Effect of enhanced supply air filtration in buildings on protecting citizens from environmental radioactive particles

Ilpo Kulmala¹, Tomasz Zwęgliński² (✉), Marcin Smolarkiewicz², Hannu Salmela¹, Tapio Kalliohaka¹, Aimo Taipale¹, Jari Kataja¹, Vesa Mäkipää³

1. VTT Technical Research Centre of Finland Ltd, 33100 Tampere, Finland

2. SGSP The Main School of Fire Service, 01-629 Warsaw, 52/54 Slowackiego St., Poland

3. Lifa Air International Ltd, Room 2002, 20/F, Kai Tak Commercial Building, 317 Des Voeux Central, Hong Kong, China

Abstract

The effect of enhanced filtration on protection citizens staying indoor against airborne radionuclides released during nuclear core melt accidents was determined by field measurements using outdoor particles as simulants. An electrically enhanced filter was installed in the HVAC system of an office building and its removal efficiency for particles was altered by using a separate particle charging section in power on and off positions. The effect of air filtration on indoor particle concentrations was determined by using an automated measurement system which was continuously sampling from the outdoor air, filtered supply air and exhaust air. With the aid of the measured outdoor and modelled indoor concentrations the indoor/outdoor ratio of particles of outdoor origin could be accurately determined. External charging of the particles increased the electret filters removal efficiency for 0.4 µm size particles from 60% to 95%, resulting in decrease of the average I/O ratio of the same size particles from 0.67 to 0.40. Despite the high improvement in the supply air filtration efficiency the indoor concentrations decreased only modestly which is likely due to the leaky construction of the building, demonstrating the detrimental effect of air infiltration on the protection provided by buildings against outdoor airborne hazards. Practical implications: The developed method allows quantification of the key parameters affecting the protection of buildings against outdoor contaminants, thus allowing accurate estimation of size resolved indoor to outdoor ratios for fine particles. The electrically enhanced filter can remove effectively also submicron particles thus reducing the occupant exposure to outdoor hazardous or harmful materials. Best results can be achieved with airtight buildings.

Keywords

I/O ratio, sheltering, civil protection, radiation protection, radioactive contamination

Article History

Received: 15 September 2019

Revised: 20 January 2020

Accepted: 12 February 2020

© The Author(s) 2020

1 Introduction

Intentional or unintentional use of hazardous materials, like chemical, biological, radiological, nuclear or explosives (CBRNe), in order to realize criminal, terrorist or military acts is an increasing risk for population. This fact is confirmed by plenty of national and international law, normative and strategic documents. Since each state owns priority in providing security for people staying on the territory of its administration, the increasing risk of CBRNe requires high level of politicians, crisis managers, first responders and society engagement. Another aspect of building society

resilience to CBRNe threats is implementation of new technologies. For example an application of a specific ventilation system in buildings could prevent the people staying indoor from negative consequences of a radioactive plume in case of a nuclear incident. Research institutes and commercial companies are constantly working on such new products, however, it is highly important to know how effective are these solutions?

The EDEN (End-User Driven Demo for CBRNe) Demonstration Project, funded by the European Commission 7th Framework Research Programme on Secure Societies, represented the biggest research effort ever made in the

CBRNe area in the European Union, with the primary objective to provide solutions to improve society resilience in this respect. Sudden and unexpected radiological and nuclear incidents can be hazardous because radioactivity is undetectable for human senses and in case of high level exposures could lead to serious health problems or even death. Therefore, one of the main goals of the project was to plan, prepare, organize, realize a series of radiological and nuclear (RN) demonstrations. They were aimed at validation of new solutions and systems towards their potential to improve society resilience against these types of threats. In case of a radiological or nuclear incident it is extremely important that citizens will be on time and well informed how they should perform to limit their exposure to radioactive materials. One of the measures to be undertaken in such situations is sheltering in place. It simply means staying indoor, especially in buildings which have appropriate ventilation systems. Measuring filtration efficiency by I/O ratio (indoor and outdoor concentration of suspended particles) is one of the method which is used in the article to check how effective could be ventilation systems towards the hazard of being exposed to radioactive plume.

In frames of the project radiological demonstrations were organized in Italy, Poland and Ukraine. The set of different scientific radiological demonstrations concerned such topics like:

- “use of the optical techniques for improved inspection in a nuclear reactor” realized on TRIGA reactor in Cassacia (Italy),
- “remote monitoring and identification of a dirty bomb” and “smuggling radiological material and subsequent blackmailing attempt” in Frascati (Italy),
- set of table-top and full scale exercises dedicated to response to radiological threats - organized in Poland and Ukraine (in exclusion zone of Pripjat/Chernobyl).

