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Cost-Effective Operations and Maintenance for COVID-19

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SUMMARY

COVID-19 is most often transmitted directly from a nearby individual and neither HVAC systems nor sanitizing can prevent this. While costly upgrades to air-conditioning and cleaning are being advocated to address the pandemic, available information suggests that relatively minor HVAC adjustments and cleaning enhancements may be sufficient to minimize Covid-19 spread. Selection of COVID-19 control measures can be prioritized by likelihood of reducing disease spread.

Understanding how Covid-19 is actually spreading in buildings is critical to evidence-based prioritization of response measures. Available information on the different pathways for COVID-19 transmission suggests:

1. "Nearby exposure" *(within several feet of an infected individual)*
   The majority of COVID-19 cases appear to be associated with nearby exposure. (see sections 1.1-1.3)
2. Airborne" *(exposure beyond several feet)*
   SARS-CoV-2 (the virus causing COVID-19) has been frequently detected in air at considerable distances from infected occupants. Exposures beyond several feet has been associated with COVID spread where ventilation is poor. Airborne transmission appears to be relatively infrequent overall. (sections 1.1-1.3)
3. "HVAC" *(circulated to another space).*
   It has not been established that systems with return air circulate virus to other areas, and no studies have found re-circulation responsible for spreading COVID-19. A study of quarantined cruise ship passengers, where a re-circulating HVAC system served some rooms housing infected individuals, found new cases only where the cabin-mate was already infected (nearby transmission). Sites have recently been documented where samples of filters and exhaust duct surfaces tested positive for total virus, but these samples were negative for infectious virus. (sections 1.2-1.4)
4. "Surface" *(contact with contaminated surfaces, also called "fomites")*
   Surface transmission of COVID-19 has not been documented but is assumed based on experience with similar viruses. Although testing has detected SARS-CoV-2 on surfaces over wide areas, analyses for infectious virus have generally been negative. (section 2.1)
5. "Sewage" *(exposure to virus-contaminated droplets)*
   In addition to exhaled breath, the virus is also present in feces and urine. There have been no studies to determine if this has been responsible for any COVID-19 cases. Droplets from sewage can be generated by flushing toilets and sewer gas. (section 3.0)

Based on these findings, Building Dynamics recommends prioritizing COVID response measures as follows (see section 4.0 for details):

#1 Enhance personal infection control measures to the extent feasible.
#2 Implement measures to reduce exposure in higher risk areas.
#3 Consider implementing HVAC and cleaning enhancements, where feasible.
#4 Maximize ventilation and filtration as a precaution but recognize that this may not provide significant additional protection (sections 1.2-1.8).

This White Paper discusses the efficacy of various options for enhancing ventilation, filtration, and sanitizing. (sections 1.8-2.8) There is very little information available to guide development of a cost-effective strategy for reducing transmission in buildings and research is urgently needed in this area.

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1.0 SHOULD VENTILATION AND FILTRATION BE MAXIMIZED?

1.1 CONTRASTING POSITIONS ON AIRBORNE VIRUS:

There has been considerable debate among scientists as to how COVID-19 spreads from person-to-person ("transmission"). This is critical for estimating how much operation of HVAC systems contributes to disease spread and when do HVAC modifications help control COVID-19. There are three opposing views of airborne transmission:

(a) Inhalation within several feet is the dominant cause of COVID-19 (nearby transmission).
Based on this assumption, airborne transmission was not considered important. No specific HVAC changes were recommended and. response thus focused on personal infection prevention measures (i.e., initial WHO and CDC Guidance).

(b) Inhalation beyond several feet is dominant (airborne transmission).
Scientists and engineers assuming this recommend maximizing ventilation and filtration.

(c) Nearby transmission is dominant, but airborne transmission also occurs under limited conditions.
This is consistent with updated positions of CDC and WHO.

1.2 INFECTIOUS VIRUS

Studies with field sampling have consistently found SARS-CoV-2 in the air well beyond several feet of infected individuals. However, most of these studies measured only total virus, a parameter which may or may not include active virus (the type that causes infection). This only establishes airborne exposure to SARS-CoV-2 over long distances, but not airborne transmission.

Exhaled SARS-CoV-2 degrades over time to a state where it no longer causes infection ("inactivation"). Although much of the exhaled virus inactivates rapidly, limited experimental studies have found infectious virus in the air after 3 hours.[1] It is not known how long infectious virus can remain in air after COVID-positive occupants leave the area. For viral infections, there is a threshold level below which an individual is not affected (this is lower for individuals in a sensitive category). Consistent with the dose/response principle, transmission risk increases with the concentration and duration of virus exposure. Since concentrations of airborne virus generally decrease with distance from the source, this factor would suggest a higher risk to nearby individuals.[52]

A few studies have included additional analyses to determine the amount of infectious virus present. These have only found infectious virus immediately adjacent to COVID patients being treated in a hospital[3] and inside a car with a COVID-positive driver.[43] Other indoor air sampling for infectious virus has been negative.[4,5,6]

