# Research Report

# Healthy Buildings & the COVID-19 Pandemic: *Building Science for HVAC Systems and Building Envelope Best Practices*

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of the American Chemistry Council

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## Introduction

During periods of crisis such as the current COVID-19 pandemic (caused by the SARS CoV-2 virus), efforts to minimize public health consequences necessarily turn to interventions (see Figure 1) that can be quickly implemented to help "slow the spread."[1] These interventions include disinfecting surfaces, washing hands frequently, social distancing, quarantining of infected individuals, protecting vulnerable individuals, and use of personal protective equipment (PPE) such as face masks. We have been here before. These types of actions are not new and were, for example, implemented during the deadly Spanish flu pandemic of 1918 over 100 years ago (see Figure 2).

The purpose of this report, however, is to look beyond the remedial interventions that are necessary in crisis but usually relaxed and then completely forgotten after the crisis fades away (except in health care settings). In this report, we will consider interventions that may be more enduring, proactive, and pre-emptive. During periods of crises, they can supplement the interventions mentioned above. At all other times they can provide more "routine" health benefits that are more convenient and less dependent on maintaining social awareness and compliance. These interventions relate to controlling the environment where we spend most of our lives: indoors.

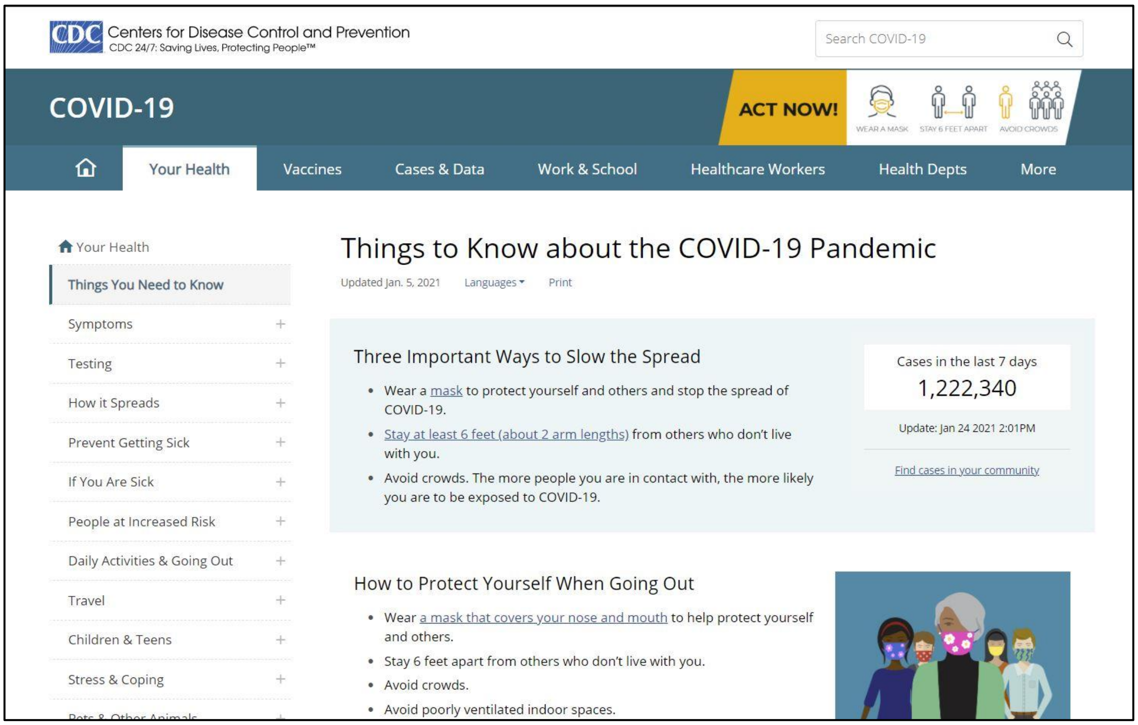


**Figure 1.** Interventions employed to slow the spread of COVID-19.

[1] https://www.cdc.gov/coronavirus/2019-ncov/your-health/need-to-know.html


**Figure 2.** Red Cross volunteers assembling flu masks and a Rochester Department of Health poster in response to the 1918 Spanish flu pandemic.
(Source: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2862330/)

A healthy indoor environment has a known role as a means to control health *hazards* caused by occupant *exposure* to various pathogens (bacteria, mold, viruses, etc.) and allergens. For example, as many as 44 pathogens with potential for airborne disease transmission in buildings are listed in Table 4 of ASHRAE *Handbook of Fundamentals*.[2] Pathogens can infect anyone; allergens are more selective in that they invoke an allergic response by individuals with specific allergies. Both are harmful to human health. A healthy indoor environment also can help reduce human *vulnerability* to infection by airborne pathogens. Because *risk* is a combination of hazard, exposure (or dose), and vulnerability, it is important to consider these risk factors in controlling the indoor environment of buildings as a means of disease intervention. These same actions also can help improve human health and productivity, or "well-being" in a more general sense.