The demonstrations put a lot of attention on protection of citizens staying in buildings from the risk of being exposed or contaminated by radioactive materials (EU Council Directive, 2013/59/EUROATOM, EU 2013) e.g. in case of at least a serious nuclear incident which is level 3 in International Nuclear and Radiological Event Scale (INES). Among creation of different tools and systems relevant for increasing the resilience against RN threat, one of the tasks during the project demonstrations was also to protect building occupants.

2 Purpose and need to react

In case of large scale outdoor intentional or accidental releases of radioactive materials usually there are two options to protect citizens from negative consequences of such incident. These two are to evacuate the people or shelter them inside

buildings. For maximum protection, sheltering indoors requires two actions to temporarily change a building's indoor-outdoor air exchange rate. The first is to reduce the air exchange rate before contaminated air begins to enter the building, by closing exterior doors and windows, and turning ventilation off. The second action is to increase the air exchange rate after the outdoor concentration has diminished to safe levels (FEMA 2008).

These guidelines can reduce occupant exposure significantly for short term releases, if the response actions are taken in timely fashion (Persily et al. 2007). However, for longer term releases lasting more than few hours the contaminants slowly infiltrate indoors, and the indoor concentration levels may eventually reach the outdoor levels. Therefore, if the building is equipped with a HVAC system that is capable to substantially remove the hazardous materials, it may be more beneficial to keep the ventilation system running (Persily et al. 2007; Kulmala et al. 2016). A case in point is the release of radioactive materials from serious nuclear power plant accidents like Chernobyl in 1986 and in Fukushima in 2011. A significant fraction of radionuclides following such incidents are in the form of radioactive particles of various size (IAEA 2011).

When evaluating whether sheltering can provide sufficient protection in a release scenario, emergency responders need to consider people located in nearby offices, commercial and public facilities as well as residential buildings. Unlike dwellings, such buildings have usually mechanical ventilation with some kind of supply air filtration which may help in the protection against outdoor particulate pollutants.

There were more than several studies quantifying the efficiency of dry-media and electrostatic filters; however, most of them were focused on the particle size range > 300 nm. Indeed some others studied ultrafine particles, however, in these cases the researches were conducted in laboratory conditions. Therefore, there is still a need for more information on in situ filter efficiency which could facilitate further understanding of filtration influence on I/O ratios of particle concentrations. In order to tackle these gaps in knowledge through providing new information supporting selection of most adequate filter types in office building HVAC systems, the research aimed to: (1) measure particle concentrations of stream flows in and out of filter devices, for outdoor and indoor office buildings; (2) quantify efficiency of filter types for above mentioned buildings; and (3) assess an impact of these filters usage on I/O ratios for indoor and outdoor scenarios.

An overview of literature proved that for now there is limited number of information on the time variation of particle concentrations as well as size distributions in case of large commercial buildings respectively relating to the particle concentrations and size distributions outdoor the

buildings. Additionally, the effectiveness of high efficiency filters in reducing indoor particle concentrations has not been well documented. The purpose of this paper is to present and discuss such data obtained during a study of the influence of high efficiency filtration on the indoor particle pollution levels.

3 Scope of risk

The key factors contributing to the ability of buildings to protect against outdoor hazardous materials are the duration of the outdoor release and entrance rate of the threat agents. In mechanically ventilated buildings the pollutants can enter indoors through uncontrolled air leakages known as infiltration and through the HVAC system. The entry rate of particulate contaminants through infiltration ER_{INF} can be expressed as

$$ER_{INF} = q_{INF} \cdot P_{INF} \cdot C \quad (1)$$

where q_{INF} is the air infiltration rate, P_{INF} is the size depended penetration of outdoor pollutants and C is the outdoor air concentration. The infiltration is driven by the wind pressure and buoyancy forces due to indoor-outdoor temperature differences and its rate depends on the buildings airtightness. Grot and Persily (1986) determined infiltration rates of eight mechanically ventilated office buildings using tracer gas techniques and found them to vary from 0.2 to 0.7 1/h. Later Chan (2006) estimated the infiltration rates of US commercial buildings based on the airtightness and weather data and concluded them to be lognormally distributed with $GM=0.35$ 1/h and $GSD=2.1$ 1/h. The particle penetration through building cracks has been found to be strongly size dependent with maximum penetration occurring typically in the size range of 0.1–1 μm (Zhao et al. 2010).

