School District IAQ Study

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Executive Summary

The following is a summary of this report's findings and recommendation.

Monitoring Results

- All classrooms had IAQ (carbon dioxide and VOC concentrations) levels commonly found in today's buildings
    - Today's building standards (ASHRAE62.1) based on odor are now known to increase airborne disease transmission, increase indoor air quality dissatisfaction, increase sick days, and reduce cognition performance
    - Healthy buildings require doubling today's fresh air ventilation (40cfm per person or 800ppm carbon dioxide concentration) and enhanced air filtration (recirculation through MERV13 or better filters)
- VOC (Volatile Organic Compounds) levels from disinfectants and cleaning products used after school decayed to background levels by the following morning
- No classrooms maintained 800 ppm carbon dioxide concentration during school hours
    - One high school classroom maintained 1000ppm CO2 while another averaged 2000ppm CO2 during school hours
        - Re-balancing the high school's central HVAC might reduce CO2 levels in classrooms with elevated concentrations
    - Two junior high classrooms and one elementary school classroom in older buildings without central HVAC systems had fluctuating carbon dioxide concentration levels characteristic of "natural" ventilation (ie, window openings)
        - High carbon dioxide concentrations (2000ppm) are expected more regularly as colder weather reduces window openings

Near-term Considerations

- Acquire a few (one per school) carbon dioxide monitors ($200 to $300 each) with +/-30ppm carbon dioxide concentration accuracy.
    - Use monitors to survey classroom IAQ at different times of day, especially near the end of the school day, to determine classroom carbon dioxide levels
- Adjust available fresh air dampers and duct balancing dampers to decrease classroom carbon dioxide to 800ppm, or as low as possible with current ventilation systems
- Consider acquiring room air filtration units with MERV13, 16 or HEPA filers
    - Two units with 250 to 300 CADR (Clean Air Delivery Rate in cfm) for a class of 20 will reduce aerosol concentrations in classrooms, reducing airborne disease transmission and improving air quality for room occupants with respiratory sensitivities (asthma, allergies)
    - Quiet filtrations units (at high speed) are essential. Noisy units are annoying and will be turned off
    - Investigate replacement filter cost for units. Filters should last 3 months. MERV13 filters for 250 to 300 CADR should cost $10 per filter or less. Many room air filters have expensive replacement filters (more than $50 per filter)

- Investigate “upper room” UVGI (Ultraviolet Germicidal Irradiation) systems. Lamps require replacement approximately once per year.
- Avoid as yet unproven air cleaning technologies such as air “ionization” units. Research is underway to assess effectiveness, with some studies showing an increase of room air pollutants due to ionization

Long-term Considerations

- Install fresh air ventilation and air recirculation system capable of maintaining 800ppm carbon dioxide concentration for 20 to 30 people in each classroom and indoor gathering spaces (cafeterias, meeting rooms, library, etc)
- Modernize comfort conditioning systems for buildings without central HVAC systems
    - Today’s low temperature heat pumps (aka, “minisplit” heat pumps) have very high efficiency ratings (HSPF=10 and SEER=20)
    - Modernize HVAC in all buildings should provide facility and administration personnel with online monitoring, control, scheduling (eg, filter replacement) and diagnostic information
    - Classroom HVAC systems should be able to operate without internet/WiFi connectivity
        - Internet/WiFi connectivity allows convenient management of control settings, status checks, data archiving, and status alerts (eg, high pollutant or humidity levels, cold temperatures, window/door opening status, occupancy, etc)
    - A “distributed” classroom IAQ and comfort conditioning system example is estimated to cost $40,000 per classroom ($50 per sqft)
        - Distributed systems provide each classroom and indoor space with independent control, redundancy, and energy efficient capacity management
        - Distributed classroom IAQ and comfort conditioning systems can be implemented on a rolling installation basis that does not require entire school shutdown or disruption
        - Estimated annual utility cost per classroom is $820 per year
            - 20% of the year (school hours) has high occupancy
            - 80% of the year (after school hours, weekends, summer) has low occupancy

Acknowledgements

The author appreciates the interest and efforts of school district staff to facilitate this study. The author hopes this report provides a road map for schools throughout North America to create healthy, productive learning environments for their children.

Forward

Schools are the foundation of a sustainable future. Our teachers pass knowledge to our children so they can learn from our past to create their future. Healthy learning environments are essential for maximizing our children's learning potentials. Much has been learned in recent years about imperceptible but real effects indoor environments on our cognition and well-being. With today's technologies, we can create excellent indoor learning environments in energy efficient manners.

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Introduction

Indoor air quality (IAQ) data and comfort data (temperature and relative humidity) were collected from September 2 through September 9, 2021 in School District. Classrooms were monitored in the High School (Figure 1), Junior High School (Figure 2) and Elementary School (Figure 3).

Figures 4, 5, and 6 show combined data for carbon dioxide concentration, total VOCs (Volatile Organic Compounds), temperature and relative humidity for the entire test period. Analysis of IAQ data provides information on fresh air flow rates in each classroom, and impacts of IAQ on sickdays, cognition performance, and IAQ dissatisfaction.

All of the classrooms have indoor air quality that are commonly found in school classrooms, homes, restaurants, churches and other public gathering places. None of the classrooms are at air quality levels that would cause significant odors, however, all classrooms would benefit from increased fresh air ventilation and air filtration. Cost saving benefits of improved IAQ (reduced sick days, improved cognition performance) are greater than capital and utility costs for improved IAQ and comfort conditioning.

Figure 7 shows how air quality dissatisfaction and carbon dioxide concentration are related to fresh air ventilation. As carbon dioxide reaches 2000ppm concentration, general populace dissatisfaction with air quality increases to 30 to 35%. Quantitative research results from Harvard's TH Chan School of Public Health demonstrates the impact of carbon dioxide and airborne particulates on cognition (1). Additionally, improved air quality will reduce absences and have been shown to improve student test performance (2,3).

The following sections discuss:

1) Carbon dioxide measurements and fresh air ventilation flow rate
2) VOC measurements and impact of chemical disinfectants on classroom air quality
3) Estimated impact of increased fresh air ventilation and air filtration on sick days, cognition performance, Covid transmission, and IAQ dissatisfaction
4) Cost (capital and operating) estimates for enhanced classroom IAQ and comfort
5) Other factors related to improved IAQ and comfort conditioning (maintenance, safety and security)

References

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2) Mark J. Mendell, Ekaterina A. Eliseeva, Molly M. Davies, Michael Spears, Agnes Lobscheid, William J. Fisk, and Michael G. Apte, "Association of Classroom Ventilation with Reduced Illness Absence: A Prospective Study in California Elementary Schools", Lawrence Berkeley National Laboratory, LBNL-6259E, May 2013
3) Improving Ventilation and Indoor Environmental Quality in California K-12 Schools, California Energy Commission report, CEC-500-2020-049, July 2020

Classroom Carbon Dioxide and Ventilation Rates

Carbon dioxide concentration plots for each school day (September 2, 3, 7 and 8, 2021; September 6 was Labor Day) during the monitoring period are included in Appendix A (High School), Appendix B (Junior High School) and Appendix C (Elementary School). Carbon dioxide is important for multiple reasons:

1) Carbon dioxide directly impacts cognition performance and sleep quality
2) Carbon dioxide acts as a "tracer" for other indoor air quality factors including chemical concentrations (VOCs from human metabolism and from non-human chemical sources), and microbial concentrations (molds, bacteria, virus and endotoxins)
3) Carbon dioxide concentration is an indicator of particulate concentrations (10micron, 2.5micron, and submicron particulates) that impact health in multiple manners
4) Analysis of carbon dioxide concentration variations indicates fresh air flow rates

We note that high fresh air flow through a room does not mean room air is healthy. The source of "fresh air" is very important. Air that is filtered (MERV13 filter or better) and comes from a known clean air source (eg, fresh air inlet for a ventilation system) should be healthy air assuming outdoor air is not polluted. Infiltrated air (air flowing through construction flaws and cracks, flue vents, unsealed drains, utility chases, elevator shafts, crawl spaces, garages, attics, etc) is generally not healthy air as it flows through the same moldy, mildewy passageways as vermin. In addition, infiltrated air is unfiltered air and can introduce significant amounts of outdoor particulates (pollens, molds, dust, etc).

High School Carbon Dioxide and Fresh Air Flow:

The High School is a modern school with central air ventilation for heating and cooling. Two classrooms were monitored. Figures in Appendix A show daily trends in carbon dioxide concentrations. High School room 114 consistently stayed at 1000ppm carbon dioxide concentration while High School room 139 consistently reached 2000ppm carbon dioxide concentration during active school hours. Table 1 shows the relation between fresh air flow per person and carbon dioxide concentration for sedentary (eg, classroom level activity) metabolism. Higher metabolism, such as an exercise class, requires increased fresh air flow rates while sleeping requires less fresh air.

Dashed lines on daily classroom carbon dioxide plots show estimated Air Changes per Hour (ACH) for each classroom (read the vertical scale on the right of each plot). An "Air Change" is a room's volume, so 1 ACH indicates a room volume of air has flowed through a space in one hour. ACH is often referred to as a metric for ventilation, however it is not a good a good metric because it ignores human occupancy and human activity. For example, airlines often state they have very high ACH (20 ACH), however this is only 8cfm per person (cubic feet per minute) because the volume per person on a commercial aircraft is very low, often resulting in poor air quality on crowded flights.

ACH can be derived from the "decay" of carbon dioxide when no one is present in the rooms (ie, when school is out). Cycling of the building HVAC (Heating, Ventilation and Air Conditioning) system, opening and closing of classroom doors, and placement of the IAQ monitor can impact the data. For both classrooms, a steady carbon dioxide concentration decay begins around 4 to 6pm on each school day. Although carbon dioxide concentrations are very different (1000ppm for HS room 114 and 2000ppm for

HS room 139), carbon dioxide decay data indicates both classrooms have similar 0.2 ACH fresh air ventilation rates during after school hours.

Assuming a classroom size of 800sqft (assuming 30 to 40sqft per student and 150sqft for teacher) with 8ft high ceiling and 0.2ACH indicates a fresh air flow rate of 20 to 25cfm (cubic feet per minute) for both classrooms. A fresh air flow of 20 to 25cfm is too low relative to expected classroom occupancy (10 to 20 students plus teacher). Carbon dioxide concentrations greater than 3000ppm would occur in the classrooms as indicated in Table 1. A change in ventilation scheduling (eg, reduced fresh air during after school hours) may be the reason for the low after school ACH values.

Temperature and humidity plots for room 114 shows HVAC cycling (thermostat setback, and possibly fresh air damper movement) around 6am and 6pm. Room 139 does not show as strong of temperature and humidity variations during transition between school hours and off-school hours, which may be related to lower school hour ventilation air flow rates for room 139 relative to room 114.

Carbon dioxide concentration levels during active classroom hours can be used for determining fresh air flows during school hours. Referring to Table 1, classroom 114 with 1000ppm indicates a fresh air flow of 20 to 25 cfm per person in the classroom, while classroom 139 with 2000ppm indicates a fresh air flow of 10cfm per person. Enrollments for the two classrooms were not examined.

If both classrooms have the same enrollments, then classroom 114 has twice as much fresh air flow as classroom 139. If this is the case, re-balancing air flow may improve room 139 air quality. Ideally, increasing air flow to room 139 and not reducing air flow to room 114 are desired. The simplest method for adjusting each room's fresh air flow is to use a carbon dioxide meter ($200 to $300 cost with +/-30ppm accuracy). Reducing carbon dioxide to 800ppm is a good target for minimizing classroom absences and improving cognition performance.

If room 114 has half as many students as room 139, then both rooms have similar fresh air flows. For example, if room 114 has 10 students with 1000ppm carbon dioxide, per Table 1, ~25cfm per person indicates 250cfm of fresh air flows into room 114. Assuming 25 students in room 139 with 10cfm per person (Table 1) also indicates 250cfm of total fresh air flow.

IAQ monitoring station placement can impact carbon dioxide concentration measurements. If a monitoring station is placed directly under a fresh air vent in room 114, but placed near a return air vent in room 139, concentrations may have different readings even though both rooms have similar student numbers and similar fresh air flow. Classrooms, restaurants, church sanctuaries and other large meeting areas are usually well-mixed with carbon dioxide differences less than 100 to 200ppm between fresh air supply and return air vent locations. A handheld carbon dioxide meter can help determine whether spatial variations of carbon dioxide concentration in each classroom are significant (>100ppm across a room).

Table 1 Relation between fresh air flow per person (cubic feet per minute per person) and carbon dioxide concentration (parts per million). Outdoor ambient carbon dioxide concentration = 400ppm. Today's ventilation standard results in 1200ppm. Ventilation that maintains 800ppm reduces sick days by 40% while improving cognition and productivity relative to today's odor-based standard.

Carbon Dioxide Conc (ppm)	Air Flow (cfm/person)
600	80
800 (improved)	40
1200 (standard)	20
2000	10
3600	5

Junior High School Carbon Dioxide and Fresh Air Flow:

The two junior high classrooms have large fluctuations in carbon dioxide concentrations during school hours. Appendix B shows daily carbon dioxide plots for classrooms 110 and 118. The Junior High school is an older building without central ventilation. During fall conditions, windows are opened for natural ventilation, and closed when room air conditioners are operated or after school hours. Although open windows can reduce carbon dioxide concentration, unfiltered outdoor air contains pollens and airborne particulates that impact staff and students with respiratory sensitivities.

Classroom 118 mostly stays at carbon dioxide concentrations less than 1500ppm, with significant periods less than 1000ppm. A few time periods have carbon dioxide levels well above 2000ppm. Carbon dioxide concentration fluctuations of this nature are characteristic of "natural ventilation" (window and door openings) in which fresh air flows are determined by wind speed, wind direction, building orientation, "wind shading" (eg, trees and shrubs), and window/door opening aperture size.

Classroom 110 has more elevated levels of carbon dioxide than classroom 118. Window openings are a likely reason for differences between the two rooms. Classroom 110's fluctuation of carbon dioxide levels likely due to the uncontrolled nature of "natural" ventilation. For example, wind coming from a specific direction may directly flow toward classroom 118 while classroom 110 may have something obstructing wind flow (building, tree/shrubs, etc).

During after school hours, both classrooms have 0.2 ACH levels similar to the high school. For these classrooms, ACH level is indicative of air infiltration leakage into the rooms. Colder weather may result in window closures and elevated carbon dioxide levels. Some of the daily carbon dioxide concentration plots show very high carbon dioxide levels, which are expected with the low ACH and no active ventilation system. Tuesday and Thursday mornings for classroom 118 have high carbon dioxide concentrations, indicating closed or partially opened windows. Every school day for classroom 110 has periods of high carbon dioxide.

Elementary School Carbon Dioxide and Fresh Air Flow:

Classroom 14 at the Elementary School is a kindergarten. Carbon dioxide plots for each class day for classroom 14 are in Appendix C. The Elementary School has no central ventilation system, similar to the Junior High School. All days have high carbon dioxide concentrations. Carbon dioxide fluctuations for classroom 14 are most probably due to the whole class leaving the room for different activities (recess, lunch, bathroom breaks).

Carbon dioxide concentrations often reach 2000ppm, indicating a fresh air ventilation level of 10cfm per person with sedentary activities. After hours ACH is about 0.2, as found in other classrooms. An ACH of 0.2 may be a general characteristic of classroom infiltration. Note: small children have lower respiration rates than older children and adults. Fresh air rates for children are somewhat lower at equivalent room carbon dioxide concentrations shown in Table 1.