[2] *Handbook of Fundamentals*, ASHRAE, Atlanta, GA, 2017, p10.10, https://www.ashrae.org/technical-resources/ashrae-handbook

## The Science Behind Healthy Buildings

The role of a healthy indoor environment in controlling the risk of illness and disease transmission is not new knowledge. It is rooted in cumulative and multi-disciplined research spanning more than a century. Let's follow the science and see where it leads…

First, let's start with *sociology* – the study of human society. As shown in Figure 3, people spend about 87% of their time indoors. This data implies that the vast majority of person-to-person transmission of respiratory viruses happens indoors.[3] Over a 70-year lifespan in developed regions, the indoor air in homes, schools, offices, shops, and other buildings account for about two-thirds of the total lifetime exposure.[4] Consequently, it stands to reason that the quality of and exposure to indoor environments have a significant role to play in human health. In fact, from a database of more than 2,000 COVID-19 superspreader events (SSEs) around the world, nearly all occurred in indoor spaces and the vast majority in conditions where people were confined for a long period of time.[5] Furthermore, the great majority of SSEs occurred during the flu season.

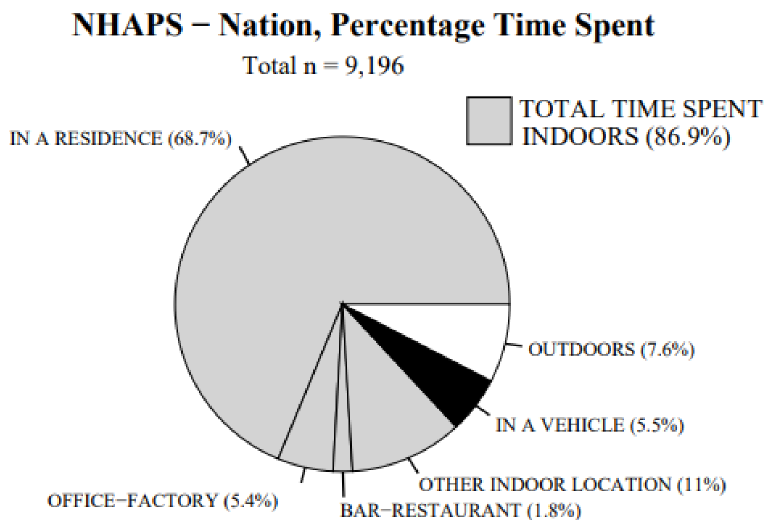


**Figure 3**. Survey of time spent in various locations.
(Source: https://indoor.lbl.gov/sites/all/files/lbnl-47713.pdf)

Awareness is a key social science factor in affecting change or responsiveness. As one might expect, the present COVID-19 crisis has served to heighten awareness of and interest in the healthiness of indoor environments. Several recent examples from a variety of sources include:

- "Your Building Can Make You Sick or Keep You Well" [6]
- "Whole Building Design Guide, Industry News: COVID-19 Updates" [7]
- "Using HVAC Design to Control Viruses and Bacteria in Buildings" [8]
- "Indoor Humidity Regulations will Reduce Burden of COVID-19" [9]

Next, let's consider the broad science of *biology* – the study of life and living organisms. Humans consume a considerable amount of oxygen from indoor air while releasing carbon dioxide and water vapor into the indoor air. Thus, at a bare minimum, buildings must be sufficiently ventilated with outdoor air to support life. Fortunately, typical buildings for human occupancy and various codes and standards require compliance with minimum ventilation requirements (though this is not always the case depending on the history of a given building). However, as addressed in greater detail below, there is

[3] https://www.annualreviews.org/doi/pdf/10.1146/annurev-virology-012420-022445
[4] *Handbook of Fundamentals*, ASHRAE, Atlanta, GA, 2017, p10.1, https://www.ashrae.org/technical-resources/ashrae-handbook
[5] Swinkels, K., SARS-CoV-2 Superspreading Events Database, https://kmswinkels.medium.com/covid-19-superspreading-events-database-4c0a7aa2342b (updated November 21, 2020)
[6] https://www.nytimes.com/2020/03/04/opinion/coronavirus-buildings.html
[7] https://www.wbdg.org/industry-news
[8] https://www.ny-engineers.com/blog/using-hvac-design-to-control-bacteria-and-viruses
[9] https://www.pbctoday.co.uk/news/building-control-news/indoor-humidity-covid-19/74747/

much more to achieving "healthy" indoor air quality for human life than simply maintaining a safe range of oxygen and carbon dioxide levels and meeting minimum code ventilation requirements.

Pathogens including viruses like the common cold, the flu, or SARS CoV-2 enter and become a part of a building's indoor environment through infected people. They require a host to be able to replicate and propagate whereas bacteria and molds can live and grow in buildings or within building systems when conditions are conducive. Viruses are "shed" to the indoor environment from infected individuals through talking, coughing, touching building surfaces, and particles of feces or urine aerosolized by flushing. These mechanisms for disease transfer have many uncertainties and variations in risk based on the type of pathogen, the vulnerability of the individual, the dose, exposure time, and indoor air quality that may serve to increase or decrease the risk of disease transfer. It is clear that much disease transfer in buildings occurs through breathing air with infectious aerosols (tiny airborne particles) or touching surfaces with infectious droplets. In these cases, the pathogen is exposed to the building's indoor environment for a period of time. This gives an opportunity to intervene by controlling a building's indoor environment to favor human health while disfavoring the viability of various pathogens.

