A Data-driven Indoor Air Quality Framework for Post-COVID-19 Workplace Re-entry

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How to read this document

This document discusses a back to work framework for responding to the disruption caused by SARS-CoV-2 or COVID-19 in 2020. Nothing contained in this document should be regarded as medical advice. This document does not contain the results of primary medical, epidemiological, or pathogen research. It is only intended to summarise information from professional societies and reliable experts in epidemiology, health, and building engineering. Following the recommendations of this document does not reduce the risk of disease transmission in your facility to zero. This document should not be used as part of a submission to fulfil a legal obligation. The authors have cited sources in good faith and as-is, meaning we assume that the reported results are correct unless proved otherwise.

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CONTENTS

1 EXECUTIVE SUMMARY

Along with the incomprehensible toll on the health and wellbeing of all nations and communities, the COVID-19 pandemic has also caused a wrenching disruption to our economic lives. This has had a major short-term impact on workplaces, as people work from home or are unable to work. However, the virus will continue to impact workplaces even as lockdowns ease, since new measures to protect workers' health must be implemented. The health-promoting aspects of buildings have always been important to our long- and short-term health, wellbeing, comfort, and productivity. The pandemic has sharpened minds to the immediate and catastrophic impacts of building design and operation on disease transmission.

It is virtually certain that social interaction and accessing public places poses a risk of transmission of virus between infected persons and others. Prevailing government guidance on prevention and public health reflects this (NHS 2020; CDC 2020). While several strategies can reduce the risk of transmission, no interventions or combinations of interventions will reduce the risk down to zero. Existing recommendations for controlling the risk of infections in workplaces should be considered by building managers and operators as part of reopening buildings after the ongoing disruption (ASHRAE 2020). Though direct transmission from droplets and surfaces is more effective, buildings need to operate assuming aerosol transmission is a sufficiently serious risk. Hence, this document proposes a protocol that captures measurable metrics for direct and aerosol transmission, recognising that a protocol that is overly focused on one will be seriously weaker.

A back to work protocol is a plan for re-populating buildings such as offices that were temporarily emptied due to the ongoing restrictions on travel and public interaction. This protocol presented here is specifically about building operation. It can help building managers reduce risk by following established frameworks and guidelines. A protocol is only as good as its implementation, which is why this one explicitly includes measurement and verification. This process will have to be iterative, and no single action alone will be enough (ASHRAE 2020; REHVA 2020).

2 Key Features

1. **Implement Engineering and Administrative Controls**
   Taking actions to manage risk through building operation, such as those recommended by professional societies (ASHRAE 2020; REHVA 2020).
2. **Measure and Verify**
   Most actions recommended for healthy building operation have measurable outcomes, either directly (e.g., temperature) or through proxies (e.g., CO_2 for ventilation). Measuring the outcomes of these actions using sensors and inspections/surveys translates engineering intent into operational reality.
3. **Inform and engage occupants**
   Push notifications and feedback or surveys can be used to both inform occupants about policies and actions and encourage them to participate in building operation. Occupants often have the best understanding of how policies are working and how hazards are developing or being controlled (OSHA 2020).
4. **Review and Improve**
   No plan survives first contact with implementation. Reviewing the plan based on the results of measurements and surveys will help to ensure that unintended consequences are minimised, and improvements implemented rapidly.

3 INTRODUCTION

Among the numerous, drastic changes that have been wrought by the COVID-19 pandemic is a profound shift in global attitudes towards workplaces. The enforced work-from-home has upended assumptions about what constitutes essential interaction and forced companies to support remote working at an unprecedented scale. This is expected to have long-lasting consequences for workers, businesses, and service providers alike. These will range from diminished requirements for real estate to house offices and retail facilities, as businesses adapt to more remote work, to changes in how workplaces and public spaces are operated, maintained, and evaluated, as workers are coaxed back into physical offices.

Buildings play a major role in the overall health of people worldwide, with many of us spending up to 90% of our lives spend indoors (Kleipis et al. 2001). In addition, while "... health-care facilities have criteria for ventilation design to mitigate airborne transmission of infectious disease ... most infections are transmitted in ordinary occupancies in the community and not in industrial or health-care occupancies" (ASHRAE 2020). Given the percentage of our lives, especially indoor time, which is spent in a commercial environment, infrastructure and protocols must be in place to satisfy potential occupant needs and concerns about the quality of the indoor air and environment.

