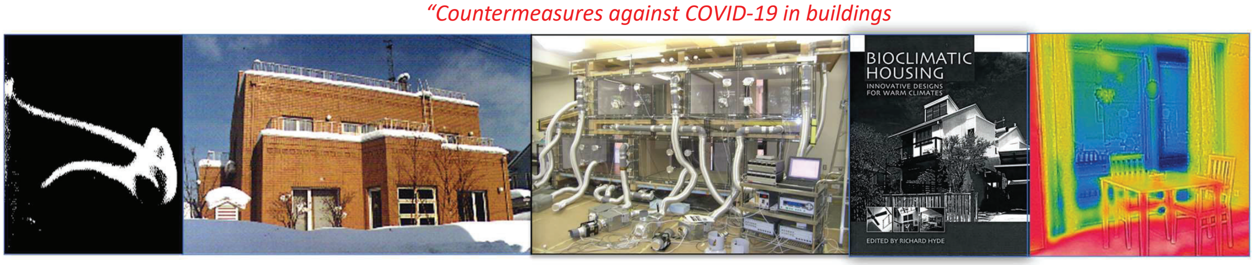
- Under COVID-19 pandemic, ventilation measures were carried out immediately (March 2020).
- Soon, the influences of ventilation measures upon indoor environment were considered (May 2020, February 2020).
- Investigations on the air environment of cluster cases showed the influence of poor ventilation upon aerosol infection (2020-2022).
- Effective ventilation methods to prevent two types of aerosol infection were recommended (July 2022).

- For “Post COVID-19”, the balance of infection control and energy saving must be studied.

Thank you very much.

Motoya Hayashi

- 1979-1988 Hokkaido University Faculty of Engineering, graduate school of Engineering (Sapporo)
  “Natural ventilation of buildings considering wind pressure fluctuation “
- 1988-1999 Sekisuihouse ltd. (Tokyo, Osaka, Shizuoka) Tokyo planning office and Research institute
  “Adaptation of light steal structure to cold climate”, “Hybrid ventilation system “
- 1999-2014 Miyagi Gakuin Women’s University Department of Lifestyle and Space Design (Sendai)
  “Countermeasures against Sick house problems (Building Standard Law on Sick House Issues, 2003)
  “Annex38 “Sustainable Solar Housing (IEA 2000-2005)”
- 2014- National Institute of Public Health (Wako) Research managing director
  “Environmental health in buildings(LEHB1970)”, “Planning of welfare facility for infection control”
- 2020 Hokkaido University Faculty of Engineering (Sapporo)
  “Countermeasures against COVID-19 in buildings



Using pathogen-free air to reduce infection risks in buildings

Dr Christopher Iddon
Dr Benjamin Jones

University College London
University of Nottingham

AIRBODS

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Airborne Infection Reduction through Building Operation and Design for SARS-CoV-2 (AIRBODS)

- UKRI funded
- Lead by Professor Malcolm Cook
- Loughborough University, University College London, the University of Cambridge, the University of Nottingham, the University of Sheffield and London South Bank University
- Aims to quantify the risk of transmission of SARS-CoV-2 in buildings, and thereby offer guidance on the ventilation operation and future design of non-domestic buildings
- Participating in the UK Government's Events Research Programme

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Overview

- Mass balance model
- Uncertainty in viral emission rates
- Personal risk
- Population risk

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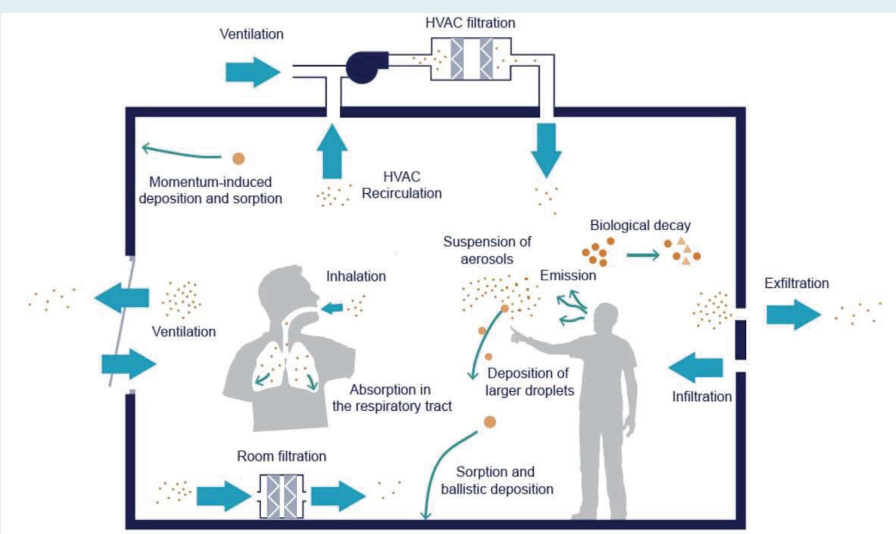
Mass balance model



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Mass balance model

1. Gains
    1. Emission from a person, G (#/s)
    2. Entry from outside via ventilation [none]
    3. Entry from outside via infiltration [none]
    4. Virus already present in the space [none]
2. Losses
    1. Dilution via ventilation, ψ (s^{-1})
    2. Surface deposition, ϒ (s^{-1})
    3. Biological decay and UVC denaturing, λ (s^{-1})
    4. Respiratory tract absorption, ζ (s^{-1})
    5. Filtration, ω (s^{-1})

Here, $\phi = \psi + \Upsilon + \lambda + \zeta + \omega$

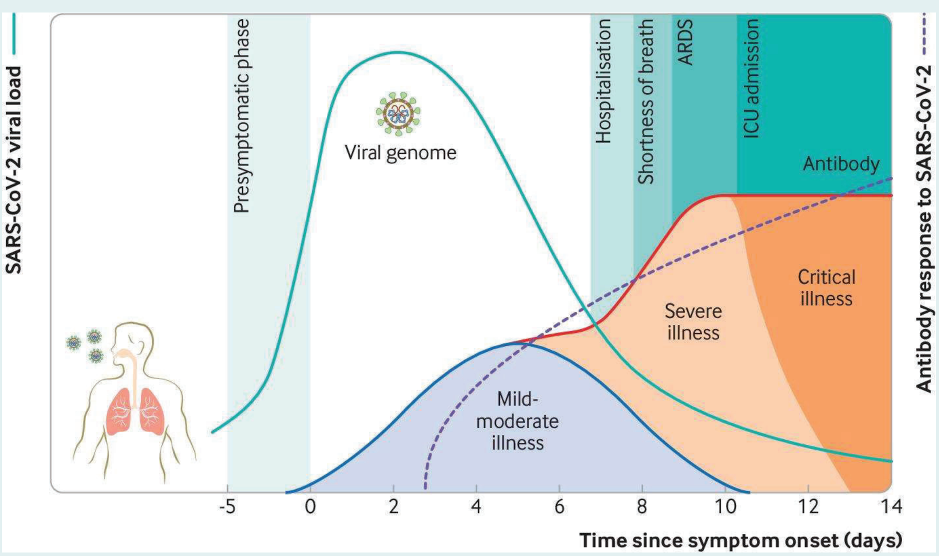
The steady state number of viral genome copies in a space as a function of time is:

$$n_{ss} = \frac{G}{\phi}$$

The concentration of viral genome copies is space dependent

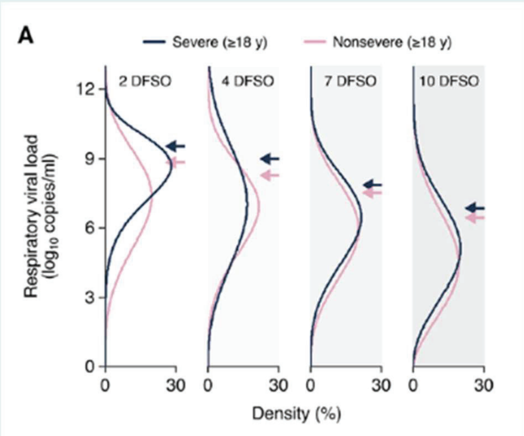
$$n_{ss}/m^3$$

Viral load



Cevik, M. *et al.* (2020) 'Virology, transmission, and pathogenesis of SARS-CoV-2', *BMJ (Clinical research ed.)*, 371, p. m3862. doi: 10.1136/bmj.m3862

Viral load



Chen et al (2021) SARS-CoV-2 shedding dynamics across the respiratory tract, sex, and disease severity for adult and pediatric COVID-19 https://doi.org/10.7554/eLife.70458

Viral load – historical perspective

Variability in the infectivity of different patients was far greater than we realized at the time of the previous report. It is now apparent that a statistical mean infectivity for far advanced tuberculosis cannot be approximated by taking the average infectivity of any 6 patients in this stage of the disease. Two of our patients produced 19 out of 22 infections in guinea pigs even though 62 patients occupied the ward during the period under consideration. The astounding infectivity of these two patients in comparison with the others was related in part to the infectivity of their sputum. The number of organisms seen on smear was high and the infectivity for guinea pigs exposed to artificially atomized sputum was also high.

Aerial dissemination of pulmonary tuberculosis: A two year study of contagion in a tuberculosis ward
Riley *et al* 1959

These calculations suggest that the index case may have been exceptionally infectious and that the secondaries may have been, on the average, only about one tenth as infectious

Airborne spread of measles in a suburban elementary school
Riley *et al* 1978

doi 10.1093/oxfordjournals.aje.a120069
doi 10.1093/oxfordjournals.aje.a112560

Relative Exposure Index

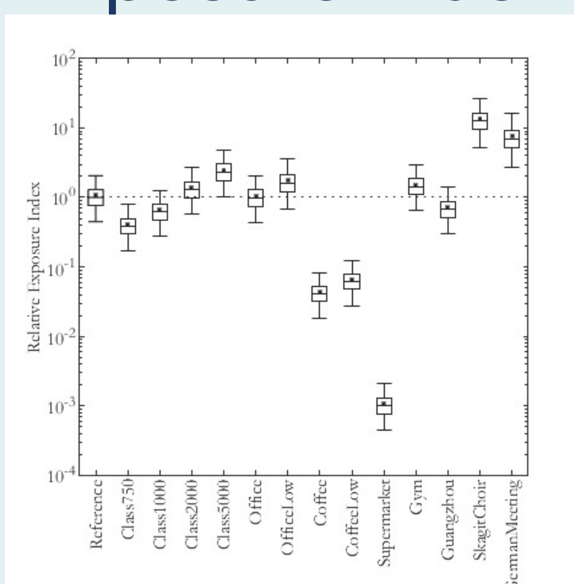
$$Relative\ Exposure\ Index = \frac{\sum n_{Scenario\ \ x}}{\sum n_{Defined\ \ scenario}}$$

Input	Value
Room Volume	$148.5m^3$
Number of Occupants	32
Breath rate	$0.44m^3/hr$
Respiratory activity	75% breathing, 25% talking
Occupation time	7 hr
Air flow rate	160l/s (equivalent 5l/s/p)

AIRBODS

UK Junior School Classroom

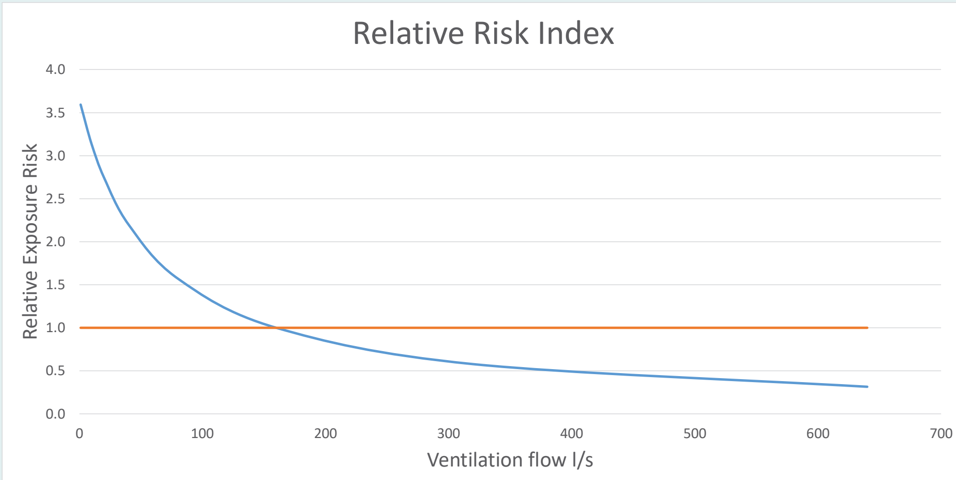
Relative Exposure Index



AIRBODS

Jones, B. *et al.* (2020) 'Modelling uncertainty in the relative risk of exposure to the SARS-CoV-2 virus by airborne aerosol transmission in Buildings', *Building and Environment*. 191:107617 doi:10.1016/j.buildenv.2021.107617

Relative Exposure Index



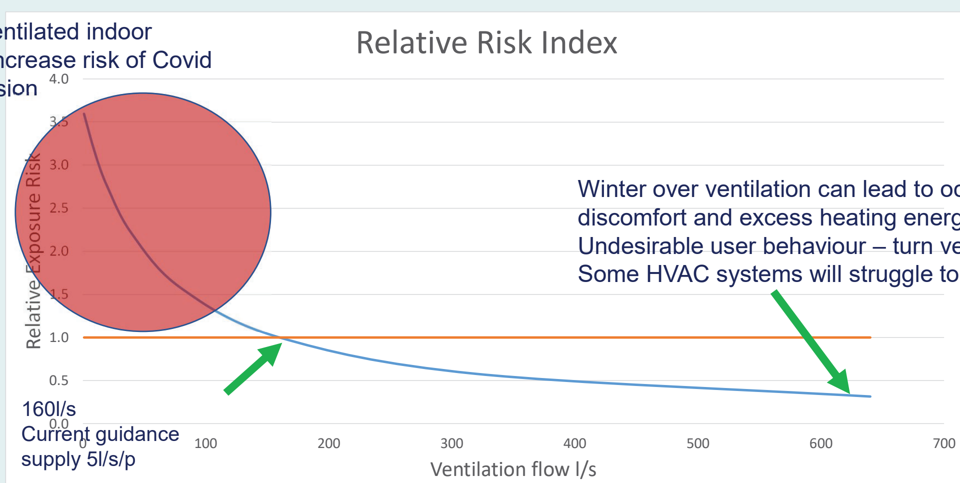
148m^3 junior classroom, 32 person, 7 hour, 25% talking, 75% breathing

AIRBODS

Jones, B. *et al.* (2020) 'Modelling uncertainty in the relative risk of exposure to the SARS-CoV-2 virus by airborne aerosol transmission in Buildings', *Building and Environment*. 191:107617 doi:10.1016/j.buildenv.2021.107617

Relative Exposure Index

Poorly ventilated indoor spaces increase risk of Covid transmission



Winter over ventilation can lead to occupant discomfort and excess heating energy
Undesirable user behaviour – turn ventilation off
Some HVAC systems will struggle to temper air

160l/s
Current guidance supply 5l/s/p

148m^3 junior classroom, 32 person, 7 hour, 25% talking, 75% breathing

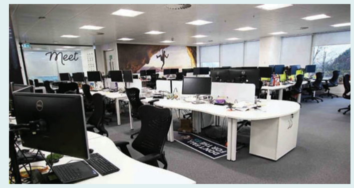
AIRBODS

Jones, B. *et al.* (2020) 'Modelling uncertainty in the relative risk of exposure to the SARS-CoV-2 virus by airborne aerosol transmission in Buildings', *Building and Environment*. 191:107617 doi:10.1016/j.buildenv.2021.107617

5 person office REI = 10

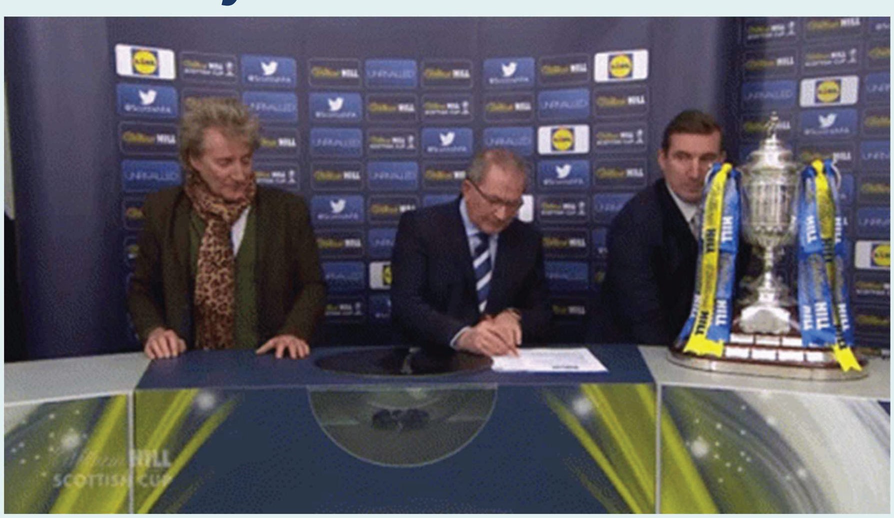
Input	Value
Room Volume	$150m^3$ ($30m^3$/person)
Number of Occupants	5
Breath rate	$0.54m^3$/hr
Respiratory activity	75% breathing, 25% talking
Occupation time	8 hr
Ventilation air flow rate ψ	50l/s (≡ 10l/s/p, 1.2ach)
Biological decay λ	0.6ach (≡ 25l/s)
Deposition γ	0.4ach (≡ 17l/s)
Total removal (equivalent ventilation) φ	2.2ach (≡ 92l/s)

50 person office REI = 1



Input	Value
Room Volume	$1500m^3$ ($30m^3$/person)
Number of Occupants	5
Breath rate	$0.54m^3$/hr
Respiratory activity	75% breathing, 25% talking
Occupation time	8 hr
Ventilation air flow rate ψ	500l/s (≡ 10l/s/p, 1.2ach)
Biological decay λ	0.6ach (≡ 250l/s)
Deposition γ	0.4ach (≡ 170l/s)
Total removal (equivalent ventilation) φ	2.2ach (≡ 920l/s)

Probability of Infector



Probability of Infector

$$P(I) = \frac{C^I(1-C)^{(N-I)}N!}{I!(N-I)!}$$

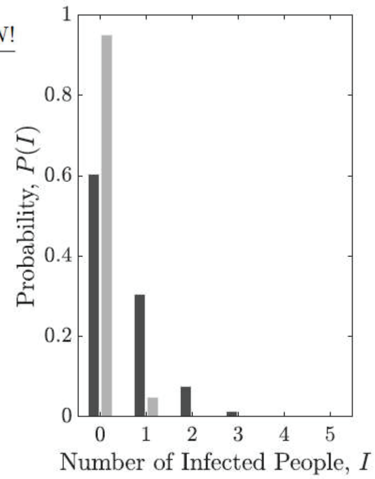
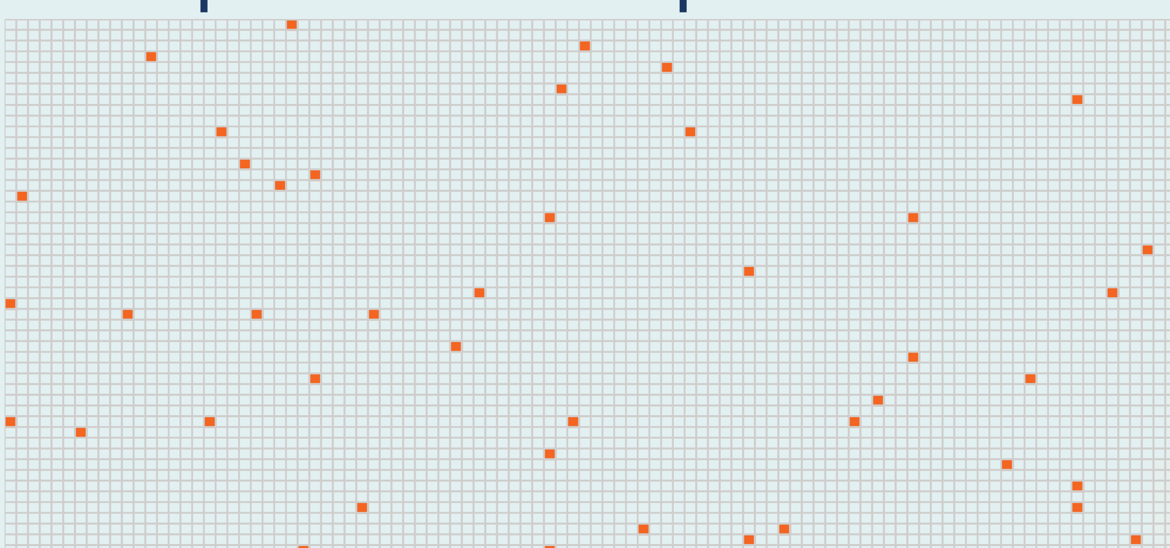
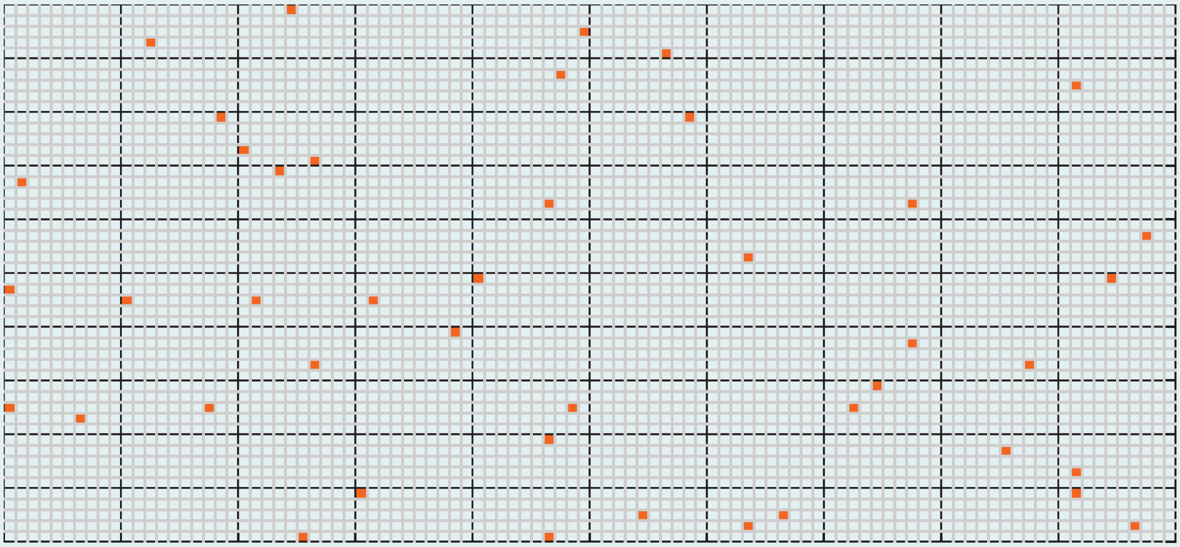


Figure 1: The probability of a number of infected people, I, present in the Big Office (dark) and Small Office (light), $P(I)$, when $C = 1\%$.