In general, air temperature and humidity conditions tend to affect virulence and stability or survivability of various pathogens when they are exposed to the environment. Interestingly (and fortunately), indoor environmental conditions for temperature and humidity that tend to be optimal for human health and comfort also tend to be less than optimal for many types of pathogens. Viruses tend to persist in colder and dryer conditions and tend to become inactivated more quickly at higher temperatures within a so-called "sweet spot" for relative humidity in the 40% to 60% range.[10,11,12,13,14] This "sweet spot" is a slightly narrowed range from the "healthy zone" of 30% to 60% indoor relative humidity as shown in Figure 4. In Figure 4, the thickness of the red marker is a relative indication of health risk for each biological hazard. Also, it is important to note that the original research[15] supporting Figure 4 indicated a "Healthy Zone" of 40% to 60% indoor relative humidity, which is consistent with more recent research showing the importance of indoor relative humidity to a variety of human health concerns.[16]


**Figure 4.** The Health Window for Indoor Relative Humidity
(Source: https://www.eeba.org/the-health-window)

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[10] ASHRAE Position Document on Infectious Aerosols, Section 3.3, April 14, 2020, https://www.ashrae.org/file%20library/about/position%20documents/pd_infectiousaerosols_2020.pdf
[11] *Handbook of HVAC Applications*, ASHRAE, 2019, https://www.ashrae.org/technical-resources/ashrae-handbook
[12] https://www.pbctoday.co.uk/news/building-control-news/indoor-humidity-covid-19/74747/
[13] https://www.dhs.gov/sites/default/files/publications/mql_sars-cov-2_-_cleared_for_public_release_20200602.pdf
[14] Moriyama, M. Hugentobler, W., Iwasaki, A. (March 16, 2020). Seasonality of Respiratory Viral Infections. *Annual Review of Virology*. https://www.annualreviews.org/doi/pdf/10.1146/annurev-virology-012420-022445
[15] Arundel, A.V., Sterling, E.M., Biggin, J.H., and Sterling, T.D. (1986). Indirect Health Effects of Relative Humidity in Indoor Environments, Environmental and Health Perspectives, Vol 65, pp.351-361, doi:10.1289/ehp.8665351, https://www.ncbi.nlm.nih.gov/pmc/articles/PMC1474709/
[16] Taylor, S.H., Scofield, C.M., and Graef, P.T., Improving IEQ to Reduce Transmission of Airborne Pathogens in Cold Climates, ASHRAE Journal, September 2020, pp.30-74, www.ashrae.org

The minimum 40% relative humidity limit is intended to avoid overly dry conditions that favor viruses and disfavor normal human respiratory defenses against airborne transmission of viruses as well as resistance to respiratory infection, allergies, and asthma. The maximum 60% relative humidity limit is meant to avoid favorable conditions for mold, bacteria, some types of viruses, and other pathogens that tend to thrive in warm, high-humidity conditions. The sweet spot strives to identify a range of humidity conditions (at normal indoor temperatures) that reduce vulnerability (e.g., improve respiratory viral defenses) and reduce the hazard (e.g., pathogen stability, burden, and dose) thereby reducing risk of disease transmission. Despite this knowledge, most homes and many offices lack the ability to effectively control indoor relative humidity levels.[17] Consequently, it is not uncommon for many buildings to have indoor relative humidity levels below 25% in the winter during the cold and flu season thereby promoting the persistence and spread of these pathogens.[14]

However, each pathogen and even each type of virus is somewhat unique. Consequently, the decay rate or stability of SARS-CoV-2 under various exposure conditions remains uncertain and under investigation. Some early findings from limited study conditions appear to predict moderate sensitivity to temperature and relative humidity.[18] Thus, interventions to “slow the spread” as mentioned at the beginning of this article remain important while the COVID-19 threat remains and research is incomplete.

In addition, it has been known for more than 100 years that sunlight, and particularly ultra-violet (UV) light at an optimal wavelength (~265 nm) and dose, can inactivate viral, bacterial, and fungal organisms making them less able to cause disease.[19] In fact, the use of UV lamps to disinfect indoor air dates back to the late 1800s and was shown to be effective in treating room upper air (to avoid exposure to occupants) in a school building in the 1930s.[19] [20] Students in schoolrooms treated in this manner during a measles outbreak had a much lower rate of airborne infectious disease transmission (e.g., 15% vs. 50%). Use of UV light for this purpose is known as Ultra-Violet Germicidal Irradiation (UVGI).

Finally, let’s turn to the science of *economics* – the study of how society uses its limited resources. Health crises are expensive and the U.S. has obligated several trillion tax dollars in response to the economic consequences of COVID-19 pandemic. Clearly, health care, healthy buildings, and healthy living is not free or guaranteed. Nevertheless, there are significant potential cost-benefits to consider for appropriate actions related to healthy buildings and reduced impact of disease.

For example, the annual occurrence and impact of flu and colds alone is estimated to be valued in the U.S. at $127 billion per year.[14] If healthier building practices resulted in only a 10% decline in the normal occurrence of colds and flus alone, the value of such practices would be $12.7 billion per year! The value determined from a broad assessment of health savings and productivity gains from improved indoor environments has been estimated at $25 to $150 billion per year.[21] Such value could rival the cost-benefits of mitigating impacts of other natural hazards including tornadoes, hurricanes, earthquakes, and flooding. And, it could help save or improve more lives. Consequently, practices to improve the health of indoor environments can justify substantial improvements in new and existing buildings.

One study of existing home “weatherization” program benefits evaluated indoor air quality measures to reduce health impacts of asthma (hospitalization, ER visits, and death). The estimated cost savings approached $600 million over a period of ten years with appropriate retrofits completed on what was assumed to be 200,000 homes of the existing 122,000,000 dwelling units in the U.S.[22] According to the same study, the potential to affect health benefits is much broader (see Figure 5). Home energy, weatherization, and related health improvements to the indoor air quality and living environment are estimated to yield $2.78 for every dollar invested, just considering the non-energy cost saving benefits.[23,24] While more work may be needed to better monetize health benefits as they relate to various potential healthy building intervention measures, it is clear that there is great potential to generate significant health and economic benefits.