While building recommendations provide the protocols to reduce the spread of infectious diseases, they are most effective supplemented with continuous measurement and workforce participation. In this paper we propose the development of an integrated hardware and software tool that uses a combination of sensors and occupant participation to evaluate the achievement of standards of care in buildings based on the best available evidence. We also discuss the innovative application of existing technologies to provide building owners and managers the tools to create healthy indoor environments that suppress the transmission of viruses such as COVID-19.

Finally, the authors urge the reader to view this report with informed scepticism, and to consider that the content is a summary of *temporary scientific hypotheses*. Your responses should be guided by the precautionary principle[1] and the necessity to take adequate steps to protect the occupants of your building based on the best available science. This issue is so new that any guidance that is summarised here must be considered in light of the fact

[1] "Incomplete information, inconclusive evidence and public controversy can make it difficult to achieve consensus over the appropriate response to hazardous substances or activities, but these are precisely the sorts of conditions that often demand hard and fast decisions... Recourse to the precautionary principle presupposes that potentially dangerous effects deriving from a phenomenon, product or process have been identified, and that scientific evaluation does not allow the risk to be determined with sufficient certainty. The implementation of an approach based on the precautionary principle should start with a scientific evaluation, as complete as possible, and where possible, identifying at each stage the degree of scientific uncertainty." (Science Communication Unit, UWE 2017, and references therein)

that the regular scientific peer-review process has not necessarily caught up with the issue. Only citations from academic journals and conferences are normally considered peer-reviewed. This report, while technical and honest, in not peer-reviewed by a committee of experts "blind" to the authors and our affiliations. Similarly, guidance from agencies and the government can change. Articles in magazines should not be considered as evidence at all, though when they summarise the recommendations and research of experts in the field they are a useful jumping-off point. They are cited here in that spirit.

4 WHY DO I NEED THIS?

- ❖ It is virtually certain that accessing public places and the accompanying social interaction pose a risk of transmission of virus between infected persons and others. Prevailing government guidance on prevention and public health reflects that (NHS 2020; CDC 2020).
- ❖ Though direct transmission from droplets and surfaces is more effective, buildings need to operate assuming aerosol transmission is a sufficiently serious risk.
- ❖ While several strategies can reduce the risk of transmission, no interventions or combinations of interventions will reduce the risk down to zero.
- ❖ Existing recommendations for controlling the risk of infections in workplaces should be considered by building managers and operators as part of reopening buildings after the ongoing disruption (ASHRAE 2020).

The transmission of a disease depends on several factors, such as "pathogen infectivity", i.e., how well and fast a pathogen can infect hosts, and what dose of a pathogen is required to cause a clinical disease (Aronson, Brassey, and Mahtani 2020); "reservoirs", i.e., how many people are infected in a given population; "routes", how the pathogen jumps from host to host; and, "secondary host susceptibility", or how susceptible a person is to being affected by a pathogen picked up from somebody or something else (ASHRAE 2020). For a disease to be transmitted from one person to another therefore, several factors need to align: a pathogen needs to be sufficiently infective (infectivity), it needs to travel from a primary host to a secondary host (via some route), it needs to be present in sufficient quantity to create an infection (dosage), and the secondary host needs to be susceptible to the pathogen (susceptibility).

The current working hypothesis for transmission of SARS-CoV-2 (COVID 19) virus is that it can be transmitted through infected aerosols (Asadi et al. 2020), like most other influenza viruses. Direct transmission through droplets, e.g., if an infected person sneezes directly in your face, and from surfaces, e.g., a person sheds the virus on a surface via a sneeze, you touch the surface and then your mouth immediately after, are likely far more effective modes of transmission. Hence, this document proposes a protocol that captures measurable metrics for direct and aerosol transmission, recognising that a protocol that is overly focused on one will be seriously weaker.