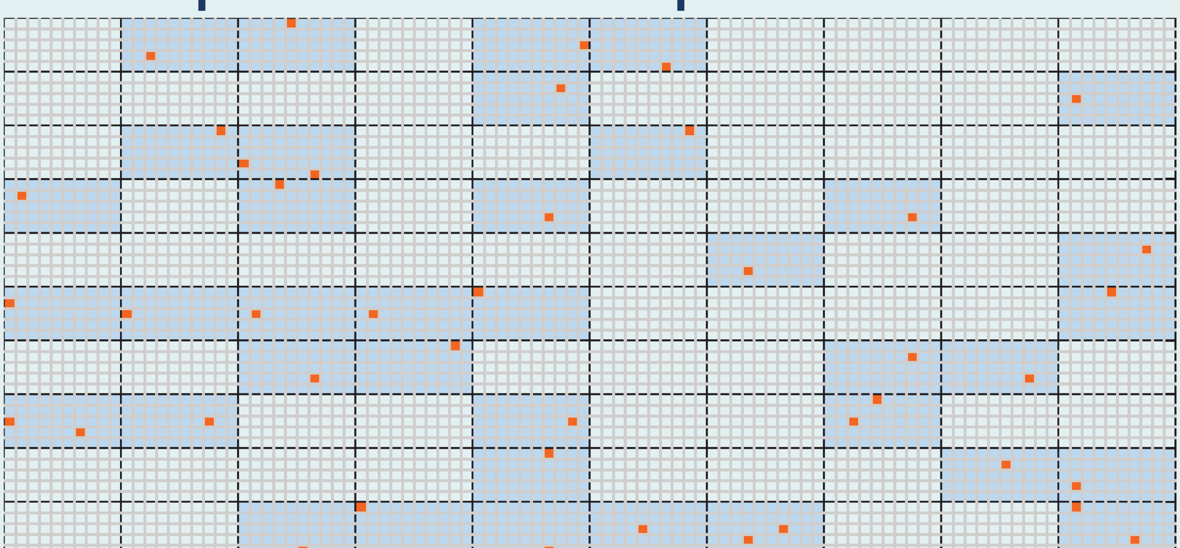
Proportion susceptible



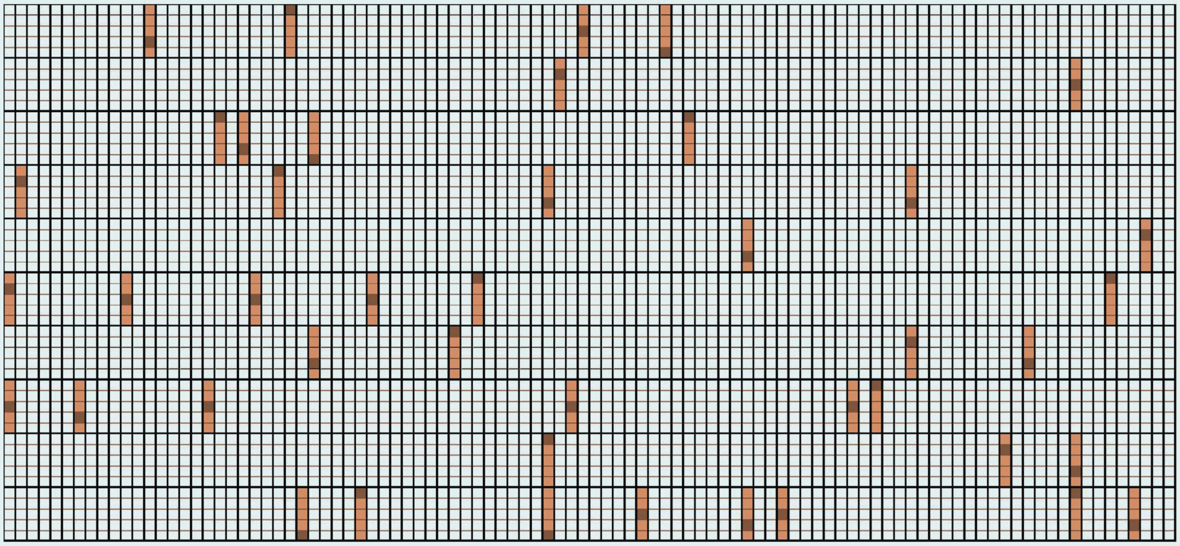
Proportion susceptible



Proportion susceptible



Proportion susceptible



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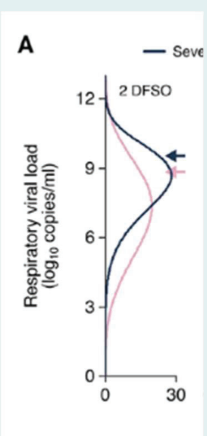
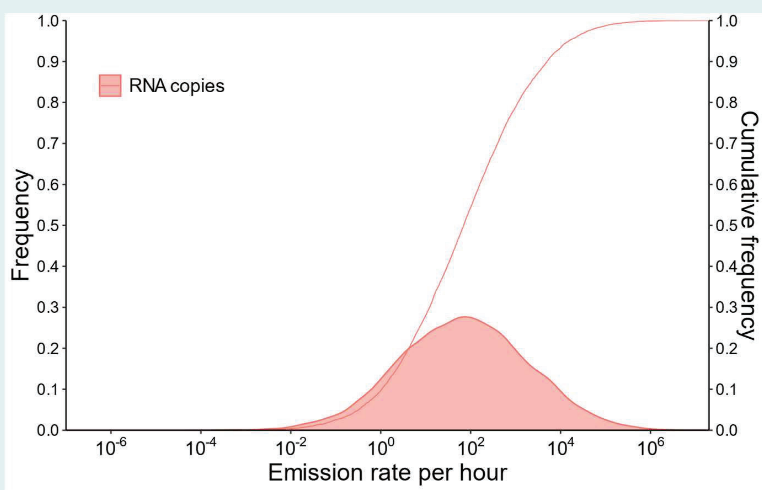
Viral load





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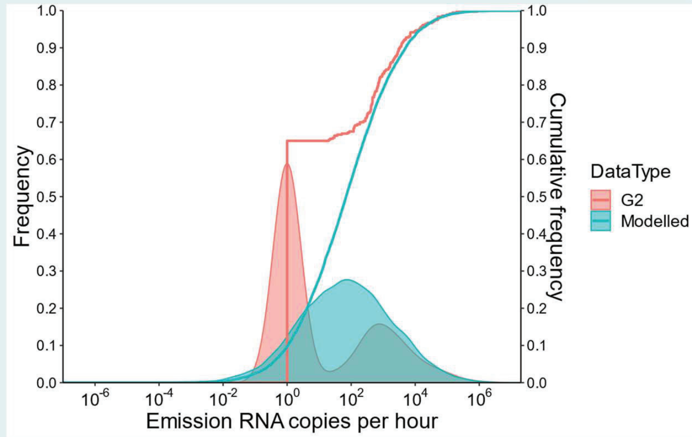
http://www.sciencedirect.com/science/article/pii/S0360132321000305
https://www.sciencedirect.com/science/article/pii/S0360132322005431

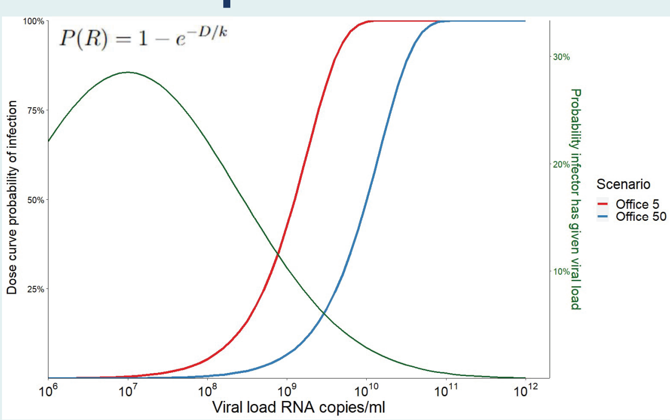
Viral load

Figure 1. Schematic representation of expiratory sample collection using the G-II exhaled breath collector inside the COVID-19 patient room. Abbreviation: COVID-19, coronavirus disease 2019.

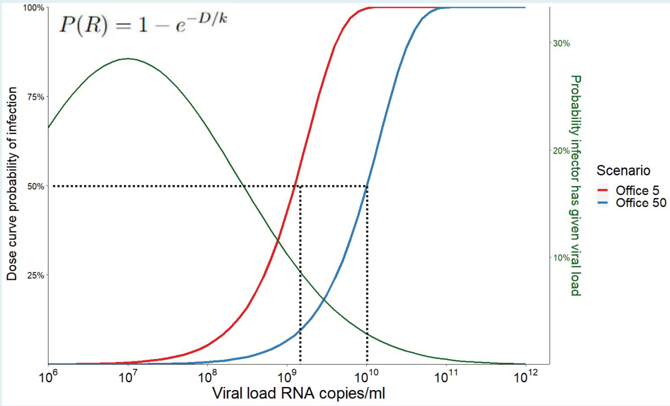


https://doi.org/10.1093/cid/ciab691

Proportion infected



Proportion infected



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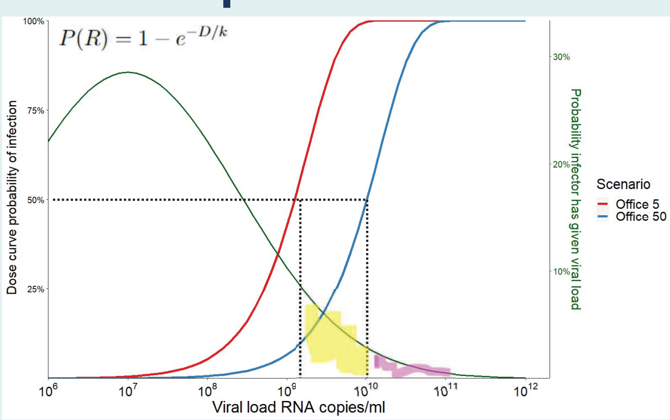
Proportion infected



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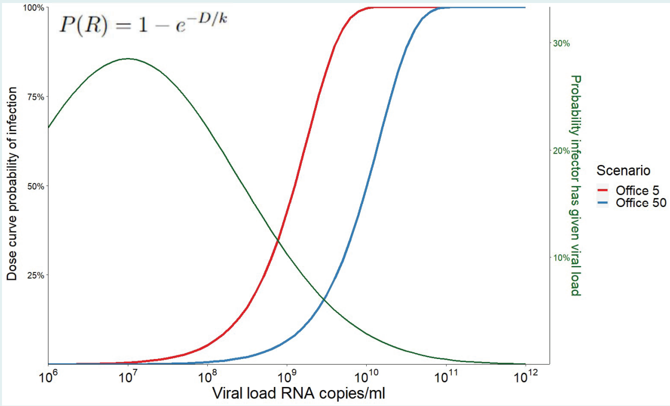
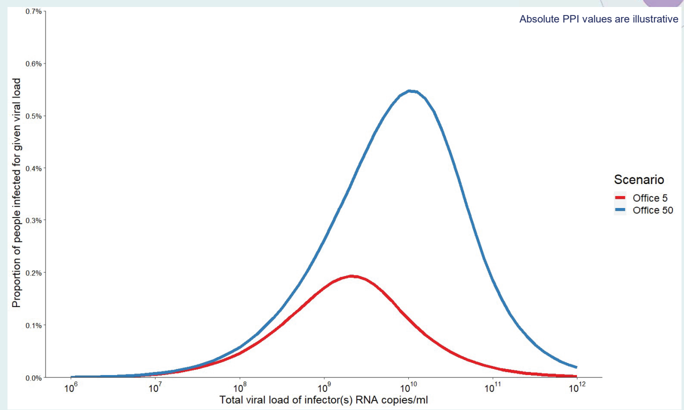
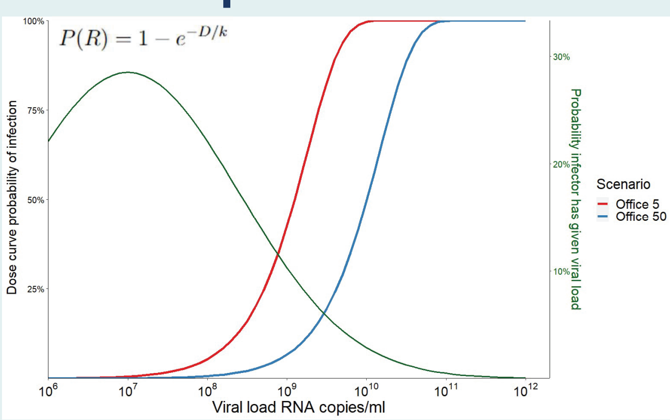
Proportion infected

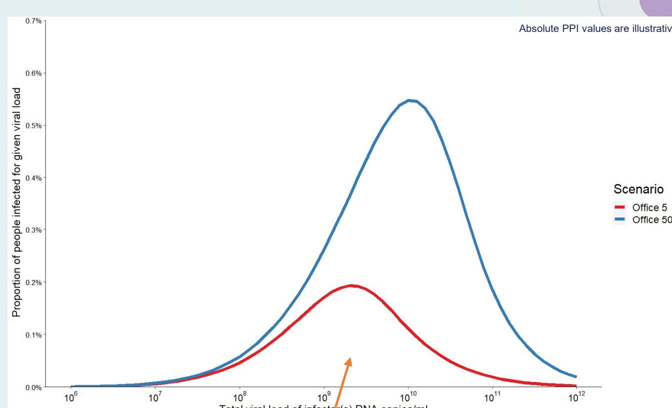




https://www.sciencedirect.com/science/article/pii/S0360132322005431

Proportion infected

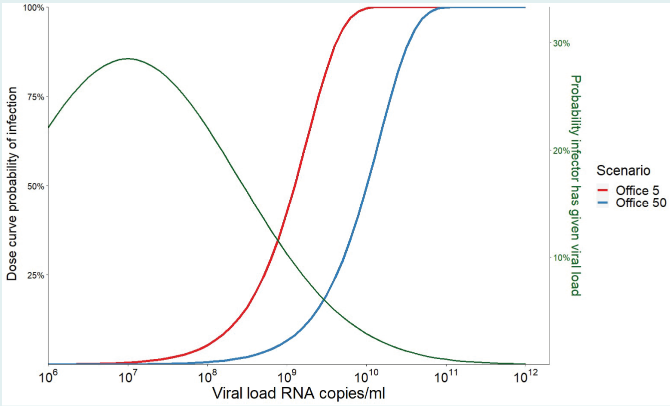


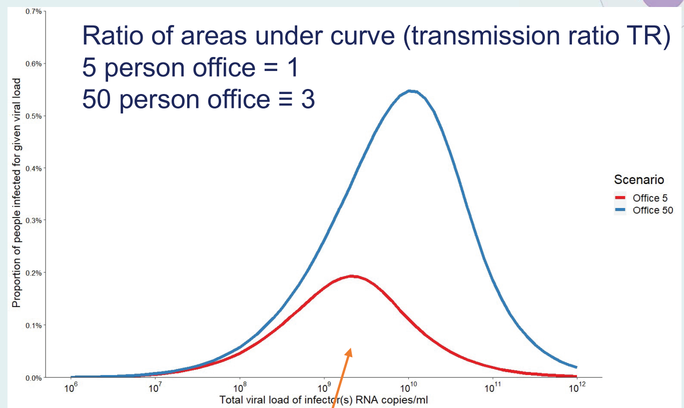


Probability an infector is present
Probability infector has given viral load
Probability that the given viral load gives rise to infection

https://www.sciencedirect.com/science/article/pii/S0360132322005431

Proportion infected



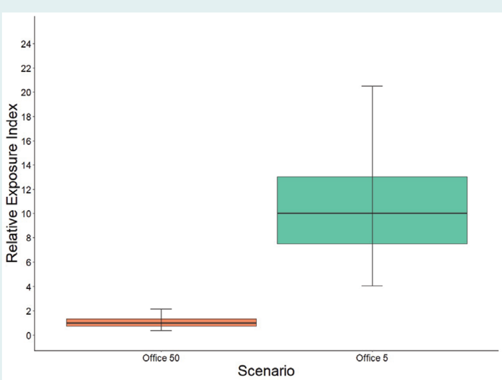


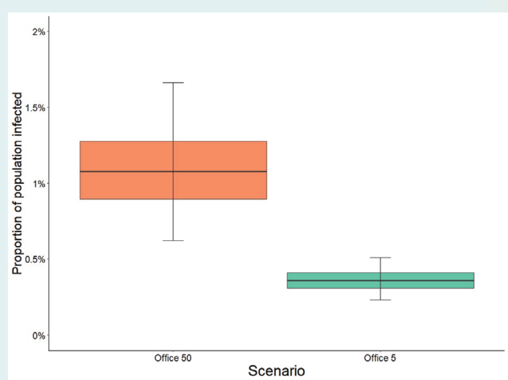
Probability an infector is present
Probability infector has given viral load
Probability that the given viral load gives rise to infection

AIRBODS

https://www.sciencedirect.com/science/article/pii/S0360132322005431

REI and PPI





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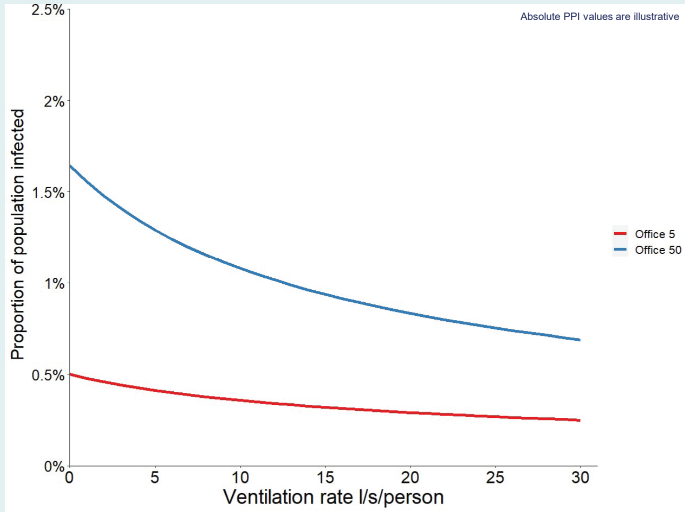
Ventilation



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https://www.sciencedirect.com/science/article/pii/S0360132322005431

Ventilation

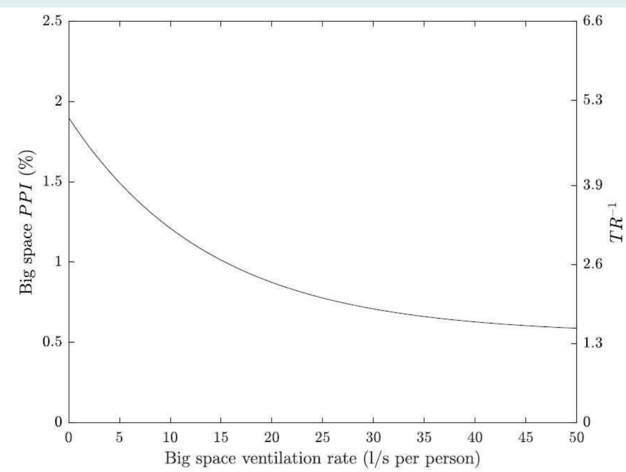

Figure 6: The effect of increasing the *per capita* ventilation rate, $\psi V N^{-1}$, in the Big Office on the *PPI* and the *TR* when the *per capita* ventilation rate in the Small Office is a constant $10 \, \mathrm{l \, s^{-1}}$ per person. All values are illustrative.

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https://www.sciencedirect.com/science/article/pii/S0360132322005431

Occupancy

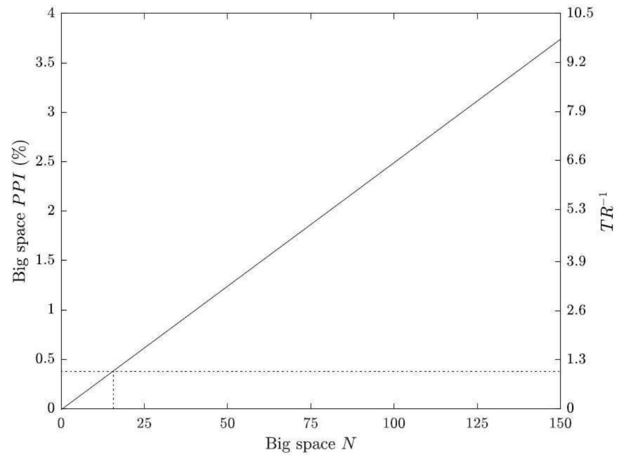

Figure 8: The effect of increasing the occupancy, N, in the Big Office where the space volume and ventilation flow rate are fixed for a designed occupancy of 50 people ($1500\,m^3$ and $500\,l\,s^{-1}$, respectively), on the PPI and TR. All values are illustrative.

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Community infection rate

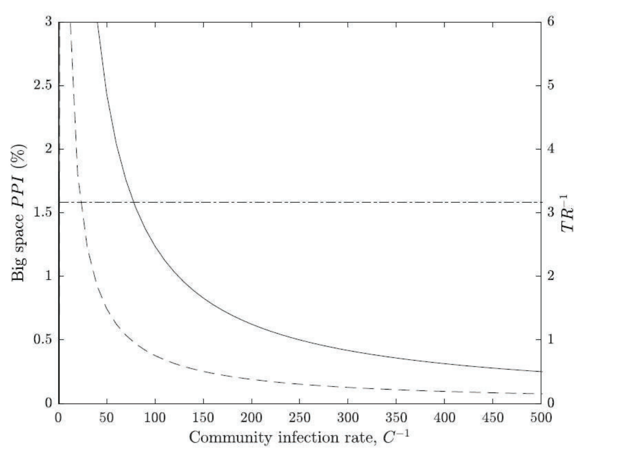

Figure 9: The effect of decreasing the community infection rate , C, on the PPI in the Big Office (solid) and the Small Office (dash) and on the TR (dot-dash). All values are illustrative.

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What next?

Part 5

AIRBODS

What next?

- A new focus in IAQ generally
- However, there are limits to what we can do to make building resilient
- There are limits to the effect ventilation can have on transmission risk in buildings (community infection rate, high emission rate, social distancing)
- Personal and population risks are different
- When a building is occupied, there is no such thing as zero risk
- We must re-evaluate existing ventilation systems
- We must consider behavior (using systems appropriately)
- Regulation? (periodic demonstration of performance e.g. Sweden)

AIRBODS

Publications

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

ELSEVIER

Modelling uncertainty in the relative risk of exposure to the SARS-CoV-2 virus by airborne aerosol transmission in well mixed indoor air

Benjamin Jones [a,*], Patrick Sharpe [a], Christopher Iddon [b], E. Abigail Hathway [c], Catherine J. Noakes [d], Shaun Fitzgerald [e]

Building and Environment
Volume 221, 1 August 2022, 109309

ELSEVIER

A population framework for predicting the proportion of people infected by the far-field airborne transmission of SARS-CoV-2 indoors

Christopher Iddon [a], Benjamin Jones [a], Patrick Sharpe [a], Muge Cevik [b], Shaun Fitzgerald [c]

- http://www.sciencedirect.com/science/article/pii/S0360132321000305
- https://www.sciencedirect.com/science/article/pii/S0360132322005431
- https://www.cibsejournal.com/general/why-space-volume-matters-in-covid-19-transmission/
- https://www.cibsejournal.com/technical/optimising-ventilation-in-the-post-covid-classroom/

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The End

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AIVC Workshop, May 2023, Tokyo

Revision of ISO17772-1 and EN16798-1 Standards Dealing with Indoor Environmental Quality

Bjarne W. Olesen

Intl. Centre for Indoor Environment and Energy,
Technical University of Denmark

International Standards
Indoor Environmental Quality

- EN16798-1 and ISO 17772-1:
- EN TR 16798-2 and ISO TR 17772:

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 16798-1

May 2019

ICS 91.120.10; 91.140.01

Supersedes EN 15251:2007

English Version

Tekst.

Energy performance of buildings - Ventilation for buildings - Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics - Module M1-6

DS/CEN/TR 16798-2:2019

TECHNICAL REPORT
RAPPORT TECHNIQUE
TECHNISCHER BERICHT

CEN/TR 16798-2

May 2019

ICS 91.120.10; 91.140.01

English Version

Energy performance of buildings - Ventilation for buildings - Part 2: Interpretation of the requirements in EN 16798-1 - Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (Module M1-6)

Suggested procedure

- There is a need to revise ISO 17772-1 and -2 (foreseen as **ISO 52007**) in parallel to the revision in Europe of EN 16798-1.
  - CEN has decided not to do the revision through a Vienna agreement. It is however still important that the two standards do not conflict with each other.
- There is a wish to make a clearer distinction between the different parts; and therefore, have separate parts for Thermal Comfort, Indoor Air Quality, Lighting, Acoustic; but still as one standard.
- It is also important that the content is aligned to the existing structure and content of ISO17772

Committees involved

- ISO/TC 163 Thermal performance and energy use in the built environment
  - ISO/TC 163/WG 4 Joint ISO/TC 163 - ISO/TC 205 WG: Energy performance of buildings using holistic approach
- ISO/TC 205 Building environment design
  - ISO/TC 205/WG 3 Building Automation and Control System (BACS) Design
- ISO/TC 274 Light and lighting
  - ISO/TC 274/JWG 1 Energy performance of lighting in buildings (joint working group with CIE-JTC 6)
- ISO/TC 43/SC 2 Building acoustics

Structure for 52007

Document and title		Responsible Committee(s)
ISO 52007-1	Overarching standard	Overarching TC163/205JWG with members from TC274 and TC43/SC 2
ISO 52007-2	Technical Report	
ISO 52007-3	Thermal Comfort	Thermal Comfort TC163/205JWG
ISO 52007-4	Technical Report and Guidance for part 3	
ISO 52007-5	Indoor Air Quality	Indoor Air Quality TC163/205JWG
ISO 52007-6	Technical Report and Guidance for part 5	
ISO 52007-7	Lighting	TC 274/JWG 1 (- CIE JTC6) Collaboration route recommendation expected from the ISO/TC 274/JAG
ISO 52007-8	Technical Report and Guidance for part 7	
ISO 52007-9	Acoustic	TC 43/SC 2
ISO 52007-10	Technical Report and Guidance for part 9	

Categories

Category	Level of expectation
IEQ_{I}	High
IEQ_{II}	Medium
IEQ_{III}	Moderate
IEQ_{IV}	Low

- The categories are related to the level of expectations the occupants may have.
- A normal level would be “Medium”.
- A higher level may be selected for occupants with special needs (children, elderly, handicapped, etc.).
- A lower level will not provide any health risk but may decrease comfort.