Classroom VOCs and Disinfectant Spraying

Volatile Organic Compounds (VOCs) are chemicals that have reactive potential. VOC reactions convert most compounds into harmless substances (carbon dioxide and water vapor), however, some may form other harmful compounds. Flammable chemicals and toxic chemicals are reactive chemicals, while carbon dioxide, nitrogen, argon and similar "inert" compounds are not. Not all VOCs are toxic or flammable. Cooking odors and inhalers (medications) are harmless and beneficial VOC examples.

Human metabolism creates many VOCs (eg, acetone, ethanol, isoprene, and methanol) that are released in exhaled breath, through the skin, and gaseous releases (burps and flatulence). Individuals vary in VOC output by a factor of 10, and an individual's VOC emission can change significantly on a day-to-day basis. Although some VOCs have noticeable odors, not all VOCs smell. Odor is not an indicator of unhealthy air, and a lack of odor is not an indicator of healthy air.

The IAQ monitoring boxes sense "total" VOCs, which are collectively any compound that will react as it moves through the VOC sensor. The VOC sensor is calibrated to a human's carbon dioxide output. Whenever VOC concentrations exceed carbon dioxide concentrations by a reasonably large margin (500ppm), non-human sources of VOCs, such as disinfectants, cleansers, adhesives, cosmetics, perfumes, magic markers, and other compounds are contributing to VOC pollutant levels. VOCs will sometimes have lower readings than carbon dioxide concentration levels because relatively inert carbon dioxide only disappears by dilution (fresh air ventilation and infiltration) while VOCs can breakdown or be absorbed into room furnishings (walls, floors, desks, papers, etc). Absorbed VOCs can be re-released at a later time when a room changes in temperature or humidity.

Overall, VOC readings widely varies classroom-by-classroom, and on a daily basis. Regardless of VOC level attained during after school hours, each classroom returned to background VOC levels by the start of the next school day.

We describe VOC characteristics of each classroom below, noting time periods when VOC levels indicate disinfectant cleansing.

High School Room 114:

All days for High School Room 114 have VOC concentrations that track carbon dioxide closely, indicating that other sources of VOCs are not significant (see Appendix A plots). Elevated VOCs above carbon dioxide concentration during after school hours are perhaps indicative of cleaning and disinfecting activities.

High School Room 139:

Significantly elevated VOCs during after school hours are very apparent on Thursday (Sept 2) and Wednesday (Sept 8) in plots shown in Appendix A. The IAQ monitor's VOC sensor "saturates" above 2000ppm, creating the flat VOC concentration level in the plots. High VOC levels that exceed carbon dioxide concentrations during afterschool hours indicate high chemical concentration levels from some non-human source, such as disinfectants. Friday (Sept 3) morning VOC concentration levels are below 500ppm by school opening, which indicates that VOCs dissipated from the day before.

Disinfectant and cleaning practices of rooms 114 and 139 should be compared to determine any noticeable differences. Room 114 may need elevated applications of cleanser and disinfectant, or perhaps cleaning and disinfectant application levels in room 139 should be reduced. If cleaning and disinfectant practices for the two rooms are identical, additional investigation for the different VOC levels is warranted.

Junior High Room 118:

Every school day for room 118 has elevated VOCs levels after school hours, indicating daily cleaning and disinfectant applications. Note that during the day, VOCs and carbon dioxide concentrations have similar fluctuations indicating classroom VOCs during the day are primarily from the class occupants and their activities. Elevated VOC levels decayed to background levels by the beginning of the next school day.

Junior High Room 110:

Slightly elevated VOC concentrations (Appendix B), relative to carbon dioxide concentrations, are noticeable for Thursday (Sept 2), Tuesday (Sept 7) and Wednesday (Sept 8). Room 110 has somewhat higher after-school ACH (air change per hour) than other classrooms, which may be due to open windows during cleaning and disinfecting activities. Comparing cleaning practices of rooms 118 and 110 is recommended to determine reasons for after school VOC differences, and whether cleaning practices should be adjusted. As in other rooms, VOCs return to low levels by the beginning of the next school day.

Elementary Room 14:

After school VOC concentrations (Appendix C) vary from day-to-day for room 14, perhaps reflecting different cleaning schedules and practices from one day to another. Thursday (Sept 2) has high VOC levels after school hours, indicating significant application of cleansers and disinfectant. More modest elevations of after school VOC concentrations, relative to carbon dioxide concentrations, are noticeable on Friday (Sept 3) and Tuesday (Sept 7). Wednesday does not display after school hour increases of VOCs above carbon dioxide, perhaps indicating a lighter clean activity. In all cases, after school hour VOC levels return to background level by the beginning of the next school day.

Impact of Ventilation Rates and Air Filtration on Covid, Sick Days, and Cognition Performance

Indoor air quality impacts cognition, productivity and sick days (absences). Today's standard ventilation rates are based on odor rather than cognition, productivity and sick days (disease transmission). Improving fresh air ventilation from today's typical 1200ppm carbon dioxide concentration (20cfm/person fresh air) to 800ppm carbon dioxide concentration (40cfm/person fresh air) results in significant human benefits that outweigh energy costs.

Figure 8 schematically shows how coordinating fresh air, air filtration and air purification synergistically create healthy indoor environments for school staff, students and visitors. The cost to achieve a healthy indoor space in terms of utility cost is less than 3 cents per hour per building occupant. The value of improved human performance, reduced sick days and increased air quality satisfaction is more than 5 cents per hour per person and will be discussed in a later section.

Carbon dioxide is a key indicator of IAQ. Air recirculation through high performance filters (MERV 13, 16 or HEPA) is important for reducing particulates that impair short term health (eg, asthma triggers) and cognition performance as well as long term health and productivity. Energy efficient, enhanced ventilation strategies can improve indoor air quality while keeping utility costs low and enhancing maintenance and operations.

We discuss the impact of fresh air ventilation, air filtration, and air sanitation effects on Covid (SARS-CoV-2) transmission, IAQ dissatisfaction, sick days, and cognition productivity in this section. Technologies and cost for improving IAQ are discussed in the next section, followed by a section discussing additional important aspects of improved IAQ.

Covid:

We're all tired of Covid, and the confusing array of what is needed, when it is needed, and how much is needed. Quantitative analyses are discussed below that defined how fresh air ventilation, air filtration, masking, and immunization affect the transmission of Covid. It is not magic. Diluting (fresh air) and capturing contagion (filtration and masks) reduces Covid transmission.

Improved IAQ is essential for fighting Covid and inhibiting disease transmission. Today's odor-based ventilation standards (ASHRAE62.1) have made our buildings airborne disease incubators. Figure 9 is a schematic of a school district's many stakeholders. Actions and decisions regarding steps for improving a school's indoor environment are ones that should involve all stakeholders.

We characterize disease transmission by two factors:

1) Infection Probability of susceptible persons becoming infected
2) Infection Multiplier, also called "building Reproductive number", Ro

The infection probability of someone susceptible to an airborne disease is related to the number of infectious persons, susceptible persons, and immune persons occupying a room, plus each person's exposure time, masking policies, and ventilation system characteristics. Disease characteristics (cold, influenza, Covid variants, and many other viruses and bacteria) also impact disease transmission.

Figure 10 is a table with results from a computational tool ("Covid Safe Space and IAQ Calculator" by Build Equinox). The Covid Safe Space IAQ Calculator is a downloadable, easy-to-use spreadsheet tool for determining the effects and costs of changes to a building's ventilation operation.

Infection Probability and Infection Multiplier for Covid are shown in Figure 10, starting with ASHRAE 62.1 (standard) ventilation practices. Standard ventilation (20cfm per person, 1200ppm carbon dioxide concentration) has infection probability of 44% for a classroom with 20 students and 1 teacher, with 1 of the classroom occupants infectious. An infection probability of 44% means than any susceptible (non-immunized) occupants are likely to become infected, if not today, then tomorrow or the day after that. Different levels of immunization (either vaccination or infection-acquired immunity) do not impact a susceptible person's infection probability. An infectious person releases an amount of contagion in the room, which builds to a concentration dictated by fresh air ventilation, air filtration and air purification. Any susceptible person who inhales a sufficient dose of contagion is likely to become infected.

Infection Multiplier is a ratio of the number of people that an infectious person is able to infect during their infectious period. Infection Multiplier greater than 1 indicates that a disease will multiply and grow within a community. In order to eradicate a disease, steps must be implemented that reduce Infection Multiplier below 1. Standard ventilation levels with increasing levels of immunization or 50% and 75% results in Infection Multiplier decreasing from 9 to 5 to 3, which helps slow the progression of Covid but does not stop the growth of the disease.

Doubling today's fresh air ventilation from 20cfm/person to 40cfm/person (reduction of room carbon dioxide concentration from 1200ppm to 800ppm) is shown in the second line of Figure 10 to reduce Infection Probability within a classroom to 25%. Infection Multiplier is also reduced, with 75% classroom immunization reducing IM to 1.7, a significant improvement but not yet sufficient to eradicate the disease.

The third line in Figure 10 improves recirculation filtration of air within a classroom. Air recirculation flow rates similar to fresh air flow rates (40cfm/person) through MERV13 or better filters are capable of removing small (submicron) particulates, reducing Infection Probability to 14%. Immunization levels of 75% reduce the Infection Multiplier to 0.9 where the disease is unable to replicate at a sustainable rate.

The lower the Infection Multiplier, the faster a disease decays and disappears. Face masks are important tools for allowing human interactions while reducing Infection Probability and Infection Multiplier. A "perfect" face mask would capture all contagion from an infectious person's breath and would capture all free contagion from a susceptible person's inhaled air, which reduces the Infection Multiplier to 0. Covid would decay within 3 weeks from any community with an Infection Multiplier of 0.

The fourth line of Figure 10 shows partial masking (50% usage) with low efficiency (20% virus capture efficiency), such as loose fitting face masks. Some additional reduction of Infection Probability and Infection Multiplier occurs, however, the IM remains above 1 except for high immunization levels. The fifth line of Figure 10 assumes high mask usage (80%) with increased mask efficiency (80%), which causes Infection Probability to drop to 2% and decreases Infection Multiplier below 1 for all levels of immunization. At 75% immunization with improved fresh air, air filtration and effective masking, Infection Multiplier is reduced to 0.1, indicating a rapid decay of Covid from a community.

Variants, such as today's dominant Delta strain, have different transmission efficiencies. The reasons for increased disease transmission are not fully understood. Some of the possible causes are higher production of virions, increased infectiousness of a virion, increased production of respiratory aerosols, other unknown factors, and perhaps a combination of all of these effects. Delta is twice as infectious as Alpha and has replaced Alpha as the dominant strain in North America. A table similar to Figure 10 with increased virus transmission efficiency would increase Infection Probability and Infection Multiplier for all cases, however. Implementing all of the steps discussed (increased fresh air, improved ventilation, effective and efficient face masks) continues to keep the Infection Multiplier below 1.

Ventilation Impact on IAQ Dissatisfaction, Sick Days, and Cognition Productivity:

Ventilation and air filtration levels affect building occupant air quality satisfaction, sick days and cognition productivity. Air quality satisfaction is measured as "dissatisfaction" with the remaining fraction of the population being either satisfied or neutral. Sick days are based on common cold and influenza viruses (ie, non-Covid). Cognition productivity is based on changes in cognition performance in 9 areas of brain function (eg, organization of information, creativity, decision making, use of information, etc) as air quality based on carbon dioxide concentration varies.

Figure 7 shows variations of air quality dissatisfaction and carbon dioxide concentration as fresh air ventilation air flow changes. All classrooms monitored have dissatisfaction levels above 20%. Note that more than 80% of buildings in a survey of over 30,000 people in over 200 buildings had air quality dissatisfaction above 20% (Center for the Built Environment, University of California at Berkeley).

Reducing carbon dioxide concentration to 800ppm during occupied hours reduces dissatisfaction to 10 to 12%. Large box stores (Walmart, Target, Home Depot, etc) already understand this, maintaining carbon dioxide concentrations at 800ppm or lower. Although air quality dissatisfaction may not directly impact a school or other public building spaces, it is one more item adding to someone's impression of an institution.

Increasing fresh air ventilation to 40cfm per person (800ppm carbon dioxide concentration) and improving (or adding) air filtration with MERV13 filters has been found to reduce sick days in businesses by 40%, which is equivalent to sick day reduction for influenza vaccinated populations. Assuming a value of $500 per sick day (lost wages and medical costs), a change from standard ventilation (1200ppm carbon dioxide) to improved ventilation and enhanced MERV13 filtration is shown in Figure 11 to reduce sick days by 40% with a net cost savings benefit of 5 cents per hour per person (based on 8760hours per year).

Ventilation has been shown in numerous studies to impact cognition and task performance. References 2 and 3 provide background on air quality impacts in schools. In order to provide a relative value of improved cognition, a methodology developed by Harvard's TH Chan School of Public Health has been incorporated into the Covid Safe Space IAQ Calculator. Figure 12 shows trends in cognition performance based on an average of 9 areas of cognition performance. Also plotted on Figure 12 is the hourly value of cognition productivity relative to standard ventilation, assuming an annual $50,000 value of human performance. Student value is not their current value, but their future value, which is difficult to assess. As shown in Figure 12, increasing ventilation from 20cfm per person to 40cfm per person is a 10%

increase in cognition performance, with an hourly value of 50cents per hour per person. One should note that an increase in cognition performance does not mean the improvement will be directed toward more productive learning as many other factors impact learning potential.

Classroom Ventilation Improvements: Capital Cost and Utility Cost Estimates

Comfort conditioning utility costs are important, however, they are less important and less expensive than the cost of sick days and poor cognition performance. Figure 13 shows the cost per hour per building occupant for fresh air ventilation during central Illinois winter conditions. Doubling today's odor-based, standard ventilation rates increases utility costs by less than 1.5cents per hour per person. In comparison, the previous section discussed 5cents per hour per person savings for sick days and up to 50cents per hour per person of potential performance productivity enhancement with improved fresh air ventilation and air filtration.

Appendix D describes a classroom concept that manages classroom IAQ and maintains comfort very efficiently during low and high occupancy periods. The concept is an example of today's available technologies that automatically maintain healthy classroom environments and comfort conditions while improving and enhancing maintenance through online monitoring, control and diagnostics.

Distributed systems, as shown in Appendix D, have the strength of redundancy and resiliency. With today's technologies, authorized facilities and administration personnel can monitor and control individual classrooms anytime and anywhere. Maintenance task scheduling (eg, filter replacements) are also conveniently managed with online BMS (Building Management Systems). Facilities personnel, system manufacturers, and installers can conduct realtime diagnostics and tests to troubleshoot problems.

The cost per classroom for a concept as described in Appendix D is estimated to be $40,000, with $20,000 for equipment costs (smart ventilation unit, bulk fresh air energy recovery unit, and comfort conditioning units) and $20,000 for local HVAC installation labor. The distributed classroom concept would be beneficial for older classrooms that currently do not have centralized HVAC ventilation systems. The concept may be viable for buildings with central HVAC systems that are unable to increase ventilation, filtration, and comfort conditioning by adding components discussed in Appendix D with reduced capacity that is sufficient to supplement existing HVAC systems.

Distributed, independent classroom IAQ and comfort conditioning systems can use a rolling installation process, avoiding an overall shutdown of a building and need for a large labor force beyond a local community's HVAC installer pool. $40,000 per classroom with an equipment lifetime of 10 years is a capital investment of $4000 per year, or about $200 per student over 10 years, assuming 20 students per classroom.

Utility costs are described in more detail in Appendix D. An annual cost of $820 for electricity based on 12 cents per kWh utility cost is estimated for a 750sqft classroom with 20 students and 1 teacher located in central Illinois. Approximately 60% of the annual utility cost is for high occupancy periods (school hours) and 40% for low occupancy periods (summer, weekends, and nightime).