The entry rate of contaminants through the HVAC system ER_{HVAC} in turn can be expressed as

$$ER_{HVAC} = q \cdot P \cdot C \quad (2)$$

where q is the outdoor air intake flow rate, P is the size dependent penetration of the air filter ($P = 1 - E$, where E is the filter removal efficiency). The removal efficiency of the supply filter for the targeted contaminants has thus a major impact on the pollutant transport indoors. Generally, non-residential commercial buildings are equipped with particle filters, which according to the European PREN standard (EN 2015) should be at least grade F7. The initial efficiency for such filters should be over 35% for 0.4 μm size particles (EN 2012). This level of filtration is not, however, very effective in removing radionuclides which are released during nuclear reactor core melt accidents and are attached to submicron particles. Measurements have

shown that after the Fukushima accident the air contained radioactive particles with activity median aerodynamic diameter (AMAD) ranging between 0.25 and 0.71 μm for ^{137}Cs , from 0.17 to 0.69 μm for ^{134}Cs , and from 0.30 to 0.53 μm for ^{131}I (Masson et al. 2013; Malá et al. 2013). These are similar to the findings made after the Chernobyl accident. However, while the atmospheric radioactivity levels outside Japan were of no concern for public health because of dispersion and dilution (Lin et al. 2015), the Chernobyl disaster demonstrated that the activity of particles can be orders of magnitudes higher closer to the accident site (Malá et al. 2013).

In order to increase filtration efficiency especially for submicron sized particles, higher grade filters can be employed. However, in general, as the filter efficiency increases so does its pressure drop. This may exceed the capacity of the supply air fans so that the HVAC system may not deliver the designed air flow rate to the occupied spaces, resulting in inadequate ventilation and decreased indoor air quality (Mead and Gressel 2002).

In an attempt to increase the removal efficiency without increasing pressure loss, electric field effects have been utilised either by using charged filter mediums or by imposing an electric field over the filter material (Bergman et al. 1984; Lehtimäki and Heinonen 1994). Charged air filters normally contain fibres made of dielectric materials that have been electrically charged or polarised during the manufacturing process. These fibres then create local electric fields that can provide electrical capture mechanisms in addition to the mechanical capture mechanisms of conventional filters thus enhancing collection efficiency considerably. While these filters provide the advantage of high initial efficiency and low pressure drop, their efficiency may deteriorate rapidly in use. The efficiency for submicron particles decreased after few weeks use over 50% of its initial value (Raynor and Chae 2003). This deterioration is assumed to be due to masking of the electrically charged fibres with small particles (Walsh and Stenhouse 1997). To overcome the rapid efficiency degradation, particle charging has been successfully employed in combination with electret materials. In this way the initial and life-time efficiency can also be boosted without increasing the pressure drop (Kulmala et al. 2005).

Although the importance of filtration in controlling the entry of outdoor contaminants indoors is widely acknowledged, the reported field experiments in real operating conditions to reduce occupant exposure through upgrading filtration are rare. The aim of this study was to determine the effect of enhanced filtration on the protection against outdoor hazardous aerosols of the same size than radionuclides observed during nuclear power plant disasters using ambient fine particles as simulants. The field

measurements were conducted in a commercial building where the electrically enhanced supply air filter was installed. Its efficiency was modified with the aid of particle charging so that the particle removal could be increased without changing other parameters giving possibility to directly compare the results. To eliminate the effect of indoor sources on the I/O ratio determination a recently developed and validated method was utilised (Kulmala et al. 2016). This method uses continuously measured outdoor concentrations with modelled indoor concentrations to eliminate the disturbing effect of indoor sources on the results.

4 Experimental setup

The field experiments were conducted in a building in Helsinki, Finland. The building was located 2 km from the city centre and 200 m from a main entryway to the city. The four-storey building included offices, storage facilities and a parking garage, and it was mechanically ventilated with two separate air handling units. Measurements were taken over a period of 4 months. The measurement system was installed in the air handling unit serving the offices and the gym with a total volume of about 4000 m³. The supply and exhaust flow rates were 1.0 m³/s corresponding to an air exchange rate of 0.9 1/h.