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[17] *Handbook of Fundamentals*, ASHRAE, Atlanta, GA, 2017, p25.16, https://www.ashrae.org/technical-resources/ashrae-handbook

[18] U.S. Department of Homeland Security, Science and Technology, Estimated Natural Decay of SARS-CoV-2, https://www.dhs.gov/science-and-technology/sars-calculator

[19] *Handbook of HVAC Applications*, ASHRAE, 2019, p62.1, https://www.ashrae.org/technical-resources/ashrae-handbook

[20] New York Times, “Scientists Consider Indoor Ultraviolet Light to Zap Coronavirus in the Air”, https://www.nytimes.com/2020/05/07/science/ultraviolet-light-coronavirus.html

[21] Harvard School of Public Health, The 9 Foundations of a Healthy Building, 2017, https://9foundations.forhealth.org/

[22] Making Health Count, ACEEE Research Report, May 2020, https://www.aceee.org/research-report/h2001

[23] U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Weatherization Works! (fact sheet), https://www.energy.gov/sites/prod/files/2019/07/f64/WAP-Fact-Sheet-2019.pdf

[24] Oak Ridge National Laboratory, ORNL/TM-2014/345, Health and Household-Related Benefits Attributable to the Weatherization Assistance Program, September 2014, https://nascsp.org/wp-content/uploads/2017/09/ORNL_TM-2014_345.pdf

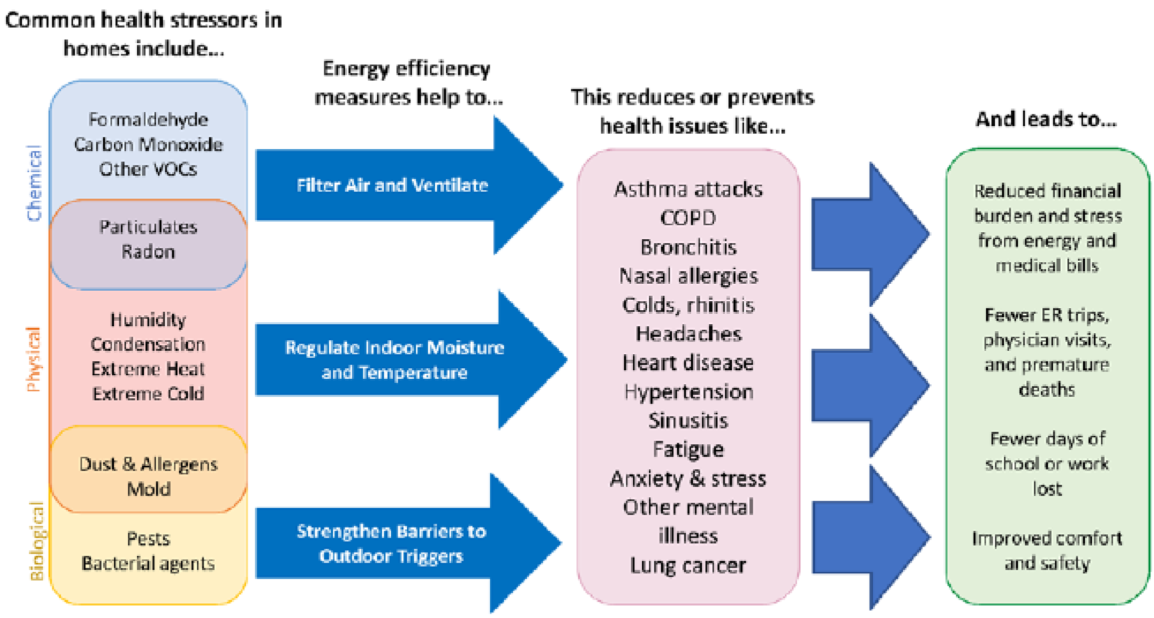


**Figure 5.** Health benefits from combined energy efficiency and health intervention measures for home occupants. (Source: ACEEE[22])

## Applications for a Healthy Building

Based on the above science from sociology, biology, and economics, there is ample reason to consider how this scientific knowledge might be applied as "building science." A healthy indoor environment is not just a Heating, Ventilating, and Air-Conditioning (HVAC) equipment and controls issue.

A healthy indoor environment requires an integrated approach. In order to effectively control indoor environmental conditions (temperature, humidity, and ventilation) at any time of the year and in any climate, while not expending excessive cost and energy doing so, one must have a good building shell or envelope as a foundation so good HVAC design can then do its job effectively and efficiently. Think of the building envelope as the protective skin or PPE of the building and the HVAC system as the internal lymphatic system to maintain internal health and help suppress pathogen propagation and survival within the building's body.

*The Role of HVAC Equipment and Controls*

First, let's consider items that relate to the use of HVAC systems to control the indoor environment. Some of these HVAC actions are straightforward, others require steps beyond current minimum code requirements, and many have interdependencies. These actions can be generally and functionally categorized as providing a means to control:

1. **Indoor temperature**.
2. **Outdoor air ventilation** to help dilute pathogen concentrations when needed.
3. **Indoor air hygiene** through filtration and UVGI treatment to remove or reduce the burden (dose) of various potential pathogens and allergens.
4. **Indoor air relative humidity** through use of adequate dehumidification and/or humidification to promote human respiratory defenses and control pathogen viability.