Conclusions

IAQ monitoring of the School District classrooms has shown that improvements to air quality will be beneficial to staff and students. Current air quality conditions are typical of those in other indoor public gathering spaces. VOC data indicates that some classrooms have very high VOC concentrations in the evening after school hours when classrooms are cleaned by custodial staff. VOCs drop to background concentration levels by the beginning of the next school day.

Fresh air flow rates of 40cfm per person coupled with 40cfm per person of air recirculation through filters would inhibit disease transmission, improve cognition performance, decrease sick days and reduce indoor air quality dissatisfaction. The key to efficient management of enhanced air management are “smart” controls with carbon dioxide and VOC sensors that automatically modulated fresh air flow as needed. Today’s technologies allow facility and administration personnel to monitor and control all classrooms and indoor spaces in convenient manner, as well as diagnose problems efficiently.

Figure 1 High School

Figure 2 Junior High School

Figure 3 Elementary School

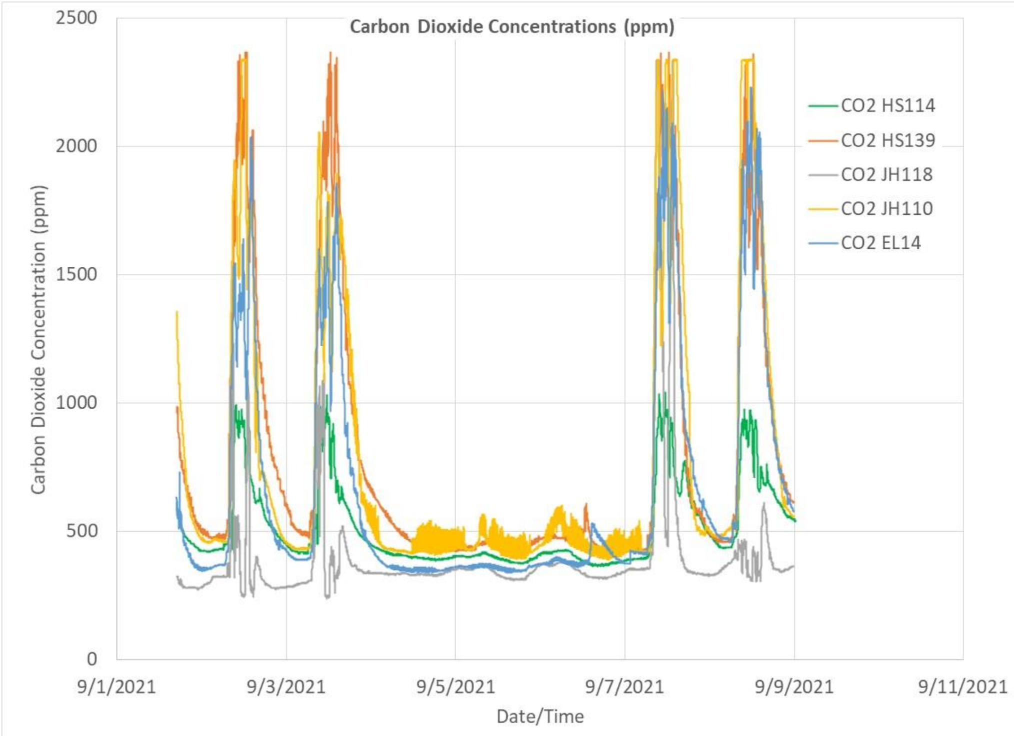


Figure 4 Carbon Dioxide concentrations for all classrooms monitored from September 2 through September 9, 2021.

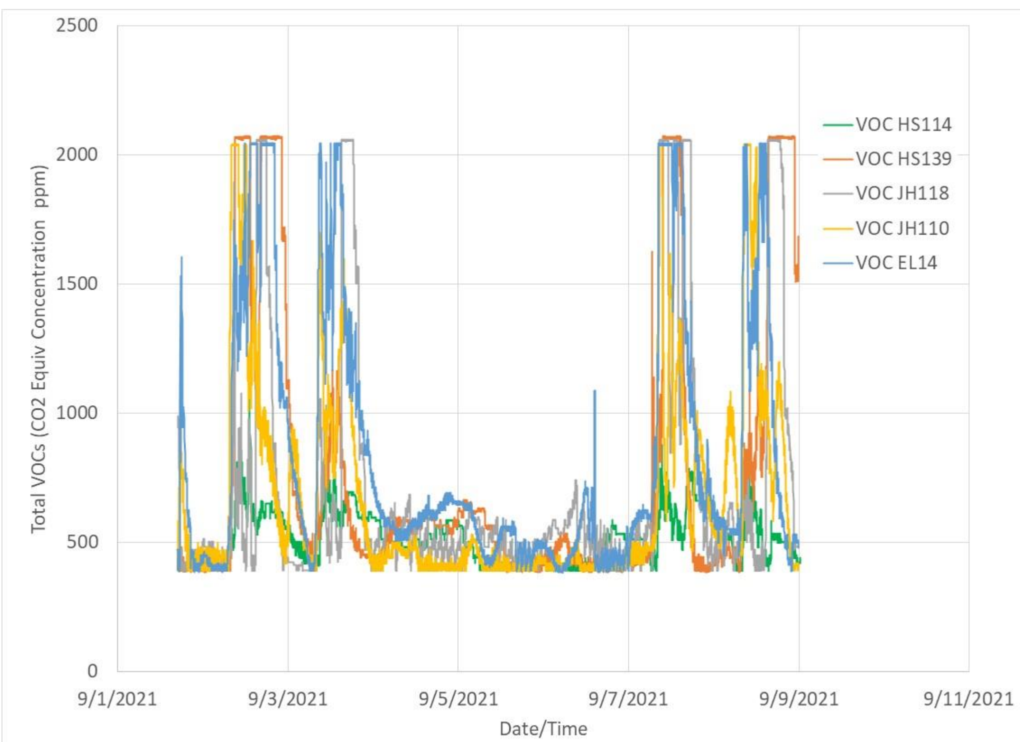


Figure 5 Total VOC (Volatile Organic Compound) concentrations for all classrooms monitored from September 2 through September 9, 2021.

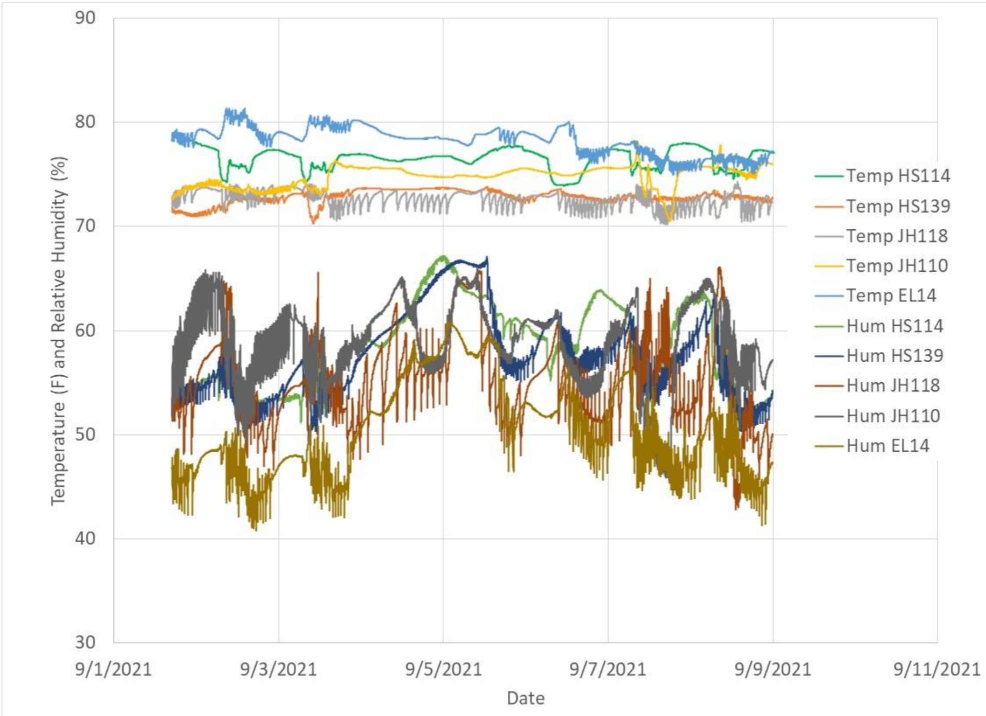


Figure 6 Temperature and Relative Humidity for all classrooms monitored from September 2 through September 9, 2021.

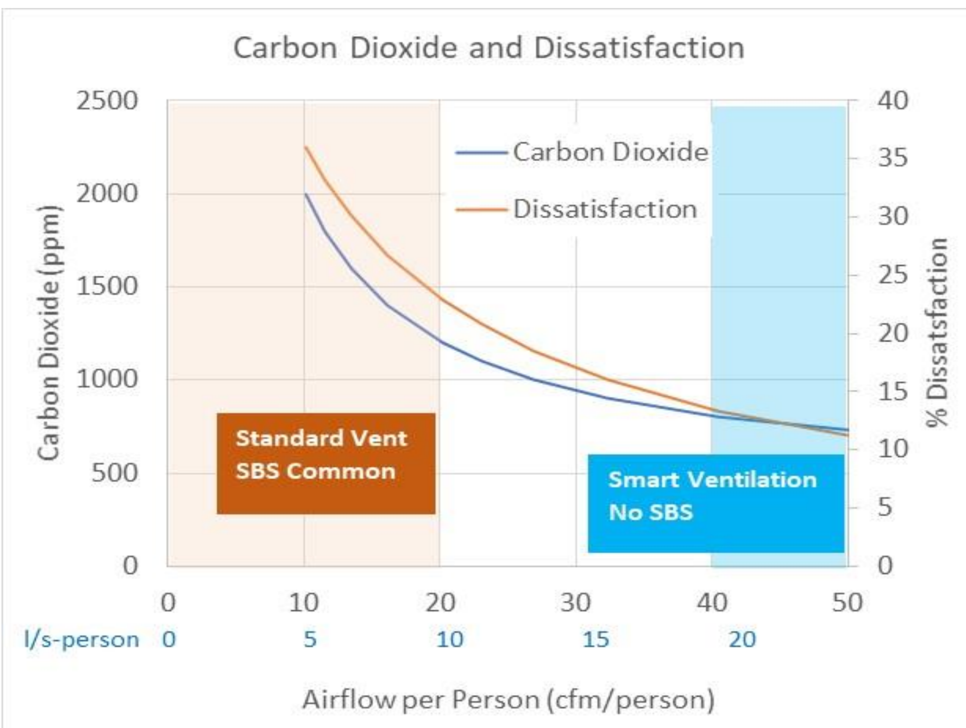


Figure 7 Relations between carbon dioxide concentration, air quality dissatisfaction, and air flow per person.

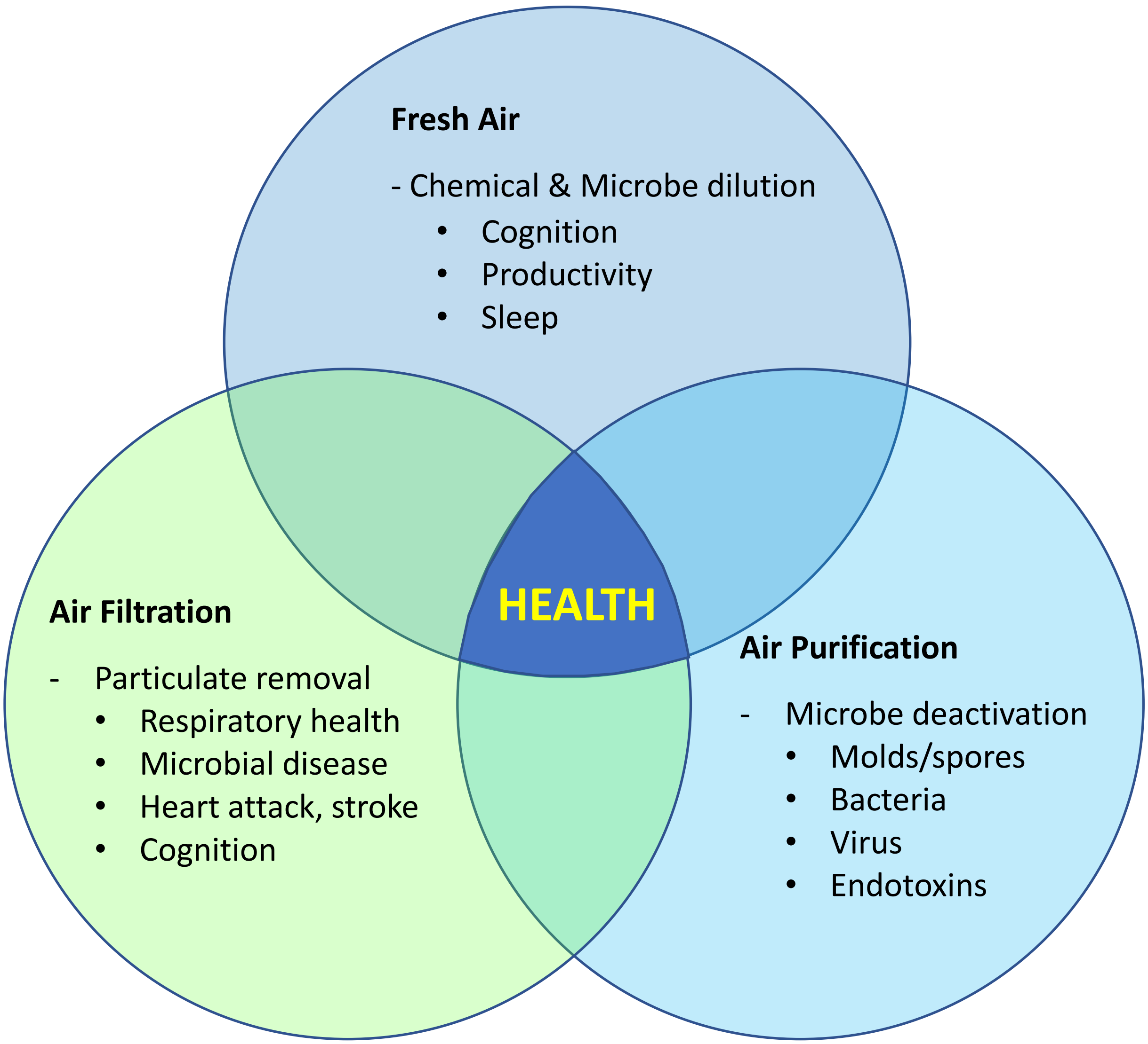


Figure 8 Coordination of fresh air, air filtration and air purification synergistically creates healthy indoor spaces that improve well-being, health and performance while inhibiting disease transmission and reducing sick days and absences.