The supply air of the AHU was taken directly from outside at roof level, filtered and led through a cross flow plate heat exchanger unit after which it was heated (when the outdoor temperature was low) and distributed to the ventilated spaces. The warm exhaust air was led through the same heat recovery unit before discharge to outdoors. The air handling unit was originally equipped with a 592 mm × 592 mm size F7 grade supply air filter which was removed and replaced with the similar size test filter. The test filter had 15 filter bags which were 700 mm deep. Each filter bag consisted of a layer of electret particle filter material followed by a layer of nonwoven material loaded with granular activated carbon particles to remove gaseous impurities like VOCs and ozone. Combined with particle charging the structure offers high particle removal efficiency with a relatively low pressure drop: the flow resistance of clean filter was 150 Pa at 1 m³/s. The pressure drop over the filter was measured on-site both with and without charging showing that the pressure drop did not depend on particle charging.

A separate particle charger was installed in the ductwork upstream the supply air filter. The charger used in the experiments was a wire type with a positive corona (7.3 kV) and ion current of 1.1 mA so that the electric power consumption of the charger was about 8 W.

The measurement system consisted of air sampling, a valve mechanism, a particle counter (Met One 237B) and

computer that controlled the system and recorded the measured data (Fig. 1). Samples were taken cyclically upstream the filter (outdoor air), after the filter (supply air) and in the exhaust air representing the average indoor air concentration. The particle counter classifies particles according to their size in six bins which are 0.3–0.5, 0.5–0.7, 0.7–1, 1–2, 2–5 and >5 µm. In addition to particle concentration and size distribution, temperature (*T*) and relative humidity (RH) of the supply air filter were also measured. The data was sent wirelessly to a server, where the data was analysed, facilitating a remote real-time measurement of the air quality and filter performance. The sample lines made of copper tubes were designed so that they were similar in size and length to minimise errors due to losses. An auxiliary pump with a flow rate of 30 lpm was used to increase flushing and reduce particle residence time in the sampling tubes. The sampling line had also a zero filter so that the zero level of the particle counter could be checked during each measurement cycle.

Fig. 1 Experimental setup for the particle concentration measurements

5 Results and discussion

The measured filtration efficiencies without and with the corona charger are presented in Fig. 2. The filter efficiency $E(d_p)$ for each particle size d_p was calculated from the measured particle counts upstream $N_U(d_p)$ and downstream $N_D(d_p)$ of the filter as:

$$E(d_p) = 1 - N_D(d_p) / N_U(d_p) \quad (3)$$

As can be seen, the charging of particles had a significant effect on the removal efficiency especially for the fine particles: the efficiency for 0.4 µm sized particles increased from 59% to 96%. Similar although lower increases have been observed by Shi (2012) who used carbon fibre ionizer to charge the upstream particles of a synthetic fibre filter.

Fig. 2 Measured filtration efficiency of the test filter without and with particle charging

Examples of the measured outdoor and indoor concentrations are shown in Figs. 3 and 4. In Fig. 3 are the concentrations with the electret filter only (charger off) and in Fig. 4 with the charger turned on. The effect of improved filtration efficiency on the reduction of indoor concentrations can be clearly seen.

The figures show also the modelled indoor concentration which is obtained by numerically solving the mass balance equation using measured outdoor concentration as input value (Kulmala et al. 2016). Both the measured and modelled indoor concentrations depended clearly on the outdoor concentrations. However, due to internal sources the measured indoor concentrations sometimes even exceeded the outdoor levels. To take into consideration only particles which are of outdoor origin the I/O ratio calculations are therefore based on the modelled indoor concentrations $C(t_i)$ which were obtained by solving the indoor concentration numerically using a forward time marching method with a time step of Δt :

$$C(t_{i+1}) = C(t_i) + \Delta C_i \quad (4)$$

$$\Delta C = [q_{\text{INF}} PC_{\text{OA}}(t_i, d) + q C_{\text{OA}}(t_i, d)(1 - E(d)) - q C(t_i, d) - q_{\text{EXF}} C(t_i, d) - kVC(t_i, d)] \cdot \frac{\Delta t}{V} \quad (5)$$

where V is the volume of the building, $C(t, d)$ is the indoor and $C_{\text{OA}}(t, d)$ the measured outdoor air particle size-resolved, time-dependent concentration and q is the mechanical ventilation flow rate. P is the contaminant penetration defined as the fraction of particles that enter through the building envelope with the infiltrating air, q_{INF} is the infiltration and q_{EXF} exfiltration flow rate and $E(d)$ is the removal efficiency of the supply air filter. The term k is the first order indoor particle deposition loss rate coefficient and takes into consideration both gravitational settling on upwards facing horizontal surfaces as well as deposition on other surfaces (Kulmala et al. 2020).