Minimum building code requirements address indoor air temperature control through required temperature targets (i.e., "set points") and standards for equipment sizing and controls (e.g., thermostat). For example, homes are typically required to have heating equipment capable of maintaining a 68°F indoor temperature during design wintertime outdoor temperature. Air conditioning (cooling) is not necessarily required by code, but when commonly provided is typically required to be designed to achieve a 75°F temperature during the design summertime outdoor condition.

Ventilation is addressed in minimum code requirements, but not necessarily with the ability to adjust outdoor air ventilation rates (as outdoor conditions allow) to higher levels that may be needed to reduce a pathogen burden by dilution during periods of crises or higher risk of disease transmission, particularly at times when building occupancy and activity levels are high for long periods of time (not just minutes). In some applications, such as patient rooms in hospitals, ventilation air-flows must also be controlled so as not to "pollute" the remainder of the building by spreading potential pathogens from a source area to other areas of the building. This same principle could be applied to a bedroom in a home used periodically to quarantine an infected occupant.

While filtration of ventilation air (i.e., outdoor and recirculated indoor air) is generally a requirement for forced air heating and cooling systems (if for no other reason than to protect the equipment from efficiency reductions and operation degradation by dust accumulation), the use of filters that are the most effective at removing microscopic airborne pathogens are generally more restrictive to air flow. Thus, a larger filter surface area may be required to avoid high system pressures that can increase energy use and degrade system operation. Alternatively, a trade-off must be made in filter efficiency. Consequently, filtration for the purpose of a healthy indoor environment is most efficiently addressed when a building's HVAC system and ductwork is initially designed and installed. In addition, filtration must exceed minimum code requirements and typical practice used in most buildings. For buildings without forced air systems or with HVAC systems incapable of operating with restrictive filters, one must turn to portable or self-contained air filtering equipment. Many useful insights and practical recommendations for ventilation and filtration are available to guide decision-making to identify relatively simple, low-cost solutions for homes and similar small buildings with conventional forced-air HVAC systems.[25]

Air treatment by UVGI can also be added within ductwork or located in particularly vulnerable areas of a building (e.g., high occupancy or public access areas) and aimed to disinfect "upper room" air to avoid human UV exposure. This also is not required by code and must be specified by a building owner as an added intervention to suppress airborne disease transmission. While effective, these systems may be most applicable to high-occupancy spaces or where occupant vulnerability is high.

In general, building codes and standards do not require a means to directly control indoor relative humidity levels within the "sweet spot" discussed earlier. Thus, above-code actions may be required such as use of automated dehumidification or humidification systems as part of an HVAC system design. Alternatively, this may be achieved by use of portable units with a means for occupants or building operators to monitor indoor relative humidity levels that can vary seasonally (and even daily or hourly) in response to the outdoor environment, ventilation rates, building use, and "tightness" of the building envelope, etc. Recently, because of growing awareness of the health impacts of damp buildings (especially in relation to use of humid outdoor air for ventilation), the ASHRAE 62.1 standard for commercial building ventilation has added a requirement that the dew point temperature of indoor air be maintained at less than 60ºF, which, for example, corresponds to relative humidity of 50% at 75ºF.[26,27] This criteria is required whether the building is occupied or not. It provides a means to help avoid the consequences of high humidity levels in buildings, but it does not address the concern with the indoor air being too dry as often occurs during the winter heating season, particularly when high levels of ventilation are present (by natural or mechanical means). It also is not required for low-rise residential buildings (like homes), but should be and is applicable there as well.[28]

With above actions in view, the ASHRAE Indoor Air Quality (IAQ) Guide recognizes the following important principle:[29]

> By the time a building's schematic design is complete, many opportunities to achieve good IAQ have been foreclosed, which can easily result in unintended consequences or expensive and inadequate "force fitting" of solutions. When IAQ, energy efficiency, and other project objectives are considered together at the initial design phases, design elements for each objective can be mutually reinforcing rather than at odds with one another.

*The Role of the Building Envelope*

Finally, the ability to control ventilation and air flows within a building and also to control indoor temperature and humidity levels requires good building envelope practices. The building envelope is what "separates" the building's indoor environment from the outdoor environment. Without a good building envelope, the previous HVAC system and design

[25] Bohanon, H. and Zaatari, M., Effect of Ventilation and Filtration on Viral Infection in Residences, ASHRAE Journal, December 2020, www.ashrae.org
[26] Harriman, L., "Damp Buildings, Human Health, and Ventilation Design", ASHRAE Journal, June 2020, www.ashrae.org
[27] ASHRAE 62.1-2019, Ventilation for Acceptable Indoor Air Quality, https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2
[28] Damp Buildings, Human Health, and HVAC Design, Report of ASHRAE Multidisciplinary Task Group: Damp Buildings, 2020, https://www.ashrae.org/technical-resources/free-resources/publications
[29] ASHRAE, Indoor Air Quality Guide, 2009, p.XIII, https://www.ashrae.org/technical-resources/bookstore/indoor-air-quality-guide

actions become more difficult and costly, and uncertain in their effectiveness. So, what are some building envelope actions that provide a foundation for effectively controlling the indoor environment?

1. The building envelope must include **effective rain water control** (e.g., cladding, roofing, water-resistive barrier, and flashings) to prevent intrusion of rainwater, protect the durability of the building, and prevent conditions conducive to pathogens that require a moisture source.
2. The building envelope must include an **effective continuous air control layer** (e.g., air-impermeable materials and sealants) to allow control of indoor air quality for optimal human health and comfort while minimizing energy use and operating cost. This also applies to HVAC ductwork.
3. The envelope must include an **effective continuous thermal control layer** to maintain optimal indoor air temperature for human health, prevent condensation with proper specification and use of insulation materials, and provide comfort while minimizing energy use and operating cost.
4. The envelope must be designed with an **effective water vapor control strategy**, including a coordinated approach to using vapor retarders and insulation, to address indoor-to-outdoor water vapor pressure differentials associated with maintaining optimal indoor relative humidity and temperature conditions for human health and comfort in all climates.