1.3 EPIDEMIOLOGY

Outbreak investigations can evaluate case patterns to identify the sources and exposure pathways responsible for disease transmission. Several such studies have associated COVID-19 with airborne transmission. A common factor in these situations was poor ventilation and, in some cases, air flow patterns concentrating virus in the breathing zone.[7,8,9,13,20,22] On the other hand, one outbreak investigation found no COVID-19 cases in rooms with good ventilation, despite the fact that air was being recirculated from rooms housing infected occupants.[10] Other epidemiological studies suggesting airborne transmission did not describe ventilation.[11,12,24,32] Results from most outbreak investigations identifying airborne transmission found that nearby transmission was also a major contributor.[7,8,23,24,25]

CDC's evaluation of global COVID-19 patterns concluded that these were consistent with nearby transmission being dominant and airborne transmission only occurring occasionally.[26] Studies of COVID-19 control measures have found that social distancing (which primarily protects against nearby exposure) is one of the most effective means of reducing transmission.[27,28,29,47] In contrast, ventilation improvements have not been shown to reduce COVID transmission. In computer models developed to estimate the contribution of different exposure pathways to outbreaks, results vary. One model concluded that airborne and surface contact contributed equally to COVID spread,[30] while two models concluded that airborne transmission was dominant.[25,31]

1.4 HVAC TRANSMISSION

No epidemiological studies have found COVID transmission associated with re-circulation of virus through HVAC systems. One study did report that occupants were infected by virus moving between floors through a transfer duct (no HVAC fan).[56] No epidemiological studies have shown a benefit from enhanced ventilating or filtration. Although studies have documented cases of tuberculosis spread by HVAC re-circulation, the bacteria responsible for TB cannot be assumed to act like SARS-CoV-2.[44,45,46]

Limited field sampling has not found SARS-CoV-2 discharged from re-circulating HVAC systems. The virus has been detected on HVAC filters in three studies.[5,33,34,35] One of these conducted additional analysis to see if the virus was infectious and it tested negative.[5] One hospital investigation found SARS-CoV-2 deposited on exhaust ducts before and after exhaust discharge filters in a hospital.[17] Another study detected it on exhaust duct surfaces serving in-patient rooms with infected patients, while tests of exhaust ducts from other hospital areas were negative.[33] Infectious virus has not been found on duct surfaces.

Research to date has been insufficient to draw firm conclusions on HVAC's actual contribution to COVID-19 spread. Available information suggests that HVAC could be a contributing factor in some cases but, it does not have a significant impact overall.

1.5 EFFECTIVENESS OF HVAC MODIFICATIONS

COVID mostly spreads indoors, where HVAC systems are a major influence on occupant exposure.[16,21] HVAC systems can reduce exposure by diluting or removing the virus but can also increase infection risk by concentrating virus in the breathing zone (problematic air flow patterns). For this discussion, ventilation is categorized as follows:

"Poor" (*negligible dilution by either mechanical or natural means*)
"Fair" (*ventilation provided, but less than ASHRAE Standard 62*)
"Good" (*ventilation rates consistent with ASHRAE Standard 62)*
"Enhanced" (*ventilation exceeds ASHRAE Standard 62*)

1.5.1 VENTILATION

Various options are available for increasing mechanical ventilation. Because many facilities are not able to keep up with maintenance, systems are often not providing the intended ventilation (i.e., out of balance, dampers stuck in the closed position, incorrect control sequence). Resolving deferred maintenance, especially in areas in with poor ventilation, is a cost-effective way to reduce virus exposure while also improving comfort and an air quality Other lower cost measures to increase ventilation include:

- Flushing spaces between occupancies.
  Although 24/7 operation or increased overnight ventilation rates have been advocated for COVID control, simply starting up the system early can provide sufficient air change before next occupancy (i.e., two hours before occupants arrive).
- Disabling CO_2 or occupancy sensors.
  Although these save energy when a space is not occupied, continued dilution of accumulated virus is still needed to reduce exposure.
- Expanding economizer operation**.**
  This can allow more periods of free cooling with outside air during mild weather.
- Setting thermostats for continuous fan operation.
  The Auto setting stops diluting the virus after room temperature is satisfied.
- Modifying VAV controls that reduce outside air if comfortable temperatures can still be maintained.
- Operating exhausts continuously.

Increasing outside air requires more energy use and raises utility costs. It can also make the building uncomfortable when the system's capacity to condition outside air is exceeded. Under some weather conditions, introducing excessive outside air can raise indoor humidity to a level causing mold growth or, conversely, dry the air to where it produces eye, nose, and throat irritation. It can also increase the introduction of outside air pollutants. These factors must be considered before increasing ventilation for Covid-19 control. Cost-benefit should be carefully considered before increasing ventilation.

1.5.2 OPENING WINDOWS

While opening windows is often advocated to protect against Covid-19, benefits are limited, and careful attention is needed to avoid causing other problems. Opening windows can reduce virus exposure in adjacent areas under some conditions.[50,55] However, SARS-CoV-2 has been found in indoor air with windows open,[53] and one model of air flow patterns after opening windows showed that it promoted directional air flow between occupants.[55] Open windows can make the room uncomfortable during hot or cold weather, increase allergens during mild weather, introduce outdoor pollutants and increase noise levels. These adverse effects might be reduced by only opening windows when the room is vacant.