Aerosols are minute particles that can stay airborne for hours, and even days, indoors. These aerosols can carry the virus around a building, potentially infecting people that have had no direct contact with an affected person (J. Allen 2020; Miller 2020). While some buildings could claim to filter out all symptomatic individuals, in itself a nearly impossible task, recent modelling indicates that COVID-19 is both present in asymptomatic and pre-symptomatic individuals, and that these individuals can "… emit large quantities of aerosol particles…"

during ordinary breathing and speech (Asadi et al. 2020). The upshot, therefore, is that "... transmission of SARS-CoV-2 through the air is sufficiently likely that airborne exposure to the virus should be controlled" (ASHRAE 2020, and references therein; Fears et al. 2020).

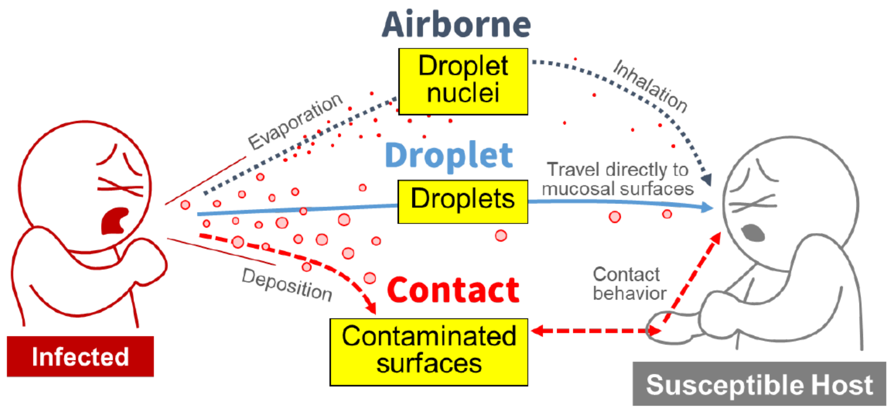

Figure 1: Modes of transmission: droplet, contact (fomite), and airborne (Fig. 2, SHASE and AIJ 2020).

While everybody should be concerned about catching the SARS-CoV-2 virus, the risks are not limited to that. Literature has indicated the presence of other pollutants and pathogens in indoor spaces that can harm health, and was doing so before the current pandemic (ASHRAE 2017, Ch. 10; NICE 2020). The relationship between poor existing health, or underlying health conditions, and risk of morbidity from COVID-19 is known, though details are emerging. In general, people who are "...particularly vulnerable to ill health as a result of exposure to poor indoor air quality include... " those with existing lung conditions such as COPD[2] and asthma, and cardio-vascular diseases (NICE 2020). Since the number of compounding vulnerabilities is unknown, and the number of afflicted in a workforce is unknown, it is prudent to consider prevention first. Conversely, people who have recovered from COVID-19 may have additional cause for concern about the air quality in their place of work due to the impact of the infection on their lungs. That is, people who have been affected by the virus could be susceptible to "opportunistic infections" in the workplace due to their weakened immune systems[3].

The upshot is that the SARS-CoV-2 (COVID-19) virus poses an immediate risk to health in buildings, and measures should be taken to slow down its spread. Directly addressing the mechanisms of viral transmission through active mitigation measures and measurement, verification, and occupant engagement will, in many cases, also improve the Indoor Environmental Quality in the workplace. This document summarises existing research to create a plan of action for getting 'back to work' after the ongoing disruption.

[2] Chronic Obstructive Pulmonary Disease
[3] Existing guidance on opportunistic infections mostly focuses on HIV/AIDS (e.g., https://www.cdc.gov/hiv/basics/livingwithhiv/opportunisticinfections.html)

5 What is a "Back to work" Protocol?

- ❖ A back to work protocol is a plan for re-populating buildings such as offices that were temporarily emptied due to the ongoing restrictions on travel and public interaction.
- ❖ This protocol presented here is specifically about building operation. It can help building managers reduce risk by following established frameworks and guidelines.
- ❖ A protocol is only as good as its implementation, which is why this one explicitly includes measurement and verification.
- ❖ This process will have to be iterative, and no single action alone will be enough (ASHRAE 2020; REHVA 2020).