Fig. 3 Concentrations of 0.3–0.5 μm size particles without charger (Filter efficiency = 0.59)

Fig. 4 Concentrations of 0.3–0.5 μm size particles with charger on (Filter efficiency = 0.96)

The size resolved I/O values based on the modelled results are presented in Fig. 5. The indoor to outdoor ratio was highest for the smallest particles and decreased with particle size. This is in line with the findings of other researchers. Chen et al. (2016) measured the I/O ratio over a wide size range from 0.01 to 10 μm and found a maximum for the I/O ratio at about 0.3 μm . Similarly, Koponen et al. (2001) observed clear size dependency of the I/O ratio of a mechanically ventilated office with F7 grade filtration. However, their measured maximum I/O ratio was clearly lower, about 0.32. This is likely due to higher mechanical ventilation rate (3.7 l/h) and more airtight building. In general, the highest I/O ratio has been observed for particle sizes of about 0.1–0.3 μm where the particle filter penetration is also highest (Hanley et al. 1994; Shi 2012). The decreasing I/O ratio for larger particles ($>1 \mu\text{m}$) is because the penetration through the building envelope decreases and deposition losses increase with increasing particle size. On the contrary, the measurements by Fisk et al. (2000) showed an opposite trend where the I/O ratio increased with particles $> 1 \mu\text{m}$ in size. This was presumably caused by substantial rate of indoor particle generation or

resuspension of particles larger than $1\ \mu\text{m}$ due to occupants activities during the measurements (Fisk et al. 2000). In the other studies, the measurements were made in unoccupied premises (Hussein et al. 2004; Chen et al. 2016), or the activities were light (Koponen et al. 2001). Nevertheless, (Fisk et al. (2000) found that improving the filter grade from G4 level to E11 decreased the I/O ratio for submicron particles significantly. Not surprisingly, the improved filtration efficiency in this study resulted in a clear reduction in the I/O ratio of submicron size particles. However, the impact of improved filtration was not as high as may be anticipated from the filter penetration: without charging the penetration for the smallest size range was about 0.4 (Filter penetration = $1 - \text{Efficiency}$) and with the enhanced filtration only 0.04 corresponding to a 90% reduction. Because in mechanically ventilated buildings without significant indoor sources the I/O ratio generally follows the filter penetration curve (Koponen et al. 2001; Hussein et al. 2004; Chen et al. 2016), the expected reduction was much larger than the observed from 0.65 to 0.41 for the smallest size range (Fig. 5). The likely reason for this only modest improvement was the high infiltration rate (0.53 1/h during the experiments) compared to the mechanical ventilation rate (0.9 1/h).

Figure 5 shows also the observed size ranges of the radioactive atmospheric aerosols after nuclear core melt accidents (activity median aerodynamic diameter, AMAD). In case of the nuclear core melt accidents the arithmetic mean of the activity median aerodynamic diameter of the most significant volatile radionuclides was found to be $0.43\ \mu\text{m}$ (Malá et al. 2013). Therefore, the smallest measured size range ($0.3\text{--}0.5\ \mu\text{m}$) to be used to assess the effect of enhanced filtration on a person (staying indoor) inhalation intake of radionuclides attached to atmospheric aerosols.

Fig. 5 Comparison of particle size dependent I/O ratios for mechanically ventilated office buildings from several references with normal and enhanced filtration. Standard deviations are depicted with vertical bars. The size ranges of atmospheric radioactive particles after high temperature nuclear accidents are shown for comparison (activity median aerodynamic diameter, AMAD)

In the studied case the exposure would be 35% lower indoors than outdoors with normal filtration, and 60% lower with enhanced filtration.

The results represent the situation at the time of the experiments. Each building is unique, and the infiltration rate affecting the sheltering efficiency depends on the driving forces behind infiltration, namely wind speed and temperature differences between indoors and outdoors, in addition to the airtightness of the building. The developed method can, however, be used to accurately quantify the key parameters having effect on the size resolved ratio of indoor particulate pollutants of outdoor origin and to evaluate the impact of different countermeasures on indoor air and occupant exposure. The measures to decrease concentration levels can thus be focused on more efficiently when the effect of different actions is better known.