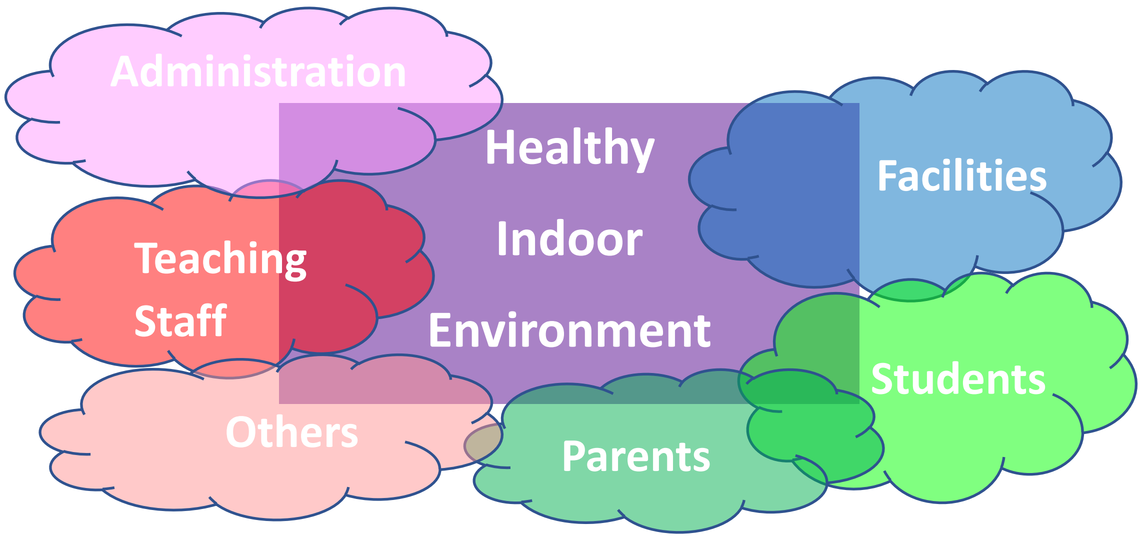


Figure 9 Conversations among school district stakeholders are important to discuss options and costs related to healthy indoor environments.

		Immunity 0%	Immunity 50%	Immunity 75%
Standard Conditions	Infect Probability %	44	44	44
	Infection Multiplier	8.9	4.9	2.9
800ppm CO_2	Infect Probability %	25	25	25
40cfm/person	Infection Multiplier	5.1	2.8	1.7
MERV 13 filter	Infect Probability %	14	14	14
40cfm/person	Infection Multiplier	2.9	1.6	**0.9**
50% Mask Use	Infect Probability %	12	12	12
20% Mask Eff	Infection Multiplier	2.4	1.3	**0.8**
80% Mask Use	Infect Probability %	2	2	2
80% Mask Eff	Infection Multiplier	**0.4**	**0.2**	**0.1**

Figure 10 Change of Covid (Alpha variant) Infection Probability and Infection Multiplier (building Ro) for a classroom with 20 students and 1 teacher. Standard conditions = 20cfm/person & MERV8 filtration.

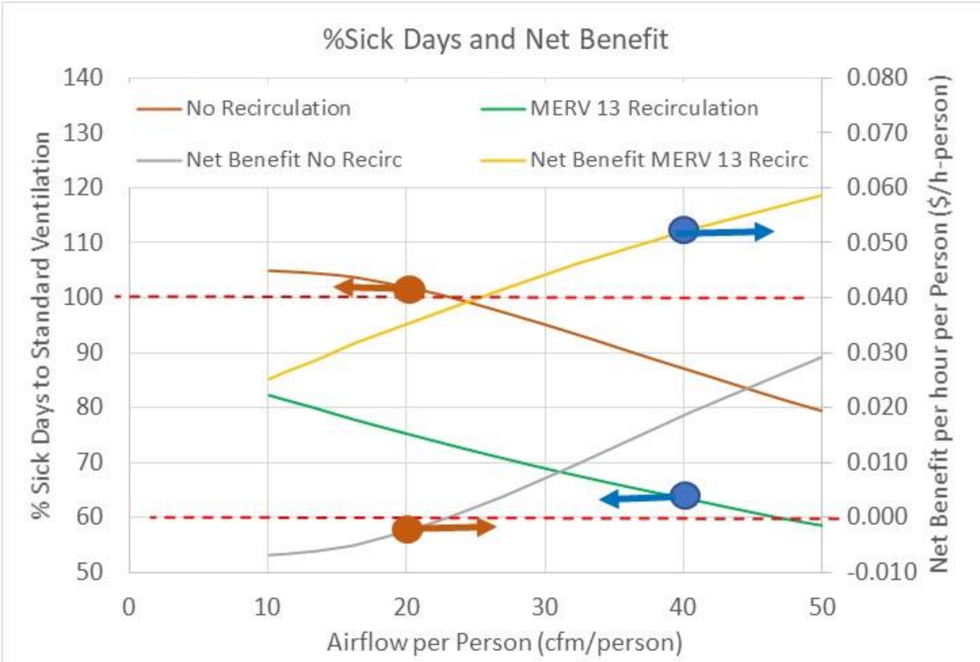


Figure 11 Effect of fresh air ventilation and air filtration on sick days and relative net benefit of reduced sick days assuming 2.5 sick days per year at standard ventilation conditions (20cfm/person with MERV8 filtration) and $500 per sick day cost.

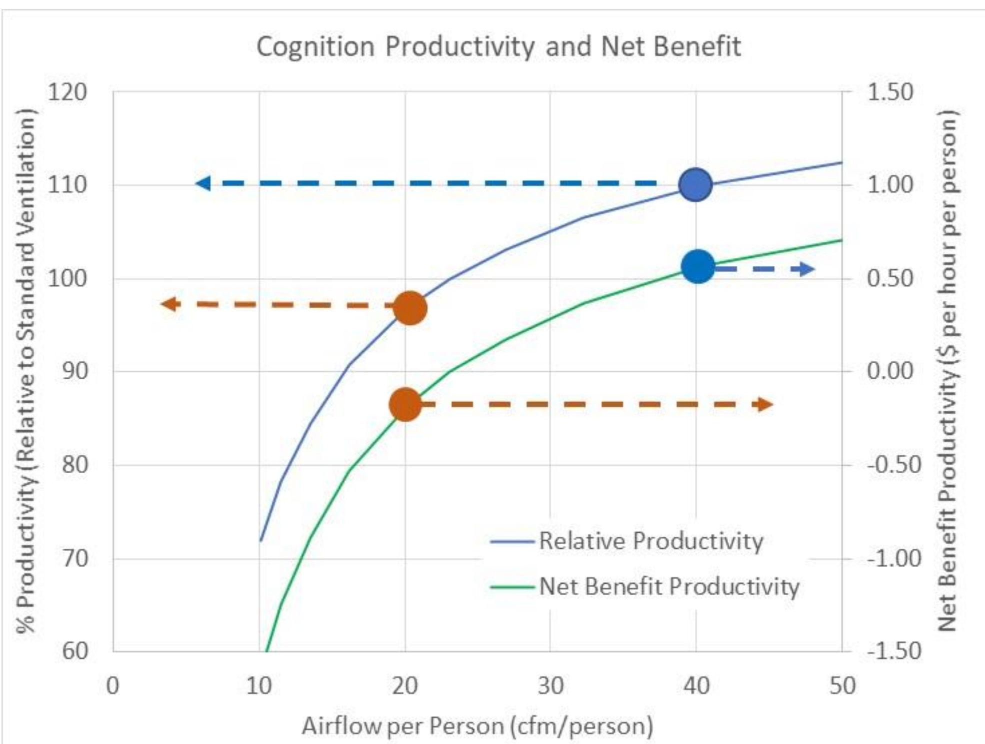


Figure 12 Cognition performance and value of cognition performance due to fresh air ventilation levels. Cognition performance is the average of 9 areas of cognition, and the value of cognition productivity is based on an assumed $50,000 annual value of human productivity.

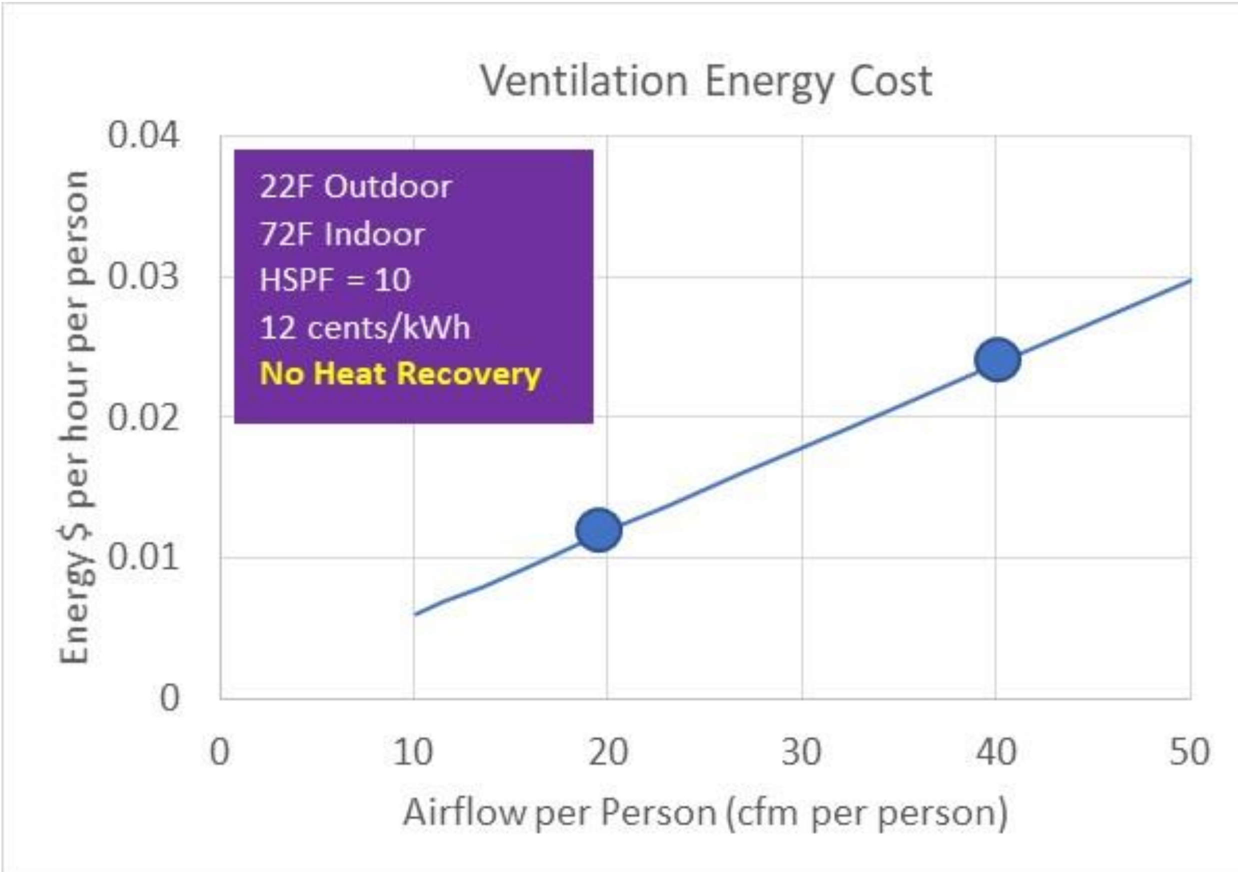
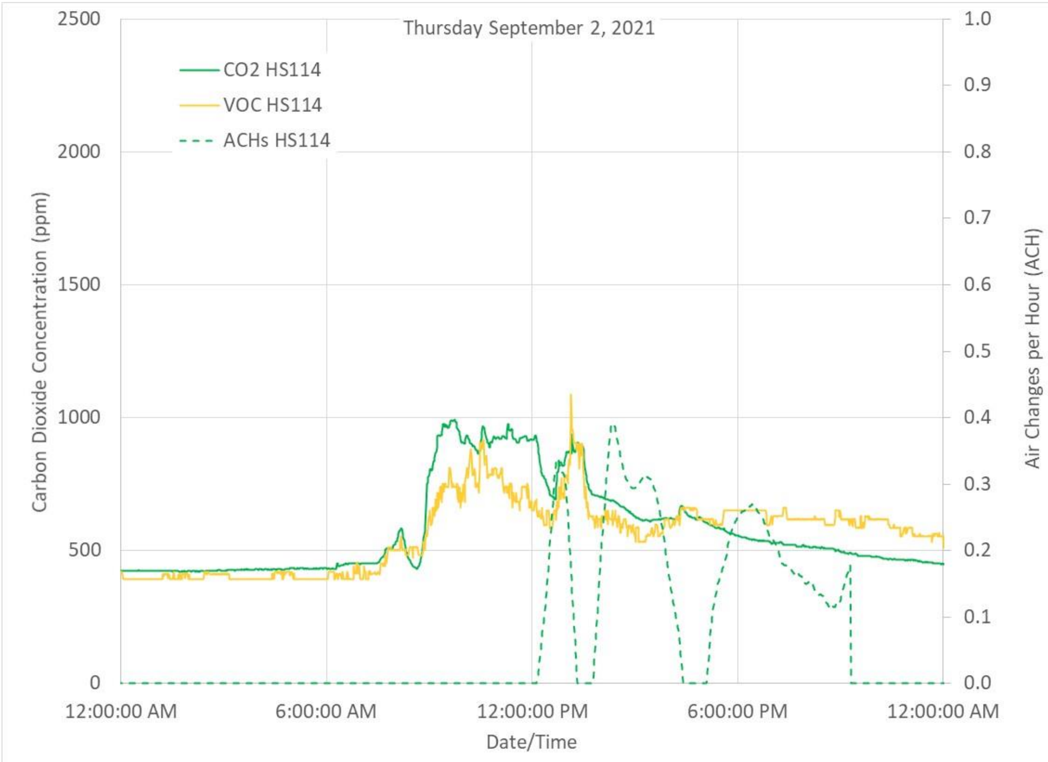


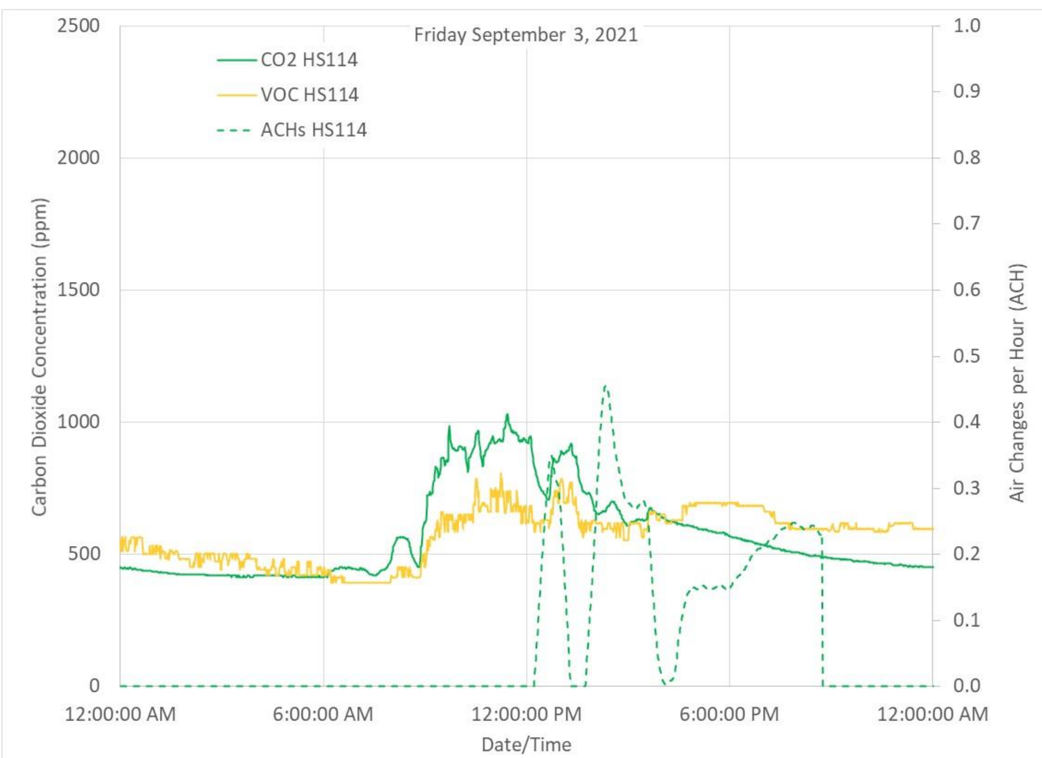
Figure 13 Cost of fresh air ventilation with energy recovery in central Illinois during January average temperature (22F) and an indoor temperature of 72F. Electricity is assumed to cost 12cents per kWh. A low temperature heat pump with HSPF (Heating Seasonal Energy Performance) of 10 is assumed for comfort conditioning.