5.1 Key Features

A so-called 'back to work' protocol is a plan of action that can be followed by managers and operators to reduce transmission in buildings, based on the best available scientific guidance and continuous improvement. It is not a substitute for medical advice or government guidelines. There will be actions required at a societal level, such as widespread testing, contact tracing, and lockdowns, over which building managers do not have control. The recommendations summarised here are diverse and not necessarily applicable to every single building. It is important to think about following them to the highest reasonable level.

1. **Implement Engineering and Administrative Controls**
   Taking actions to manage risk through building operation, such as those recommended by professional societies (ASHRAE 2020; REHVA 2020). These are explored in more detail below (5.3, 5.4).
2. **Measure and Verify**
   Most actions recommended for healthy building operation have measurable outcomes, either directly (e.g., temperature) or through proxies (e.g., CO_2 for ventilation). Measuring the outcomes of these actions using sensors and inspections/surveys translates engineering intent into operational reality.
3. **Inform and engage occupants**
   Push notifications and feedback or surveys can be used to both inform occupants about policies and actions and encourage them to participate in building operation. Occupants often have the best understanding of how policies are working and how hazards are developing or being controlled (OSHA 2020).
4. **Review and Improve**
   No plan survives first contact with implementation[4]. Reviewing the plan based on the results of measurements and surveys will help to ensure that unintended consequences are minimised, and improvements implemented rapidly.

[4] Andy Weir, *The Martian*, 2012. Also, Helmuth von Moltke the Elder, *Uber Strategie*, 1817.

5.2 A FRAMEWORK FOR RISK MANAGEMENT

The protocol is based on the concept of the 'Hierarchy of Controls' framework originally proposed to deal with occupational hazards (CDC and NIOSH 2015). An adaptation of this for building operation during times of high risk is presented in Figure 2 (J. G. Allen and Macomber 2020). The actions noted here fall mostly in the third and fourth category from the bottom – engineering controls in spaces and administrative controls.

5.3 ENGINEERING CONTROLS

This is a summary of actions recommended by professional societies in their evolving COVID-related guidance (ASHRAE 2020; REHVA 2020). This advice only applies to non-healthcare buildings, i.e., places where viral loads are expected to be relatively light or at 'background' levels, no more than in the general populace. We present the guidance here, along with the measurable outcomes where applicable.

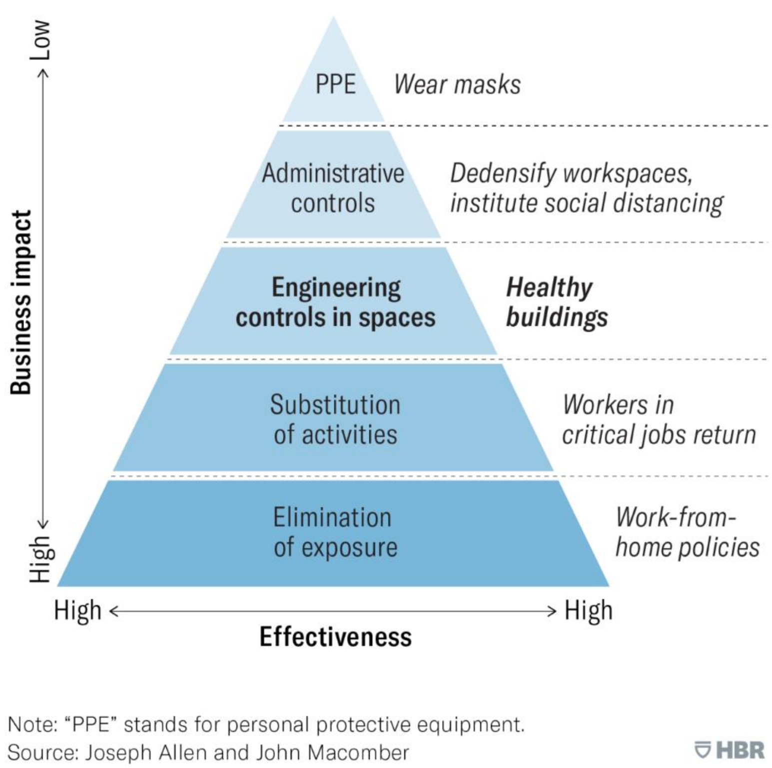

Figure 2: Hierarchy of controls, adapted for healthy building operation (J. G. Allen and Macomber 2020).