The electret filter with charging of particles proved to be an efficient method to improve the collection efficiency especially for submicron particles. The charging of particles used electric power of about 8 W. This increase in power consumption is quite small compared to the power consumption of filtration, which can be calculated by

$$\phi = qd_p / \eta \quad (6)$$

Here q is the airflow rate, d_p pressure drop over the filter and η the fan efficiency, which is defined to be fixed at 0.50 in the Eurovent standard (EUROVENT 2014). Using the values for the test filter (air flow rate $1\ \text{m}^3/\text{s}$, pressure drop $150\ \text{Pa}$), we get the energy consumption due to filtering to be 300 Watts. Thus the filtration efficiency can be enhanced with minimal modifications to existing HVAC system and increase in power consumption.

The electrically enhanced filtration is a promising method to improve the protection of occupants of mechanically ventilated buildings against several types of particulate hazardous agents. Here the target agents were radioactive particles released during nuclear power plant core melt accidents but the results can be generalised to other hazardous or harmful particulate materials as well. Such materials are formed e.g. during wildfires, or other pollution episodes.

6 Conclusions

The developed tool consisting of the field measurement system combined with mass balance model can be used to quantify the size resolved ratio of indoor particulate pollutants of outdoor origin in mechanically ventilated buildings. This information can be used to more accurately estimate the risk to citizens' health due to intentionally or accidentally released radioactive particles in the environment as well as to evaluate the effect of different countermeasures

on indoor air and occupant exposure. Definitely, the decisions and following them measures which aim at decreasing indoor concentration levels can be far more efficient when the impact of different actions is known better. The field experiments realized in EDEN research project proved that the effect of enhanced filtration on the protection from outdoor hazardous agents could be clearly quantified.

Corona charging of particles in combination with electret filters may improve the removal efficiency significantly. In the studied case, external charging of the particles increased the test filter removal efficiency for 0.4 μm size particles from 60% to 95%. Despite the very high efficiency the average I/O ratio of the same size particles decreased from 0.67 to 0.40. This only rather modest improvement is likely due to the leaky construction of the building, demonstrating the detrimental effect of air infiltration on the protection provided by buildings against outdoor airborne hazards. In leaky buildings even with very high efficient supply air filters cannot protect operators and other users due to uncontrolled entry of outdoor pollutants through unintentional paths through the building envelope.

The electrical enhancement proved to be an effective way to improve the filtration efficiency and thus the rate of entry of contaminants through the HVAC system. The increases in the efficiency can be achieved with fairly low electric power and with minimal requirements for retrofitting of the HVAC system.

Acknowledgements

This study was financially supported by the European Union in frames of FP7 grant agreement no. 313037 and the Government of the Republic of Poland under a grant no. 2962/7.PR/13/2014/2.

Open Access: This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made.