The above "control layers" for a building envelope are illustrated generically in Figure 6 and discussed below. It should be noted that Figure 6 represents one of many possible exterior wall assembly solutions; however, it was chosen to reflect what is conceptually considered to be the "perfect wall" concept whereby all environmental control layers are continuous and on the exterior side of the building envelope assembly.[30,31] This approach is applicable to all climates and provides maximum protection to the structure as well as interior surfaces or finishes. It is also the most tolerant of or amenable to indoor relatively humidity levels being maintained in the "sweet spot" during the winter (i.e., flu and cold season). Other solutions can also achieve adequate performance with proper design (see Resources at the end of this article).

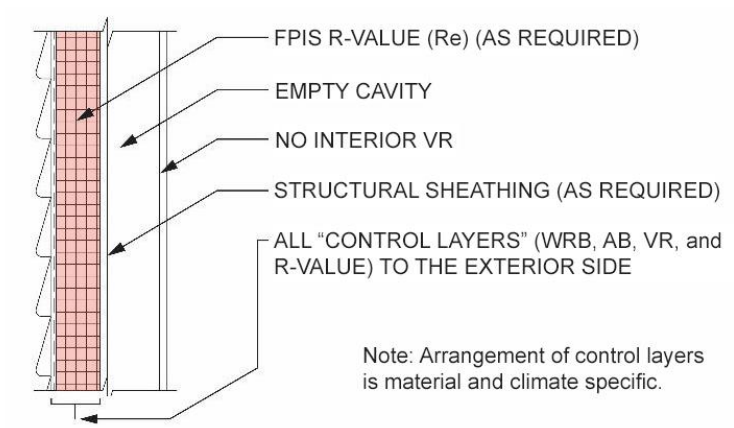


**Figure 6.** Key Control Layers of an Exterior Building Wall Assembly where WRB = water-resistive barrier, AB = air barrier, VR = vapor retarder and R-value = insulation for thermal control. Foam plastic insulating sheathing (FPIS) is shown as an example continuous insulation material that can serve multiple control functions as the WRB, AB, R-value, and VR control layers. (Source*:* ABTG[32])

[30] https://www.buildingscience.com/documents/insights/bsi-001-the-perfect-wall
[31] https://www.continuousinsulation.org/content/creating-perfect-wall-simplifying-water-vapor-retarder-requirements-control-moisture
[32] Assessment of Water Vapor Control Methods for Modern Insulated Light-Frame Wall Assemblies, ABTG Research Report No. 1410-03, 2015, https://www.appliedbuildingtech.com/rr/1410-03

*Rain Water Control* – Rain water leakage is generally addressed in modern building codes and its effectiveness is primarily a matter of enforcement and compliance to ensure all parts of the building envelope intended to resist rain intrusion are properly integrated (e.g., cladding, flashing, water-resistive barrier, and various components). However, in moist, wind-driven rain environments additional measures, such as use of roof overhangs and pressure-equalized or well-drained cladding systems, should be considered for added protection against rainwater intrusion that could lead to building durability and health problems.[33] Maintenance is also very important.

*Air Control Layer* – The building envelope air leakage or air barrier requirements in various code editions may vary substantially. Often they are modified locally to allow greater uncontrolled air leakage and sometimes to avoid verification by “blower door” pressure testing of the whole building.[34] With significant or uncertain amounts of uncontrolled air leakage through the building envelope, it becomes increasingly difficult and energy intensive to design a HVAC system to control the indoor air quality within the temperature and relative humidity “sweet spot” discussed earlier. The indoor air quality will tend to vary more substantially with variation in outdoor weather conditions (e.g., a hot and humid period or a cold and windy period). A leaky building envelope will also make it difficult to control ventilation flows because of uncontrolled air flows into and out of the building. Such air flows through the building envelope also can result in moisture accumulation and subsequent rot, mold, and corrosion hidden within the building envelope assembly. Newer model energy codes (that have not been subject to local weakening amendments) will tend to provide better air leakage control for energy efficiency, human health, and building durability. But, building owners and the reliable design of HVAC systems can benefit significantly from stringent air leakage control with confirmation by testing (which is the only way to really know what the building is doing or going to do and how to design the HVAC system accordingly).

*Thermal Control Layer* – Newer model energy codes (when adopted locally without weakening amendments) have made great progress in energy efficiency by controlling heat loss or gain to the building interior or conditioned space. However, these codes are based on a minimum energy efficiency perspective that only accounts for the market cost of energy vs. cost of insulation over a portion of the life of a building. They do not consider the so-called “hidden costs of energy” related to pollutants and greenhouse gas. [35] Thus, the narrowly-focused economics applied to such model energy codes tend to undervalue or ignore major environmental and health benefits.

Some of the ignored benefits of a well-insulated building envelope include:

- Moderating the temperature of interior surfaces of the building, providing less likelihood of mold growth.
- Providing for a more uniform distribution of indoor temperature and humidity conditions for human comfort and health.
- Minimizing thermal bridging by use of continuous insulation (see Figure 6) to protect the structure from moisture damage or accumulation for improved building durability and occupant health.
- Providing a resilient place of shelter with better ability to maintain human health and comfort in periods of temporary power loss.