1.5.3 AIR FLOW PATTERNS

Even where overall ventilation is adequate, the risk of airborne transmission can be higher where room air is not well mixed and air flow patterns create elevated virus concentrations in the breathing zone. Examples include:

- Wall-mounted fan coil units may increase exposure of adjacent occupants. *(i.e., breathing zone is impacted by supply and return air pathways).*
- Vent location leaves some areas with poor air exchange. *(i.e., spaces with no air supply or return).*
- Air discharge blows the virus between occupants. *(i.e., occupants' portable fans or air purifiers may be significant).*

1.5.4 BARRIERS

Setting up plexiglass barriers between occupants or increasing the height of workstation partitions reduces the risk of nearby transmission by stopping larger droplets. However, potential for airborne transmission continues as smaller droplets still mix with room air. Barriers can be considered where social distancing is not possible but are not a substitute for masking. Barrier installation may also interfere with air mixing and create stuffy conditions.

1.5.5 ACCOMODATING HVAC DEFICIENCIES BY ADJUSTMENTS TO OCCUPANCY

The most cost-effective way to address HVAC deficiencies may be to simply adjust occupancy. For example:

1. Delay occupancy of areas with HVAC deficiencies.
2. Limit occupancy in the building as a whole or within specific spaces to increase ventilation per person.
3. Implement social distancing in crowded areas.
4. Designate buffer zones around HVAC vents which could concentrate virus in adjacent breathing zones. *(i.e., move desks away from wall-mounted fan coil units or floor level return vents).*
5. Require one-way traffic in halls and stairwells.
6. Leave doors open to promote air exchange in spaces subject to virus accumulation. *(i.e., toilet stalls, elevators, rooms with lower ventilation).*
7. Wait between use of spaces where virus can accumulate. *(i.e., individual bathrooms).*
8. Instruct occupants in crowded areas to not talk loudly. *(i.e., elevators and stairwells).*
9. Encourage sensitive occupants to use respirators instead of masks. *(i.e., N- or KN-95's, where available).*
10. Avoid wastewater/sewer gas release by closing toilet lids while flushing, keeping traps wet and resolving venting of sewer gas into the building.

1.5.6 HVAC FILTRATION

If infectious virus makes it through ductwork (i.e., does not inactivate or deposit on surfaces), filtration could reduce airborne concentrations. Because higher MERV-rated filters remove more smaller particles, it is commonly recommended that filters be upgraded to MERV 13 (where airflow restricted to where it adversely affect building conditions). Higher efficiency filters raise costs and have not been shown to reduce COVID-19 transmission. Only one study has examined this issue (measured virus deposited on duct surfaces before and after filters). Investigators found the MERV-10 pre-filter reduced the amount of deposited SARS-CoV-2 by approximately 70%, but the downstream MERV-15 final filter did not further reduce virus.[17]

Rather than upgrading to higher efficiency filters, a lower-cost way to improve removal of SARS-CoV-2 from the airstream is to identify and seal by-pass around currently used filters. HVAC filters often do not fit tightly in their frames, allowing air to pass through without particle removal. Eliminating by-pass also improves general IAQ and protects against soiling of HVAC surfaces.

1.5.7 PORTABLE FILTRATION UNITS

Portable HEPA-filter units remove virus in their immediate vicinity. However, they can also increase occupant exposure by directing air between occupants, drawing return air through the breathing zone, or blowing virus settled on surfaces back into the air.[48,49,50] Noise generated by these units can also be problematic. Careful design, placement, operation, and maintenance of portable HEPA units is necessary for their effective use. Well-placed HEPA units may be particularly beneficial in areas subject to greater virus exposure, such as bathrooms and elevators.

1.5.8 AIR CLEANING/ UV

UV light inactivates virus with sufficient contact time and can be effective in controlling some airborne pathogens in hospital settings. Review of the literature indicates that UV systems and other air cleaning technologies promoted for COVID control (i.e., electrostatic precipitators, hydroxy radical and ozone generators) have not been shown to reduce SARS-CoV-2 exposure and transmission in non-healthcare buildings. A recent evaluation of bipolar ionization efficacy contradicted claims that this system significantly reduced contaminant concentrations and also formed it formed new chemical contaminants in indoor air.[54] No data have been reported on the efficacy of bipolar ionization with respect to SARS-CoV-2 under realistic building conditions.