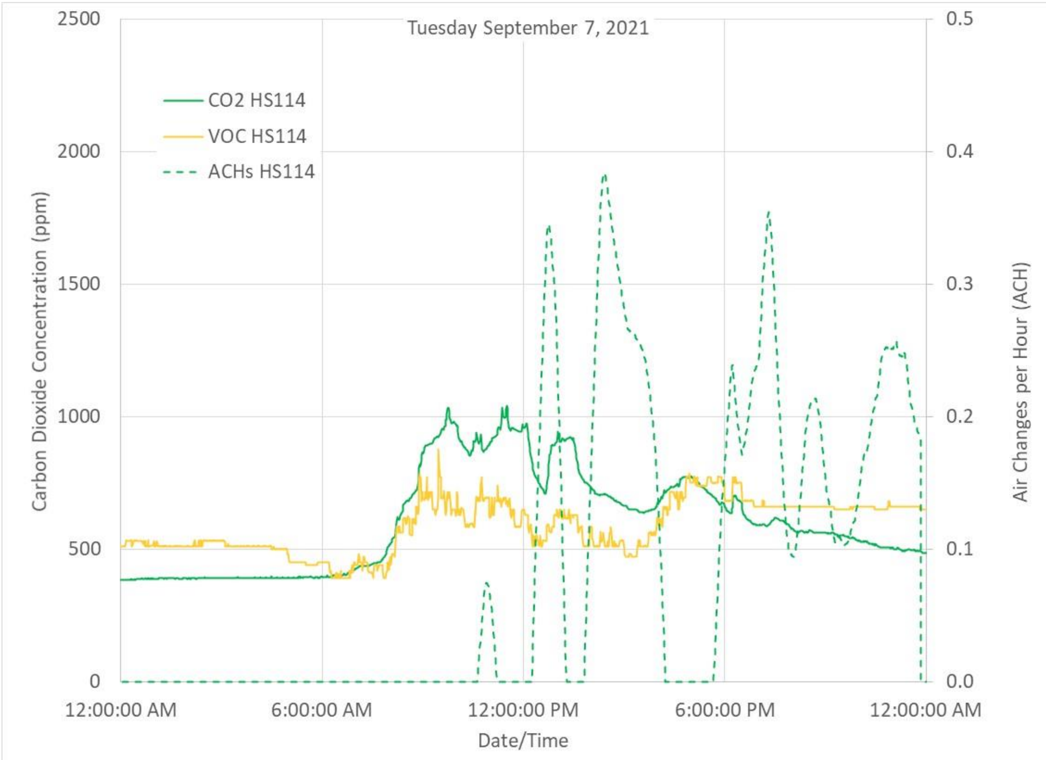
Appendix A: High School Classrooms: Daily Carbon Dioxide, total VOC and ACH Plots

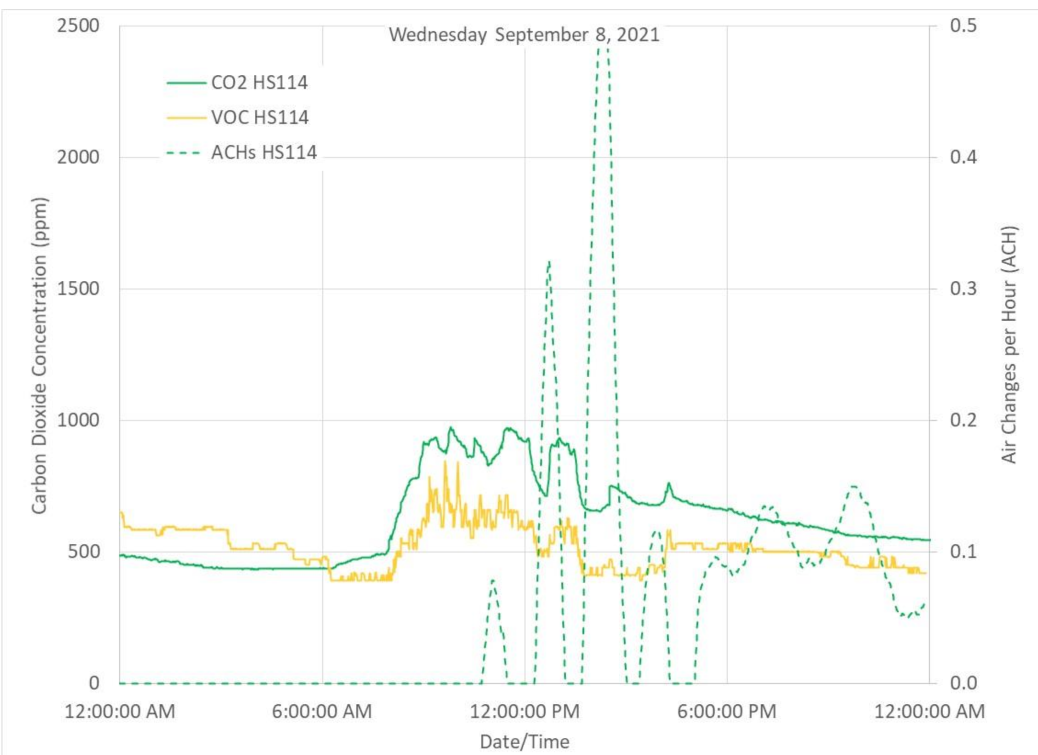
High School #1

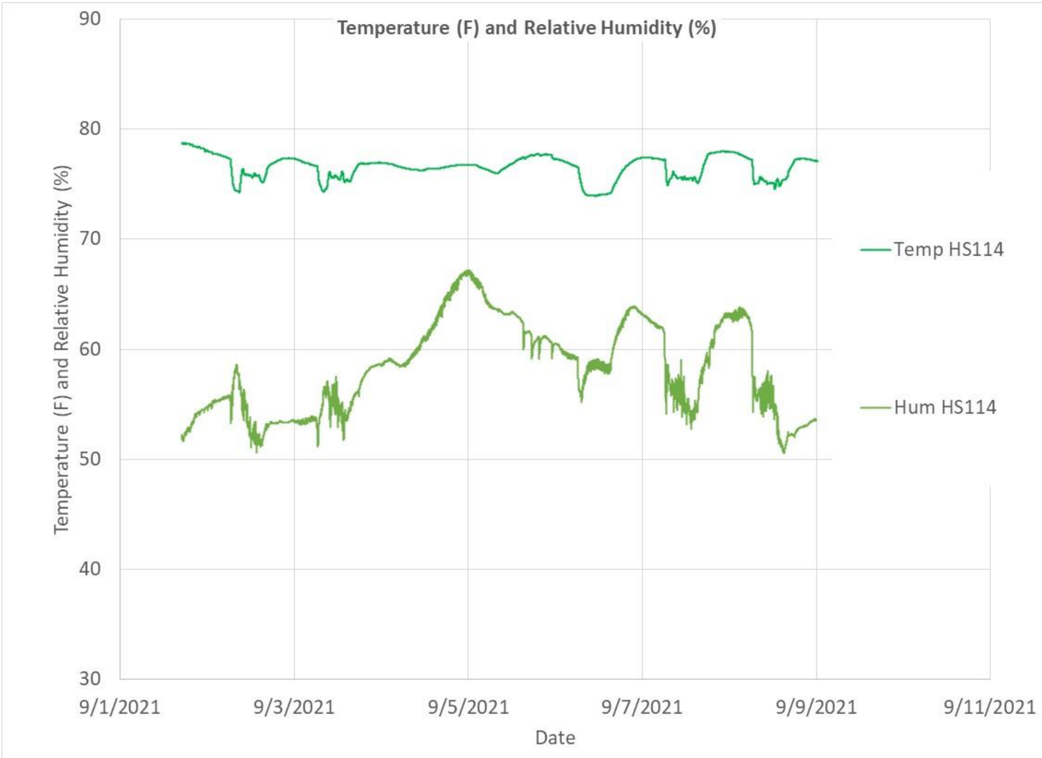
High School #2

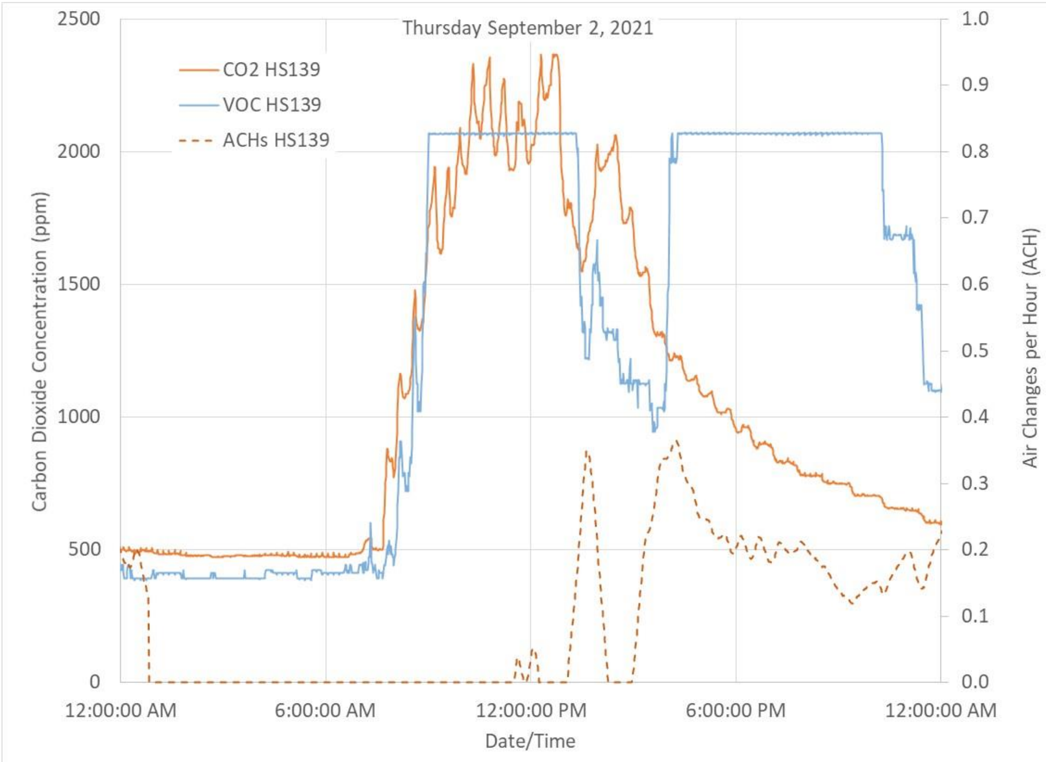

Thursday September 2, 2021
CO2 HS114
VOC HS114
ACHs HS114
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
2500
2000
1500
1000
500
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM

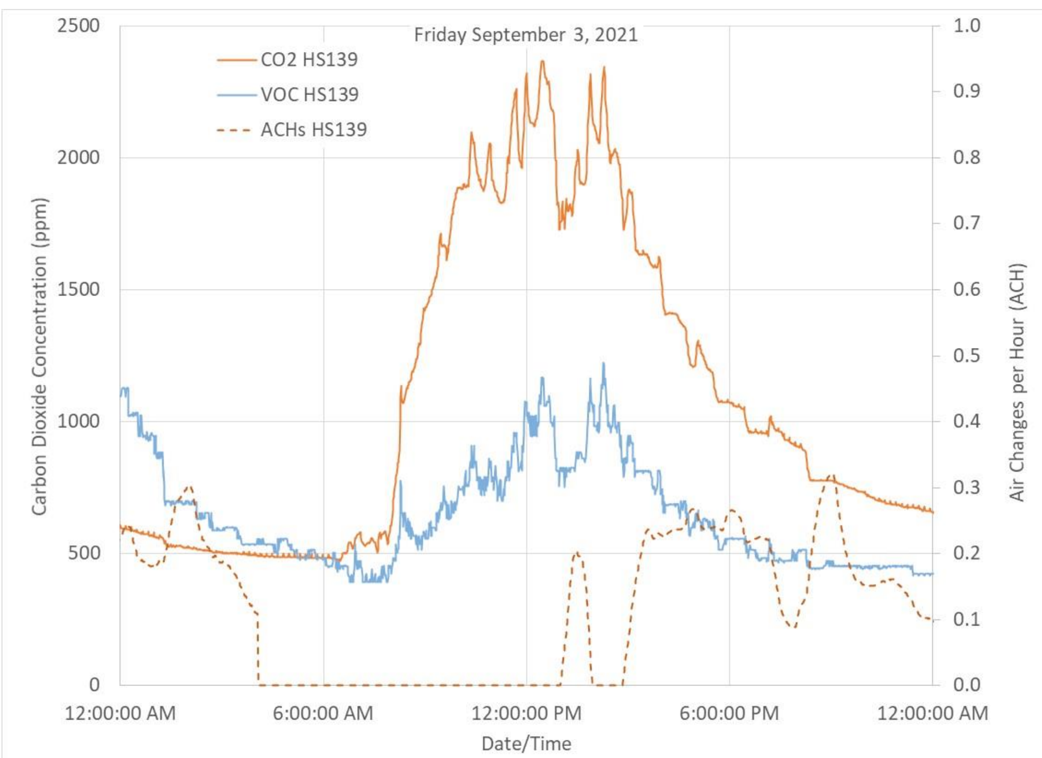

Friday September 3, 2021
CO2 HS114
VOC HS114
ACHs HS114
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
2500
2000
1500
1000
500
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM

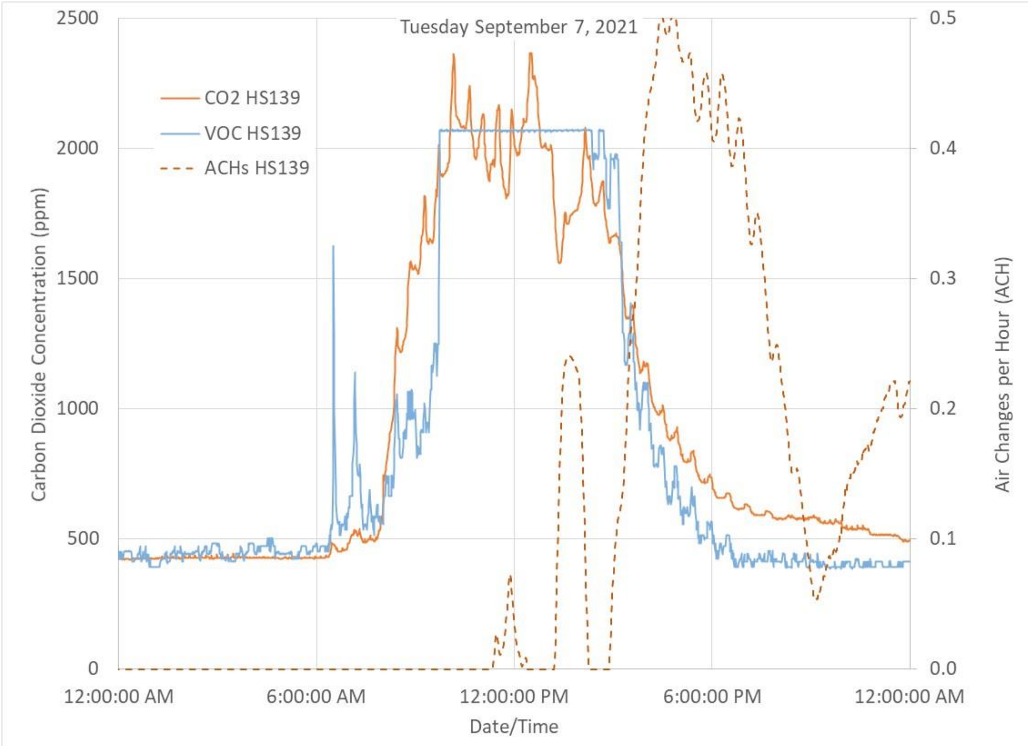

Tuesday September 7, 2021
CO2 HS114
VOC HS114
ACHs HS114
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
2500
2000
1500
1000
500
0
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM

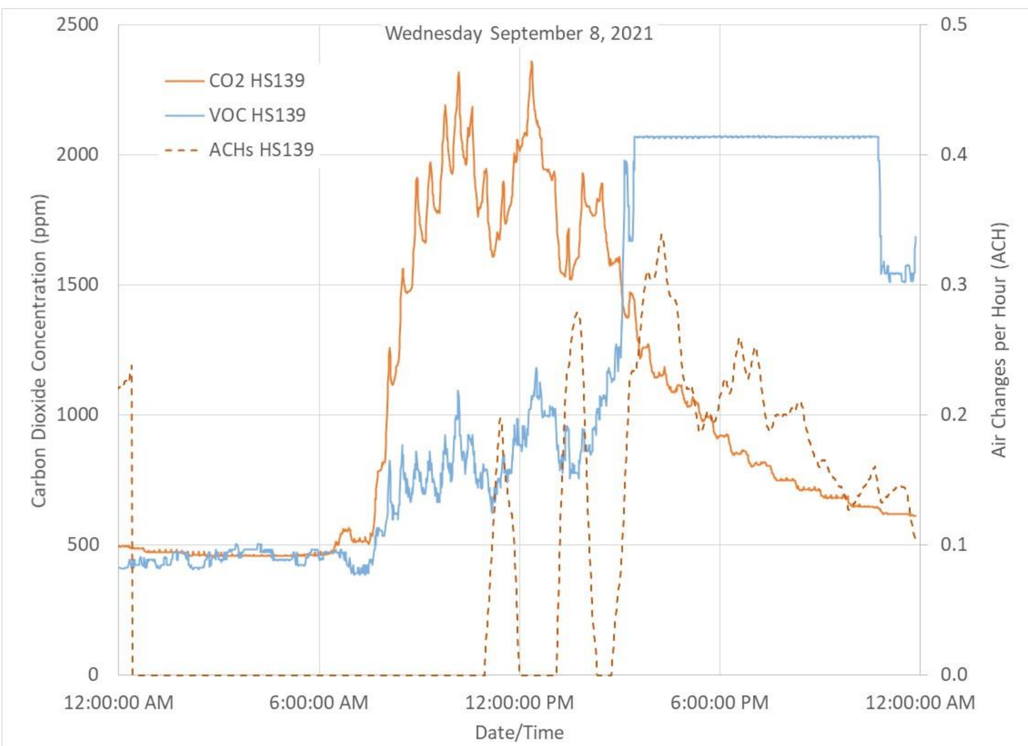

Wednesday September 8, 2021
CO2 HS114
VOC HS114
ACHs HS114
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
2500
2000
1500
1000
500
0
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM

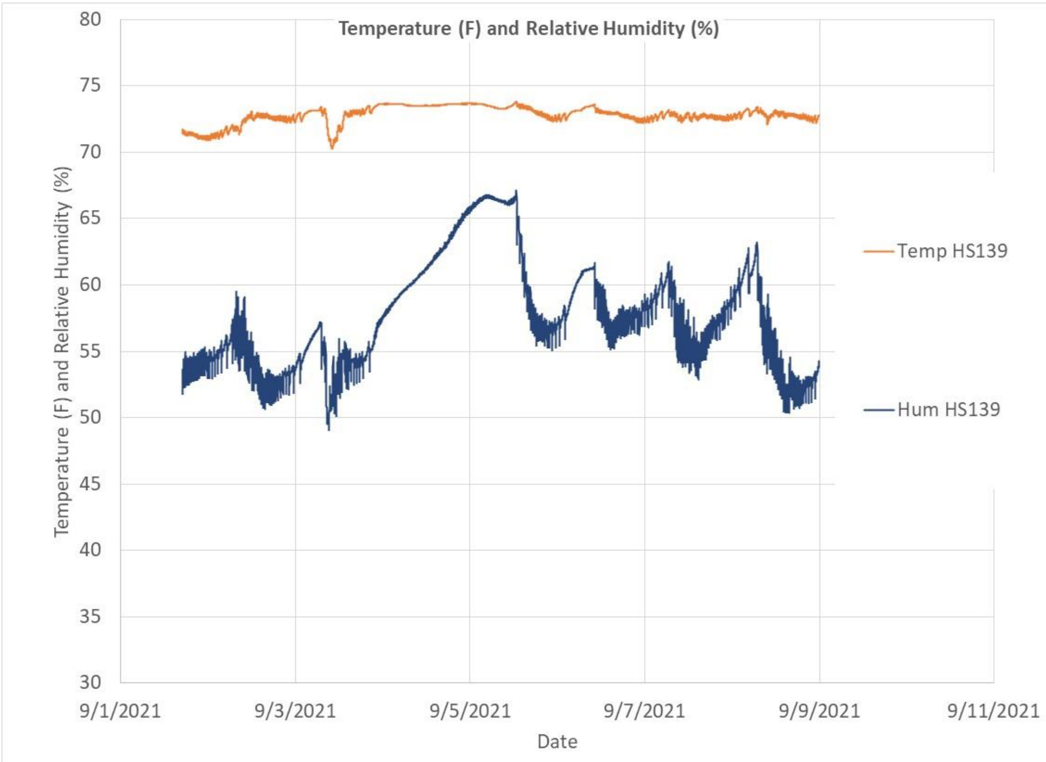

Temperature (F) and Relative Humidity (%)
Temperature (F) and Relative Humidity (%)
90
80
70
60
50
40
30
9/1/2021
9/3/2021
9/5/2021
9/7/2021
9/9/2021
9/11/2021
Date
Temp HS114
Hum HS114


Thursday September 2, 2021
CO2 HS139
VOC HS139
ACHs HS139
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
2500
2000
1500
1000
500
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM
Date/Time


Friday September 3, 2021
CO2 HS139
VOC HS139
ACHs HS139
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
2500
2000
1500
1000
500
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM
Date/Time


Tuesday September 7, 2021
CO2 HS139
VOC HS139
ACHs HS139
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
2500
2000
1500
1000
500
0
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM
Date/Time

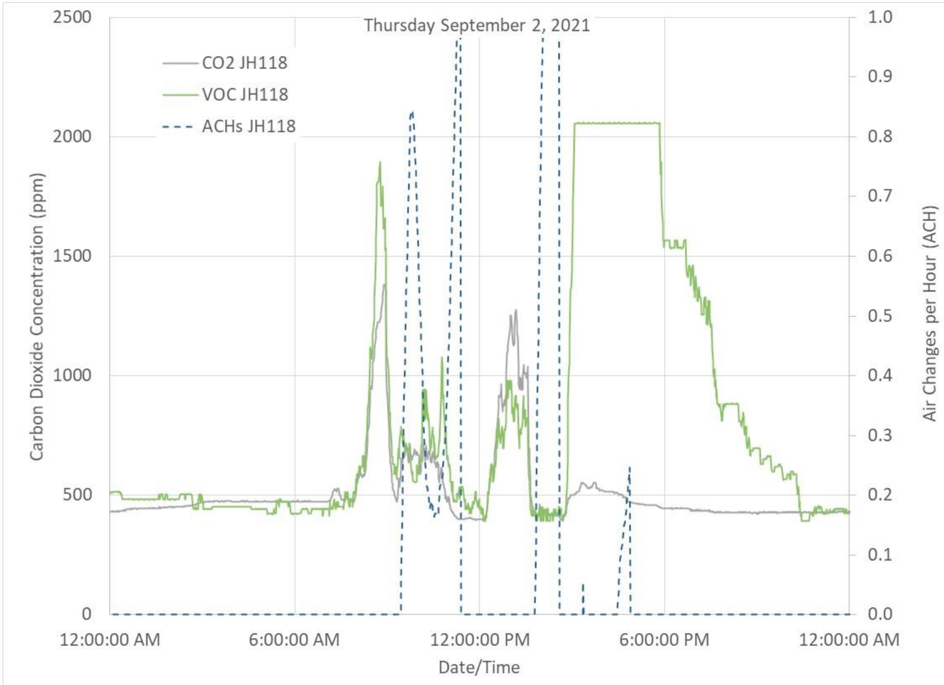

Wednesday September 8, 2021
CO2 HS139
VOC HS139
ACHs HS139
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
2500
2000
1500
1000
500
0
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM
Date/Time

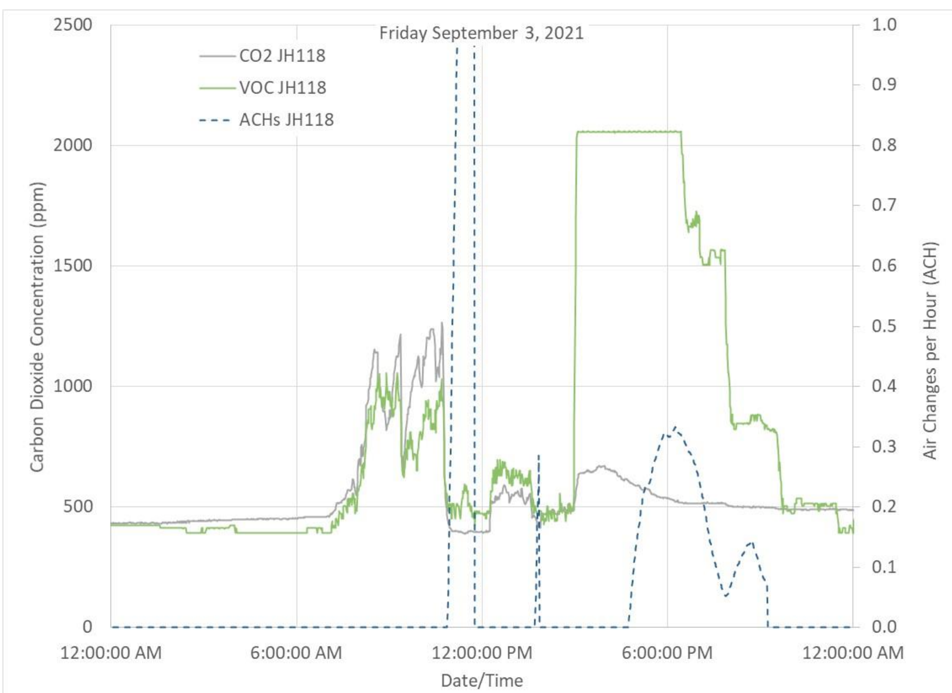

Temperature (F) and Relative Humidity (%)
80
75
70
65
60
55
50
45
40
35
30
Temperature (F) and Relative Humidity (%)
9/1/2021
9/3/2021
9/5/2021
9/7/2021
9/9/2021
9/11/2021
Date
Temp HS139
Hum HS139

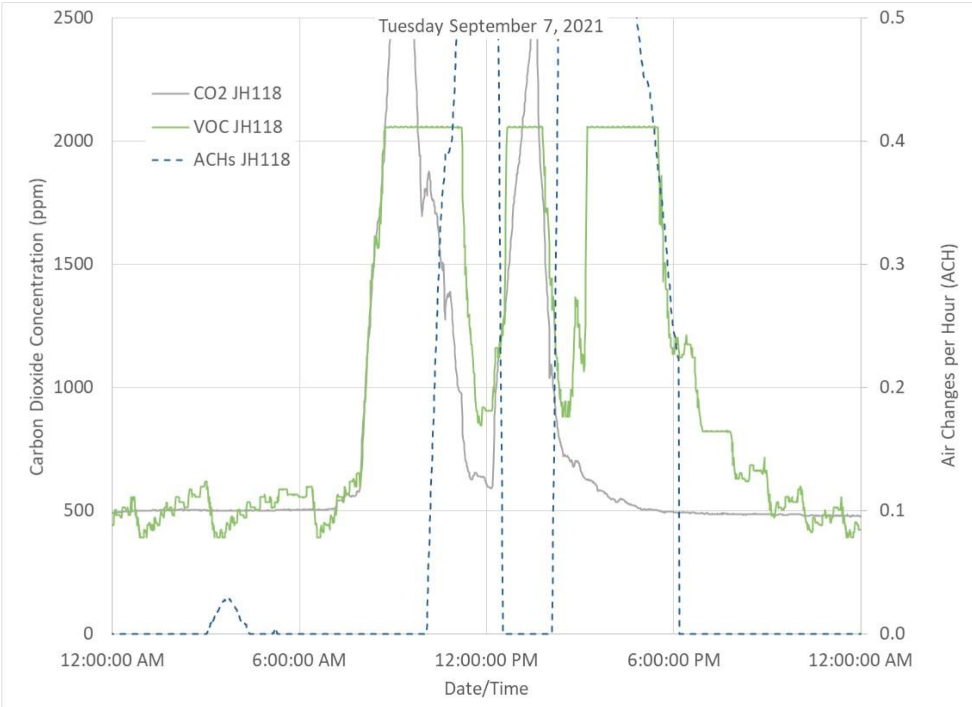
Appendix B: Junior High School Classrooms: Daily Carbon Dioxide, total VOC and ACH Plots