Category	Action	Intentional Measurable Outcomes	Potential Unintended Consequences
General Ventilation	1. Increase outdoor air ventilation 2. Increase window ventilation 3. No recirculation	1. Lower Carbon Dioxide (CO_2) 2. Lower Total Volatile Organic Compounds (VOC)	1. Increased outdoor PM ingress 2. Increased energy use 3. Uncomfortable air speeds
Air treatment / filtration	1. Improve HVAC filtration to MERV-13 or better 2. Upper-room or in-duct UVGI[5]	1. Lower Particulate Matter (PM)	1. Reduced outdoor PM 2. Higher Ozone levels
Local air treatment	1. Portable room cleaners	1. Potentially lower VOCs 2. Potentially lower PM	1. Probably ineffective
Source Control / Elimination	1. Toilet exhaust / extract / ventilation 2. Toilet operation and flushing	1. Change in VOC? 2. Higher Relative Humidity (RH)	1. Energy penalty
Indoor Environmental Quality	1. Maintain Temperature and Relative Humidity	1. Temperature 2. RH	

5.3.1 General Ventilation

This might include disable demand-controlled ventilation and opening outdoor air dampers to 100%. ASHRAE has recently recommended 24/7 operation of ventilation systems if possible. REHVA has recommended the same, though both acknowledge the higher penalty energy penalty. While an increase in ventilation is encouraged, there is currently no established evidence on how much is adequate (SHASE and AIJ 2020; Lu et al. 2020). During the SARS outbreak, exposure controls were proposed for ventilation systems that could be relevant to the coronavirus, which is a minimum of 6 ACH and 12 ACH where feasible (Schentag et al. 2004; Memarzadeh and Xu 2012).

For most buildings, there is unlikely to be any gains from running ventilation for more than 1-2 hours after the CO_2 concentration reported by distributed sensors in a space is down to fresh air levels (350-450 ppm).

[5] UVGI – Ultraviolet Germicidal Irradiation

Additionally, the recommendations is to bypass or suspend air circulation through "… systems such as energy recovery ventilation systems that leak potentially contaminated exhaust air back into the outdoor air supply" (ASHRAE 2020, 10).

5.3.2 HVAC Operation

> *Changes to building operations, including the operation of heating, ventilating, and air-conditioning systems, can reduce airborne exposures… Ventilation and filtration provided by heating, ventilating, and air-conditioning systems can reduce the airborne concentration of SARS-CoV-2 and thus the risk of transmission through the air. (ASHRAE 2020, 2)*
>
> *While ventilation systems cannot interrupt the rapid settling of large droplets, they can influence the transmission of droplet nuclei infectious aerosols. (ASHRAE 2020, 5)*

Unconditioned spaces can cause thermal stress to people that may be directly life threatening and that may also lower resistance to infection. **In general, disabling of heating, ventilating, and air-conditioning systems is not a recommended measure to reduce the transmission of the virus** (ASHRAE 2020). Most available guidance suggests maintaining temperature and humidity according to existing guidelines.

Enacting enhanced building HVAC operational practices can reduce the potential for spread of SARS-CoV-2. "Though ASHRAE 170-2017 permits a wider range of RH from 20% to 60%, maintaining a RH between 40% and 60% indoors may help to limit the spread and survival of SARS-CoV-2 … while minimizing the risk of mould growth and maintaining hydrated and intact mucosal barriers of human occupants" (Dietz et al. 2020). Current understand of SARS-CoV-2 indicates that it has much reduced viability above 80% humidity, but this is not desirable indoors due to other complications such as microbial growth and discomfort (CIBSE 2020b).

5.3.3 Ventilation Hotspots / Vulnerable Spaces

The presence of a pathogen such as COVID-19 in the general populace demands special consideration to transmission hotspots such as toilets and lifts/elevators. This would be in addition to the recommendations for placing sensors in working areas, conference rooms, etc. that we have published previously (Rastogi et al. 2020).