1.5.9 AVAILABLE HVAC MODIFICATIONS WHICH ARE NOT COST-EFFECTIVE

Building Dynamics' evaluation has found the following unlikely to be effective, too costly, or both:

- Increasing ventilation rates beyond ASHRAE minimums
- Increasing filter MERV rating
- Humidification:
  Although increased humidity may decrease virus survival and increase occupant susceptibility to respiratory infection, other factors can override these effects, and COVID epidemiology shows major spread when building RH is above 40%. Humidification can also contribute to mold growth and increase utility costs.
- Duct cleaning[52]
- Disabling energy recovery wheels:
  Although ASHRAE made this recommendation due to the possibility of discharged virus infiltrating the incoming air stream, this type of cross-contamination is generally negligible.
- UV Disinfection
- Air cleaning

2.0 HOW MUCH SANITIZING IS NEEDED TO MINIMIZE COVID SPREAD?

2.1 AVAILABLE INFORMATION ON SURFACE TRANSMISSION

Intensive sanitizing programs are being put into place because COVID-19 infection by fomite (surface) contact is generally assumed to be significant, However, a review of available information suggests that surface transmission may only play a relatively minor role in the overall spread of COVID-19. Although COVID spreads by surface contact is based on similarity to other respiratory infections, such as flu, no conclusive epidemiological data could be found supporting surface transmission of viruses. Two COVID-19 outbreak investigations have suspected that surface transmission might be a contributing factor,[38,39] and one epidemiological study suggested that COVID-19 transmission was reduced by more frequent sanitizing.[23]

Surface testing for SARS-CoV-2 finds the virus widely dispersed in facilities with COVID-19 patients.[35,36] However, those tests were generally limited to "total" virus,[2,5] and more specific testing has detected infectious virus at only one site.[6] Although much of the virus settled on surfaces inactivates rapidly, infectious virus can persist. Recent work has extended the maximum documented time from one week[42] to one month.[37]

Two researchers have developed computer models for COVID spread which estimate the contribution of surface transmission. One suggested that 8% of the cases in a modelled outbreak were due to surface transmission[30] and the other estimated a surface contribution of one-third.[14]

No studies were available which identify types of surfaces presenting elevated risk for infection. Based on available information, any space potentially occupied by a COVID-positive individual should be sanitized regularly as a precaution. More frequent attention is suggested for bathrooms, elevators, drinking water fountains and crowded spaces.

2.2 PRODUCTS USED TO TREAT SARS-COV-2

SARS-CoV-2 is easily inactivated by a variety of disinfectants and has even been shown to be controlled by soap.[18] The EPA "N-List" of accepted disinfectants for COVID includes a variety of effective, but lower-cost products. Sanitized surfaces are easily re-contaminated and must be frequently re-treated to prevent occupant exposure. A product that continues sanitizing after re-soiling would significantly lower labor costs. One product approved for immediate inactivation of SARS-CoV-2 has also been registered for 24-hour disinfection, even with re-soiling, but this is for bacteria only.[19] That product has potential for similar control of SARS-CoV-2. Other anti-microbial treatments and coatings are being promoted for long-term protection against SARS-2-CoV without evidence that they continue to be effective after re-soiling.

2.3 SCOPE OF SANITIZING

Frequent touchpoints are generally the focus of COVID response. However, occupants also contact other surfaces and virus settled on any surface can be re-suspended into the air. Consideration should be given to periodically sanitizing surfaces not considered high touch as a precaution.

2.4 APPLICATION TECHNIQUES

Little has been done to measure SARS-CoV-2 reduction by different cleaning methods. One study found surface sanitizing generally lowered virus concentrations, but that regular vacuuming of carpets left significant virus residue.[35] Wiping a sanitizer directly on the surface can be very effective, and a microfiber cloth used systematically to remove contaminants may provide the most complete inactivation. Spraying can also be effective if all surfaces are coated (the most complete coverage may be obtained using an electrostatic sprayer).

Fogging has not been established as effective against SARS-CoV-2. Although HEPA-vacuuming is sometimes used in the sanitizing process, it could also re-suspend some virus back into the air. Exposing surfaces to UV light is also being used to control SARS-CoV-2. This inactivates virus only where UV shines directly on that surface and is limited by the duration of exposure and surface cleanliness and its efficacy has not been established.

2.5 QUALITY CONTROL

Sanitizing is only effective if surfaces are properly treated. Worker training and oversight of work practices help ensure effective sanitizing. Indicator tests are available to determine how effective a small area has been cleaned.

For example, ATP-based tests can be used to evaluate and improve worker's technique. However, this test does not detect virus and does not fully evaluate a large area.

2.6 VERIFICATION

Testing cannot determine whether SARS-CoV-2 has been effectively inactivated on surfaces throughout a space. Acceptance of sanitizing can be based on observing proper application technique and passing a visual inspection. Work should not be considered acceptable if visual inspection finds visible dust after treatment. Because sanitized surfaces are easily re-contaminated, it cannot be concluded that occupants will not become infected after sanitizing.