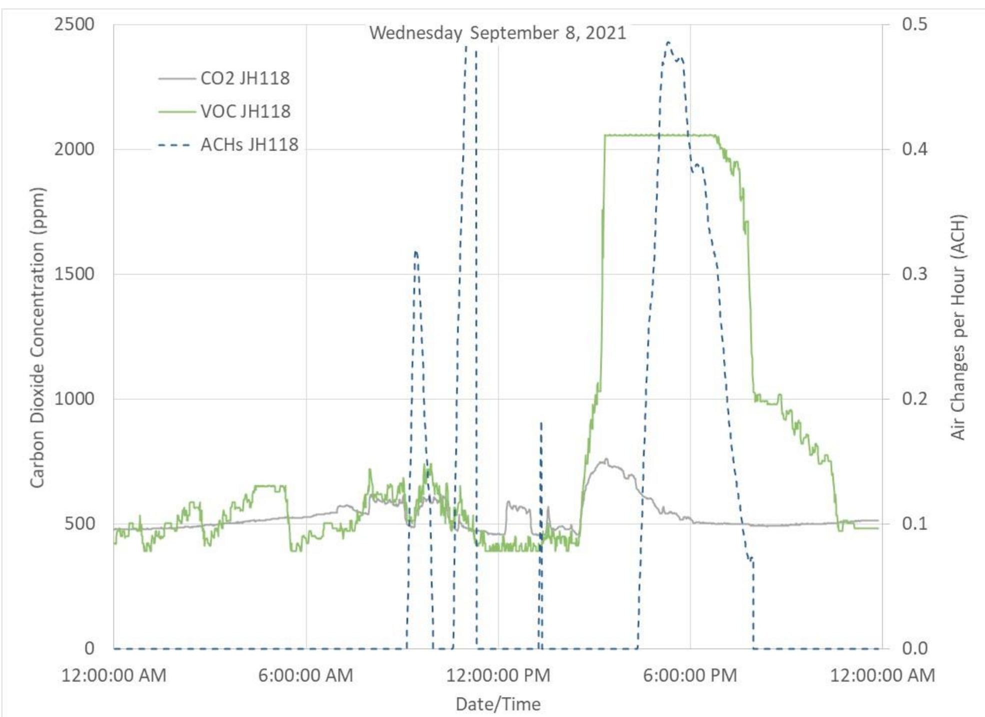
8th Grade

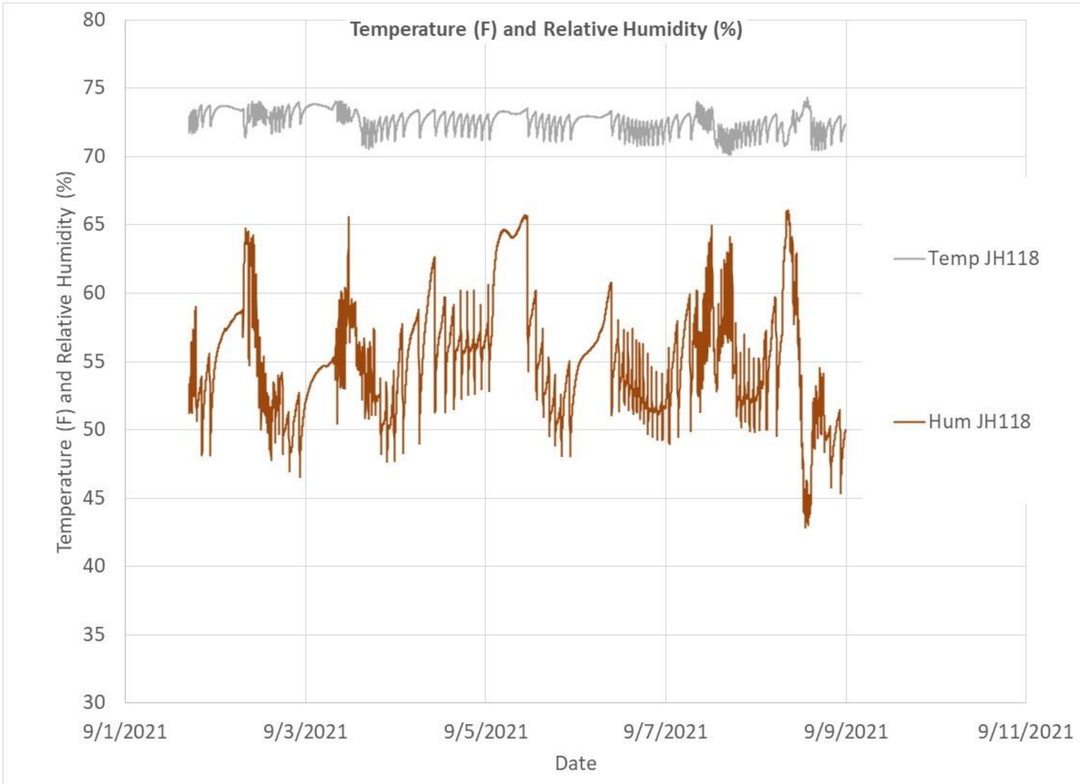
6th Grade


Thursday September 2, 2021
CO2 JH118
VOC JH118
ACHs JH118
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
0
500
1000
1500
2000
2500
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM

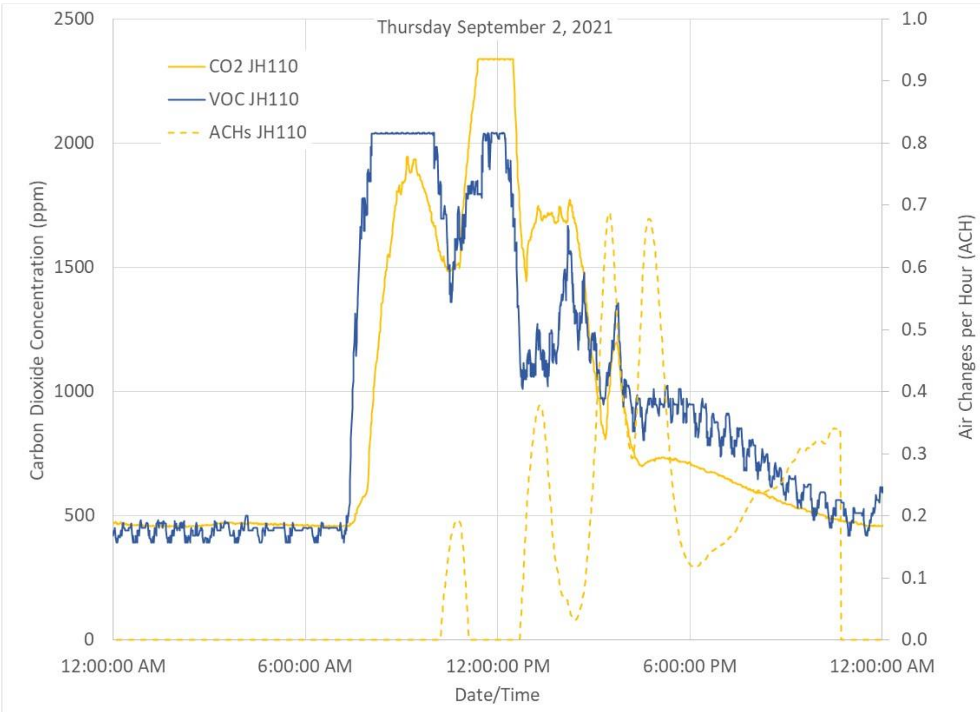

Friday September 3, 2021
CO2 JH118
VOC JH118
ACHs JH118
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
0
500
1000
1500
2000
2500
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM


Tuesday September 7, 2021
CO2 JH118
VOC JH118
ACHs JH118
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
2500
2000
1500
1000
500
0
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM

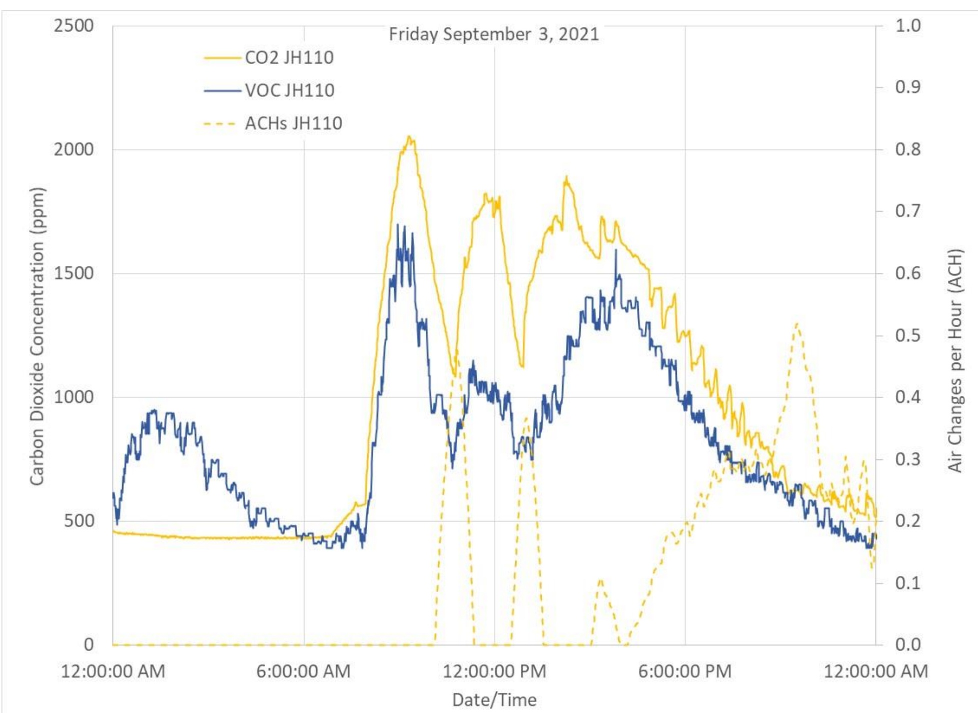

Wednesday September 8, 2021
CO2 JH118
VOC JH118
ACHs JH118
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
2500
2000
1500
1000
500
0
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM



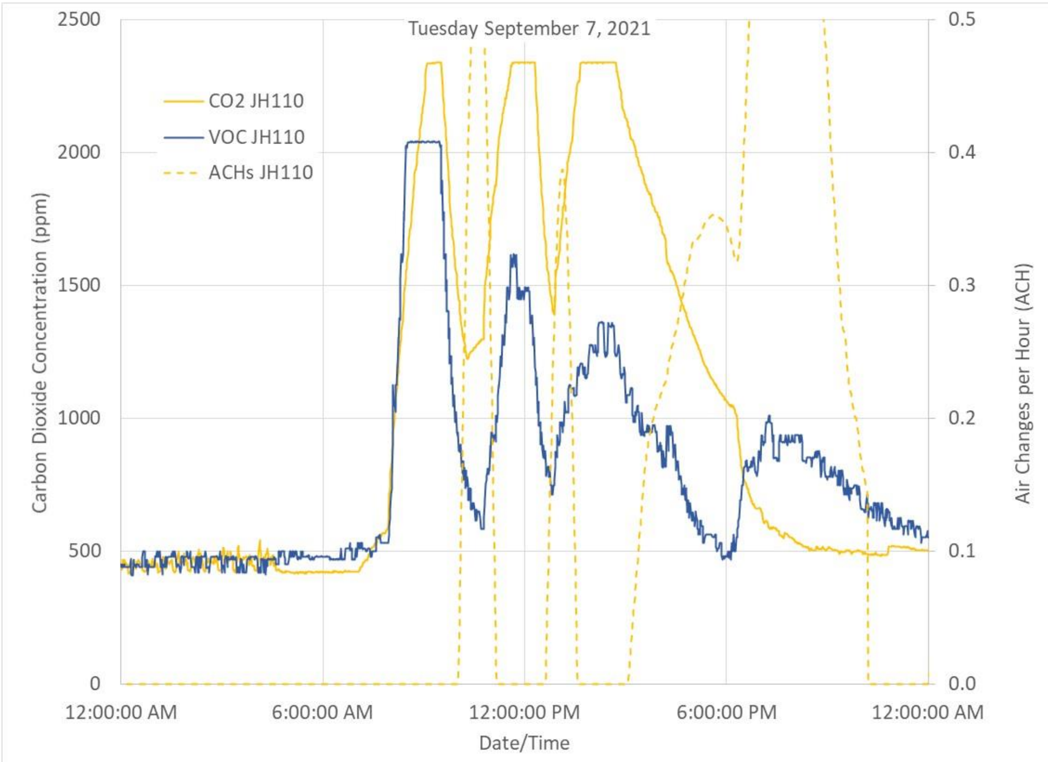
Temperature (F) and Relative Humidity (%)
Temperature (F) and Relative Humidity (%)
Date
80
75
70
65
60
55
50
45
40
35
30
9/1/2021
9/3/2021
9/5/2021
9/7/2021
9/9/2021
9/11/2021
Temp JH118
Hum JH118



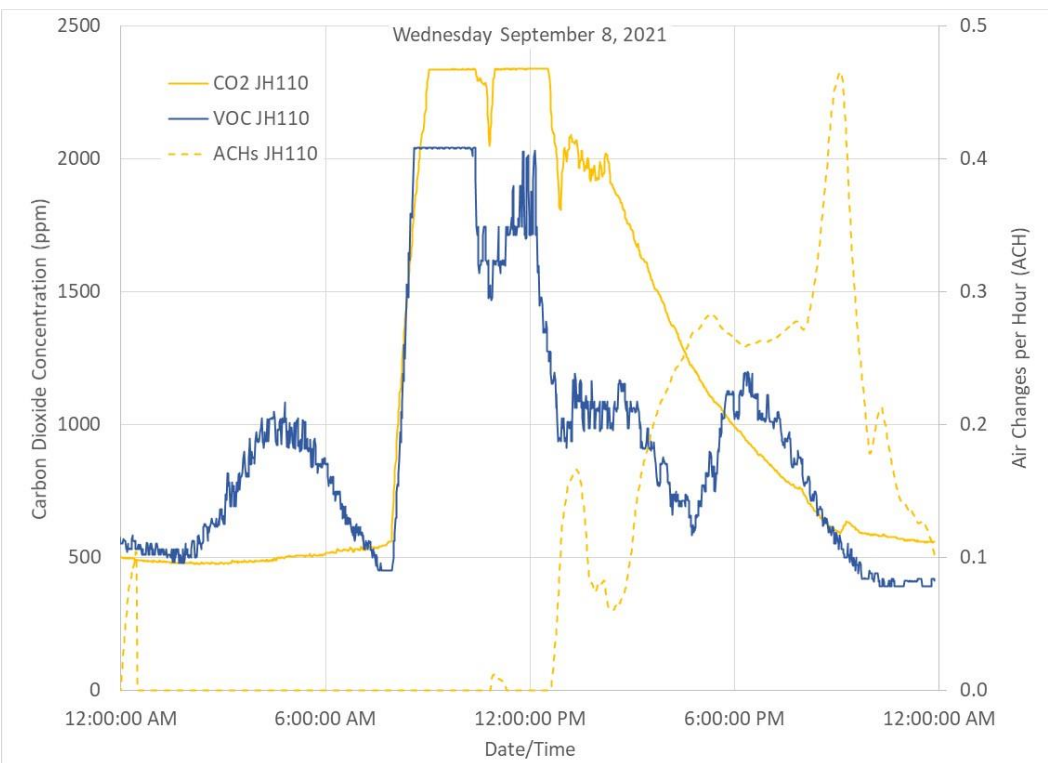
Thursday September 2, 2021
CO2 JH110
VOC JH110
ACHs JH110
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
2500
2000
1500
1000
500
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM
Date/Time



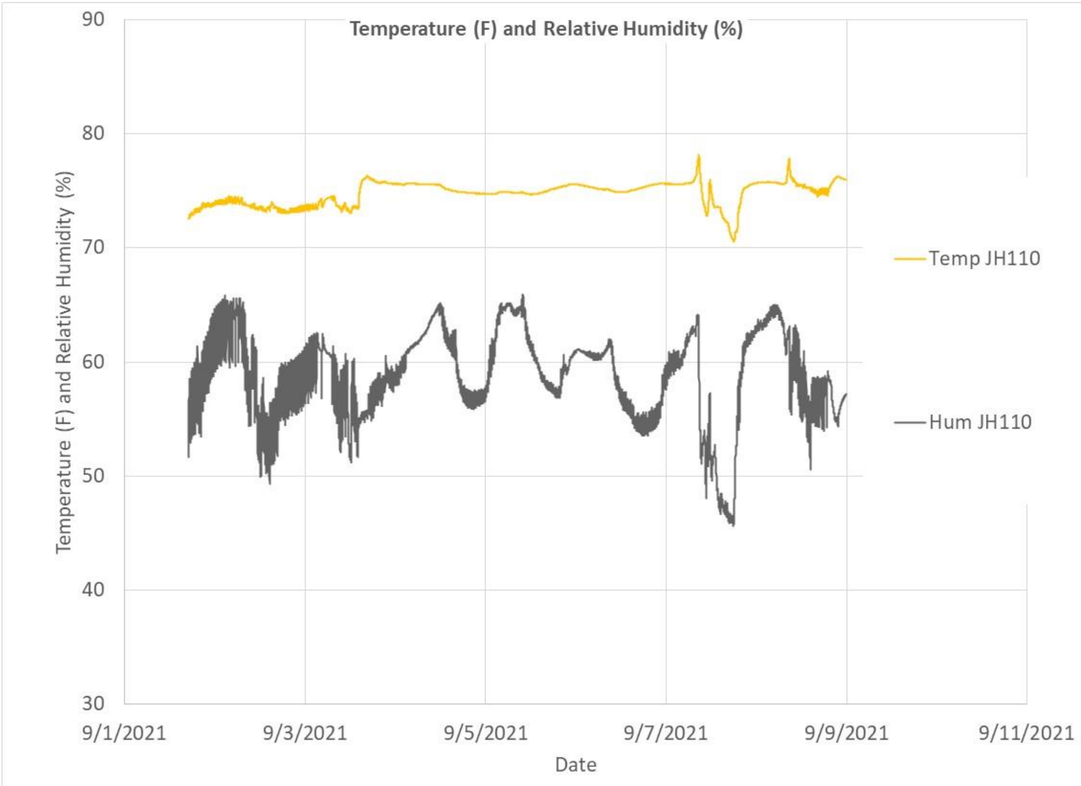
Friday September 3, 2021
CO2 JH110
VOC JH110
ACHs JH110
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
2500
2000
1500
1000
500
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM
Date/Time