Recommended thermal comfort categories for design of mechanical heated and cooled buildings

Category	Thermal state of the body as a whole	
	PPD %	Predicted Mean Vote
I	< 6	-0.2 < PMV < + 0.2
II	< 10	-0.5 < PMV < + 0.5
III	< 15	-0.7 < PMV < + 0.7
III	< 25	-1.0 < PMV < + 1.0

*Temperature ranges for **dimensioning** and hourly calculation of cooling and heating energy in three categories of indoor environment*

Type of building/ space	Category	Operative Temperature for Energy Calculations °C	
Offices and spaces with similar activity (single offices, open plan offices, conference rooms, auditorium, cafeteria, restaurants, class rooms, Sedentary activity ~1,2 met		Heating (winter season), ~ 1,0 clo	Cooling (summer season), ~ 0,5 clo
	I	21,0 – 23,0	23,5 - 25,5
	II	20,0 – 24,0	23,0 - 26,0
	III	19,0 – 25,0	22,0 - 27,0
	IV	17,0 – 26,0	21,0 - 28,0

Temperature ranges for dimensioning and hourly calculation of cooling and heating energy in four categories of indoor environment

Cat.	Heating season (1.0 clo) °C	Cooling season, (0.5 clo) °C
I	21.0 - 23.0	23.5 - 25.5
II	20.0 - 24.0	23.0 - 26.0
III	19.0 - 25.0	22.0 - 27.0
IV	17.0 - 25.0	21.0 - 28.0

- Temperature ranges consider for the four categories of indoor environment recommended for sedentary work (1.2 met) in ISO 17772-1.
- Air velocity is assumed below 0.1 m/s and the relative humidity is 40% for heating seasons and 60% for cooling seasons.

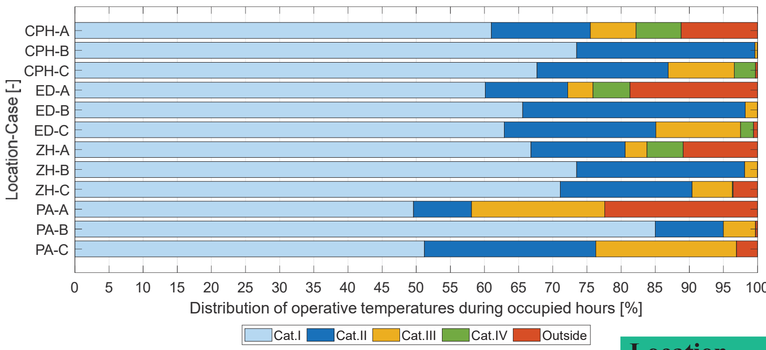
This will work for establishing design values for dimensioning of heating and cooling systems by using the lower value in heating season for the heating system and the upper value in cooling season for the cooling system.

Issues

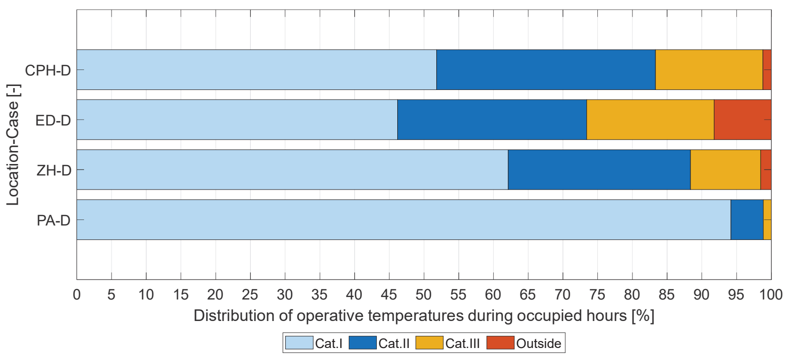
- The method do not explain what to do regarding room temperatures in shoulder seasons (spring, fall)
  - The standard recommends defining heating season when the outside running mean temperature is below 10 ^{o}C and cooling season when it is above 15 ^{o}C.
  - As comfort criteria for spring/fall you may use 0.75 clo or use the adapted model during those seasons

- No yearly Key Performance Indicator (KPI) for thermal comfort, while for energy you have one value kWh/m^2 per year
  - A KPI can be calculated based on the percentage of occupied hours inside the categories of indoor environmental quality defined in ISO 17772-1.
  - The score assigned weighted values for % time spent in each category, and provides a single value from 1 (Best) to 5 (Worst) equation (2)

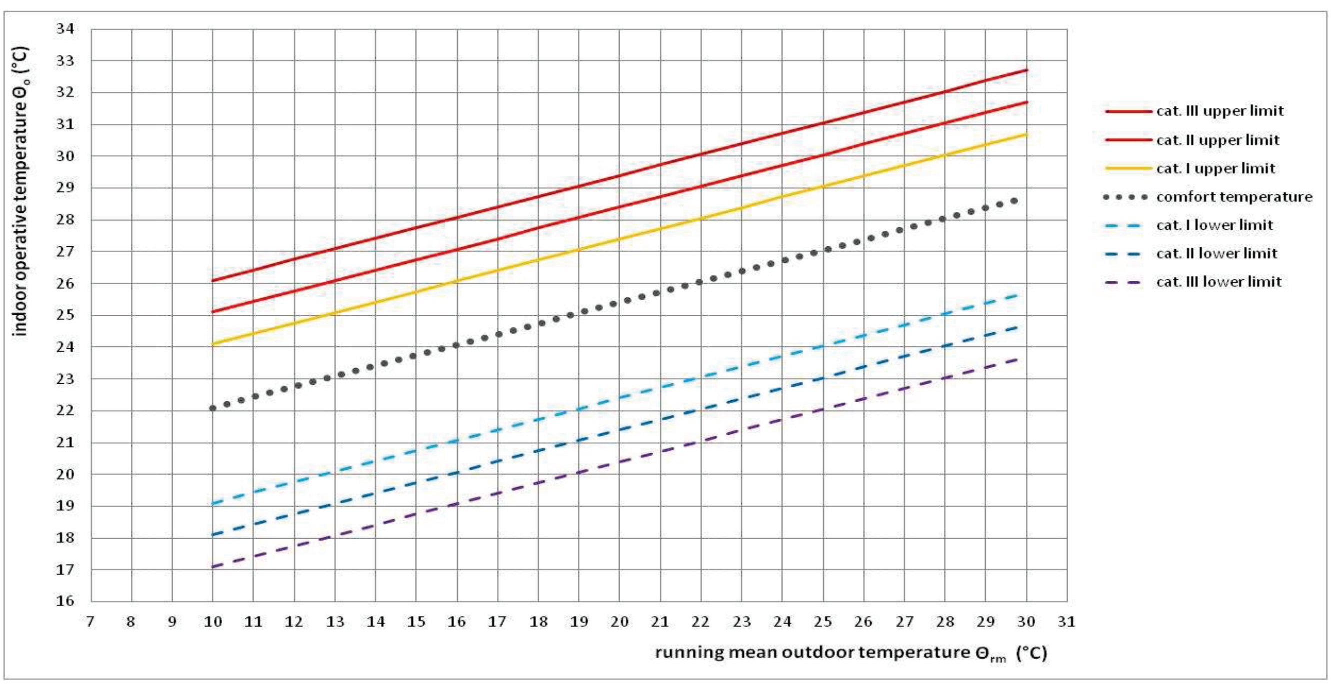
$$TCS = \%Cat.I * 1 + (\%Cat.II - \%Cat.I) * 2 + (\%Cat.III - \%Cat.II) * 3 + (\%Cat.IV - \%Cat.III) * 4 + \%outside * 5 \quad (2)$$



Location	CPH	ED	ZH	PA
TCS A	1.93	2.11	1.80	2.37
B	1.27	1.36	1.28	1.21
C	1.49	1.55	1.46	1.79
TCS D ACM	1.71	2.00	1.56	1.10



Adapted method in ISO17772-1



$$\Theta_{rm} = (\Theta_{ed\,-1} + 0{,}8\ \Theta_{ed\,-2} + 0{,}6\ \Theta_{ed\,-3} + 0{,}5\ \Theta_{ed\,-4} + 0{,}4\ \Theta_{ed\,-5} + 0{,}3\ \Theta_{ed\,-6} + 0{,}2\ \Theta_{ed\,-7})/3{,}8$$

- activity levels lie most of the time in the range of 1,2 - 1,6 met
- clothing insulation can be varied according to momentary preferences from 0,5 to 1,0 clo
- access to operable windows
- less than 4 persons per room
- such as dwellings and office buildings.

Issues-Adapted Method

- When to use adapted method is still unclear
- What to do in mixed-mode buildings?

CRITERIA FOR INDOOR AIR QUALITY ~VENTILATION RATES

COMFORT (Perceived Air Quality)

HEALTH

PRODUCTIVITY

ENERGY

~~Cross contamination~~

Indoor Air Quality

- Design parameters for indoor air quality shall be derived using one or more of the following methods:

1. Method 1: Method based on perceived air quality;
2. Method 2: Method using limit values for individual substances
3. Method 3: Method based on predefined ventilation air flow rates.

Concept for calculation of design ventilation rate
Method 1

People Component

Building Component

Breathing Zone
Outdoor Airflow

$$V_{bz} = R_p P_z + R_a A_z$$

R_p: Minimum l/s/Person

P_z: Number of People

A_z: Building Area

R_a: Minimum l/s/m²

Basic required ventilation rates for diluting emissions (bio effluents) from people for different categories

Category	Expected Percentage Dissatisfied	Airflow per non-adapted person l/(s.pers)
I	15	10
II	20	7
III	30	4
IV	40	2,5*

***The total ventilation rate must never be lower than 4 l/s per person**

ASHRAE Standard 62.1 : Adapted persons 2,5 l/s person (Cat. II)

Design ventilation rates for diluting emissions from buildings

Category	Very low polluting building l/(s m²)	Low polluting building l/(s m²)	Non low-polluting building l/(s m²)
I	0,5	1,0	2,0
II	0,35	0,7	1,4
III	0,2	0,4	0,8
IV	0,15	0,3	0,6
Minimum total ventilation rate for health	4 l/s person	4 l/s person	4 l/s person

Example on how to define low and very low polluting buildings

SOURCE	Low emitting products for low polluted buildings	Very low emitting products for very low polluted buildings
Total VOCs TVOC (as in CEN/TS 16516)	< 1.000 µg/m³	< 300 µg/m³
Formaldehyde	< 100 µg/m³	< 30 µg/m³
Any C1A or C1B classified carcinogenic VOC	< 5 µg/m³	< 5 µg/m³
R value (as in CEN/TS16516)	< 1.0	< 1.0

Issues

- Need for better emission data for building materials, furniture etc.
- Difficult to estimate what building type you have

Total ventilation rate

$$q_{tot} = n \cdot q_p + A_R \cdot q_B$$

$$q_{supply} = q_{tot} / \varepsilon_v$$

- Where
- ε_v = the ventilation effectiveness (EN13779)
- q_{supply} = ventilation rate supplied by the ventilation system
- q_{tot}= total ventilation rate for the breathing zone, l/s
- n = design value for the number of the persons in the room,
- q_p = ventilation rate for occupancy per person, l/s, pers
- A_R= room floor area, m^2
- q_B = ventilation rate for emissions from building, l/s,m^2

Example of design ventilation air flow rates for a single-person office of 10 m² in a low polluting building (un-adapted person)

Cate-gory	Low-polluting building l/(s*m²)	Airflow per non-adapted person l/(s*person)	Total design ventilation air flow rate for the room l/s	l/(s*person)	l/(s* m²)
I	1,0	10	20	20	2
II	0,7	7	14	14	1,4
III	0,4	4	8	8	0,8
IV	0,3	2,5	5,5	5,5	0,55

Design ventilation rates

Type of building or space	Category	Floor area m²/person	q_p minimum ventilation rate for occupancy only l/(s m²)	q_p minimum ventilation rate for occupancy only l/s pers.	q_B for very low-polluted building l/s, m²	q_{tot} for very low-polluted building l/s, m²	q_{tot} for very low-polluted building l/s,pers	q_B for low-polluted building l/s, m²	q_{tot} for low-polluted building l/s, m²	q_{tot} for low-polluted building l/s,pers	q_B for non-low-polluted building l/s, m²	q_{tot} for non-low-polluted building l/s, m²	q_{tot} for non-low-polluted building l/s,pers
Single office	I	10	1	10	0,5	1,5	15	1	2,0	20,0	2	3,0	30
	II	10	0,7	7	0,35	1,1	11	0,7	1,4	14,0	1,4	2,1	21
	III	10	0,4	4	0,2	0,6	6	0,4	0,8	8,0	0,8	1,2	12
	IV	10	0,25	2,5	0,15	0,4	4	0,3	0,6	5,5	0,6	0,9	9
Landscaped office	I	15	0,7	10	0,5	1,2	18	1	1,7	25,0	2	2,7	40
	II	15	0,5	7	0,35	0,8	12	0,7	1,2	17,5	1,4	1,9	28
	III	15	0,3	4	0,2	0,5	7	0,4	0,7	10,0	0,8	1,1	16
	IV	15	0,2	2,5	0,15	0,3	5	0,3	0,5	7,0	0,6	0,8	12
Conference room	I	2	5	10	0,5	5,5	11	1	6,0	12,0	2	7,0	14
	II	2	3,5	7	0,35	3,9	8	0,7	4,2	8,4	1,4	4,9	10
	III	2	2	4	0,2	2,2	4	0,4	2,4	4,8	0,8	2,8	6
	IV	2	1,25	2,5	0,15	*(1,4) 1,8*	*(3) 4*	0,3	*(1,6) 2*	*(3,1) 4*	0,6	1,9	4

Tekst

Type of building/ space	Occupancy person/m²	Category CEN	Occupants only l/s person		Additional ventilation for building (add only one) l/s·m²			Total l/s·m²	
			ASHRAE Rp	CEN	CEN low-polluting building	CEN *Non*-low-polluting building	ASHRAE Ra	CEN Low Pol.	ASHRAE
Single office (cellular office)	0,1	A	2,5	10	1,0	2,0	0,3	2	0,55
		B		7	0,7	1,4		1,4	
		C		4	0,4	0,8		0,8	
Landscaped office	0,07	A	2,5	10	1,0	2,0	0,3	1,7	0,48
		B		7	0,7	1,4		1,2	
		C		4	0,4	0,8		0,7	
Conference room	0,5	A	2,5	10	1,0	2,0	0,3	6	1,55
		B		7	0,7	1,4		4,2	
		C		4	0,4	0,8		2,4	

$1\ l/s\ m^2 = 0.2\ cfm/ft^2$

HEALTH CRITERIA FOR VENTILATION ISO 17772-1 and prEN16798-1

Minimum 4 l/s/person

Specific Pollutants-Method 2

The ventilation rate required to dilute a pollutant shall be calculated by this equation:

$$Q_h = \frac{G_h}{C_{h,i} - C_{h,o}} \cdot \frac{1}{\varepsilon_v} \qquad \text{Eq (2)}$$

where:

Q_h is the ventilation rate required for dilution, in litre per second;
G_h is the pollution load of a pollutant, in micrograms per second;
$C_{h,i}$ is the guideline value of a pollutant, see Annex B6 , in micrograms per m^3;
$C_{h,o}$ is the supply concentration of pollutants at the air intake, in micrograms per m^3;
ε_v is the ventilation effectiveness

NOTE. $C_{h,i}$ and $C_{h,o}$ may also be expressed as ppm (vol/vol). In this case the pollution load G_h has to be expressed as l/s.

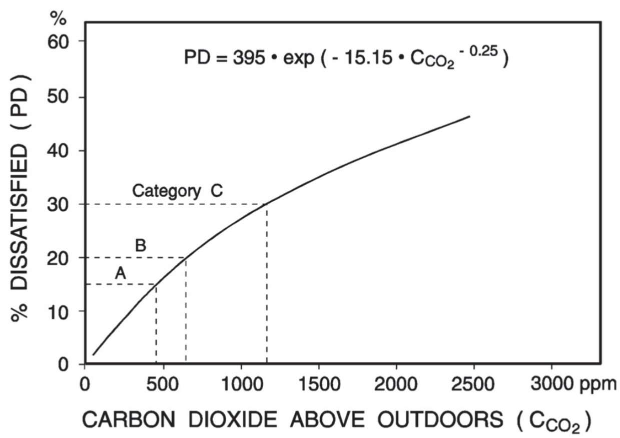
Pollutant	**WHO Indoor Air Quality guidelines 2010**	**WHO Air Quality guidelines 2005**
Benzene	No safe level can be determined	-
Carbon monoxide	15 min. mean: 100 mg/m³ 1h mean: 35 mg/m³ 8h mean: 10 mg/m³ 24h mean: 7 mg/m³	-
Formaldehyde	30 min. mean: 100 µg/m³	-
Naphthalene	Annual mean: 10 µg/m³	-
Nitrogen dioxide	1h mean: 200 µg/m³ Annual mean: 40 mg/m³	-
Polyaromatic Hydrocarbons (e.g. Benzo Pyrene A B[a]P)	No safe level can be determined	-
Radon	100 Bq/m³ (sometimes 300 mg/m³, country-specific)	-
Trichlorethylene	No safe level can be determined	-
Tetrachloroethylene	Annual mean: 250 µg/m³	
Sulfure dioxide	-	10 min. mean: 500 µg/m³ 24h mean: 20 mg/m³
Ozone	-	8h mean:100 µg/m³
Particulate Matter PM 2,5	-	24h mean: 25 µg/m³ Annual mean: 10 µg/m³
Particulate Matter PM 10	-	24h mean: 50 µg/m³ Annual mean: 20 µg/m³

WHO guidelines values for indoor and outdoor air pollutants

There is a need for health/comfort criteria for other substances

Particles must be included in the standard

CO_2 as reference not consistent with Method 1



Category	Corresponding CO_2 concentration above outdoors in PPM for non-adapted persons
I	550 (10)
II	800 (7)
III	1 350 (4)
IV	1 350 (4)

Table B2.5 - Example of equivalent increase in CO_2 levels indoor for the total ventilation rates specified in Table B2.3

Type of building or space	Category	occupancy	ΔCO_2 [ppm]		
		person/m²	Very low-polluting	low-polluting	Not low-polluting
Single office	I	0,1	370	278	185
	II	0,1	529	397	265
	III	0,1	926	694	463
	IV	0,1	1389	1010	654
Land-scaped office	I	0,07	317	222	139
	II	0,07	454	317	198
	III	0,07	741	556	347
	IV	0,07	1235	794	483
Conference room	I	0,5	505	463	397
	II	0,5	722	661	567
	III	0,5	1263	1157	992
	IV	0,5	*1462*	*1389*	1502
Auditorium	I	1,33	535	517	483
	II	1,33	765	738	690
	III	1,33	1347	1300	1208
	IV	1,33	*1576*	*1398*	*1576*

Issues

- Target CO_2 concentration should correctly be set as difference between inside and outside
- Target CO_2 concentration for the same level of air quality depends on occupant density
- Should we allow to use a dynamic formular for individual substances (meeting rooms, class rooms, etc.)
- If air cleaning technologies are used and partly substituting for outside air the resulting room concentration of CO2 will be higher for the same level of air quality.

Cat.	Method 2 CO_2 above outdoors PPM (l/s*pers.)	Method 1 Single office Low-pol. building CO_2 above outdoors PPM (l/s*pers.)
I	550 (10)	278 (20)
II	800 (7)	397 (14)
III	1350 (4)	694 (8)
IV	1350 (4)	1010 (5.5)

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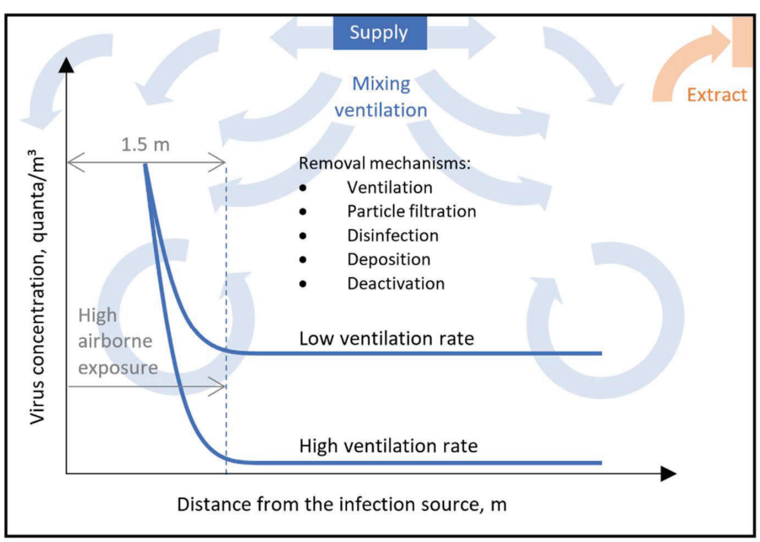
journal homepage: www.elsevier.com/locate/buildenv

Risk-based ventilation design

Respiratory infection risk-based ventilation design method

Jarek Kurnitski [a,b], Martin Kiil [a,*], Pawel Wargocki [c], Atze Boerstra [d,e], Olli Seppänen [f], Bjarne Olesen [c], Lidia Morawska [g,h]



Ventilation rate equation at given probability

Assuming steady state and substituting C_{avg} and E, and considering that outdoor air ventilation rate $Q = \lambda_v V$ results:

$$p = 1 - e^{-\frac{(1-\eta_i)Iq\;\;_b(1-\eta_s)D}{Q+(\lambda_{dep}+k+k_f)V}}$$

- Solving this equation for outdoor air ventilation rate Q (m^3/h) gives

$$Q = \frac{(1-\eta_i)IqQ_b(1-\eta_s)D}{\ln\left(\frac{1}{1-p}\right)} - \left(\lambda_{dep} + k + k_f\right)V$$

- (masks and air cleaner included)

Example criteria for personalized systems

Aspect	Requirement
'Temperature' control winter	At workstation level, the (operative/equivalent) temperature is adjustable with a response speed of at least 0,5 K/minute within a range of 5 K, from 18 °C to 23 °C.
'Temperature' control summer	At workstation level, the (equivalent) temperature is adjustable (with a response speed of at least 0,5 K/minute within a range of 5 K, from 22 °C to 27 °C.
Fresh air supply control	Local fresh air supply (per workstation) is adjustable from around 0 to at least 7 l/s.
Delivered air quality	For requirements related to air cleaning technology: see Annex K.
Installation noise	Noise level – with the personalized system in the highest setting – should not be higher than 35 dB(A).

This is a topic under IEA -EBC Annex 87 "PECS"

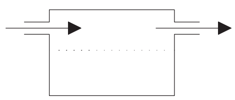
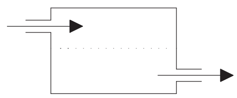
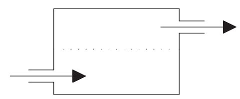
Air Distribution Effectiveness

$$\varepsilon_V = \frac{C_E - C_S}{C_I - C_S}$$

Concentrations:

C_E	**exhaust air**
C_S	**supply air**
C_I	**breathing zone**

CEN Report CR 1752 (1998)

Mixing ventilation		Mixing ventilation		Displacement ventilation		Personalized ventilation	
							
T supply - T inhal °C	Vent. effect. -	T supply - T inhal °C	Vent. effect. -	T supply - T inhal °C	Vent. effect. -	T supply - T room °C	Vent. effect. -
< 0	0,9 - 1,0	< -5	0,9	<0	1,2 - 1,4	-6	1,2 - 2,2
0 - 2	0,9	-5 - 0	0,9 - 1,0	0-2	0,7 - 0,9	-3	1,3 - 2,3
2 - 5	0,8	> 0	1	>2	0,2 - 0,7	0	1,6 - 3,5
> 5	0,4 - 0,7						

Issues-PECS

- No. available test standard
- Must be designed/dimensioned for a more narrow temperature range
- How much can you relax requirements to the ambient system?
- Issues are part of EBC-IEA Annex 87

ISSUES for REVISION

- Not consistent requirements based on CO_2
- Need to include criteria for particles
- Need criteria for substances not included in WHO guideline
- Demand Control Ventilation based on CO_2 requires different set-points:
  - Influenced by occupant density
  - If required ventilation is partly substituted by air cleaning
- Ventilation and cross contamination (pandemic, flue, etc.)
- Personalized Environmental Control Systems (personalized ventilation)
- More focus on ventilation efficiency
- KPI's for yearly performance

Thank You

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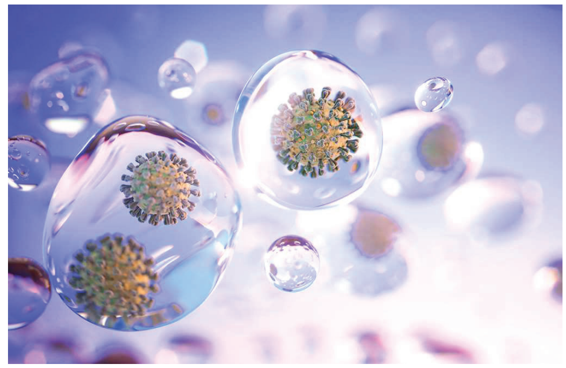
Role of air cleaning in infection control

Preface

WILD WILD WEST of air cleaning...
What will it take to make diners feel safe indoors? Nearly 60% feel uneasy eating inside, so restaurants try sterilizing UV wands, tabletop air purifiers as winter looms.
Chicago Tribune
The New York Times
How to Keep the Coronavirus at Bay Indoors
By Apoorva Mandavilli
Sept. 27, 2020
Tips for dodging the virus as Americans retreat from colder weather: Open the windows, buy an air filter — and forget the UV lights.
Study uncovers safety concerns with some air purifiers
EurekAlert!
Joint university research finds some air purifiers may actually increase harmful airborne chemicals
CLEARING THE AIR
More Than 100 Missouri Schools Have Bought 'Often Unproven' Air-Cleaning Technology
KHN
The Magic Molekule
There has never been a better business (or planetary) climate in which to calm and stoke your anxieties about dirty air.
Do Air Filters In HVAC Systems Offer Protection Against Coronavirus Indoors? It Depends
DISCOVER
There are air filters that can catch particles laden with SARS-CoV-2. But whether or not the filtration happens depends on other factors.
By Leslie Nemo | Jul 17, 2020 11:45 AM
Schools spending millions on air purifiers often sold using overblown claims
By Lauren Weber and Christina Jewett, Kaiser Health News
Updated 6:06 PM ET, Tue May 11, 2021
CNN health
Mother Jones
Caution to the Wind
Desperate to reopen and loaded with stimulus cash, schools are spending millions on high-tech purifiers. But are they safe?
MADISON PAULY MAY 27, 2021
WIRED
The Ionizer in Your School May Not Do Much to Fight Covid
Manufacturers say the devices remove 99 percent of viruses. Researchers say such claims are unproven, and cheaper air filters are more effective.