2.7 REOPENING SPACES

- Where a space was previously occupied by an infected individual, deep cleaning of all surfaces, including sanitizing, should be considered before re-occupying.
- Although it has been suggested that sanitizing is not needed if a space has been vacant for more than a week, it should be considered that some surface virus has been found to remain infectious at the end of the longest period evaluated (one month),

2.8 POTENTIAL COST SAVING OPTIONS FOR CONTROLLING SURFACE TRANSMISSION

- Treating only areas that were occupied that day.
- Purchasing lower-cost sanitizers.
- Cleaning only (no sanitizing):
  Although cleaning may reduce surface virus substantially, additional sanitizing can provide further reduction.
- Omitting initial pre-cleaning step:
  Surfaces must be visibly clean for effective sanitizing. Consideration might be given to omitting the pre-cleaning step on surfaces which appear to be clean (i.e., non-touchpoints). If a surface is dusty or dirty, it must be cleaned first.
- Reducing dwell time:
  Although label directions specify a minimum time for keeping a surface wet after applying a sanitizing solution, monitoring this, and providing a second application can be expensive. Allowing a shorter period of time can still provide substantial virus deactivation.
- Reducing application frequency by using a persistent disinfectant:
  Although such a product has not yet been registered for virus, a 24-hour bacterial spray might also provide sufficient virus inactivation to consider less frequent sanitizing.
- Reducing both contamination of surfaces and transfer back to occupants by:
  - increasing frequency of handwashing
  - facilitating hands-free operation (i.e., motion-activated drinking water fountains)
  - protecting hands from direct contact (i.e., pressing elevator buttons with an object, use of a handle grabber)
- Delegating responsibility for sanitizing some surfaces to occupants or employees in that area.

3.0 SHOULD EXPOSURE TO WASTEWATER BE ADDRESSED?

SARS-CoV-2 is also found in feces and urine,[41] making exposure to droplets from toilet flushing, sewage, and sewer gas a potential risk factor. Potential sources of exposure may also include sewer backups, sewage pumping and discharge of untreated sewage. Although no COVID studies have specifically looked for sewage transmission, one outbreak investigation did suspect a possible association with diarrhea.[23] A 2003 SARS outbreak study suggested transmission from exposure to sewer gas released through dry traps.[40]

4.0 HOW CAN COVID RESPONSE MEASURES BASED BE PRIORITIZED BASED ON AVAILABLE EVIDENCE?

Priority #1: <u>Enhance personal infection control practices.</u>

- Test all occupants as frequently as possible, followed by detailed contact tracing and mandatory quarantine.
- Social distance to the extent feasible, including difficult-to-manage activities.
- Wear face coverings whenever possible.
- Wash hands frequently

Priority #2: <u>Address higher risk areas.</u>

Examples:

- Poor ventilation (i.e., no outside air introduced)
- Air flow patterns concentrating virus (i.e., fans blowing virus between occupants)
- Dense occupancy (i.e., elevators)
- Additional sources of virus. (i.e., bathrooms)
- Sensitive occupants (i.e., elderly)

HVAC Control options for higher risk areas:
- Delay occupancy.
- Repair HVAC equipment and controls deficiencies which impact ventilation.
- Make occupancy adjustments to compensate for HVAC deficiencies (see Section 1.5.5)
- Provide better ventilation and air mixing.
- Adjust VAV to increase ventilation.
- Disable demand-controlled ventilation.
- Operate exhausts continuously (i.e., bathrooms).
- Start-up HVAC with outside air dampers open prior to occupancy.
- Eliminate filter by-pass.
- Consider portable filtration.

Bathrooms (always higher risk):
Virus concentrations can be higher in bathrooms because, in addition to exhalation, spray from toilet flushing is also a source. Virus exposure within bathrooms can be reduced by ensuring supply and exhaust air flow is operating per design, exhausts run continuously during occupied hours, stall doors are left open between use, and electric hand driers are disabled (these can blow virus between occupants). HEPA filter units may be a helpful supplement, if set up properly.

Elevators (always higher risk):
Because there is a high potential for airborne virus to accumulate in elevators, properly designed portable HEPA units may reduce passenger exposure, especially where they can be discharged to the elevator shaft. Virus exposure can also be reduced in elevators by keeping the doors open between rides, having passengers face the corners and not touching the buttons with bare fingers.

Sanitizing for higher risk areas:

- Sanitize high touch surfaces regularly (bathrooms and elevators frequently).
- Periodically sanitize surfaces not considered high touch.
- Oversee cleaning to ensure quality control.
- Facilitate hands-free contact.

Priority #3: <u>Implement lower-cost improvements to ventilation, filtration, and sanitizing throughout the facility:</u>

Enhancing ventilation, filtration and sanitizing is a prudent precaution for all occupied areas. However, the allocation of resources for these actions should consider the relative benefits from other COVID response measures.

Priority #4: <u>Maximize Ventilation and Filtration (lowest priority)</u>
- Increase ventilation beyond ASHRAE minimums.
- Increase MERV filter rating.
- UV air disinfection.

<u>Precautions against sewage transmission</u>
- Close toilet lids while flushing, where available
- Keep toilet stall doors open between use
- Immediately resolve any sewage release or backup
- Sanitize bathrooms frequently
- Keep traps wet
- Regularly inspect the building for detectable sewer gas odor and eliminate it as quickly as possible

Because transmission and control of the new variant viruses appears to be the same the original SARS-CoV-2, prioritization of occupant infection control measures over operational changes over HVAC and cleaning modifications does not change. Overall stringency of COVID response measures should consider current community infection rates and rapid spread of a variant would suggest upgrading response measures.