Faecal-oral transmission is an acknowledged route for SARS-CoV-2 and many other pathogens. Droplets created by open-lid toilet flushing are a potentially large source of pathogens and ensuring adequate localised exhaust or extraction of these is an effective strategy. This will have the additional benefit of evacuating odours and other common pathogens such as norovirus and stomach bugs.

Lifts (elevators) are vulnerable spots, for obvious reasons. They are enclosed spaces with poor ventilation, they have high traffic, and people are forced to be in close quarters. Increasing ventilation or extraction from lifts or lift shafts is recommended. This may require some retrofit, but a good first step is to at least measure the ventilation levels in lifts using a CO_2 measurement.

The use of HVAC strategies supported by the evidence-based literature should be considered. This includes, but is not limited to, the following (ASHRAE 2020):

1. Enhanced filtration and UVGI
2. Local exhaust ventilation for source control
3. Local ventilation systems for certain high-risk tasks. Most office buildings are unlikely to have high-risk tasks such as triaging incoming patients. If you think you have a potential high-risk task or area in your building, please consult specialised advice such as that from Public Health England (PHE 2020).
4. Free-standing high-efficiency particulate air (HEPA) filters. Ionizing filters are not recommended.

5.4 Administrative Controls and Personal Protective Equipment (PPE)

The administrative controls expected to be most effective are those related to enhanced cleaning, access to disinfection, and physical distancing (ASHRAE 2017; BOMA Canada 2019; REHVA 2020; ASHRAE 2020; WHO 2020; CIBSE 2020a; 2020b; NHS 2020; CDC 2020). While disinfection protocols and physical distancing cannot usually be measured directly like a physical parameter, e.g., RH, we suggest proxies that indicate their uptake or effectiveness.

Hand washing and disinfection with alcohol-based rubs is widely recommended because of its effectiveness (Kampf and Kramer 2004), as is disinfecting and cleaning surfaces with alcohol-based cleaning agents (Kampf et al. 2020). Buildings will need to promote more hand washing and disinfection through messaging and reinforcement. This both protects the individual and, in case they are a carrier, others. While this is not particularly cumbersome, complacency is natural and will need to be reinforced through easy access to disinfection, hand washing and messaging.

Physical distancing of up to 2 metres (6 feet) is recommended by most organisations (PHE 2020; CDC 2020) and can be reinforced through changing spatial layouts to favour spread-out work stations and lighter utilisation of space in offices. If the entire workforce is not mandated to be at work together, i.e., workplaces are deliberately kept at less than 100% capacity, and the existing space is modified through design interventions to reinforce physical distancing, considerable reductions in transmission may be achieved. Practicing physical distancing may have to be reinforced through consistent, constant messaging.

Additional messaging around behavioural actions such as wearing masks or 'Catch it, bin it, kill it' (PHE 2020) are effective and will need to be reinforced. While we mention administrative actions such as encouraging employees to work from home and staggered occupancy, these may not strictly part of a building managers remit. We propose that the impact and uptake of these measures be assessed.

Category	Action	Intentional Measurable Outcomes	Potential Unintended Consequences
Enhanced Disinfection	1. Enhanced cleaning schedules 2. Access to alcohol-based disinfection 3. Access to hand washing	1. Surveys of occupants asking about disinfection	1. Increased Total Volatile Organic Compounds (VOC) 2. Increased Formaldehyde
Physical distancing	1. Work-from-home and staggered occupancy 2. Deliberate distancing through separation of desks, physical barriers, etc. 3. Guidelines on social interaction 4. Preventing overcrowding 5. Statistical assessment of occupancy through measurement systems	1. Uptake and response (through surveys) 2. Staff reactions and compliance 3. Lower space utilisation 4. Spatially-resolved occupancy over time 5. Dwell times / interaction times	1. Compliance fatigue 2. Lower space efficiency 3. Resistance to occupancy measurement
Behavioural	1. 'Cough hygiene' 2. Face-masks 3. Hand-washing 4. Avoidance of overcrowding	1. Effectiveness of communication 2. Uptake and response	1. Compliance fatigue
Access Control	1. Access control to prevent overcrowding 2. Body surface temperature measurement to control entry of symptomatic individuals	1. Visitor and entry logging 2. Body surface temperature readings	1. Crowding at entrance 2. Resistance to invasiveness of body surface temperature measurement

5.5 MEASUREMENT AND VERIFICATION

The arbn well standard sensor network covers most areas of regular occupancy, as specified in our Best Practice Guide (Rastogi et al. 2020, Sec. 1.5). The Guide outlines two levels of sensor spatial coverage: minimum and optimum. The optimum sensor layout should be sufficient under most conditions to evaluate the intended measurable outcomes and many unintended potential consequences of the measured summarised here. The standard arbn well sensor network includes distributed measurement of CO_2, VOC, PM, Temperature, and Humidity.