Objective

- The **true** (*I hope*) story about the effects of filtration and air cleaning on reducing the risk of infectious disease in occupied buildings (with no potential of adverse effects).



Introduction

Recommendations

ASHRAE EPIDEMIC TASK FORCE

Core Recommendations for Reducing Airborne Infectious Aerosol Exposure

The following recommendations are the basis for the detailed guidance issued by ASHRAE Epidemic Task Force. They are based on the concept that within limits ventilation, filtration, and air cleaners can be deployed flexibly to achieve exposure reduction goals subject to constraints that may include comfort, energy use, and costs. This is done by setting targets for equivalent clean air supply rate and expressing the performance of filters, air cleaners, and other removal mechanisms in these terms.

1. *Public Health Guidance* – Follow all current regulatory and statutory requirements and recommendations, including vaccination, wearing of masks and other personal protective equipment, social distancing, administrative measures, circulation of occupants, hygiene, and sanitation.

2. *Ventilation, Filtration, Air Cleaning*
   - 2.1 Provide and maintain at least required minimum outdoor airflow rates for ventilation as specified by applicable codes and standards.
   - 2.2 Use combinations of filters and air cleaners that achieve MERV 13 or better levels of performance for air recirculated by HVAC systems.
   - 2.3 Only use air cleaners for which evidence of effectiveness and safety is clear.
   - 2.4 Select control options, including standalone filters and air cleaners, that provide desired exposure reduction while minimizing associated energy penalties.

3. *Air Distribution* - Where directional airflow is not specifically required, or not recommended as the result of a risk assessment, promote mixing of space air without causing strong air currents that increase direct transmission from person-to-person.

4. *HVAC System Operation*
   - 4.1 Maintain temperature and humidity design set points.
   - 4.2 Maintain equivalent clean air supply required for design occupancy whenever anyone is present in the space served by a system.
   - 4.3 When necessary to flush spaces between occupied periods, operate systems for a time required to achieve three air changes of equivalent clean air supply.
   - 4.4 Limit re-entry of contaminated air that may re-enter the building from energy recovery devices, outdoor air, and other sources to acceptable levels.

5. *System Commissioning – Verify that HVAC systems are functioning as designed.*

The *Lancet* COVID-19 Commission Task Force on Safe Work, Safe School, and Safe Travel

The First Four Healthy Building Strategies Every Building Should Pursue to Reduce Risk from COVID-19

JULY 2022

3. UPGRADE AIR FILTERS TO MINIMUM EFFICIENCY REPORTING VALUE (MERV) 13

HVAC systems often have air filters to remove airborne particles from outdoor air that is brought indoors and from air that is recirculated within the building.

- **Benefits related to reducing the risk of COVID-19 and other infectious disease transmission:** Upgrading filters on recirculated air to those with ratings of MERV 13 or higher will reduce the transport of airborne particles while systems are operating, which may help reduce airborne infectious disease transmission within rooms and between rooms.
- **Benefits beyond disease transmission:** Enhanced filtration can reduce indoor concentrations of airborne particles of either indoor origin (e.g., cooking, cleaning or vacuuming, frequent use of printers) or outdoor origin (e.g., vehicle traffic, wildfires, desert dust storms). Exposure to fine particulate matter is associated with reduced cognitive function and reduced respiratory and cardiovascular health.[26,27,28,29,30,31,32,33,34,35,36,37]
- **Feasibility:** Filter upgrades may not be possible for all HVAC systems; HVAC professionals should be consulted before filter changes are made in a building. Annual material, labor, and fan energy costs associated with the use of MERV 13 filtration in a hypothetical 500 m^2 office are estimated to be $156.[38]

4. SUPPLEMENT WITH PORTABLE AIR CLEANERS, WHERE NEEDED

Free-standing, plug-in portable air cleaners with high efficiency particulate air (HEPA) filters capture airborne particles in rooms where they are deployed, when sized correctly.[39]

- **Benefits related to reducing the risk of COVID-19 and other infectious disease transmission:** Properly sized portable air cleaners with HEPA filters can reduce in-room concentrations of airborne particles, including those carrying viral material.
- **Benefits beyond disease transmission:** Portable air cleaners can reduce indoor concentrations of any airborne particles and reduce the risk of harmful particle-induced impacts on neurological/cognitive, respiratory, and cardiovascular health.
- **Feasibility:** Portable air cleaners are cost-effective, flexible solutions to reduce the risk of airborne infectious disease transmission in spaces where other ventilation and filtration modifications are impossible, or where building occupants seek additional reassurance about air quality.[40]

Non-infectious air delivery rate (NADR)

The Lancet COVID-19 Commission Task Force on Safe Work, Safe School, and Safe Travel

Proposed Non-infectious Air Delivery Rates (NADR) for Reducing Exposure to Airborne Respiratory Infectious Diseases

NOVEMBER 2022

TABLE 1.
Proposed Non-infectious Air Delivery Rates (NADR) for Reducing Exposure to Airborne Respiratory Diseases; The Lancet COVID-19 Commission Task Force on Safe School, Safe Work, and Safe Travel

	Volumetric flow rate per volume	Volumetric flow rate per person		Volumetric flow rate per floor area	
	ACHe	cfm/person	L/s/person	cfm/ft²	L/s/m²
Good	4	21	10	0.75 + ASHRAE minimum outdoor air ventilation	3.8 + ASHRAE minimum outdoor air ventilation
Better	6	30	14	1.0 + ASHRAE minimum outdoor air ventilation	5.1 + ASHRAE minimum outdoor air ventilation
Best	>6	>30	>14	>1.0 + ASHRAE minimum outdoor air ventilation	>5.1 + ASHRAE minimum outdoor air ventilation

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May 12-2023: ASHRAE 241 and CDC

ASHRAE

ASHRAE Standard 241P

Advisory Public Review Draft

Control of Infectious Aerosols

Table 5-1 Minimum Equivalent Outdoor Air per person for Infection Control Rates in *Breathing Zone*

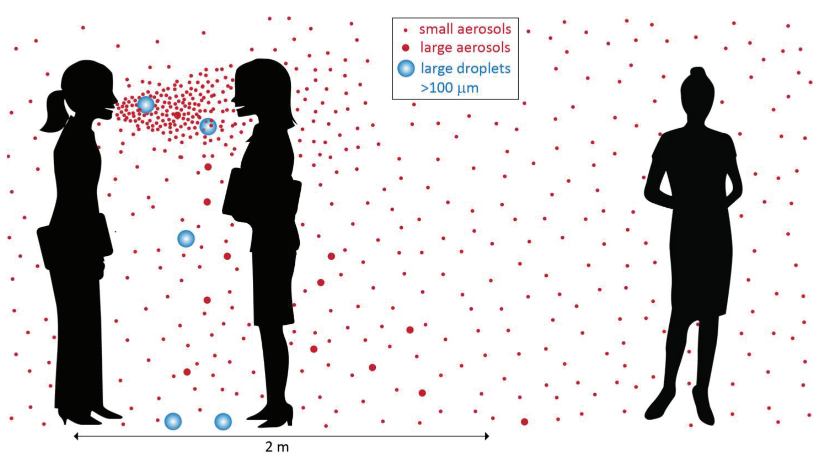
Occupancy Category	EOAi	
	CFM/person	L/s/person
Office	40	20
Educational Facilities	50	25
Food and Beverage Facilities	40	20
Residential	50	25
Retail	20	10
Gym	80	40
Public Assembly spaces	20	10
Place of religious worship	30	15
Healthcare exam room	60	30
Healthcare patient room	180	90
Healthcare resident room	80	40
Common treatment area	90	45
Healthcare waiting room	120	60

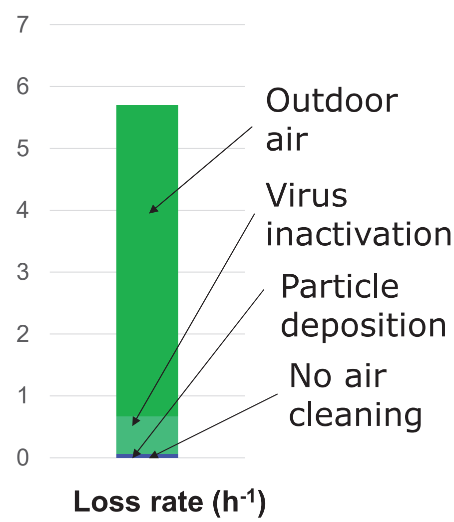
CDC Centers for Disease Control and Prevention
CDC 24/7: Saving Lives, Protecting People™

5 ach

DTU

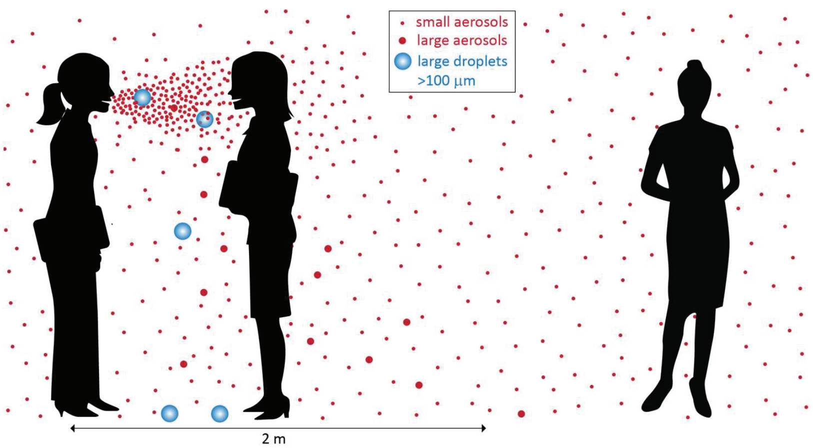
Aerosol transmission, long range

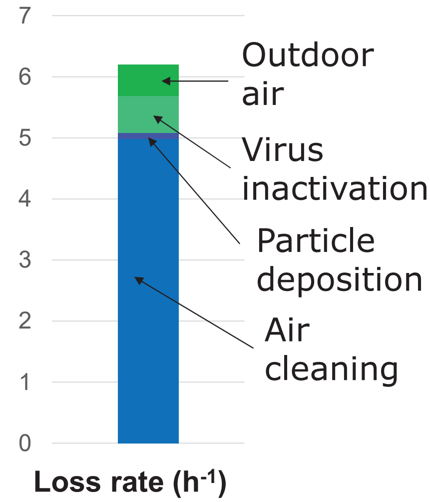




Sources: Morawska et al. (2020); Johnson et al. (2004); Van Dormalen et al. (2020); Hussein and Kulmala (2008); ANSI/AHAM AC-1

Aerosol transmission, long range

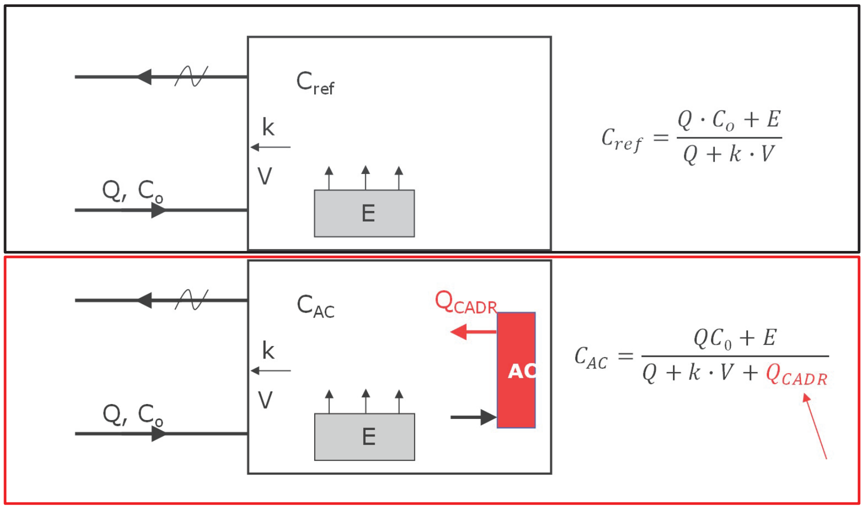


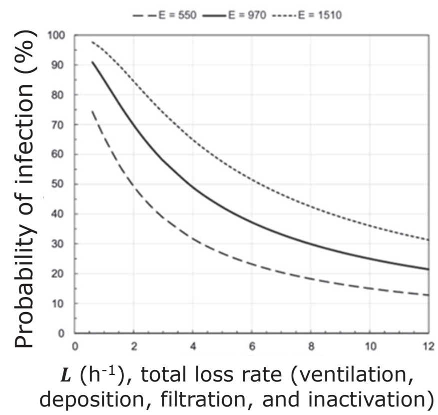


Sources: Morawska et al. (2020); Johnson et al. (2004); Van Dormalen et al. (2020); Hussein and Kulmala (2008); ANSI/AHAM AC-1

Air cleaning

The effect of air cleaner => additional dilution/removal => lower risk





Sources: Miller et al. (2021)

Air cleaning technologies

Technology	Mechanism of action	Key parameters	Example
"Subtractive" technologies (filters, sorbents)	Removing or inactivating targeted contaminants from indoor air when they come in contact with the technology	• Airflow rate • Face velocity • Single-pass efficiency • Potential for by-product formation	Filters, electrostatic precipitators (ESPs), sorbent media (for gases), excitation media, UVGI
"Additive" technologies (electronic and reactive air cleaners)	Adding constituents to the air to remove particles, inactivate microorganisms and/or react with chemical contaminants	• Type, concentration and dose of additives • Potential toxicity of additives • Potential for by-product formation • Airflow • Face velocity • Location with respect to space • Recirculated vs 100% OA	Ionizers, bipolar ionization, needle point discharge, ozone, plasma, hydrogen peroxide, PCO, reactive oxygen species, oxidants, fumigation, UVGI
Hybrid			

Courtesy of Gall and Stephens

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Common test standards

Technology	Target Pollutant(s)	Test Standards (Rating Metrics)
Fibrous media filters	Particles	ASHRAE 52.2 (MERV) ISO 16890 (ePM) ISO 29463 (HEPA) Proprietary standards (FPR,MPR) Portable air cleaners: AHAM AC-1 (CADR)
Sorbent	Gases	ASHRAE 145.2
Ultraviolet germicidal irradiation (UVGI)	Microbial particles	Air: ASHRAE 185.1 Surfaces: ASHRAE 185.2
Electrostatic precipitators (ESPs)	Particles+	No rating; some ozone emission standards (UL 2998)
Ionizers, plasma, PCO, H2O2, etc.	Particles+	No rating; some ozone emission standards (UL 2998)

ASHRAE Standard 62.1-2019 requires any air cleaning technologies to comply with UL 2998 (0 ppb ozone)

Courtesy of Gall and Stephens

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Position documents providing guidelines

All filtration and air-cleaning technologies should be accompanied by data documenting their performance regarding removal of contaminants; these data should be based on established industry test standards. If not available, scientifically controlled third-party evaluation and documentation should be provided.

Devices that use the reactivity of ozone for the purpose of cleaning the air should not be used in occupied spaces because of negative health effects that arise from exposure to ozone and its reaction products. Extreme caution is warranted when using devices that emit a significant amount of ozone as by-product of their operation, rather than as a method of air cleaning. These devices pose a potential risk to health.

Commissioning, active maintenance, and monitoring of filtration and air-cleaning devices are needed to ensure design performance.

In the absence of robust information regarding safe levels of ozone, the precautionary principle should be used. Any ozone emission (beyond a trivial amount that any electrical device can emit) should be seen as a negative and use of an ozone-emitting air cleaner, even though the ozoneis an unintentional by-product of operation, may represent a net negative impact on indoor air quality and thus should be used with caution. If possible, non-ozone-emitting alternatives should be used.

Attentionmust be paid to certain air-cleaning technologies that claim to produce radicals (e.g.,hydroperoxy, peroxy, and hydroxyl radicals) that become airborne (gaseous state) as a means of effecting air cleaning/treatment

ASHRAE®

ASHRAE Position Document on Filtration and Air Cleaning

Approved by ASHRAE Board of Directors
January 29, 2015

Expires
January 29, 2018

ASHRAE
1791 Tullie Circle, NE • Atlanta, Georgia 30329-2305
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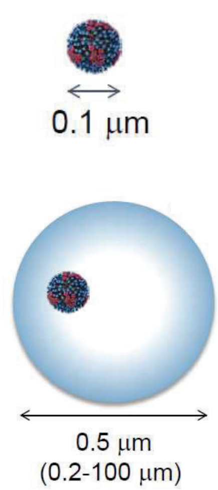
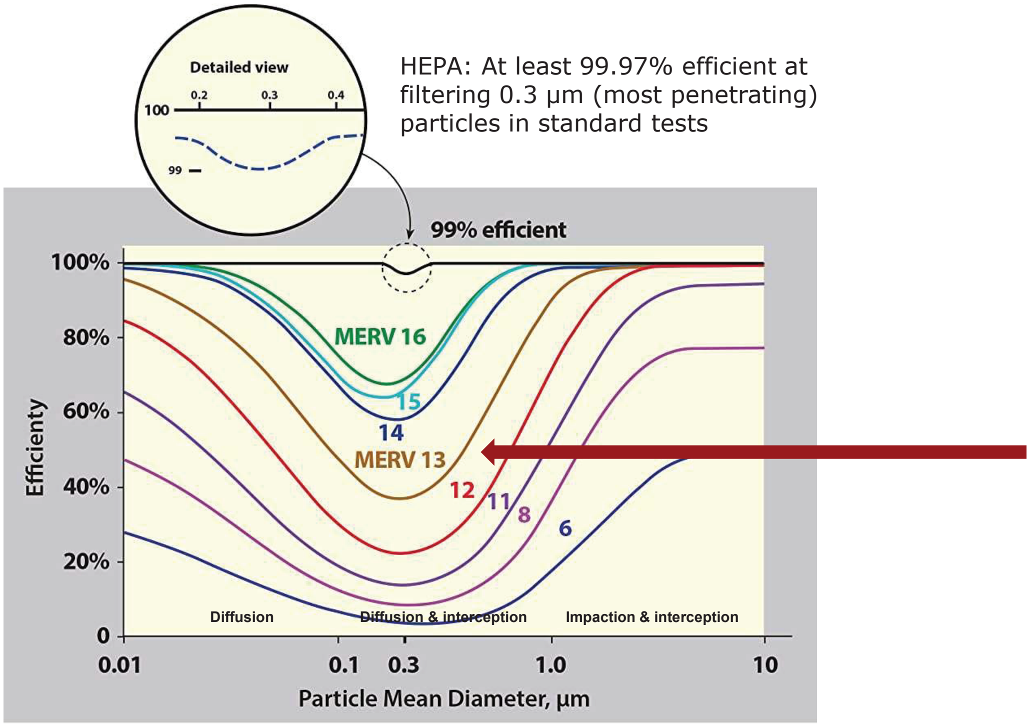
Air filtration



Sources: *Visual Capitalist*



ASHRAE Recommendations: MERV 13

MERV 8 + MERV 11 = **MERV 13**

MERV 11 + UVC 60% = **MERV 13**

MERV 8 + UVC 80% = **MERV 13**

MERV 11 + HEPA CADR 150= **MERV 13**

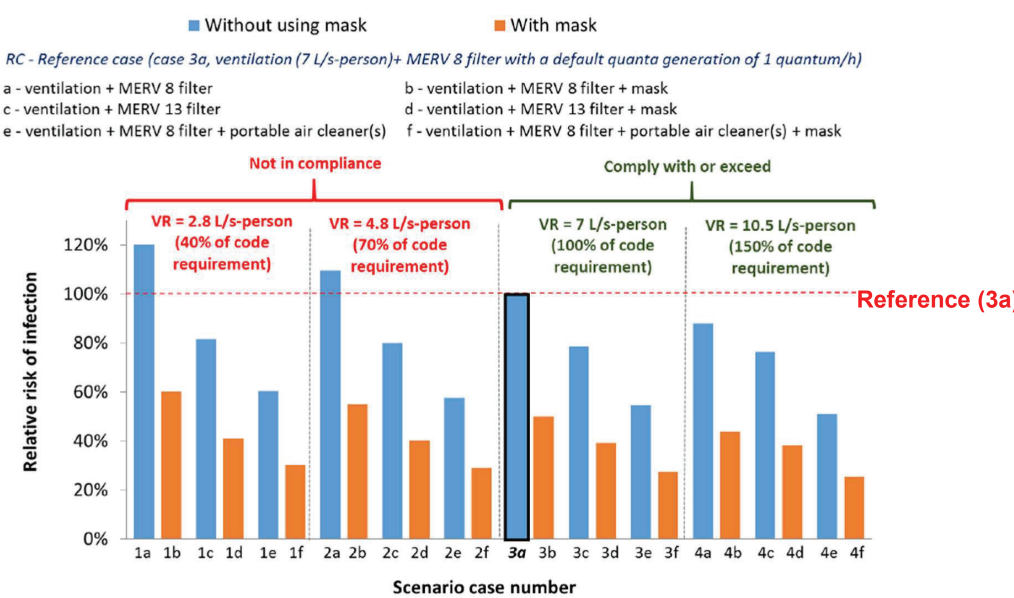
MERV 8 + HEPA CADR 300= **MERV 13**

Courtesy of Zaatari

Do-it-yourself (DIY) portable air cleaners, e.g. Corsi-Rosenthal

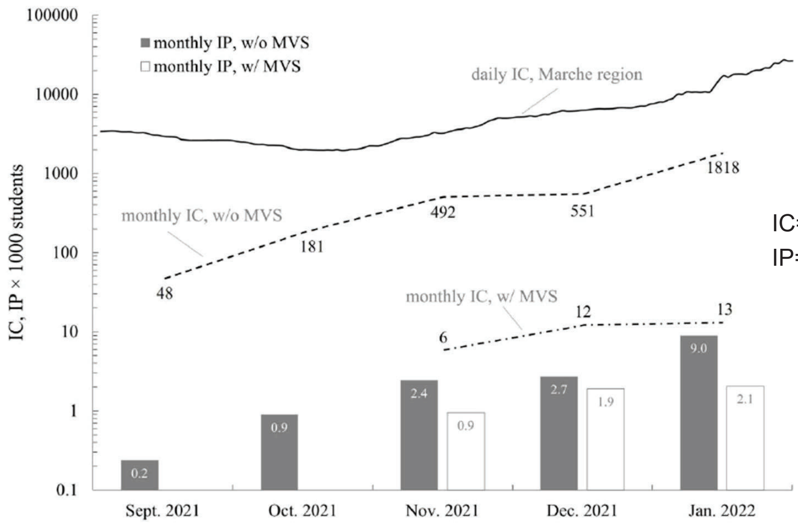
Sources: Sactown Magazine

No field data, only modeling



Sources: California Department of Public Health

Field validation with increased ventilation



IC=incidence cases
IP=incidence proportion

Sources: Buonanno et al. (2022)

Other air cleaners

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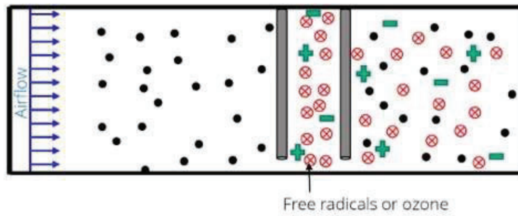
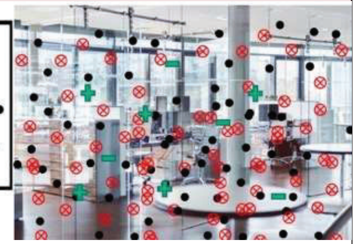
Electronic Air Cleaners – EACs, or additive air cleaners





Names

4 broad categories and MANY MANY names

- **Photocatalytic Oxidation (PCO) and Dry Hydrogen Peroxide (DHP)**
- **Bipolar Ionization/Corona Discharge/ Needlepoint Ionization**
- **Oxidants**
- **Fumigation**

Mechanism

But the mechanism is the same:

Create reactive ions, mixtures of reactive oxygen species (ROS), ozone, hydroxyl radicals, superoxide anions, etc. in air that react with airborne contaminants

Facts

Fact 1: Free radicals and/or ozone produced

Fact 2: Indiscriminate and unpredictable reactions

Fact 3: unproven to be safe or effective

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UVGI and UVC

UV-C energy: 265 nm optimum wavelength for damaging DNA and RNA.