5.0 WHAT RESEARCH IS NEEDED TO SUPPORT MORE COST-EFFECTIVE COVID RESPONSE?

Review of the scientific literature for this White Paper found little, if any, conclusive information to guide selection of measures for operating and maintaining buildings during the pandemic. Valuable data for this purpose could be compiled quickly by research utilizing readily available information:

- Environmental Epidemiology. Location and timing of COVID-positive individuals (from public testing, contact tracing and outbreak investigations) should be followed by characterization of environmental factors and identification of trends and associations. Genomic sequencing of positive tests can be useful in distinguishing sources.
- Field sampling studies. With the pandemic, all buildings are now a natural laboratory for collecting data on total and infectious virus following sampling strategies allowing comparison of exposures under various scenarios. These data would be most helpful in understanding the significance of environmental factors and the efficacy of control measures.
- CFD modelling. Computational fluid dynamics can be used to identify mechanical and natural ventilation configurations which increase or decrease virus exposure.

More detailed information on many of the HVAC-related issues discussed in this White Paper are available from ASHRAE: https://www.ashrae.org/technical-resources/resources

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REFERENCES

1. Van Doremalen, N. and Bushmaker, B. "Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1" *New England Journal of Medicine.* April 2020. https://www.nejm.org/doi/full/10.1056/NEJMc2004973
2. OCLC (2020) The REALM Project. https://www.oclc.org/realm/faq.html and https://www.oclc.org/realm/research.html#test6
3. Lednicky et al. (2020) Viable SARS-CoV-2 in the air of a hospital room with COVID-19 patients. Pre-print. https://www.medrxiv.org/content/10.1101/2020.08.03.20167395v1.full.pdf
4. Binder et al. (2020) Environmental and Aerosolized Severe Acute Respiratory Syndrome Coronavirus 2 Among Hospitalized Coronavirus Disease 2019 Patients. *The Journal of Infectious Diseases*, Volume 222, Issue 11, 1. https://doi.org/10.1093/infdis/jiaa575
5. Ben-Shmuel et al. (2020) Detection and infectivity potential of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) environmental contamination in isolation units and quarantine facilities. pre-print. https://www.clinicalmicrobiologyandinfection.com/article/S1198-743X(20)30532-2/pdf
6. Zhou et al. (2020) Investigating SARS-CoV-2 surface and air contamination in an acute healthcare setting during the peak of the COVID-19 pandemic in London. Pre-print. https://www.who.int/news-room/commentaries/detail/transmission-of-sars-cov-2-implications-for-infection-prevention-precautions
7. Li, Y. Qian, H., Hang, J. et al. "Evidence for probable aerosol transmission of SARS-CoV-2 in a poorly ventilated restaurant" *Preprint*. https://www.medrxiv.org/content/10.1101/2020.04.16.20067728v1.full.pdf
8. Shen, Y., Dong, H., Chen X. 2020. "Airborne transmission of COVID-19: epidemiologic evidence from two outbreak investigations." *Preprint.* April 2020. https://www.researchgate.net/publication/340418430_Airborne_transmission_of_COVID-19_epidemiologic_evidence_from_two_outbreak_investigations.
9. Park, S., Young-Man. K., Yi, S., et al. "Coronavirus disease outbreak in a Korean call center." MMWR 26 (8). Center for Disease Control. 2020. https://wwwnc.cdc.gov/eid/article/26/8/20-1274_article
10. Xu, P., Qian, H., Miao, T. et al. "Transmission routes of COVID-19 virus in the Diamond Princess Cruise Ship." Preprint. https://microbe.net/2020/04/14/covid19-preprint-journal-club-transmission-routes-of-covid-19-virus-in-the-diamond-princess-cruise-ship/
11. Park et al. (2020) Coronavirus disease outbreak in a Korean call center." MMWR 26 (8). Center for Disease Control. https://wwwnc.cdc.gov/eid/article/26/8/20-1274_article