Since pathogen transmission considerations have been exacerbated by the current pandemic, we recommend additional measurement points in vulnerable places. These include potential sources such as toilets and elevators. Since the best protection in these places is adequate ventilation/exhaust (ASHRAE 2020; REHVA 2020), a simple CO_2 measurement will suffice for general prevention.

5.6 EMERGING SOLUTIONS AND ISSUES

As the properties of COVID-19 are better known, the guidance will change. While it may not feel intuitive, guidance that changes when the evidence demands it is *more* reliable. Much of the guidance here is based on the understanding of previous epidemics such as SARS, MERS, and H1N1. Some solutions and actions will be modified once more is known about how the virus infectivity and routes change over time. An example of this is the estimation of viral load in an enclosed space based on CO_2 measurements. While an equation exists to approximate this, it relies on knowing the emission rate of COVID-19 from people, which is still to be reliably determined.

To improve recommendations for the operation and design of air conditioning and ventilation, we need to be able to determine how long people have spent in a location (dwell time), the directional pathways of airflow around these locations (local, directional airflow), and the level of ventilation necessary to remove airborne transmission of droplets among people in the same space (Pantelic 2019).

6 BACKGROUND

6.1 ADDITIONAL BENEFITS

There is nothing fundamentally new contained in this protocol, or in the expert advice cited here. Most research updates have highlighted the effectiveness of existing strategies to counter the new SARS-CoV-2 virus most effectively. Some strategies discussed here do have potential negative outcomes such as increased VOCs through enhanced cleaning, increased energy use or PM from increasing outdoor air, or reduced space use. However, there are several additional benefits to be gained from these strategies as well. Some examples are given here:

1. The ventilation and HVAC changes recommended here, if implemented properly, should lead to cleaner, fresher indoor air. This should improve productivity and wellbeing, as several previous publications have shown.
2. Enhanced source control such as forced exhaust from toilets will also exhaust other pathogens and odours.
3. Additional cleaning will help eliminate pathogens other than SARS-CoV-2 as well.
4. Improved filtration of outdoor air will reduce indoor pollution.
5. Increased engagement with occupants may improve satisfaction, as occupants feel more like stakeholders than passive consumers.

6.2 ASHRAE HOF 2017, CH. 10

> *Over a 70-year lifespan in a developed region, indoor air (in homes, schools, day cares, offices, shops, etc.) constitutes around 65% of the total lifetime exposure (in mass), whereas outdoor air, air during transportation, food, and liquid makes up the rest. For more vulnerable populations, such as newborns, the elderly, and the homebound ill, indoor air in homes makes up around 80% of the exposure. (ASHRAE 2017)*

6.3 ASHRAE POSITION DOCUMENT ON INFECTIOUS AEROSOLS

> *Transmission of disease varies by pathogen infectivity, reservoirs, routes, and secondary host susceptibility (Roy and Milton 2004; Shaman and Kohn 2009; Li 2011). The variable most relevant for HVAC design and control is disrupting the transmission pathways of infectious aerosols. [p. 4]*
>
> *Pathogen dissemination through the air occurs through droplets and aerosols typically generated by coughing, sneezing, shouting, breathing, toilet flushing, some medical procedures, singing, and talking (Bischoff et al. 2013; Yan et al. 2018). The majority of larger emitted droplets are drawn by gravity to land on surfaces within*

about 3–7 ft (1–2 m) from the source… General dilution ventilation and pressure differentials do not significantly influence short-range transmission. Conversely, dissemination of smaller infectious aerosols, including droplet nuclei resulting from desiccation, can be affected by airflow patterns in a space in general and airflow patterns surrounding the source in particular. Of special interest are small aerosols (<10 µm), which can stay airborne and infectious for extended periods (several minutes, hours, or days) and thus can travel longer distances and infect secondary hosts who had no contact with the primary host. [pp. 4-5]