What?

- Air and/or surface
- Upper room, in duct, portable

How much?

- On the fly air disinfection: Minimum target UVC dose (254 nm) of 1,500 μW•s/cm^2 (1,500 μJ/cm^2) to get 99% removal.
- Should be coupled with mechanical filtration

https://www.ashrae.org/technical-resources/filtration-disinfection

Challenges

Major misconceptions and problems

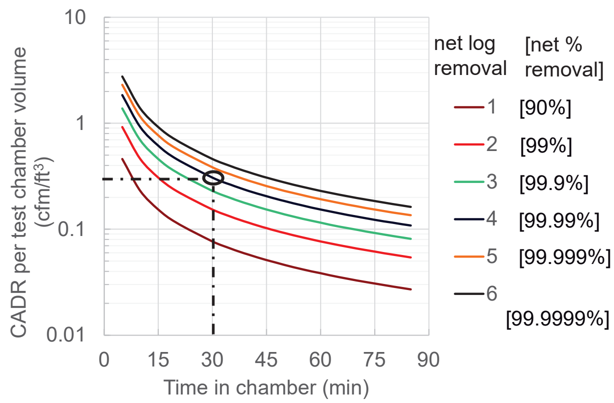
- Efficiency vs. effectiveness or efficiency vs. CADR
- Production of ozone or other reactive species
- Chemical transformations producing new species, (potentially) toxic pollutants
- CADR vs. noise, noise vs. Efficiency

- Commissioning, maintenance, operation, monitoring, documentation

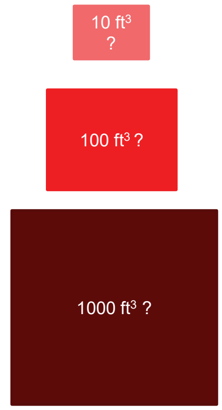
CADR Scales With Volume of Test Chamber

Consider the following test result:

- 99.99% removal in 30 minutes



What is the CADR if the tested in a chamber with volume…



CADR
3 cfm
30 cfm
300 cfm

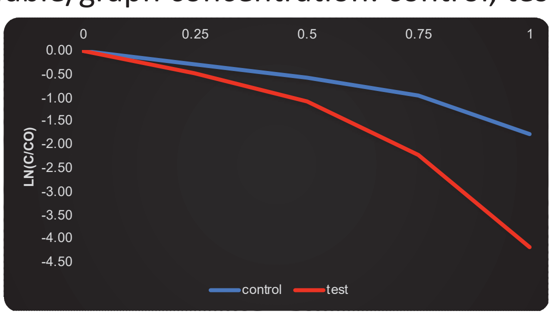
A wide range of CADRs can all claim 99.99% removal in 30 minutes, depending on test chamber volume

Calculation of efficiency in realistic indoor environments

https://www.pdx.edu/healthy-buildings/ace-it

Consider the following test result:

- 98.3% removal in 60 minutes
- Table/graph concentration: control, test



2) Comparison calculation		
	loss rate (1/h)	
control (w/ device off)	1.5	
test (w/ device on)	3.5	
Effect of device	2.0	
3) Scaling to indoor setting		
Floor area	1,000	ft²
Ceiling height	8	ft
Volume	8,000	ft3
Clean air changes per hour (ACH) provided by device	0.31	1/h

To get 5 ACH, we need to install in this classroom 16 units.

→ Manufacturer recommendation is 1 device for 4 classrooms:

→ For 4 classrooms to achieve 5 ACH, you would need 4 x 16 = 64 devices!!!

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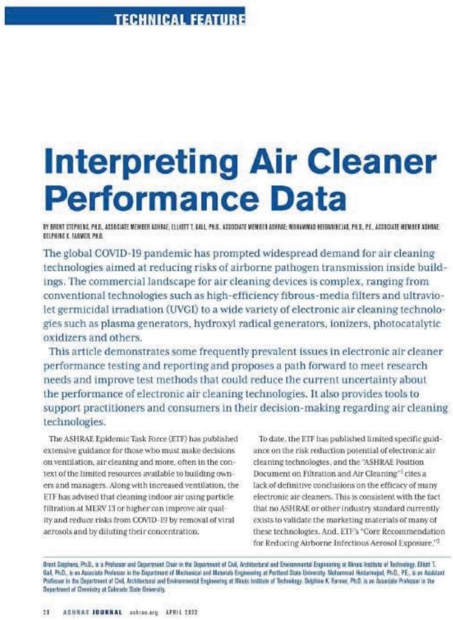
More examples



TECHNICAL FEATURE

Interpreting Air Cleaner Performance Data

BY BRENT STEPHENS, PH.D., ASSOCIATE MEMBER ASHRAE; ELLIOTT T. GALL, PH.D., ASSOCIATE MEMBER ASHRAE; MOHAMMAD HEIDARINEJAD, PH.D., P.E., ASSOCIATE MEMBER ASHRAE; DELPHINE K. FARMER, PH.D.

The global COVID-19 pandemic has prompted widespread demand for air cleaning technologies aimed at reducing risks of airborne pathogen transmission inside buildings. The commercial landscape for air cleaning devices is complex, ranging from conventional technologies such as high-efficiency fibrous-media filters and ultraviolet germicidal irradiation (UVGI) to a wide variety of electronic air cleaning technologies such as plasma generators, hydroxyl radical generators, ionizers, photocatalytic oxidizers and others.

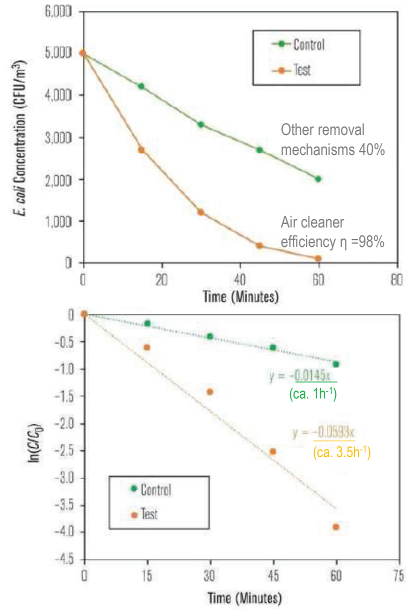
This article demonstrates some frequently prevalent issues in electronic air cleaner performance testing and reporting and proposes a path forward to meet research needs and improve test methods that could reduce the current uncertainty about the performance of electronic air cleaning technologies. It also provides tools to support practitioners and consumers in their decision-making regarding air cleaning technologies.

The ASHRAE Epidemic Task Force (ETF) has published extensive guidance for those who must make decisions on ventilation, air cleaning and more, often in the context of the limited resources available to building owners and managers. Along with increased ventilation, the ETF has advised that cleaning indoor air using particle filtration at MERV 13 or higher can improve air quality and reduce risks from COVID-19 by removal of viral aerosols and by diluting their concentration.

To date, the ETF has published limited specific guidance on the risk reduction potential of electronic air cleaning technologies, and the "ASHRAE Position Document on Filtration and Air Cleaning"[1] cites a lack of definitive conclusions on the efficacy of many electronic air cleaners. This is consistent with the fact that no ASHRAE or other industry standard currently exists to validate the marketing materials of many of these technologies. And, ETF's "Core Recommendation for Reducing Airborne Infectious Aerosol Exposure."[2]

Brent Stephens, Ph.D., is a Professor and Department Chair in the Department of Civil, Architectural and Environmental Engineering at Illinois Institute of Technology. Elliott T. Gall, Ph.D., is an Associate Professor in the Department of Mechanical and Materials Engineering at Portland State University. Mohammad Heidarinejad, Ph.D., P.E., is an Assistant Professor in the Department of Civil, Architectural and Environmental Engineering at Illinois Institute of Technology. Delphine K. Farmer, Ph.D., is an Associate Professor in the Department of Chemistry at Colorado State University.

ASHRAE JOURNAL ashrae.org APRIL 2022



Removal rate difference in a 14.2 m^3 chamber: CADR=50-13=37 m^3/h (2.5 h^{-1})

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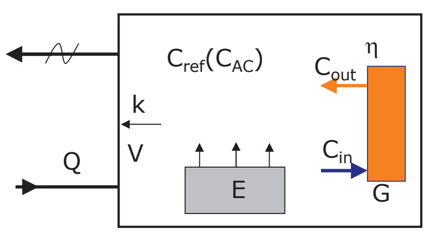
Removal effect (ε) Effectiveness (f)



$$\varepsilon = \frac{C_{ref} - C_{AC}}{C_{AC}} \cdot 100\ [\%]$$

or

$$\varepsilon = \frac{f}{f+1} \quad where\ f = \frac{CADR}{Q + k \cdot V}$$

- Fractional reduction in pollutant concentration that results from application of an air cleaner in indoor volume/space.
- Effectiveness is judged against other removal processes (by deposition rate and ventilation)

Ozone

Standard/Protocol	Methods	Measuring time	Measuring space /volume	Thresholds
Standards for Electric Air Cleaners, US Underwriters Laboratory (UL standard 867)	Measuring ozone concentration	24 h	Chamber/ $33.1m^3$	**50 ppb**
Electric Air Cleaners, Canadian Standard Association (CSA C-187 C1.7.4)	Measuring ozone concentration	24 h (8h time weight average)	Chamber/Similar to UL standard	**20 ppb**
Reduced Energy Use Through Reduced Indoor Contamination in Residential Buildings, NCEMBT (NCEMBT 061101), US report	Calculate ozone generation rate	-	Chamber/ $55m^3$	**-**
National Research Council Canada (NRC) standard	Calculate ozone generation rate	-	Chamber/ $55m^3$	**(suggest not exceed 50 ppb)**

Sources: Afshari et al. (2022)

Byproduct generation, incomplete oxidation

- Aldehydes → **formaldehyde**, formic acid, CO
- **Alcohols** → aldehydes → acids → shorter carbon chain alcohols and acids →**formaldehyde**, methanol → CO_2 and H_2O
- Benzene → phenol
- 1-Butanol → butanal (butyraldehyde), butanoic acid, ethanol, acetaldehyde, (propanal (propionaldehyde) and propanol, propanoic acid) → (ethanol, **formaldehyde**) → methanol, **formaldehyde** and formic acid
- Ethanol → methanol, acetaldehyde, **formaldehyde**, acetic acid, formic acid
- Methanol → methyl formate (measured in liquid form only), **formaldehyde**, methylal (formaldehyde dimethyl acetal
- Toluene → benzaldehyde, benzoic acid, cresol, benzyl alcohol, phenol, benzene, formic acid

Sources: Mo et al. (2009)

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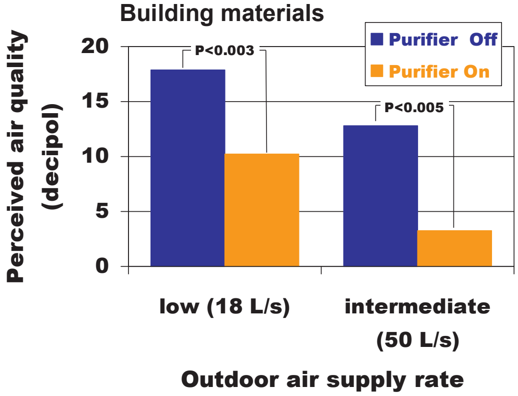
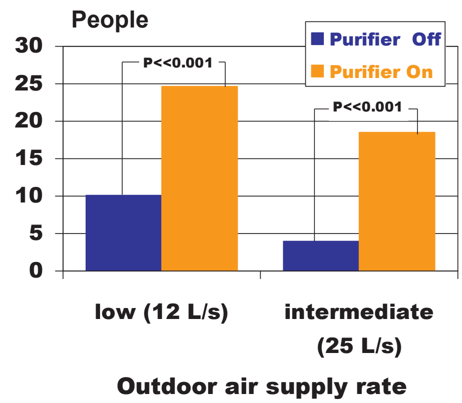
By-product, example





Sources: Kolarik and Wargocki (2010)

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New evidence: human oxidation field

- The presence of any ozone should be avoided (also in the reactor)
- Skin oils + ozone => non insignificant yields of OH radical => significant reactions in the air

RESEARCH

INDOOR AIR QUALITY

The human oxidation field

Nora Zannoni[1]*†, Pascale S. J. Lakey[2], Youngbo Won[3], Manabu Shiraiwa[2]*, Donghyun Rim[3]*, Charles J. Weschler[4,5], Nijing Wang[1], Lisa Ernle[1], Mengze Li[1]‡, Gabriel Bekö[4], Pawel Wargocki[4], Jonathan Williams[1,6]*

Hydroxyl (OH) radicals are highly reactive species that can oxidize most pollutant gases. In this study, high concentrations of OH radicals were found when people were exposed to ozone in a climate-controlled chamber. OH concentrations calculated by two methods using measurements of total OH reactivity, speciated alkenes, and oxidation products were consistent with those obtained from a chemically explicit model. Key to establishing this human-induced oxidation field is 6-methyl-5-hepten-2-one (6-MHO), which forms when ozone reacts with the skin-oil squalene and subsequently generates OH efficiently through gas-phase reaction with ozone. A dynamic model was used to show the spatial extent of the human-generated OH oxidation field and its dependency on ozone influx through ventilation. This finding has implications for the oxidation, lifetime, and perception of chemicals indoors and, ultimately, human health.

North Americans and Europeans spend, on average, ~90% of their time indoors (including home, workplace, and transport) (1, 2). Within this enclosed space, occupants are exposed to a multitude of chemicals from various sources, including outdoor pollutants that penetrate indoors, gaseous emissions from building materials and furnishings, and products of human activities such as cooking and cleaning (3). In addition, the occupants themselves are a potent mobile source of gaseous emissions from breath and skin (human bioeffluents) as well as primary and secondary particles (4). Characterization of these indoor sources and the main indoor removal mechanisms are key to understanding indoor air quality (5).

Chemical removal of gas-phase species in outside air during daytime is mostly initiated by hydroxyl (OH) radicals, which are formed when a short-wavelength photolysis product of ozone (O_3) [an excited oxygen atom, O (^1D)] reacts with water. Longer-wavelength photolysis of nitrous acid (HONO) and formaldehyde (HCHO) also provides small additional OH sources outside, as does the light-independent ozonolysis of alkenes via Criegee intermediate formation (6). By contrast, the indoor environment is less influenced by direct sunlight, in particular ultraviolet light, which is largely filtered out by glass windows, so that primary production of OH indoors via O (^1D) is negligible. Although some OH can be generated by longer-wavelength artificial light by photolysis with natural light of formaldehyde and HONO if present, O_3 entering the building from outside is generally considered to be the principal oxidant indoors (7). Nevertheless, previous studies have highlighted the potential importance of alkene ozonolysis (8–11) in generating OH via Criegee intermediates in indoor environments, particularly when reactive molecules such as limonene from air fresheners or cooking are abundant. Previous estimates and measurements of indoor OH concentrations have ranged from 10^5 to 10^7 molecules cm^{-3}, which is substantially higher than outdoor nighttime concentrations and comparable to daytime atmospheric OH concentration levels in some regions (8–15).

None of the aforementioned model or measurement studies considered occupied indoor environments and therefore the underlying chemical influence of humans. Yet with every breath, humans exhale reactive alkenes such as isoprene, which can oxidize to further alkenes such as methyl vinyl ketone (MVK) and methacrolein (MACR) (16). Moreover, O_3 reacting at the skin surface with the skin-oil squalene ($C_{30}H_{50}$), a triterpene responsible for almost 50% of the unsaturated carbon atoms on human skin, releases a host of alkene-containing compounds to the air, including geranyl acetone, 6-methyl-5-hepten-2-one (6-MHO), OH-6-methyl-5-hepten-2-one (OH-6-MHO), 4-methyl-8-oxo-4-nonenal (4-MON), 4-methyl-4-octene-1,8-dial (4-MOD), and *trans*-2-nonenal (17). These species have the potential to react further in the gas phase, either to generate OH through reaction with O_3 or to deplete OH through direct reaction with the alkene. Therefore, humans have the potential to profoundly affect the oxidative environment indoors, particularly in areas of high occupancy (18), larger exposed body surface, and higher air temperature and humidity (19).

In this study, measurements were conducted in a climate-controlled stainless-steel chamber (see Fig. 1) with three different groups of four adult subjects on four separate days (including two replicates from the same group) (20). The air change rate (ACR) (3.2 $hour^{-1}$) and O_3 concentration [100 parts per billion (ppb) at the inlet and 35 ppb indoors] used in this experiment were chosen for reproducing a realistic scenario based on the expected O_3 decrease due to occupancy (21). (ACR is the number of times that the total air volume in a room or space is completely replaced by outdoor air in an hour.) From this data, we have determined the indoor concentrations and spatial distribution of OH radicals generated by humans upon exposure to O_3. This oxidative field is produced in isolation from other indoor sources or sinks of OH. A steady-state approach was applied, combining measured total OH reactivity (OH loss frequency in s^{-1}), measured concentrations of compounds containing an alkene double bond, and available literature values of OH yields from O_3 with alkene reactions. For comparison, the OH levels were also determined by an independent method using isoprene and its oxidation products. In the final step, the empirically derived OH levels and measurements were compared with those obtained from a detailed multiphase chemical kinetic model, and these results were used to simulate high spatial and time-resolved OH distributions in a room using a computational fluid dynamics (CFD) model. To investigate the existence and variability of spatial concentration gradients, we tested four scenarios: (i) an evaluation of the experimental results using the same underfloor air distribution from a perforated floor along with intensive air mixing at the average indoor O_3 concentration of 35 ppb as in the experiment, (ii) the same ventilation condition of the experiment without any mixing fans at an indoor O_3 concentration of 35 ppb to simulate a residential condition, (iii) air jets supplied at ceiling height and an indoor O_3 concentration of 35 ppb to simulate an office condition, and (iv) same as (iii) except the indoor O_3 concentration was 5 ppb.

Results

Total OH reactivity of human emissions

Figure 2 shows the OH loss frequency (total OH reactivity) measured directly in the chamber. The total OH reactivity of the gas-phase human bioeffluents was, on average, 8 ± 4 s^{-1} in the absence of O_3 and 34 ± 16 s^{-1} when O_3 was present (mean value ± measurement error, determined at equilibrium in the last 15 min before volunteers left the chamber). In the absence of O_3, the dominant OH sinks were reactive compounds in human breath (e.g., isoprene 64%), whereas in the presence of O_3,

[1]Atmospheric Chemistry Department, Max Planck Institute for Chemistry, Mainz, Germany. [2]Department of Chemistry, University of California, Irvine, CA, USA. [3]Department of Architectural Engineering, Pennsylvania State University, University Park, PA, USA. [4]International Centre for Indoor Environment and Energy, Environmental and Resource Engineering, DTU Sustain, Technical University of Denmark, Lyngby, Denmark. [5]Environmental and Occupational Health Sciences Institute, Rutgers University, Piscataway, NJ, USA. [6]Energy, Environment and Water Research Center, The Cyprus Institute, Nicosia, Cyprus.
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‡Department of Climate and Space Sciences and Engineering, University of Michigan, Ann Arbor, MI, USA.

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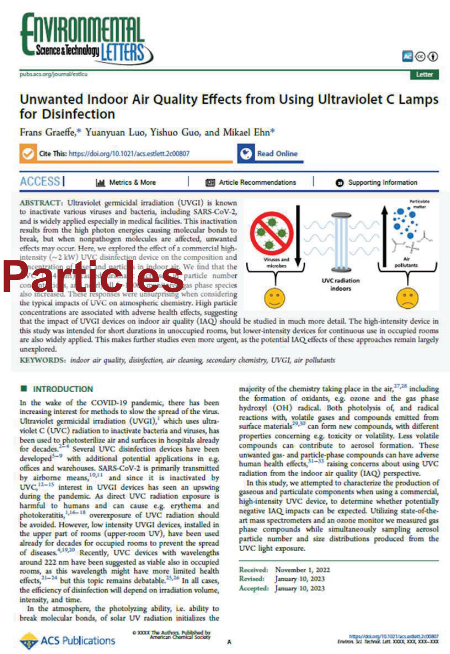
Toxic pollutants?



Particles

Gaseous toxic pollutants

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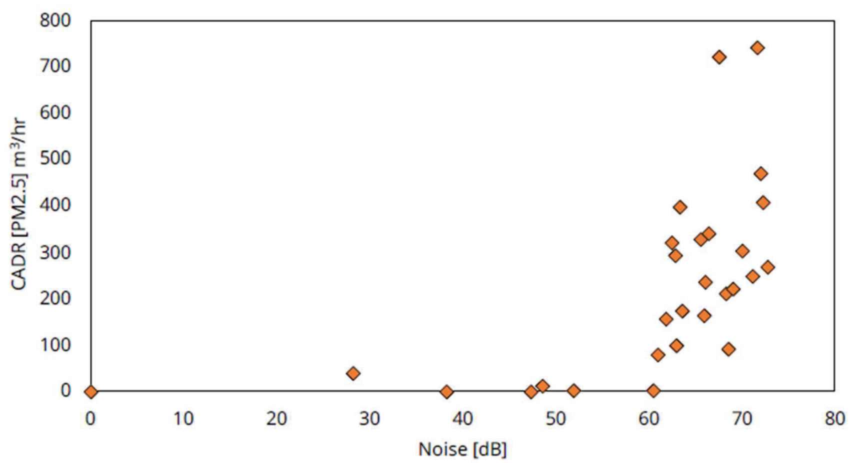
Noise



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Impact on energy use, cost-benefit

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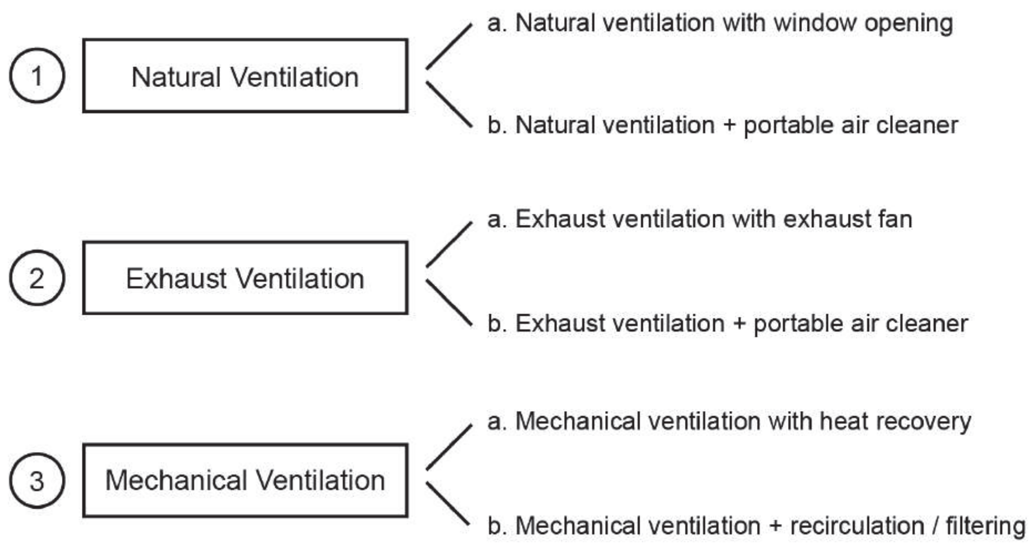

Unpublished: Tsafara (and Wargocki) (2021)