12. Gunther et al. (2020) Investigation of a superspreading event preceding the largest meat processing plant-related SARS-Coronavirus 2 outbreak in Germany. https://poseidon01.ssrn.com/delivery.php?ID=447071097117024119013123115127084122033040063036031057022081083090121127018080118029045114020060007100109066003098006087067127122078037060059118030105090016029084107036079030006121085085126023114108080021118099093076095080009067113092067091003013125115&EXT=pdf&INDEX=TRUE
13. deMan et al. (2020) Outbreak of Coronavirus Disease 2019 (COVID-19) in a Nursing Home Associated with Aerosol Transmission as a Result of Inadequate Ventilation https://academic.oup.com/cid/advance-article/doi/10.1093/cid/ciaa1270/5898577
14. Azimi et al. (2020) Mechanistic Transmission Modeling of COVID-19 on the Diamond Princess Cruise Ship Demonstrates the Importance of Aerosol Transmission. Pre-print. https://www.medrxiv.org/content/10.1101/2020.07.13.20153049v1.full.pdf
15. Light et al. (2020) HVAC and COVID-19: Filling the Knowledge Gaps. ASHRAE Journal Sept. 2020 https://www.building-dynamics.com/s/covid-19-ashrae-journal-published.pdf
16. Taylor. (2020). COVID-19 White Paper. https://taylorengineers.com/taylor-engineering-covid-19-whitepaper
17. Horve et al. (2020). Identification of SARS-CoV-2 RNA in Healthcare Heating, Ventilation, and Air 2 Conditioning Units. Pre-print. https://www.news-medical.net/news/20200630/Identification-of-SARS-CoV-2-RNA-in-healthcare-HVAC-units.aspx
18. Chin et a. (2020) Stability of SARS-CoV-2 in different environmental conditions. Pre-print. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7214863/
19. Schmidt et al. (2020) In situ evaluation of a persistent disinfectant provides continuous decontamination within the clinical environment. https://www.ajicjournal.org/action/showPdf?pii=S0196-6553%2819%2930101-4
20. Kwon et al (2020) "Evidence of long-distance droplet transmission of SARS-CoV-2 by direct air flow in a restaurant in Korea." Korean Med. Nov 30:35(46). https://pubmed.ncbi.nlm.nih.gov/33258335/
21. SAGE. (2020) Role of ventilation in controlling SARS-CoV-2 transmission. UK Scientific Advisory Group for Emergencies. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/928720/S0789_EMG_Role_of_Ventilation_in_Controlling_SARS-CoV-2_Transmission.pdf
22. Shen et al. (2020) Community Outbreak Investigation of SARS-CoV-2 Transmission Among Bus Riders in Eastern China. *JAMA Intern Med*. 2020;180(12):1665-1671. https://www.researchgate.net/publication/344062680_Community_Outbreak_Investigation_of_SARS-CoV-2_Transmission_among_Bus_Riders_in_Eastern_China
23. Wang et al. (2020) Reduction of secondary transmission of SARS-CoV-2 in households by face mask use, disinfection, and social distancing: a cohort study in Beijing, ChinaBMJ Glob Health. 2020; 5(5): e002794. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7264640/pdf/bmjgh-2020-002794.pdf
24. Hammer et al. (2020) High SARS-CoV-2 attack rate following exposure at a choir practice- Skagit County, Washington Morb. Mort. Weekly 2020:69:606. https://www.cdc.gov/mmwr/volumes/69/wr/mm6919e6.htm
25. Azimi et al. (2020) Mechanistic Transmission Modeling of COVID-19 on the Diamond Princess Cruise Ship Demonstrates the Importance of Aerosol Transmission. Pre-print. https://www.medrxiv.org/content/10.1101/2020.07.13.20153049v1.full.pdf+html
26. CDC (2020) Scientific Brief: SARS-CoV-2 and Potential Airborne Transmission https://www.cdc.gov/coronavirus/2019-ncov/more/scientific-brief-sars-cov-2.html
27. Juni et al. (2020) CMAJ Impact of climate and public health interventions on the COVID-19 pandemic: a prospective cohort study https://www.cmaj.ca/content/192/21/E566.long
28. Bae et al. (2020) Epidemiological Characteristics of COVID-19 Outbreak at Fitness Centers in Cheonan, Korea J Korean Med Sci. 2020 Aug 10; 35(31): e288. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7416003/pdf/jkms-35-e288.pdf
29. Zhang et al. (2020) Identifying airborne transmission as the dominant route for the spread of COVID-19 2020 Proc Natl Acad Sci Jun 30;117(26):14857-14863. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7334447/
30. Jones, R. (2020) Relative contributions of transmission routes for COVID-19 among healthcare personnel providing patient care J Occup Environ Hyg 2020 Sep;17(9):408-415. https://www.tandfonline.com/doi/pdf/10.1080/15459624.2020.1784427
31. Buononaet al. (2020) Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications. Environ Int. 2020 Dec; 145. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7474922/
32. Letizia et al. (2020) SARS-CoV-2 Transmission among Marine Recruits during Quarantine N Engl J Med 2020; 383:2407-2416. https://www.nejm.org/doi/10.1056/NEJMoa2029717?url_ver=Z39.88-2003&rfr_id=ori:rid:crossref.org&rfr_dat=cr_pub%20%20pubmed
33. Nissen et al. (2020). Long-distance airborne dispersal of SARS-CoV-2 in COVID-19 wards. https://www.cdc.gov/library/covid19/112420_covidupdate.html
34. Mouchtouri et al. (2020) Environmental contamination of SARS-CoV-2 on surfaces, air-conditioner, and ventilation systems Int J Hyg Environ Health. 2020 Sep; 230: 113599. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7425762/
35. Maestre et al. (2020) Distribution of SARS-CoV-2 RNA Signal in a Home with COVID-19 Positive Occupants. Pre-print. https://www.medrxiv.org/content/10.1101/2020.11.30.20234393v1.full.pdf+html