Ventilation and filtration provided by heating, ventilating, and air-conditioning systems can reduce the airborne concentration of SARS-CoV-2 and thus the risk of transmission through the air. Unconditioned spaces can cause thermal stress to people that may be directly life threatening and that may also lower resistance to infection. In general, disabling of heating, ventilating, and air-conditioning systems is not a recommended measure to reduce the transmission of the virus. [pp. 2-3]

While ventilation systems cannot interrupt the rapid settling of large droplets, they can influence the transmission of droplet nuclei infectious aerosols… Even the most robust HVAC system cannot control all airflows and completely prevent dissemination of an infectious aerosol or disease transmission by droplets or aerosols. An HVAC system's impact will depend on source location, strength of the source, distribution of the released aerosol, droplet size, air distribution, temperature, relative humidity, and filtration. Furthermore, there are multiple modes and circumstances under which disease transmission occurs. Thus, strategies for prevention and risk mitigation require collaboration among designers, owners, operators, industrial hygienists, and infection prevention specialists. [p. 5]

Generally speaking, designs that achieve higher ventilation rates will reduce risk. However, such buildings will be more affected by local outdoor air quality, including the level of allergens and pollutants within the outdoor air, varying temperature and humidity conditions, and flying insects. [p. 6]

Ventilation with effective airflow patterns (Pantelic and Tham 2013) is a primary infectious disease control strategy through dilution of room air around a source and removal of infectious agents (CDC 2005). However, it remains unclear by how much infectious particle loads must be reduced to achieve a measurable reduction in disease transmissions (infectious doses vary widely among different pathogens) and whether these reductions warrant the associated costs (Pantelic and Tham 2011; Pantelic and Tham 2012). [pp. 6-7] ***(ASHRAE 2020)***

6.4 PRECAUTIONARY PRINCIPLE

> *Incomplete information, inconclusive evidence and public controversy can make it difficult to achieve consensus over the appropriate response to hazardous substances or activities, but these are precisely the sorts of conditions that often demand hard and fast decisions. (Science Communication Unit, UWE 2017)*

6.5 TEMPERATURE, HUMIDITY, AND TRANSMISSION

Current guidance does not recommend turning off HVAC systems. It is necessary to maintain comfort conditions and adequate ventilation to ensure that occupants do not suffer needlessly. In addition, temperature and relative humidity (RH) can also improve or degrade the viability of pathogens. The "… scientific literature generally reflects the most unfavorable survival for microorganisms when the RH is between 40% and 60%" (ASHRAE 2020, 8).

RH below 40% is associated with three factors that increase infections:

1. Infectious aerosols (droplets) shrink rapidly to become droplet nuclei. This means they can travel further and stay aloft longer in air.
2. Many bacteria and viruses are "anhydrous resistant" and show increased viability in low-RH conditions.
3. Low RH impairs mucus membranes and other steps in immune system protection in mammals (Kudo et al. 2019).
4. RH below or equal to 23% is associated with 70.6–77.3% infectivity of nebulized influenza, but RH above 43% was associated with only 14.6-22.2%. "Maintaining indoor relative humidity >40% will significantly reduce the infectivity of aerosolized virus". (Noti et al. 2013)

6.6 AIR CONDITIONING

Air-conditioned was determined to be the cause of spread of the coronavirus to 9 people sitting near an infected person in a windowless restaurant in Guangzhou, China (Lu et al. 2020)[6]. The spread was caused by a combination of local droplet transmission from patient zero (to others sitting less than 1m) and strong airflow from the air conditioner, which propagated droplets to other sitting more than 1m away. The key factor for infection caused by the air conditioning was the direction of airflow: Patient zero was sitting in the middle of 3 tables, which were in line with the air outlet and the return air inlet for the central air conditioner. None of the other 73 diners and 8 employees were infected.

[6] This paper is not peer reviewed. Please approach this result with caution.

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