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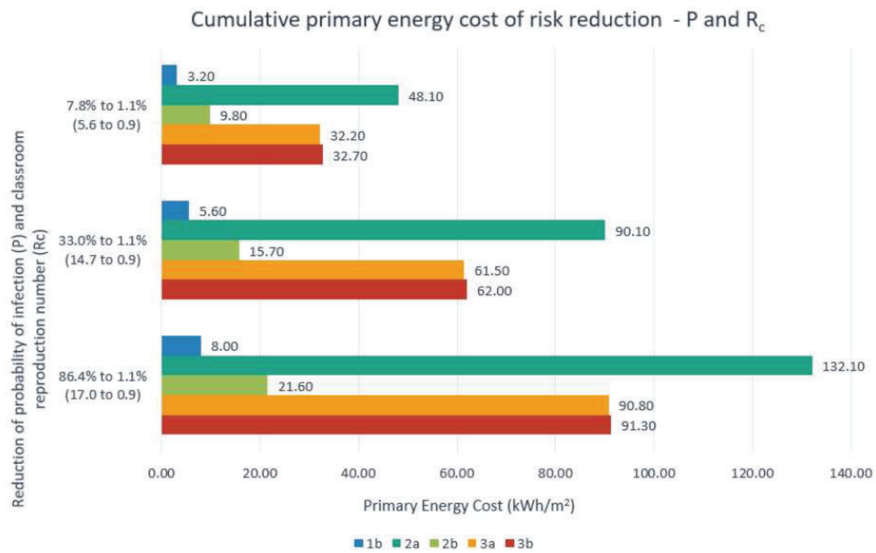
Energy Implications, Danish School



Unpublished: Tsafara (and Wargocki) (2021)

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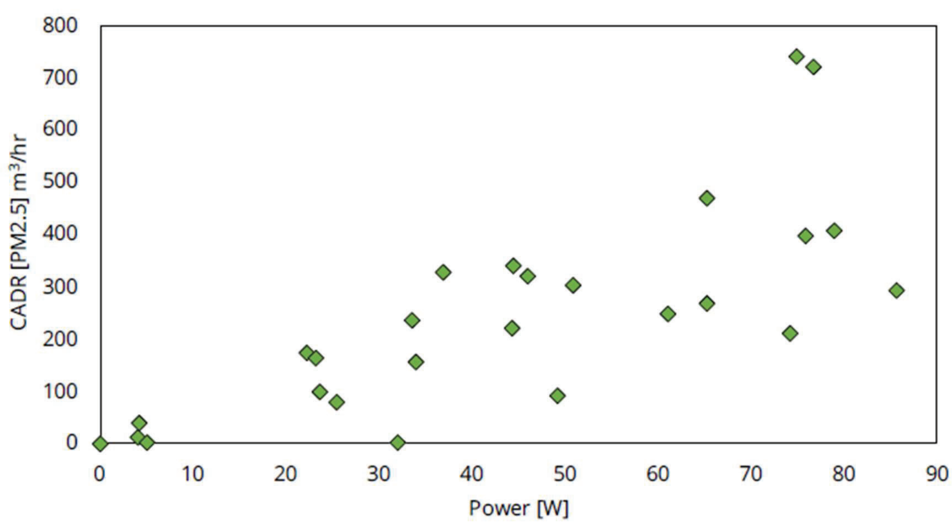
Power



Sources: DTI (2022)

Cost vs. Benefit - Boston 50k ft2, 250 Occupants

Total Annual Outside Air + Filtration Cost

	Bare Minimum (3-4 ACH)	Good (4-5 ACH)	Excellent (5-6 ACH)	Ideal (6 ACH)
100% OA	n/a	n/a	n/a	$85,827
	MERV 7	MERV 11	MERV 13	HEPA
VRP+30%	$18,100	$18,738	$19,834	$46,566
VRP	$15,384	$16,047	$17,182	$44,871
IAQP	$10,340	$11,050	$12,261	$41,838

Cost per Effective ACH

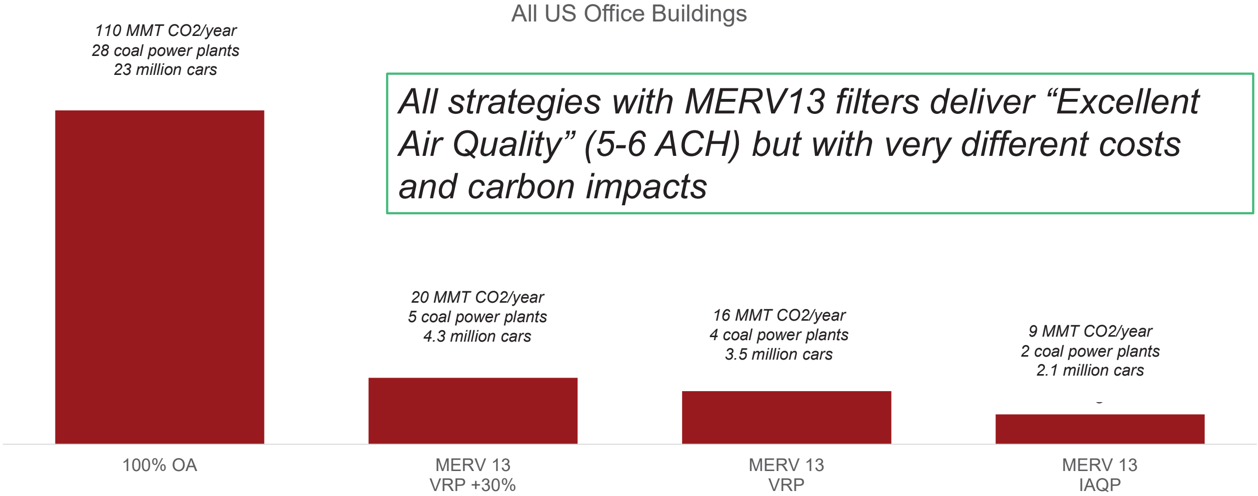
	Bare Minimum (3-4 ACH)	Good (4-5 ACH)	Excellent (5-6 ACH)	Ideal (6 ACH)
100% OA	n/a	n/a	n/a	$14,305
	MERV 7	MERV 11	MERV 13	HEPA
VRP+30%	$6,033	$4,685	$3,967	$7,761
VRP	$5,128	$4,012	$3,436	$7,479
IAQP	$3,447	$2,763	$2,452	$6,973

Courtesy of Zaatari

US Office Carbon Impact of Different Strategies

Million Metric tons of CO2/year
All US Office Buildings

All strategies with MERV13 filters deliver "Excellent Air Quality" (5-6 ACH) but with very different costs and carbon impacts



Courtesy of Zaatari

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Epilogue

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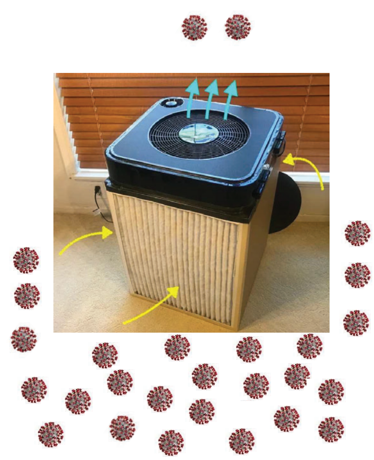
Take home messages (w/strong personal bias)

Air cleaning as a measure to reduce infection risk

- Outdoor air: yes (and no)
- Air cleaning and filtration: yes and no

- MERV13 and higher: yes
- Portable air cleaners (HEPA): probably yes
- UVC/UVGI: probably yes
- Additive technologies: (probably) no
- Reactive species: (probably) banned

- Lack of proper testing methods
- Lack of verification in actual applications
- Weighting risks



pawar@dtu.dk

Thank You

Developing regulations to improve IAQ and ventilation in Belgian buildings

Peter Wouters – Arnold Janssens

Structure of the presentation

- **Introduction**
- 2006 - Ventilation related requirements in the context of the EPBD
- 2015 - On site performance checks of declared building airtightness levels
- 2016 - On site performance checks of residential ventilation systems
- 2019 - Federal regulation regarding wellbeing on workplaces
- 2022 - Federal regulation on indoor air quality
- Conclusions

Introduction

- **1991**: Belgian standard NBN D50-001 with specifications regarding ventilation in residential buildings
  →In practice very limited impact due to no compliance framework
- **Since 2006**: Starting with the adoption of the EPBD: stepwise evolution in regulatory specifications regarding ventilation in buildings
- **Regulatory context:** Belgium is a federal country
  - Federal government
  - 3 regional governments (Brussels capital – Flemish Region – Walloon Region)
    - In charge of energy policy in buildings

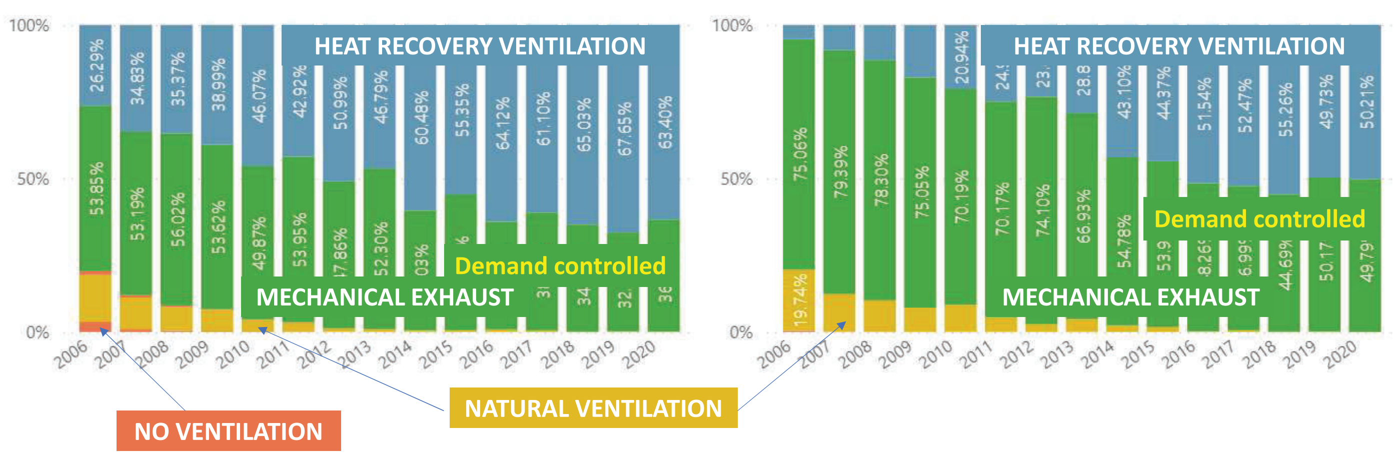
2006 - Ventilation related requirements in the context of the EPBD

- EPBD? → see presentation by Jaap Hogeling
- EPBD refers since first version in 2003 to indoor air quality
- Belgian context:
  - Transposition of this EPBD directive is the responsibility of the 3 Regions, in practice for new buildings to a large extent a similar approach
- What type of points of attention in Belgian context?
  1. Minimum air flow requirements for all new buildings
  2. Energy efficiencient ventilation is stimulated – see next slides
  3. Legal framework for allowing innovative solutions – see next slides
  4. Database with reliable product data
  5. Energy performance declaration at the end of the works ('as build')
  6. Strict compliance and infringement framework

NEW buildings

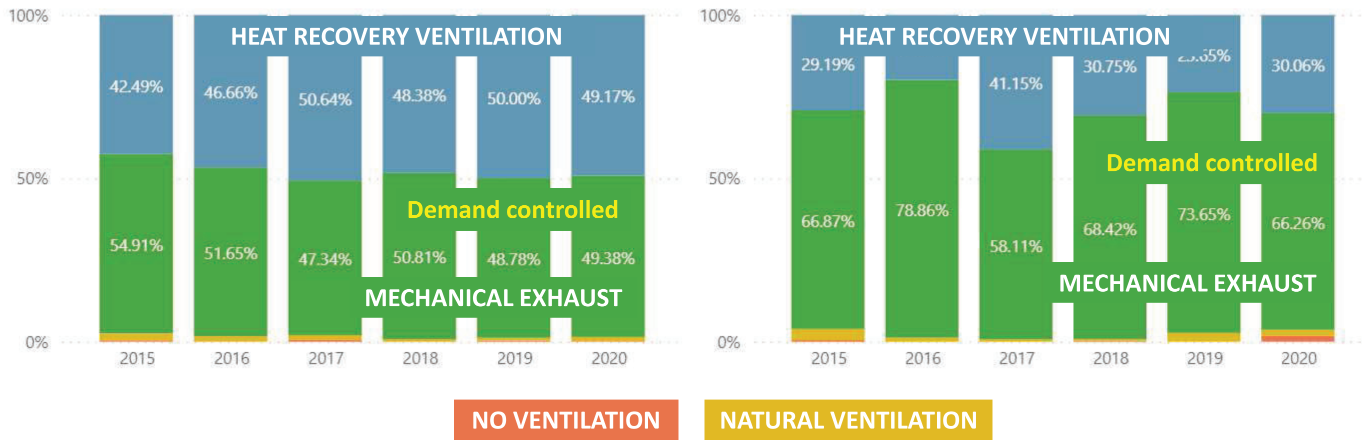
Single family dwellings

Apartments in multifamily buildings



DEEP energy RENOVATIONS

Single family dwellings | Apartments in multifamily buildings



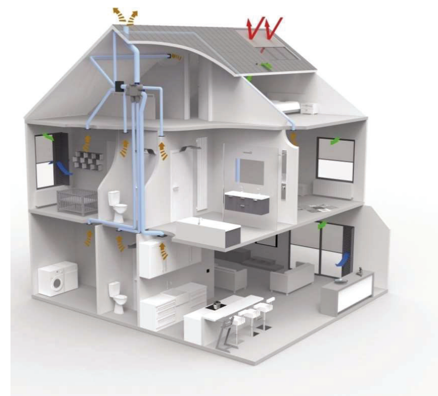
2006- Ventilation related requirements in the context of the EPBD

Belgian energy legislation **<u>stimulates energy efficient ventilation</u>** **by various ways:**

- Benefits in case of **heat recovery ventilation**
- Benefits in case of **demand controlled ventilation**
- **Fan power** is taken into account
- **Airtightness of ductwork** can be taken into account
- **Quality of installation** can be taken into account (installed flow rates, balancing of flow rates,…)

Assessment of innovative systems

- **By principle of equivalence**
  - Manufacturers can submit a request
  - Based on the identified performances, a reduction factor is determined based on extensive simulations
- **In practice since 2010:**
  - Regulations allow for the application of residential demand controlled ventilation (DCV)
    - ±30 ventilation systems assessed through equivalence, mainly MEV
  - Generic DCV-classification method with reduction factors in regulatory calculations since 2016
    - ±50 ventilation systems with declared performance on the residential market



Strict compliance framework

- EPB-assessor reports status <u>after completion of works</u>
- Non-compliance with regulations = <u>fines</u>
- Rules are <u>very clear and integrated in software tool</u>:
  - E.g. Ventilation: 4 € per missing m³/h
    - Example:
      - Requirement in bathroom: 50 m³/h
      - If in reality only 10 m³/h: fine = 4*(50-10) = 160 €
- No need to involve judge in decision process

"Reliable" product data

… these data will be accepted by the government in context of this regulation

www.epbd.be

Vlaanderen is energie

bruxelles environnement leefmilieu brussel .brussels

Wallonie

Example: Performance data heat recovery systems

Name	*Max. Power FAN 1* (W)	*Max. Power FAN 2* (W)	*POSITION 1*		*POSITION 2*		*POSITION 3*	
			EFFICIENCY (%)	*m³/h*	*EFFICIENCY (%)*	*m³/h*	*EFFICIENCY (%)*	*m³/h*
AAA	110	110	86%	120	83%	251	81%	310
BBB	121	121	87%	181	85%	229	84%	279
CCC	120	120	87%	179	86%	228	85%	328
DDD	179	179	84%	263	83%	319	80%	400
EEE	178	178	86%	259	85%	320	83%	393

Vlaanderen is energie

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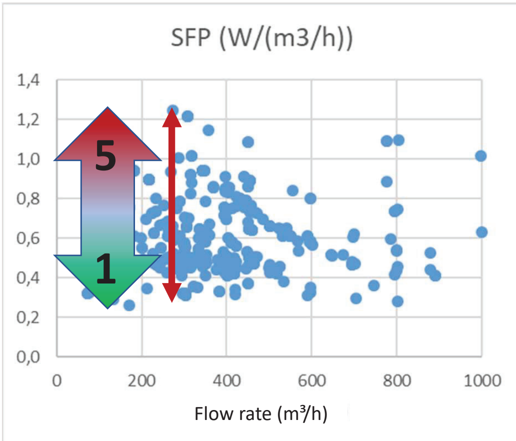
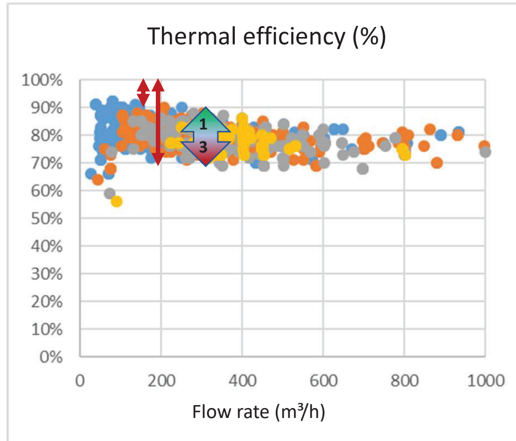
Wallonie

Examples of typical performance data for residential heat recovery units from EPB-productdatabase





Max. power/ max. flow rate

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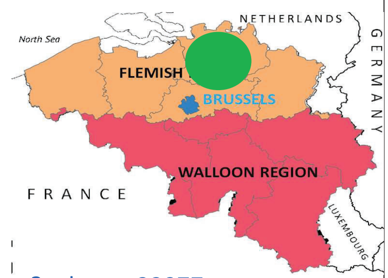
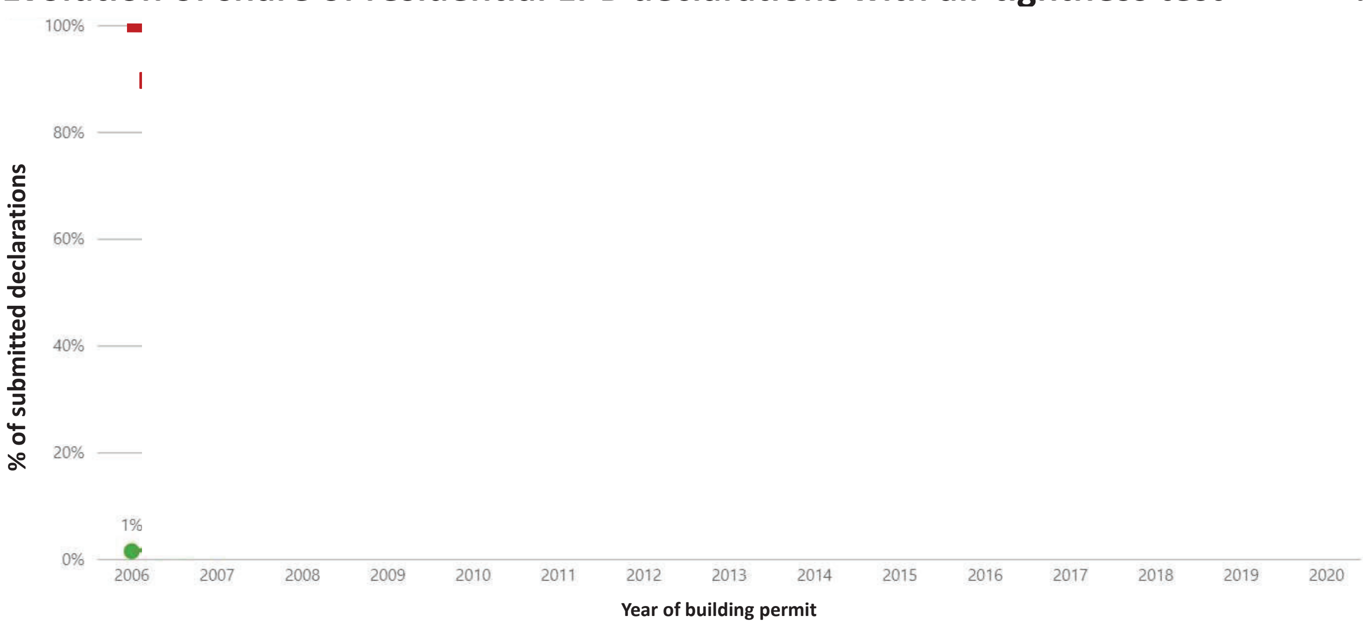
2015 - On site performance checks of declared building airtightness levels

- **Observations:**
  - Energy performance calculations take airtightness into account. If no test results available, default value to be used (12 m³/h.m² at 50 Pa)
  - In NZEB buildings, poor building airtightness has a big impact
    - Airtightness testing becomes important (and good results!)
  - Not evident to assume that test results are always reliable
- **Approach:**
  - Quality framework developed by Flemish government (2015)
  - 150 to 190 qualified airtightness tester companies
  - Random onsite audits for min. 10% of tests
  - All measurement data gathered in database
  - More than 100.000 tests done

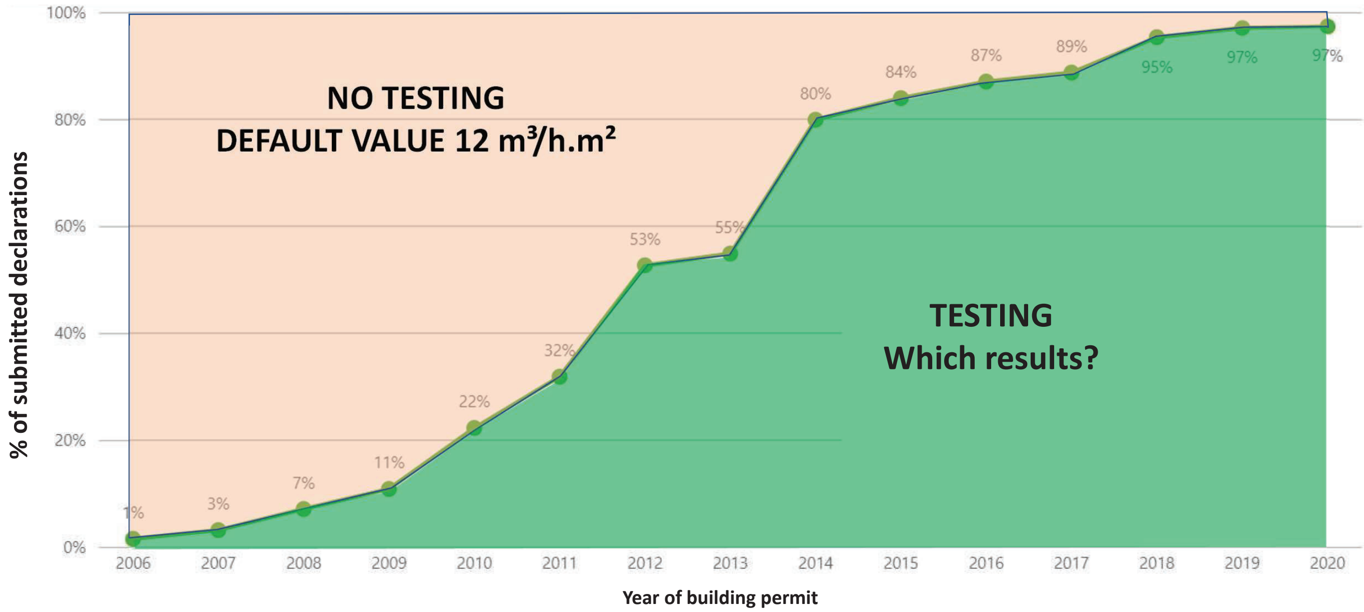


https://www.aivc.org/resource/vip-454-trends-building-and-ductwork-airtightness-belgium?volume=33977

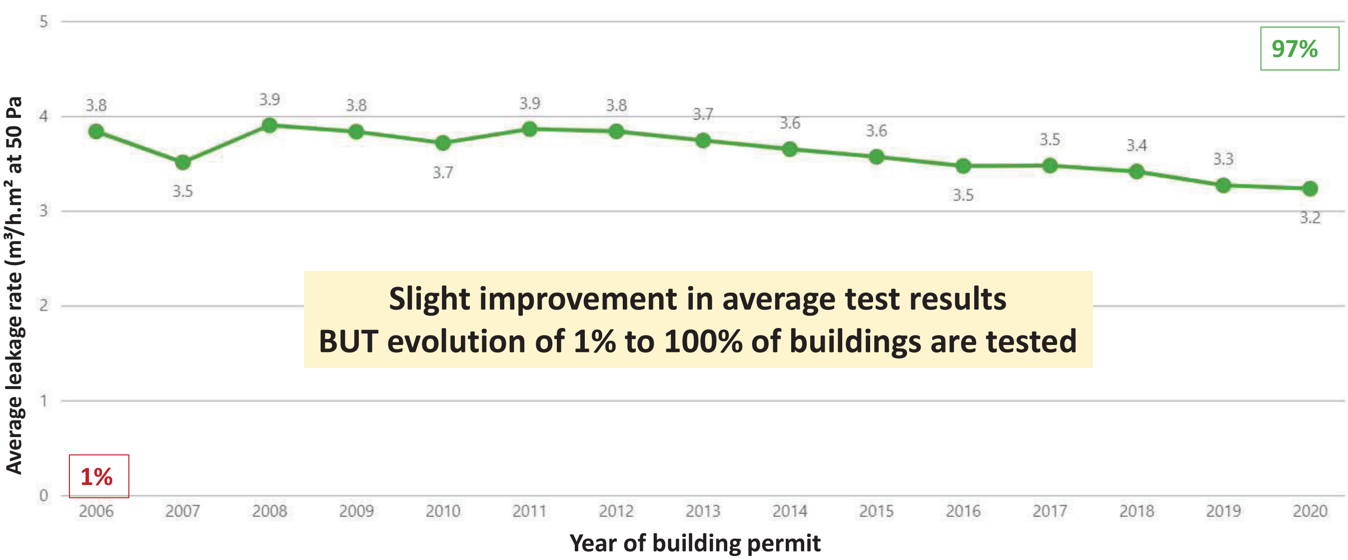
Evolution of share of residential EPB declarations with air tightness test