36. Tang et al. (2020) Transport of indoor aerosols to hidden interior spaces Aerosol Science and Technology Volume 54, 2020 - Issue 1 https://www.tandfonline.com/doi/abs/10.1080/02786826.2019.1677854?journalCode=uast20
37. Riddell et al. (2020) The effect of temperature on persistence of SARS-CoV-2 on common surfaces. Virol J 2020 Oct 7;17(1):145. https://pubmed.ncbi.nlm.nih.gov/33028356/
38. Cai et al. (2020) Indirect Virus Transmission in Cluster of COVID-19 Cases, Wenzhou, China, 2020 Emerg Infect Dis. 2020 Jun;26(6):1343-1345. https://pubmed.ncbi.nlm.nih.gov/32163030/
39. Briek et al. (2020) Possible indirect transmission of COVID-19 at a squash court, Slovenia, March 2020: case report Epidemiol Infect. 2020; 148: e120. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7327185/
40. Hung, S. (2020) PMID: 12893851 The SARS epidemic in Hong Kong: what lessons have we learned? J R Soc Med. 2003 Aug; 96(8): 374–3 https://www.ncbi.nlm.nih.gov/pmc/articles/PMC539564/
41. Elsamadony et al. (2020) Possible transmission of viruses from contaminated human feces and sewage: Implications for SARS-CoV-2 Sci Total Environ. 2021 Feb 10; 755: 142575. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7522648/
42. OCLC and Institute of Museum and Library Services (2020) "REALM Project (Natural attenuation of SARS-CoV-2)" https://www.oclc.org/realm/research.html
43. Lednicky et. (2020). Isolation of SARS-CoV-2 from the air in a car driven by a COVID patient with mild illness. Pre-print. https://www.medrxiv.org/content/10.1101/2021.01.12.21249603v1.full.pdf
44. Houk (1980) Spread of Tuberculosis via recirculated air in a naval vessel: the Byrd study. Annals of the NY Academy of Science. 353:1:10-24. https://nyaspubs.onlinelibrary.wiley.com/doi/abs/10.1111/j.1749-6632.1980.tb18901.x?sid=nlm%3Apubmed
45. Ehrenkranz and Kicklighter. (1972) Tuberculosis outbreak in a general hospital: evidence for airborne spread Ann Intern Med Sep;77(3):377-82. https://pubmed.ncbi.nlm.nih.gov/5053729/https://pubmed.ncbi.nlm.nih.gov/5053729/
46. Haley et al. (1989) Tuberculosis epidemic among hospital personnel. Infection Control & Hospital Epidemiology. 10:5.https://utsouthwestern.pure.elsevier.com/en/publications/tuberculosis-epidemic-among-hospital-personnel
47. Chu et al. (2020) Physical distancing, face masks, and eye protection to prevent person-to-person transmission of SARS-CoV-2 and COVID-19: a systematic review and meta-analysis. Lancet 2020: 395: 1973. https://www.thelancet.com/pdfs/journals/lancet/PIIS0140-6736(20)31142-9.pdf
48. Dbouk and Drikakis. (2021) On airborne virus transmission in elevators and confined spaces Physics of Fluids. 33 https://aip.scitation.org/doi/10.1063/5.0038180
49. Bluyssen et al. (2021) The effect of a mobile HEPA filter system on 'infectious' aerosols, sound, and air velocity in the SenseLab. Building and Environment:15:107475.https://reader.elsevier.com/reader/sd/pii/S0360132320308428?token=1D7F0526782A81E0E3B94E72521D095C0CBCB47E8FDFAB0A749BF59AA155A90E1D5B880D01EEC80E8F8F4C527278A8F0
50. Curtius et al. (2020) Testing mobile air purifiers in a school classroom: Reducing the airborne transmission risk for SARS-CoV-2. Pre-print. https://www.medrxiv.org/content/10.1101/2020.10.02.20205633v2.full.pdf
51. Tang et el. (2021) Dismantling myths on the airborne transmission of severe acute respiratory syndrome coronavirus (SARS-CoV-2). J. Hosp. Infect. 2021 Jan 13 J Hosp Infect. https://pubmed.ncbi.nlm.nih.gov/33453351/#affiliation-1
52. McCarthy and Coghlan. (2021) Preparing HVAC systems before reoccupying a building. ASHRAE Journal. January 2021. https://www.ashrae.org/file%20library/technical%20resources/ashrae%20journal/2021journaldocuments/january2021_022-027_mccarthy.pdf
53. Munoz-Price et al. (2021) Air contamination of households versus hospital infection rooms occupied by SARS-CoV-2 positive patients. Infection Control and Hos[ital Epidemiology. Feb. 27, 2021. https://www.cambridge.org/core/services/aop-cambridge-core/content/view/C115FE32E38C948122266D300B3CEFC4/S0899823X21000453a.pdf/div-class-title-air-contamination-of-households-versus-hospital-inpatient-rooms-occupied-by-sars-cov-2-positive-patients-div.pdf
54. Zeng et al. (2021) Evaluating a commercially available in-duct bipolar ionization device for pollutant removal and potential byproduct formation. Building and Environment. Online March 7, 2021. https://www.sciencedirect.com/science/article/pii/S036013232100158X
55. Bartzokas et al. (2021) Why opening windows is a key to reopening schools. NY Times Feb. 26, 2021. https://www.nytimes.com/interactive/2021/02/26/science/reopen-schools-safety-ventilation.html
56. Hwang et al. (2020) Possible Aerosol Transmission of COVID-19 associated with an outbreak in an apartment in Seoul, Korea. Int J Infect Disease. Dec. 17, 2020. https://pubmed.ncbi.nlm.nih.gov/33346125/