Therefore, providing insulation that exceeds minimum energy code requirements should be a consideration, and it will help reduce the cost and environmental impacts of operating a healthy building. However, as discussed next, a well-insulated building must also have an adequate water vapor control strategy for the building envelope (coupled with an HVAC system designed to also control indoor relative humidity).

*Water Vapor Control* – Assuming that air leakage is adequately controlled to allow the HVAC system to be designed to target the “sweet spot” for indoor relative humidity and that the envelope is well-insulated to reduce the size of HVAC equipment and cost of operation, the building envelope must be designed accordingly to handle the water vapor pressure drives that are then induced across it. While an effective water vapor control approach will promote more reliable control of the indoor relative humidity levels by a properly designed HVAC system, it also helps prevent moisture accumulation in the form of condensation on or moisture adsorption within building materials (resulting in potential mold, rot, corrosion, etc.).

[33] Durability by Design – 2nd Edition, U.S. Department of Housing and Urban Development, Office of Policy Development & Research, 2017, https://www.huduser.gov/portal/publications/reports/Guide-Durability-by-Design.html

[34] https://www.continuousinsulation.org/content/blower-door-friend-or-foe

[35] Hidden Costs of Energy – Unpriced Consequences of Energy Production and Use, National Research Council of the National Academies, 2010, https://www.ourenergypolicy.org/wp-content/uploads/2012/06/hidden.pdf

Provided basic minimum building code vapor retarder requirements are satisfied, water vapor control is generally not a problem in warmer or mild climates (with appropriately designed air conditioning having sufficient dehumidification capability). Where this becomes a problem is the colder climates (e.g., the northern half of the United States or Climate Zones 4 and higher). In these climates, the building code vapor retarder provisions generally rely on an assumption of a low (<40 percent) indoor relative humidity in the winter. However, for a healthy building, dry indoor conditions (<40 percent relative humidity) in the winter can result in greater viral stability and weakened human respiratory defenses as discussed earlier. So, to protect the building envelope from experiencing moisture problems in a healthy building, a better-than-minimum-code method for handling outward vapor drives during the winter, such as featured in Figure 6, should be considered using concepts illustrated and referenced in Figure 7. For additional information on design of building envelopes to address water vapor control, refer to the resources provided at the end of this article, particularly Model Moisture Control Guidelines.[36]

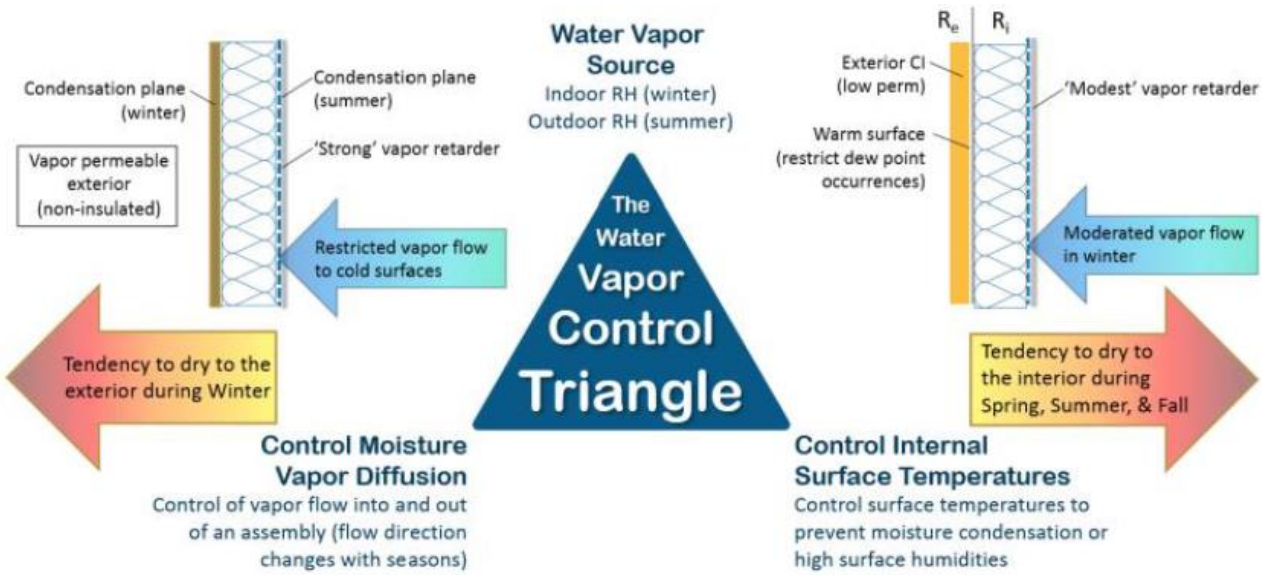


**Figure 7.** Illustration of two accepted water vapor control design approaches for building envelopes. (Sources: ABTG[32], ASTM[37])

[36] Model Moisture Control Guidelines for Light-Frame Walls, ABTG Research Report No. 1701-01, 2017, https://www.appliedbuildingtech.com/rr/1701-01

[37] J. H. Crandell, "Assessment of Hygrothermal Performance and Design Guidance for Modern Light-Frame Wall Assemblies," in *Advances in Hygrothermal Performance of Building Envelopes: Materials, Systems and Simulations*, ed. P. Mukhopadhyaya and D. Fisler (West Conshohocken, PA: ASTM International, 2017), 362-394. https://doi.org/10.1520/STP159920160097

## Conclusion

For the past 100 years, science has been building a case and leading us to better understand the importance of the indoor environment for human health. It has better defined appropriate target conditions for the indoor environment (e.g., temperature, humidity, and air quality) for optimal human health, comfort, and productivity. Furthermore, these advancements in science have pointed to various "building science" opportunities to design and construct building systems to better control optimal indoor conditions for a healthy indoor living environment. This topic has been taken more seriously for health care facilities (for obvious reasons) than other buildings such as homes, offices, shops, schools, restaurants, and other enclosed spaces where people may be more routinely exposed to risk of disease transmission. COVID-19 is not the only reason to consider applying this "healthy building" knowledge to a broader array of buildings, but perhaps it is the crisis that will finally cause appropriate action to be more broadly considered, accepted, and implemented.