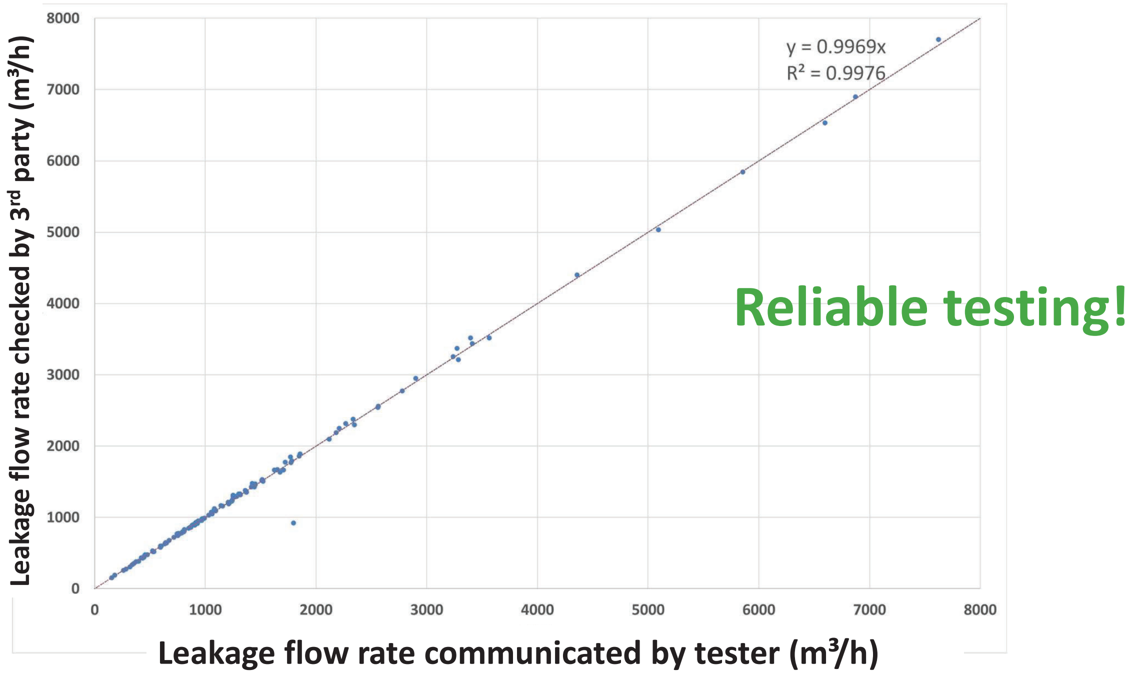
Evolution of share of residential EPB declarations with air tightness test



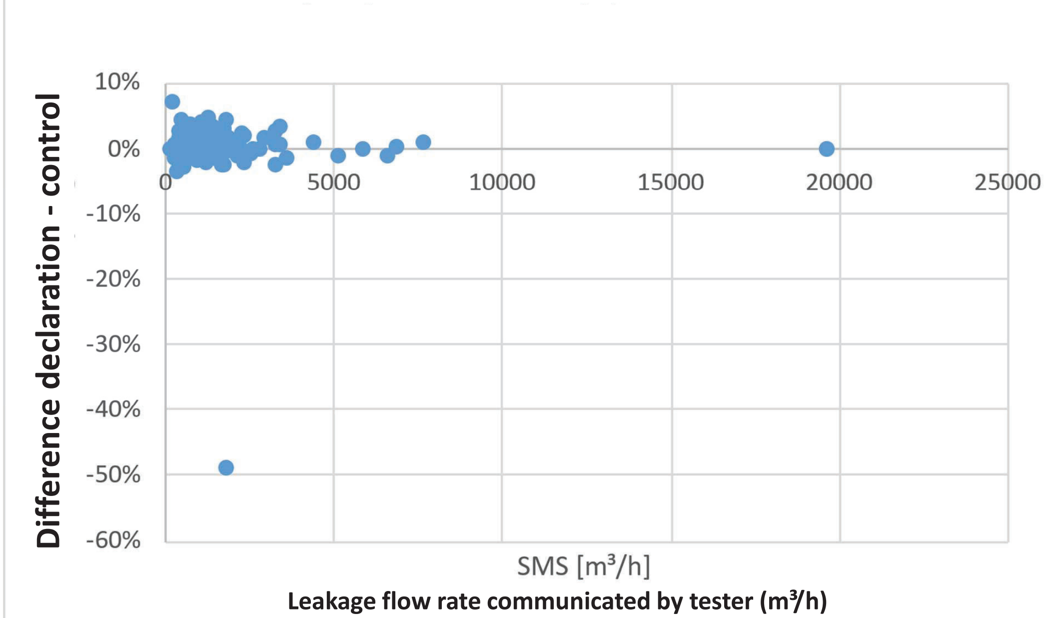
Average air permeability (m³/h/m²): leakage flow rate @50 Pa divided by heat loss area



Control of declared airtightness results



Control on declared air flow rates



Conclusions regarding airtightness approach

- No requirement to test – no minimum airtightness requirement – default value of 12 m³/h.m² building envelope
- In practice testing not needed in the beginning (2006 - no strong energy requirements) but now (2023) in practice necessary with the severe energy requirements
- Quality control framework leads to reliable test results
- Overall large societal acceptance for airtightness testing
- Indirect advantages are important: better design – better execution – better acoustics – less risk of moisture problems
- It has been a major driver for innovation by industry

Structure of the presentation

- Introduction
- 2006 - Ventilation related requirements in the context of the EPBD
- 2015 - On site performance checks of declared building airtightness levels
- **2016 - On site performance checks of residential ventilation systems**
- 2019 - Federal regulation regarding wellbeing on workplaces
- 2022 - Federal regulation on indoor air quality
- Conclusions

2016 - On site performance checks of residential ventilation systems

- **Observations:**
  - Air flow rates in practice depend to a large extent on the quality of the works
  - Substantial part of installed residential ventilation systems didn't perform in practice as specified in EPB calculations
- **Action:**
  - Implementation of a quality framework with on-site performance checks
  - Main features:
    - Only assessment of <u>air flow rates</u> and <u>fan energy</u>
    - Measurements <u>only after installation</u>
    - To be done by competent person with appropriate measurement equipment
    - It can be done by an independent person or a person involved in the project
    - 10% of systems are checked immediately afterwards by control body

2016 - On site performance checks of residential ventilation systems

- **In practice impact of quality framework residential ventilation:**
  - Very good coherence between declarations and control measures
- **Overall impact of EPB for ventilation systems?**
  - Ventilation systems installed in ALL new buildings
  - Clear tendency towards very energy efficient ventilation systems
  - In more recent years correct air flow rates in residential buildings when installed (FL)
  - Missing: checks on acoustical performances and performances during lifetime

https://www.aivc.org/resource/quality-framework-residential-ventilation-systems-flemish-region-belgium-feedback-after

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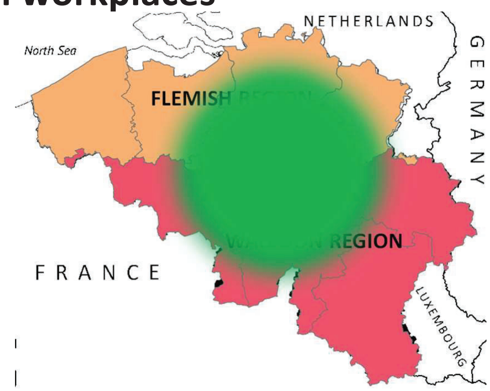

2019 - Federal regulation regarding wellbeing on workplaces

- **Till 2016:**
  - Requirement of 30 m³/h for each employee (not for other persons)
  - In practice often no ventilation or poorly performing ventilation
  - In practice not possible to enforce
- **Since 2019 new regulation**
  - Requirement in terms of minimal air flow rate or maximum increase in CO_2 concentration
  - Requirements depend on other pollutants:
    - If in line with low-polluting building: 25 m³/h.person **OR** maximum CO_2 increase of 800 ppm
    - In other cases: 40 m³/h.person **OR** maximum CO_2 increase of 500 ppm
  - All employers must carry out a risk analysis and set up an action plan
  - For existing buildings in practice large freedom in terms of duration for implementation
  - But <u>potentially</u> very strong incentive if transparency in performances

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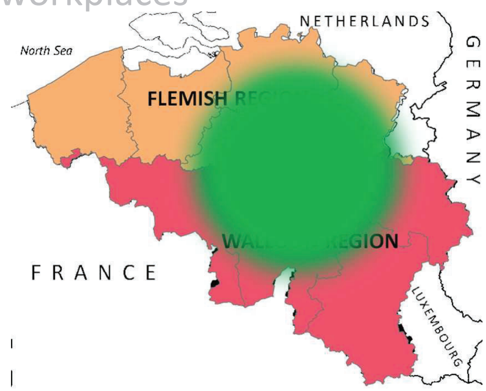

November 2022 - Federal regulation on indoor air quality in public spaces

- In context of COVID (2020-2021)
  - Maximum concentrations of CO_2 concentrations was imposed during certain periods for hotels, restaurants, pubs, cultural sector and sports sector
  - There was a strong increase in awareness of the importance of good indoor air quality
- In October 2022, the federal parliament adopted a law with requirements in terms of indoor air quality in public spaces
  - IAQ-sensors to be installed, at least CO_2 sensors
  - Risk analysis and action plan to be implemented
  - Certification and labelling of these spaces
  - There is a potential role for air cleaning devices
- In practice:
  - Law becomes only effective after adoption of Royal and Ministerial decrees
  - These decrees are expected in 2023 and 2024

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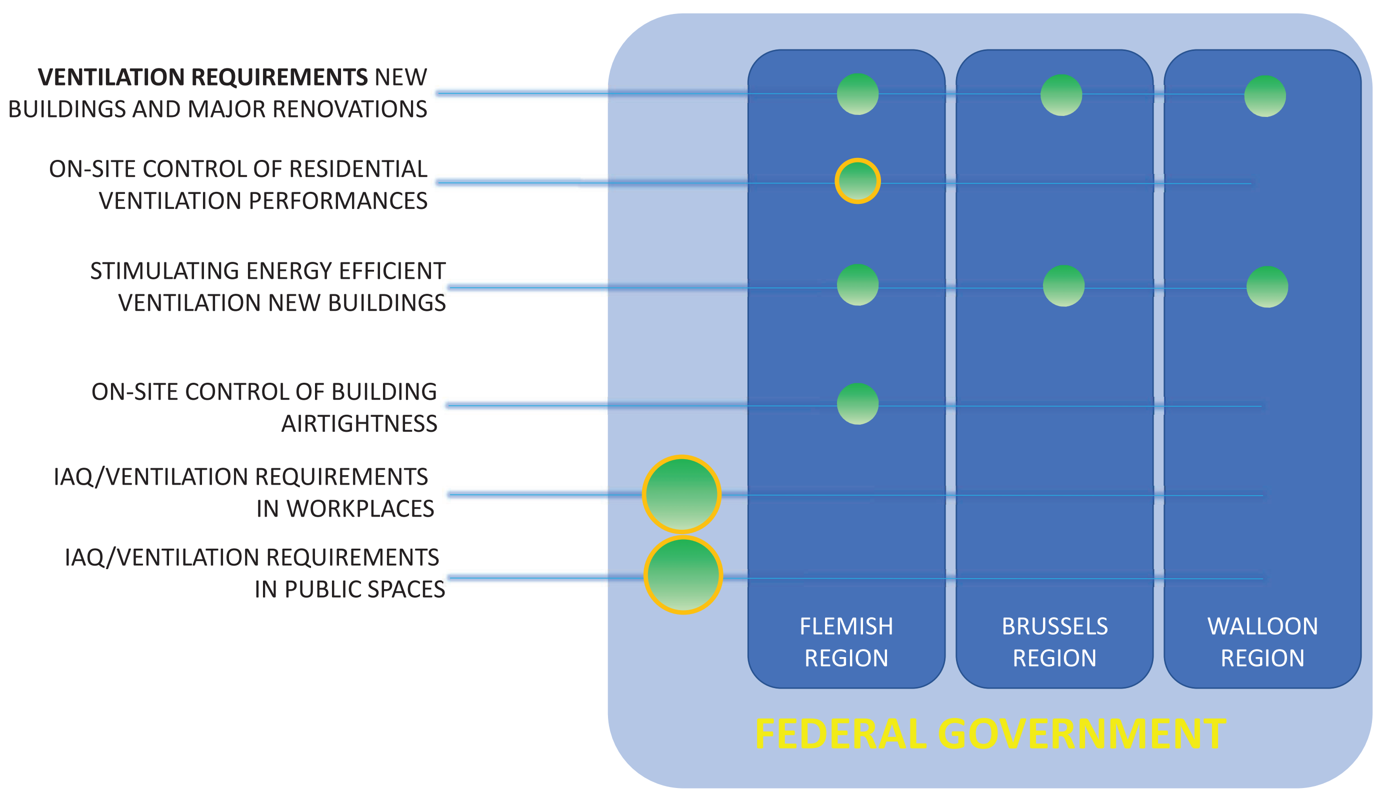
- **Conclusions**



Conclusions

- **The role of regulations is crucial** in Belgian context for wide scale uptake of good IAQ and ventilation
- **Since 2006, substantial progress has been achieved**
  - In terms of air flow specifications and compliance
  - In terms of energy efficiency and compliance
  - In terms of stimulating innovative ventilation systems
  - In terms of achieving more airtightness buildings
- **However, still substantial further steps needed**, e.g.:
  - Performances during lifetime of installations, including maintenance
  - Acoustical performances
  - Robust approach for existing buildings

Airtightness and internal air flows in multifamily buildings

Iain Walker
Scientist
Building Technology & Urban Systems Division

Why is internal leakage important?

- Contaminant Transport
  - Odours (cooking, tobacco smoke)
  - Moisture
  - Health (particles, airborne pathogens)
- Pest control
  - Insects, mice, rats, etc.
- Heating and cooling energy use
  - Stack and wind effects
- Fire Safety
  - Fire and smoke spread
- HVAC air flow & pressure control

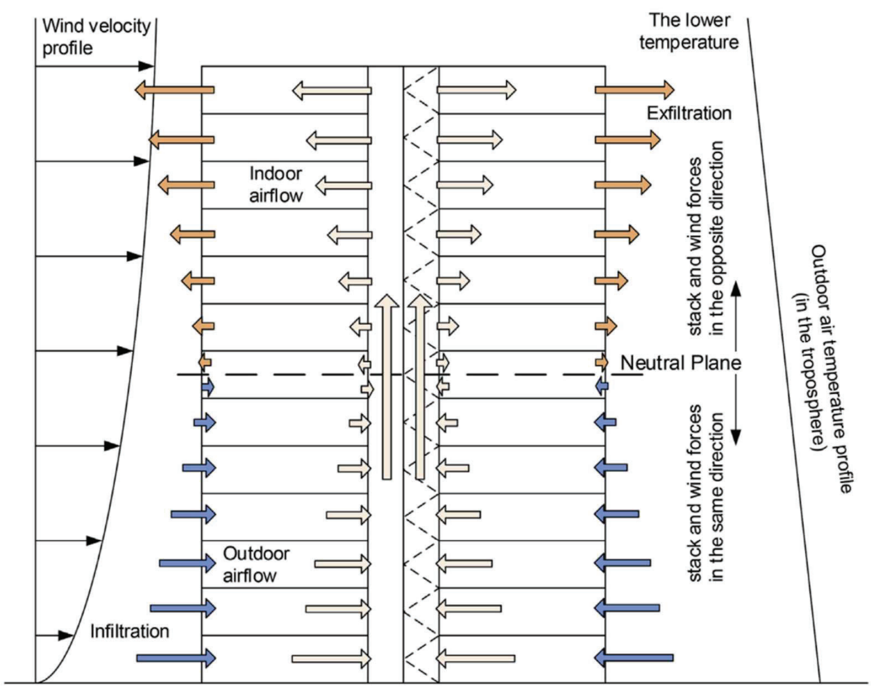
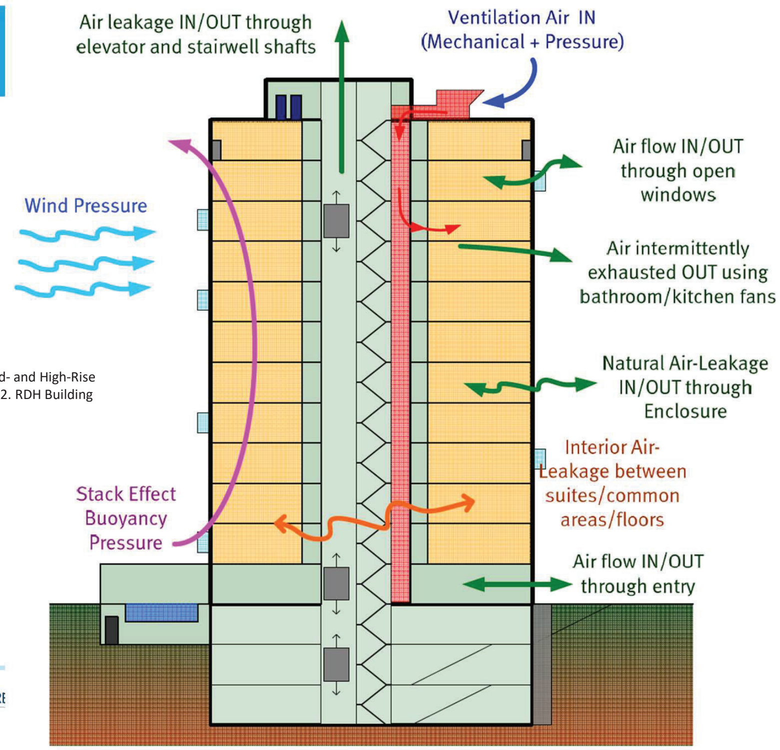
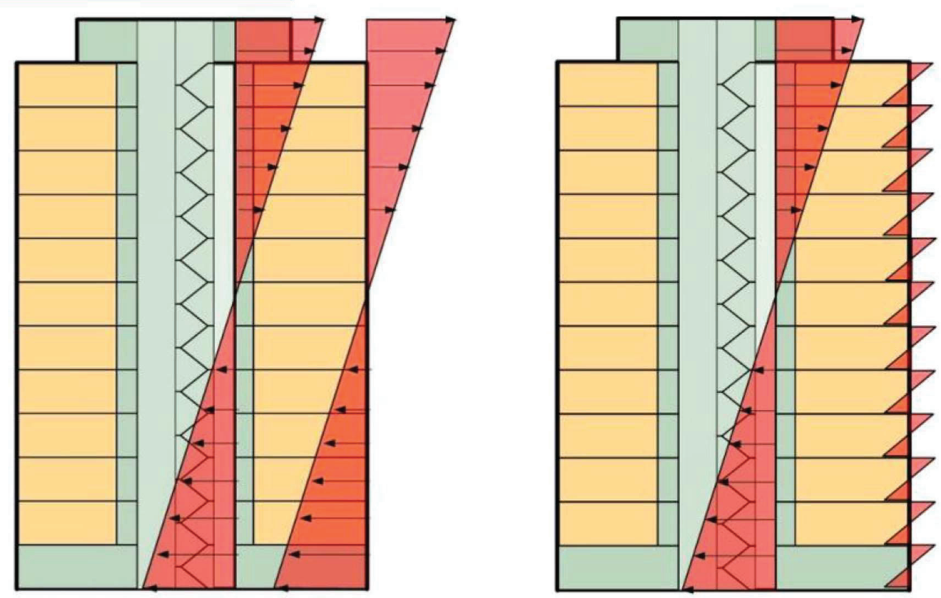


Fig. 1. Airflow in high-rise buildings caused by the stack effect and wind pressure in winter.



"Energy Consumption and Conservation in Mid- and High-Rise Residential Buildings in British Columbia." 2012. RDH Building Engineering.



Stack Effect - Typical Highrise Conditions

Stack Effect - Compartmentalized Floors and Suites

"Energy Consumption and Conservation in Mid- and High-Rise Residential Buildings in British Columbia." 2012. RDH Building Engineering.

Where are the leaks?

Electric wiring

Plumbing

Wall cavities

Images form Rohr et al. 2018. Individual unit and guard-zone air tightness tests of apartment buildings. AIVC Conference Proceedings.

Airtightness Metrics

- Air flows at fixed test pressure of 50 Pa: cfm50/ft^2 or L/s/m^2 or m^3/h/m^2
  - Sometimes 75 Pa is used for high rise applications
- Total leakage: all surfaces ← most common
- Leakage to outside
- Leakage to inside
- Normalization Areas: *boundary areas* or *exterior envelope*
- Can be volume normalized to Air Changes per Hour (ACH)

North America Standardized tests

Tests for exterior envelopes also applied to testing individual units – no standard tests for interior leakage

- CGSB 149.10 – exterior envelope testing
- CGSB 149.15 – uses building HVAC system for envelope leak testing
- ASTM E779 – confirms single zone conditions and has limit on stack effect of 200 °Cm (building height x temperature difference)
- ASTM E1827 – confirms single zone conditions and has single point testing
- ISO 9972 – exterior envelope testing
- ATTMA Technical Standard L1-2012 & L2-2010 – UK standards for enclosure testing, L2 has guidance for testing large buildings

Testing "row" houses

Internal leakage measurement principles:

1. Neutralize unit to unit pressures

2. Subtract "guarded" result from total to get leakage to outside separate from unit to unit leakage

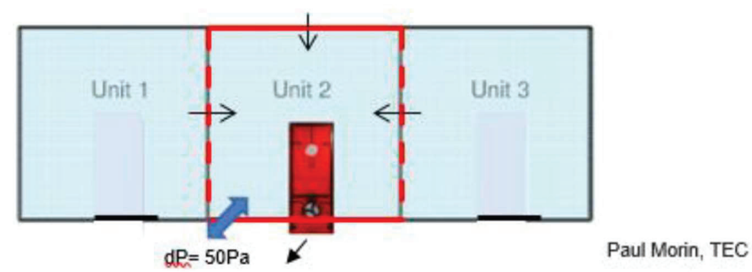


Figure 5. Compartmentalization test of single unit in a garden-style building

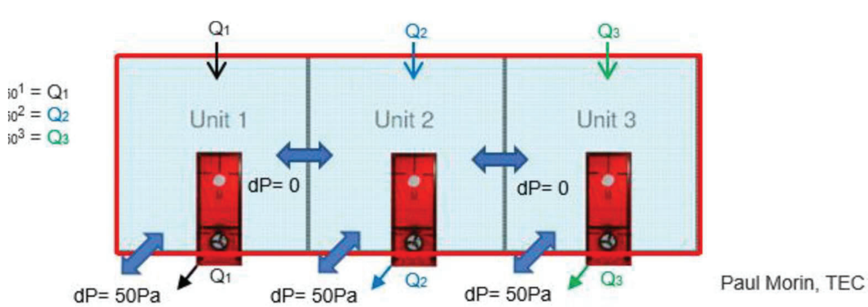


Figure 7. Single-unit exterior test for three units in a single-story garden-style building

David Bohac, Lauren Sweeney, Robert Davis, Collin Olson, and Gary Nelson. 2020. "Energy Code Field Studies: Low-Rise Multifamily Air Leakage Testing." Washington, DC: US DOE. https://www.mncee.org/sites/default/files/report-files/LRMF_AirLeakageTesting_FinalReport_2020-07-06.pdf.