The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>

References

- Bergman W, Biermann A, Kuhl W, Lum B, Bogdanoff A, et al. (1984). *Electric Filtration: Theory, Laboratory Studies, Hardware Development and Field Evaluations*. Lawrence Livermore National Laboratory.
- Chan W (2006). *Assessing the effectiveness of shelter-in-place as an emergency response to large-scale outdoor chemical releases*. PhD Thesis, University of California, USA.
- Chen A, Cao Q, Zhou J, Yang B, Chang VWC, Nazaroff WW (2016). Indoor and outdoor particles in an air-conditioned building during and after the 2013 haze in Singapore. *Building and Environment*, 99: 73–81.
- EN (2012). CEN standard EN 779 2012. Particulate air filters for general ventilation. Determination of the filtration performance. Brussels, Belgium: European Committee for Standardization.
- EN (2015). CEN draft standard prEN 16798-3 -2015. Energy Performance of Buildings. Part 3: Ventilation for Non-residential Buildings—Performance requirements for ventilation and room-conditioning systems. Brussels, Belgium: European Committee for Standardization.
- EU (2013). Council Directive 2013/59/EURATOM of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom. Available at <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2014:013:0001:0073:EN:PDF>. Accessed 14 Jan 2020.
- EUROVENT (2014). EUROVENT Standard 4/21-2014. Calculation method for the energy use related to air filters in general ventilation systems. Paris, France: EUROVENT Association.
- FEMA (2008). FEMA P-459/08255-1. Incremental Protection for Existing Commercial Buildings from. Principles of design for risk reduction related to CBR threats. US Department of Homeland Security. Federal Emergency Management Agency.
- Fisk WJ, Faulkner D, Sullivan D, Mendell MJ (2000). Particle concentrations and sizes with normal and high efficiency air filtration in a sealed air-conditioned office building. *Aerosol Science and Technology*, 32: 527–544.
- Grot RA, Persily AK (1986). ASTM STP 904. Measured air infiltration and ventilation in eight federal office buildings. In: Treschel HR, Lagus PL (ed), *Measured Air Leakage of Buildings*. Philadelphia, PA, USA: American Society for Testing and Materials. pp. 151–183.
- Hanley JT, Ensor DS, Smith DD, Sparks LE (1994). Fractional aerosol filtration efficiency of in-duct ventilation air cleaners. *Indoor Air*, 4: 169–178.
- Hussein T, Hämeri K, Aalto P, Asmi A, Kakko L, Kulmala M (2004). Particle size characterization and the indoor-to-outdoor relationship of atmospheric aerosols in Helsinki. *Scandinavian Journal of Work, Environment & Health*, 30(Suppl 2): 54–62.
- IAEA (2011). IAEA TECDOC No. 1663. Radioactive Particles in the Environment: Sources, Particle Characterization and Analytical Techniques. Vienna, Austria: International Atomic Energy Agency.
- Koponen IK, Asmi A, Keronen P, Puhto K, Kulmala M (2001). Indoor air measurement campaign in Helsinki, Finland 1999 - the effect of outdoor air pollution on indoor air. *Atmospheric Environment*, 35: 1465–1477.

- Kulmala I, Taipale A, Heinonen K, Christiansen V, Jalonen T, et al. (2005). High security filtration system for protecting buildings from airborne chemical, biological and radiological hazards. In: Proceedings of Indoor Air 2005, Beijing, China, pp. 3370–3374.
- Kulmala I, Salmela H, Kalliohaka T, Zwęgliński T, Smolarkiewicz M, et al. (2016). A tool for determining sheltering efficiency of mechanically ventilated buildings against outdoor hazardous agents. *Building and Environment*, 106: 245–253.
- Kulmala I, Parviainen H, Hall I, Pasanen P (2020). A novel method for determining infiltration of mechanically ventilated buildings. *Science and Technology for the Built Environment*, 26: 250–256.
- Lehtimäki M, Heinonen K (1994). Reliability of electret filters. *Building and Environment*, 29: 353–355.
- Lin W, Chen L, Yu W, Ma H, Zeng Z, et al. (2015). Radioactivity impacts of the Fukushima nuclear accident on the atmosphere. *Atmospheric Environment*, 102: 311–322.
- Malá H, Rulík P, Bečková V, Mihalík J, Slezáková M (2013). Particle size distribution of radioactive aerosols after the Fukushima and the Chernobyl accidents. *Journal of Environmental Radioactivity*, 126: 92–98.
- Masson O, Ringer W, Malá H, Rulík P, Długosz-Lisiecka M, et al. (2013). Size distributions of airborne radionuclides from the Fukushima nuclear accident at several places in Europe. *Environmental Science & Technology*, 47: 10995–11003.
- Mead KR, Gressel MG (2002). Protecting building environments from airborne chemical, biological, or radiological attacks. *Applied Occupational and Environmental Hygiene*, 17: 649–658.
- Persily A, Chapman R, Emmerich S, Dols W, Davis H, et al. (2007). Building retrofits for increased protection against airborne chemical and biological releases. National Institute of Standards and Technology, NISTIR-7379. Available at https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=861035. Accessed 15 Jan 2020.
- Raynor PC, Chae SJ (2003). Dust loading on electrostatically charged filters in a standard test and a real HVAC system. *Filtration & Separation*, 40: 35–39.
- Shi B (2012). Removal of ultrafine particles by intermediate air filters in ventilation systems. Evaluation of performance and analysis of applications. Building Services Engineering. PhD Thesis, Chalmers University of Technology, Sweden.
- Walsh DC, Stenhouse JIT (1997). The effect of particle size, charge, and composition on the loading characteristics of an electrically active fibrous filter material. *Journal of Aerosol Science*, 28: 307–321.
- Zhao B, Chen C, Yang X, Lai ACK (2010). Comparison of three approaches to model particle penetration coefficient through a single straight crack in a building envelope. *Aerosol Science and Technology*, 44: 405–416.