This report is written as an "open file" document to allow updating and improvement as new information becomes available. Certainly, there is more expected from future research and implementation activities. For example, ASHRAE has updated position documents aimed at summarizing current knowledge, various practice recommendations, and research needs related to airborne disease transmission.[38,39] ASHRAE has also formed an Epidemic Task Force to take on short-term and long-term threats of COVID-19 in buildings with a view toward improving healthy building environments.[40] In addition, the Department of Energy's Lawrence Berkeley National Laboratory has launched a study of the risk of airborne transmission of viruses within buildings and how to mitigate those risks.[41] Furthermore, the Department of Homeland Security's Science and Technology Division has a master question list to guide research on COVID-19 and document progress.[42]

Hopefully, if there is one good thing that comes from COVID-19, it will be that we gain a greater appreciation for "building science" and the ability to create better and healthier buildings.

[38] ASHRAE Position Document on Airborne Infectious Diseases, February 5, 2020, https://www.ashrae.org/file%20library/about/position%20documents/airborne-infectious-diseases.pdf
[39] ASHRAE Position Document on Infectious Aerosols, April 14, 2020, https://www.ashrae.org/file%20library/about/position%20documents/pd_infectiousaerosols_2020.pdf
[40] https://livingbuilding.kendedafund.org/2020/04/03/william-bahnfleth-ashrae-panel-covid-19-threats-in-buildings/
[41] https://newscenter.lbl.gov/2020/05/13/new-research-launched-on-airborne-virus-transmission-in-buildings/
[42] https://www.dhs.gov/sites/default/files/publications/mql_sars-cov-2_-_cleared_for_public_release_20200602.pdf

## Resources

For information and guidance on best practices for HVAC and building envelope design to achieve a healthy and resilient building, refer to the following sample of resources:

- ASHRAE Indoor Air Quality Guide, 2009, https://iaq.ashrae.org/
- ASHRAE Damp Buildings, Human Health, and HVAC Design, 2020, https://www.ashrae.org/technical-resources/free-resources/publications
- ASHRAE *Handbook of Fundamentals*, 2017, https://www.ashrae.org/technical-resources/ashrae-handbook
- ASHRAE *Handbook of HVAC Applications*, 2019, https://www.ashrae.org/technical-resources/ashrae-handbook
- ASHRAE Position Document on Infectious Aerosols, April 14, 2020, https://www.ashrae.org/file%20library/about/position%20documents/pd_infectiousaerosols_2020.pdf
- ASHRAE Position Document on Airborne Infectious Diseases, February 5, 2020, https://www.ashrae.org/file%20library/about/position%20documents/airborne-infectious-diseases.pdf
- Harvard School of Public Health, The 9 Foundations of a Healthy Building, 2017, https://9foundations.forhealth.org/
- Whole Building Design Guide, https://www.wbdg.org/resources/indoor-air-quality-and-mold-prevention-building-envelope
- WHO Guidelines for Indoor Air Quality: Dampness and Mould, 2009, https://www.who.int/airpollution/guidelines/dampness-mould/en/
- EPA, Moisture Control Guidance for Building Design, Construction and Maintenance, 2013, https://ehs.uky.edu/docs/pdf/ohs_epa_moisture_control_guidance.pdf
- U.S. DOE, Better Buildings, Presentation and Seminar, “Managing HVAC Systems to Reduce Infectious Disease Transmission”, May 4, 2020, https://betterbuildingssolutioncenter.energy.gov/webinars/managing-hvac-systems-reduce-infectious-disease-transmission
- Bohanon, H. and Zaatari, M., Effect of Ventilation and Filtration on Viral Infection in Residences, ASHRAE Journal, December 2020, www.ashrae.org
- Taylor Engineering, COVID-19 White Paper, October 13, 2020, https://taylorengineers.com/taylor-engineering-covid-19-whitepaper
- Durability by Design – 2nd Edition, U.S. Department of Housing and Urban Development, Office of Policy Development & Research, 2017, https://www.huduser.gov/portal/publications/reports/Guide-Durability-by-Design.html
- ABTG Research Report No. 1701-01, Model Moisture Control Guidelines for Light-Frame Walls, 2017, https://www.appliedbuildingtech.com/rr/1701-01

For additional resources, design tools, and best practices to support building envelope design and construction for healthy buildings, refer to www.continuousinsulation.org including specifically:

- Thermal Insulation - https://www.continuousinsulation.org/thermal-insulation
- Water-Resistive Barrier - https://www.continuousinsulation.org/topical-library/water-resistive-barrier
- Water Vapor Control - https://www.continuousinsulation.org/topical-library/water-vapor-control
- Air Barrier - https://www.continuousinsulation.org/air-barrier
- Wall Calculators for Thermal and Vapor Control - https://www.continuousinsulation.org/calculators