Testing common–entry buildings

Figure 6. Compartmentalization test of single unit in a common-entry bu

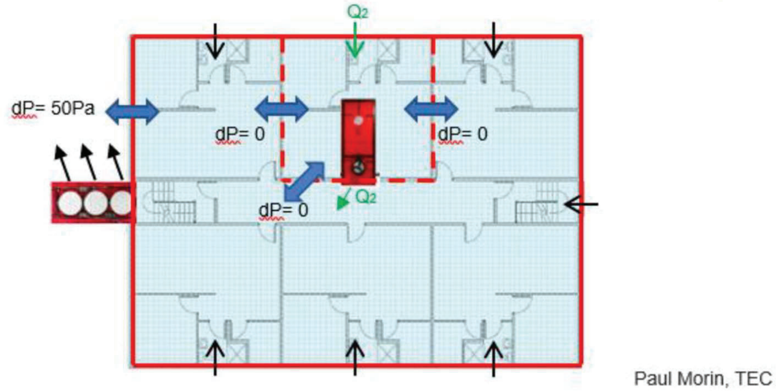


Figure 8. Single-unit exterior test for a single-story common-entry building with six units

David Bohac, Lauren Sweeney, Robert Davis, Collin Olson, and Gary Nelson. 2020. "Energy Code Field Studies: Low-Rise Multifamily Air Leakage Testing." Washington, DC: US DOE. https://www.mncee.org/sites/default/files/report-files/LRMF_AirLeakageTesting_FinalReport_2020-07-06.pdf.

Testing with corridors

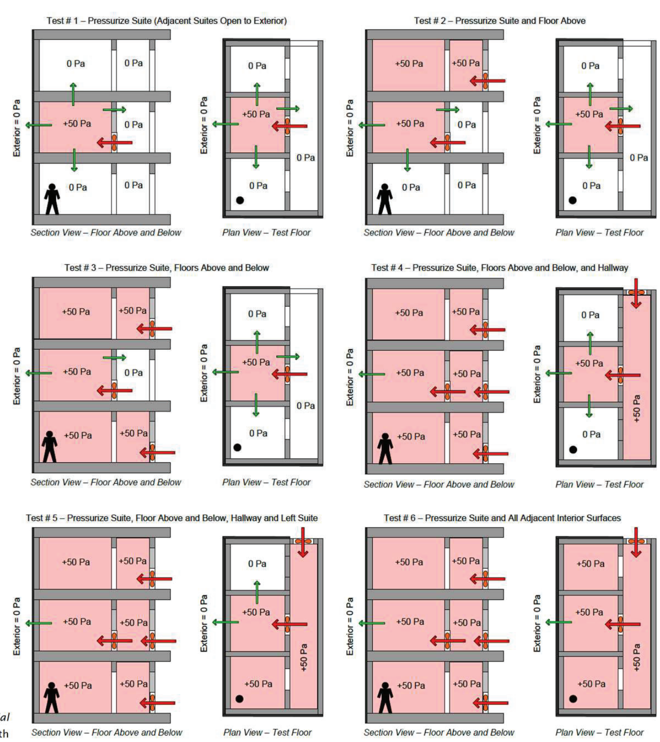
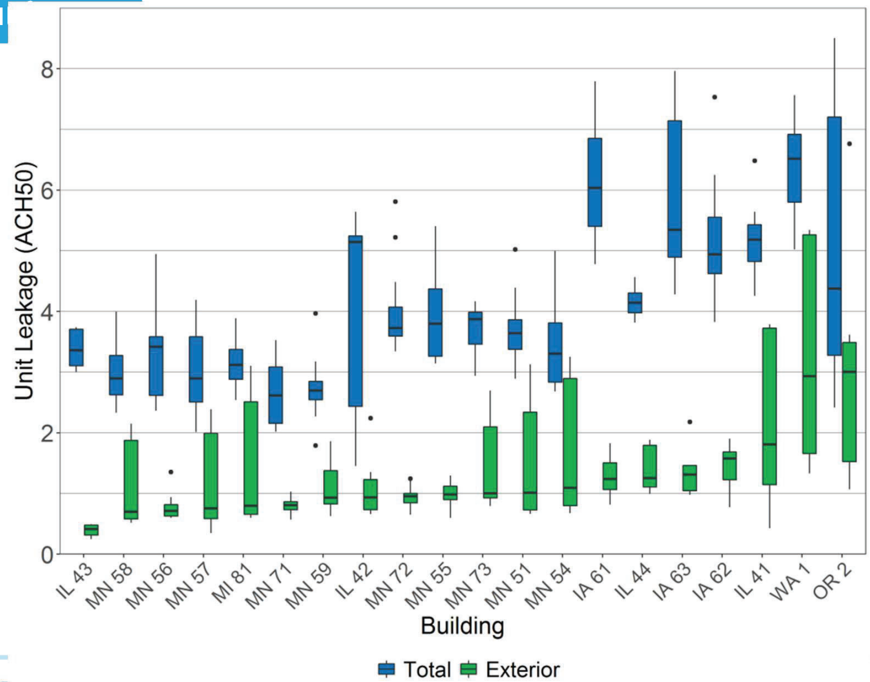


Figure 6.5: Balanced Fan Pressurization/Depressurization Method Schematic (Finch, 2007)

Finch, G, Straube, J., & Genege, C. (2009) *Air Leakage Within Multi-Unit Residential Buildings: Testing and Implications for Building Performance.* Proceedings of 12th Canadian Conference on Building Science and Technology. Montreal: National Building Envelope Council. 529-544.

Results vary building to building and unit to unit



Bohac et. al. (2020) (Report) LRMF study. Center for Energy and Environment MN

Results vary unit to unit

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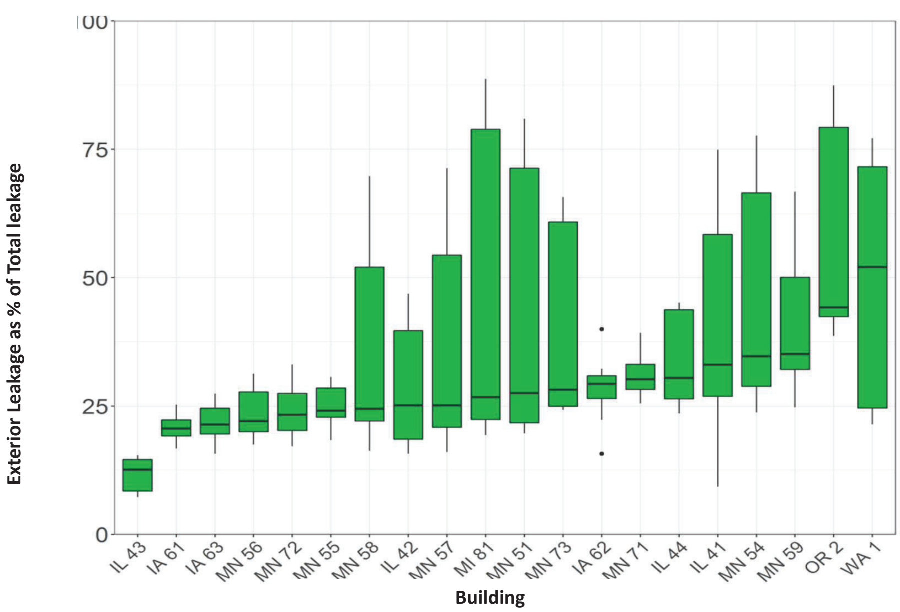
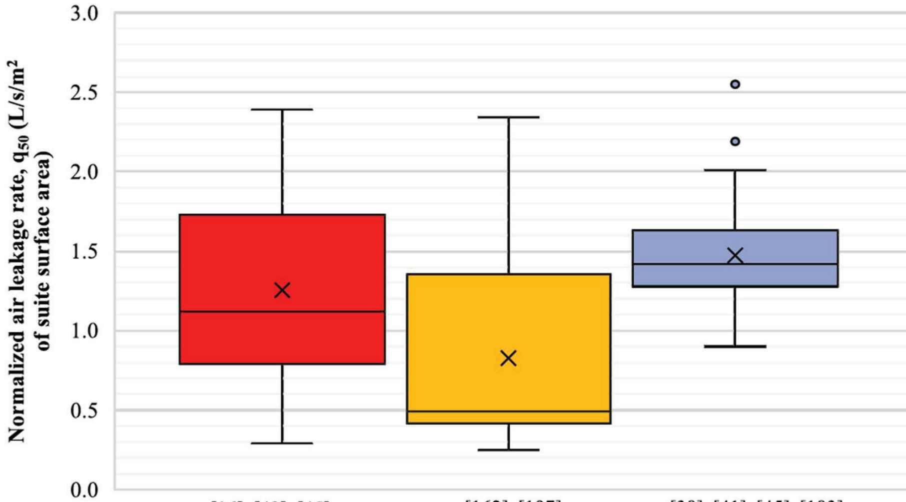
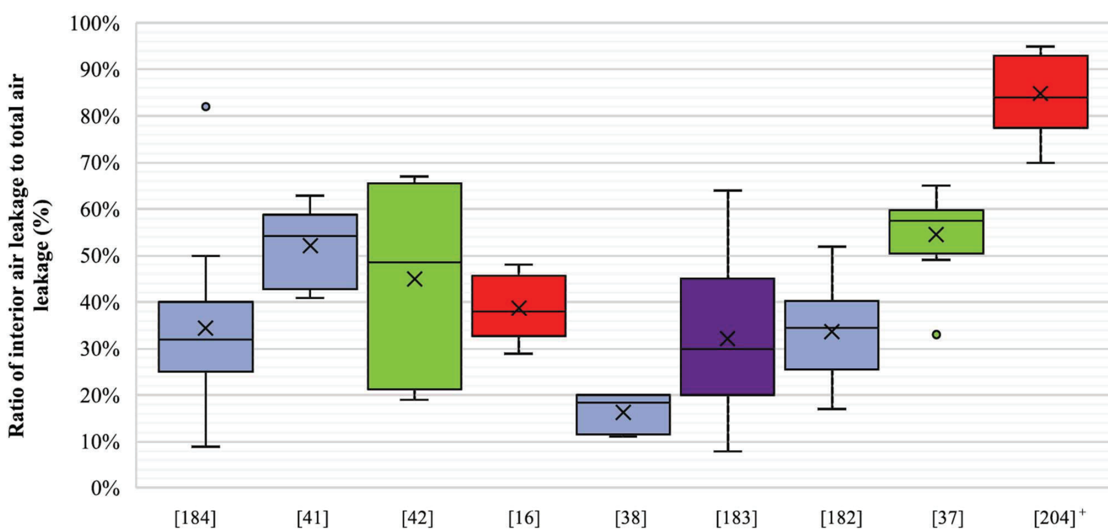


Corner vs. middle
Unit size
Construction variability

Construction Type



Lozinsky, Cara H., and Marianne F. Touchie. 2020. "Inter-zonal Airflow in Multi-unit Residential Buildings: A Review of the Magnitude and Interaction of Driving Forces, Measurement Techniques and Magnitudes, and Its Impact on Building Performance." Indoor Air 30 (6): 1083–1108. https://doi.org/10.1111/ina.12712.

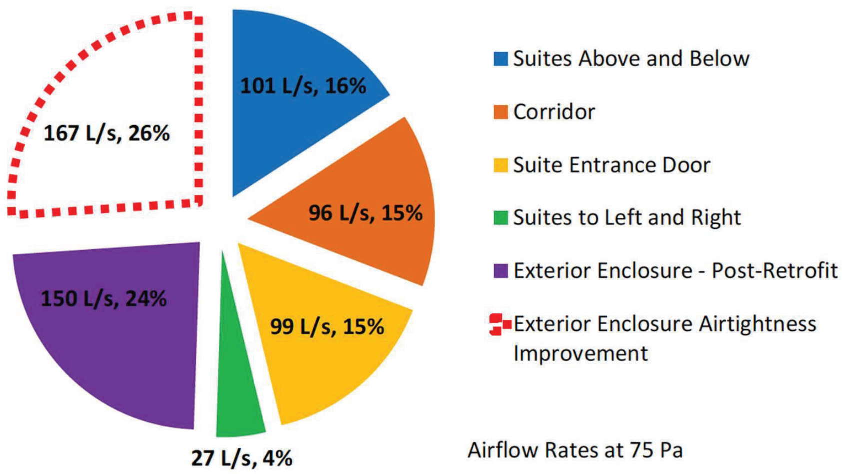


+ Interior air leakage includes suite entrance door air leakage.

Lozinsky, Cara H., and Marianne F. Touchie. 2020. "Inter-zonal Airflow in Multi-unit Residential Buildings: A Review of the Magnitude and Interaction of Driving Forces, Measurement Techniques and Magnitudes, and Its Impact on Building Performance." Indoor Air 30 (6): 1083–1108. https://doi.org/10.1111/ina.12712.

Apartment leakage breakdown

Testing before and after exterior envelope sealing



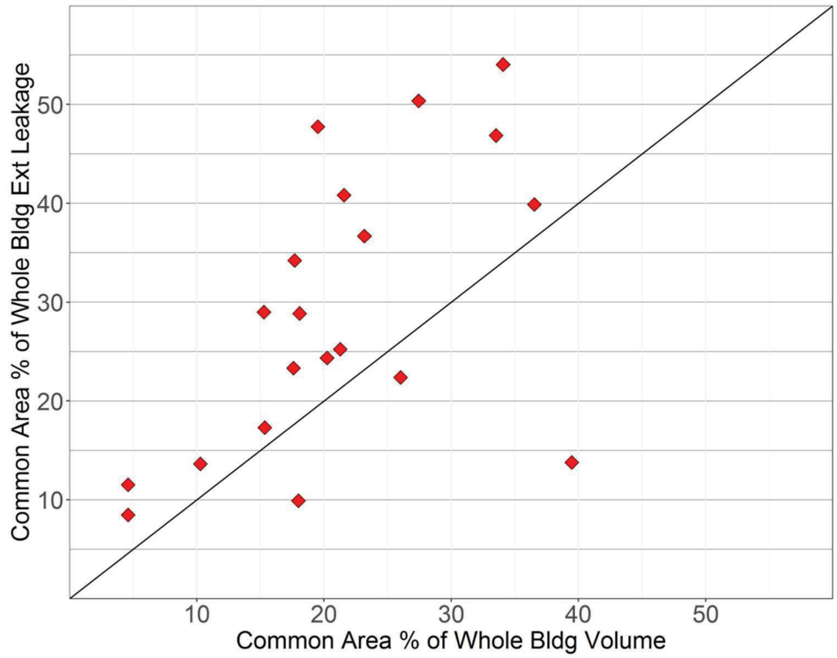
Ricketts, L, and J Straube. 2014. "A Field Study of Airflow in Mid to High-Rise Multi-Unit Residential Buildings." In , 1414th Canadian Conference on Building Science and Technology - Toronto, Ontario 2014

US New Construction Leak Breakdown Summary

- High rise/common corridor
  - 2-3% to each unit to each side
  - 10-15% to each unit above or below
  - 20-35% to corridor
  - 30-55% to outside
- Midrise/walkup – no corridor
  - 2-3% to each unit to each side
  - 10-15% to each unit above or below
  - 75% to outside

Air Leakage of Common Areas

Common areas can be more leaky than dwellings



How much air flow?

Pressure differences are lower than across envelope therefore air flows much lower

Tracer gas studies: typically 4% … but sometimes 40%

Bohac, D. L., M. J. Hewett, S. K. Hammond, and D. T. Grimsrud. 2011. "Secondhand Smoke Transfer and Reductions by Air Sealing and Ventilation in Multiunit Buildings: PFT and Nicotine Verification: Secondhand Smoke Transfer and Reductions by Air Sealing and Ventilation." *Indoor Air* 21 (1): 36–44. https://doi.org/10.1111/j.1600-0668.2010.00680.x.

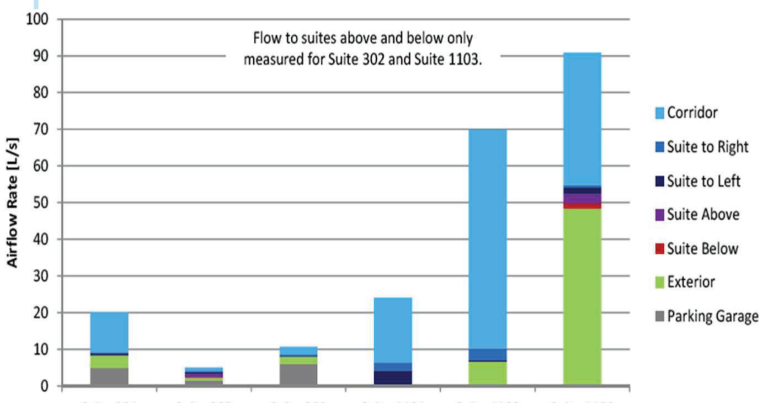


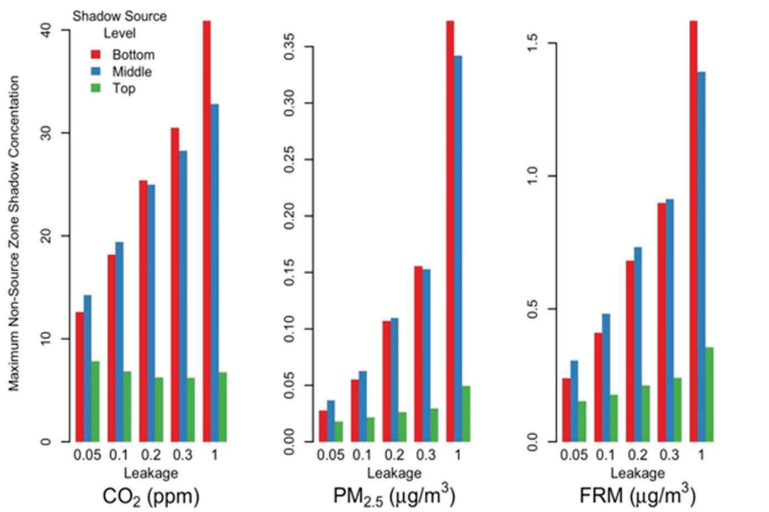
FIGURE 2: Chart showing source of airflow into suites for six suites at the case study building

Ricketts, L and Straube, J, 2014. A field study of Airflow in Mid to High-Rise Multi-Unit Residential Buildings. 14th Canadian Conference on Building Science and Technology, Toronto, ON. http://rdh.com/wp-content/uploads/2015/01/CCBST-2014-A-Field-Study-of-Airflow-in-High-Rise-Multi-Unit-Residential-Buildings-LR-JS.pdf

Contaminant Concentrations

CONTAM Modeling Study

Worst-case annual concentration of shadow contaminants found in non-source zone



Worst case contributions at 62.2 leakage level:

- CO_2 25ppm (~4%)
- PM2.5 0.1 μg/m³ (~2.5%)
- Formaldehyde 0.7 μg/m³ (~3%)

Typical contribution from other units at is about fifty times lower than the worst case

Bottom and middle level sources transport much more to other units

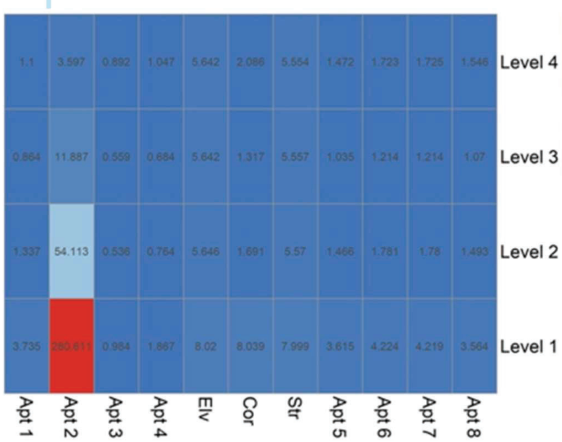
PM and Formaldehyde more sensitive to leakage due to deposition mechanisms

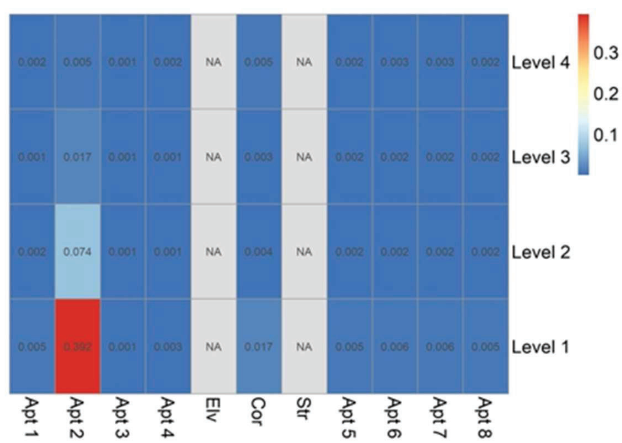
Measured contaminant transport in "tight construction": CO_2 (0-3%), PM2.5 (unmeasureable)

Modera, M., Adler, S., Harrington, C., Bennett, D., Moran, R. and Goebes, M. 2023. Final Report Improving Indoor Air Quality, Energy Efficiency, and Greenhouse Gas Reductions Through Multifamily Unit Compartmentalization. Calfornia Air Resources Board TEREport.

Contaminant Concentrations

CONTAM Modeling Study





Most transport is vertical

Energy Saving Example

M. Carlsson, M. Touchie and R. Richman / Energy & Buildings 199 (2019) 20–28

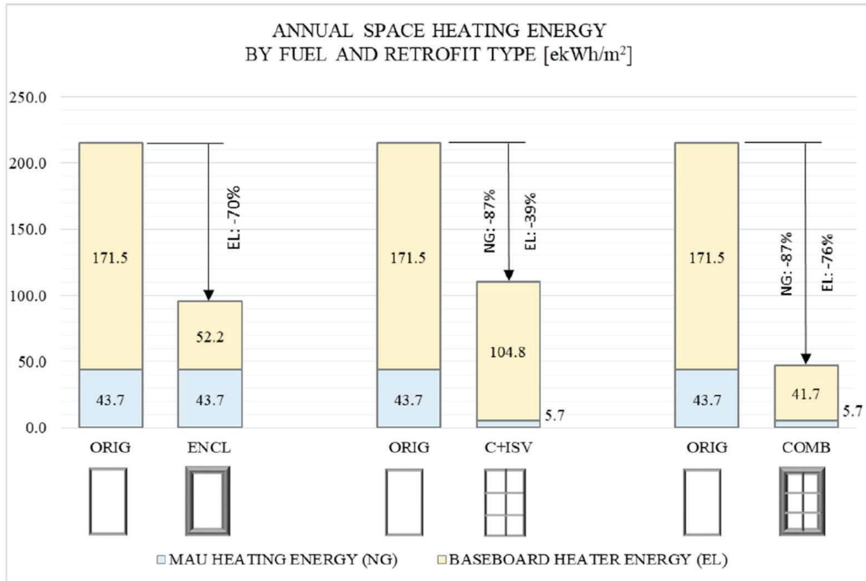
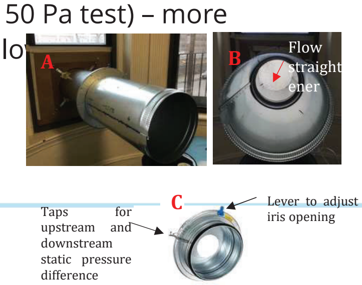
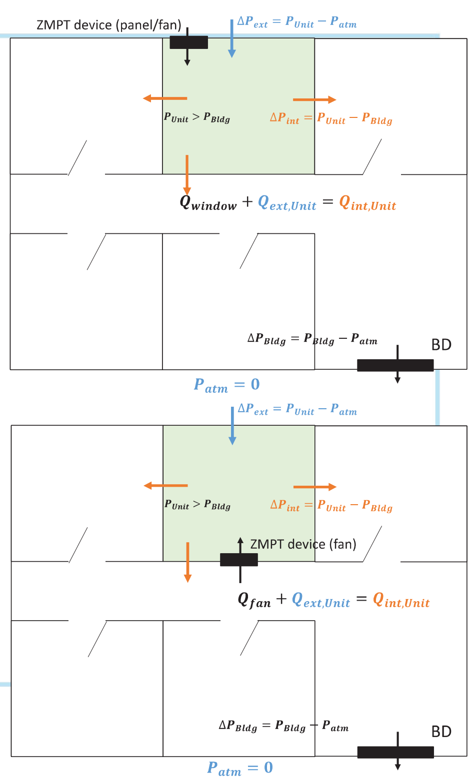


Fig. 2. Simulated annual space heating energy by fuel and retrofit type

Recent Advances

- New test methods to save time and improve accuracy of separating internal and external leakage
- Use a second flow measuring and modulating device
- Manipulate and record a range of pressures and flows
- Multipoint fitting (c/w fixed 50 Pa test) – more accurate representation of lo[...] flow/pressure behaviour





Jayarathne. 2023. Advancing Building Air Leakage Measurement and Modeling: New Measurement Methods And Experimental Analysis Of Crack Flow Behavior. PhD. Thesis, Boston University

Tightness Standards

- ASHRAE 62.2: 0.2 cfm50/ft^2 (100 L/s/100 m^2)
  - Was 0.3 cfm50/ft^2 (150 L/s/100 m^2) – standards are getting tighter
- LEED certification by the US Green Building Council: up to 2 points for certification rating based on different tightness levels between 0.0675 to 0.195 cfm50/ft^2
- Passive House (exterior envelope):
  - 0.08 cfm50/ft^2 (40 L/s/100m^2) for more than 5 stories
  - 0.06 cfm50/ft^2 (30 L/s/100m^2) 5 stories and under

Questions/comments

Contact info: iswalker@lbl.gov