Tuesday September 7, 2021
CO2 JH110
VOC JH110
ACHs JH110
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
2500
2000
1500
1000
500
0
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM



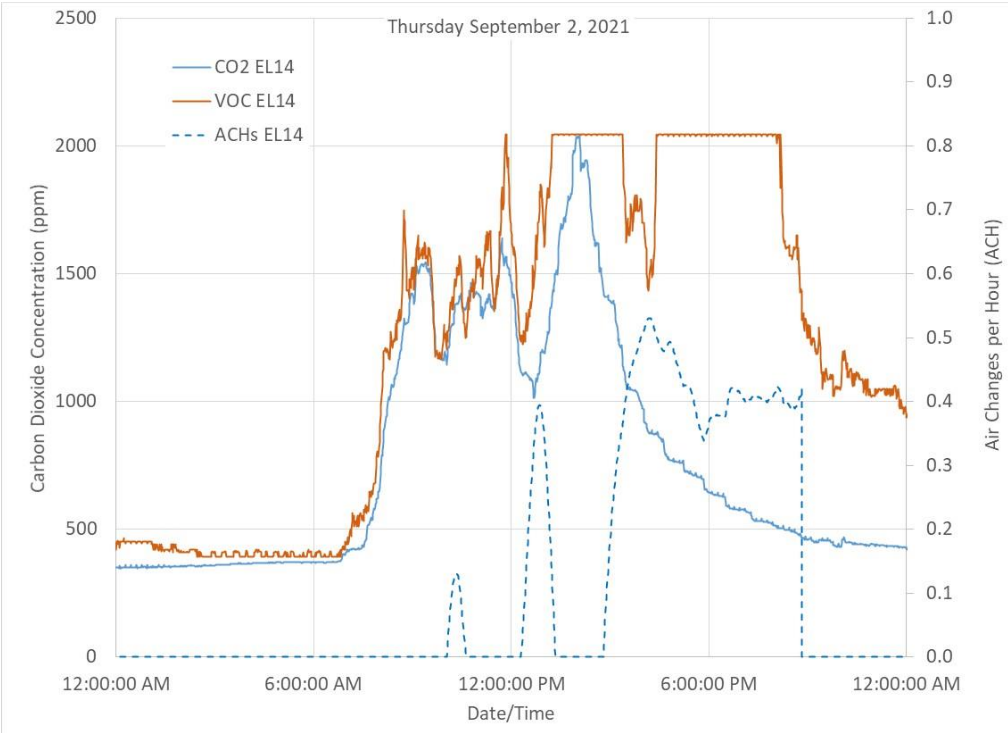
Wednesday September 8, 2021
CO2 JH110
VOC JH110
ACHs JH110
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
2500
2000
1500
1000
500
0
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM

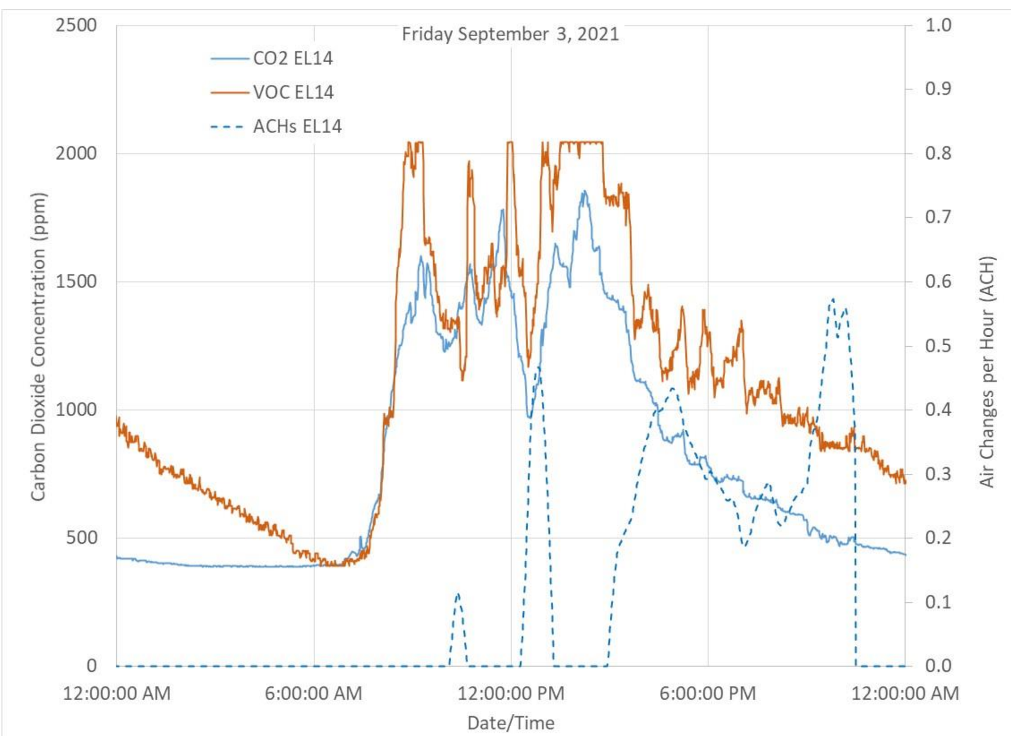


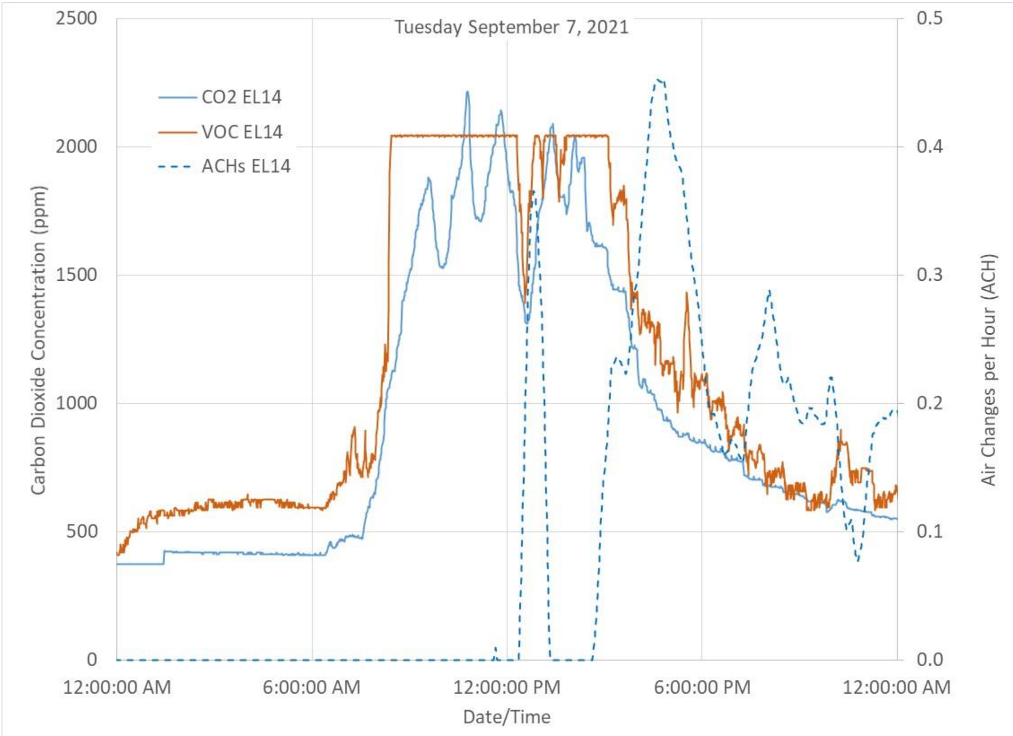
Temperature (F) and Relative Humidity (%)
90
80
70
60
50
40
30
Temperature (F) and Relative Humidity (%)
9/1/2021
9/3/2021
9/5/2021
9/7/2021
9/9/2021
9/11/2021
Date
Temp JH110
Hum JH110

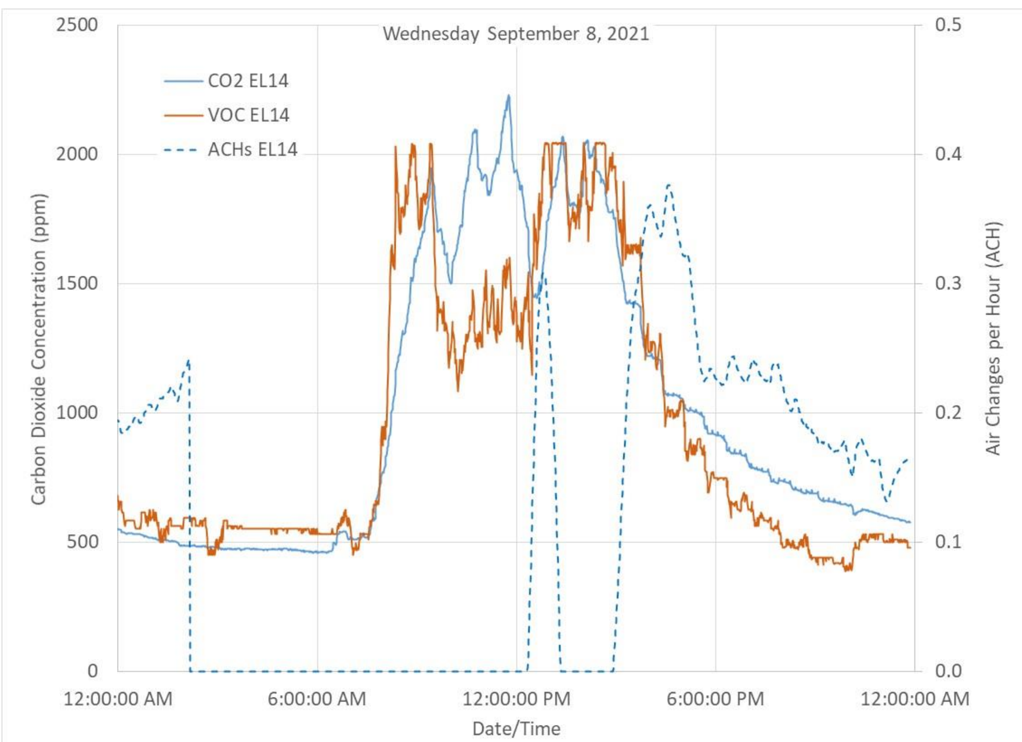
Appendix C: Elementary School Classroom: Daily Carbon Dioxide, total VOC and ACH Plots

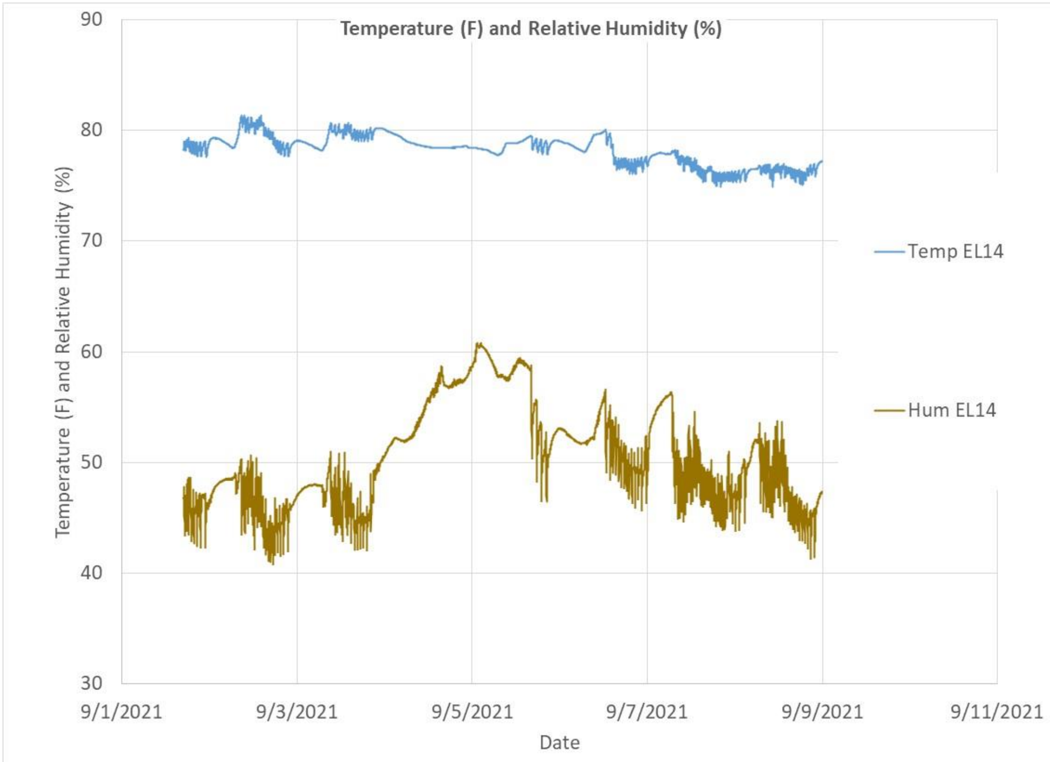
Kindergarten Classroom


Thursday September 2, 2021
CO2 EL14
VOC EL14
ACHs EL14
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
2500
2000
1500
1000
500
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM


Friday September 3, 2021
CO2 EL14
VOC EL14
ACHs EL14
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
2500
2000
1500
1000
500
0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM


Tuesday September 7, 2021
CO2 EL14
VOC EL14
ACHs EL14
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
0
500
1000
1500
2000
2500
0.0
0.1
0.2
0.3
0.4
0.5
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM


Wednesday September 8, 2021
CO2 EL14
VOC EL14
ACHs EL14
Carbon Dioxide Concentration (ppm)
Air Changes per Hour (ACH)
Date/Time
0
500
1000
1500
2000
2500
0.0
0.1
0.2
0.3
0.4
0.5
12:00:00 AM
6:00:00 AM
12:00:00 PM
6:00:00 PM
12:00:00 AM


Temperature (F) and Relative Humidity (%)
90
80
70
60
50
40
30
Temperature (F) and Relative Humidity (%)
Temp EL14
Hum EL14
9/1/2021
9/3/2021
9/5/2021
9/7/2021
9/9/2021
9/11/2021
Date

Appendix D: Smart Classroom IAQ and Comfort Conditioning System Configuration

Smart ventilation management of classroom and similar indoor environments with large occupancy variations requires flexibility to operate efficiently during low occupancy and high occupancy periods. An advanced concept for efficient management of IAQ and comfort (temperature and humidity) is presented in this appendix. The concept is based on three main components:

1) Smart ventilation system (CERV2, Figure D2)
2) Bulk fresh air "ERV", energy recovery unit (Renewaire HE1XINV, Figure D6)
3) Discrete, low temperature heat pump units with efficient turndown capacity control (Mitsubishi 1 ton, ducted "HyperHeat", Figure D7)

Figure D1 is a schematic of the classroom IAQ-Comfort concept. This concept is decentralized with independent IAQ and comfort control of each classroom. Plainfield School in New Hampshire renovated school classrooms with a similar distributed classroom IAQ and comfort conditioning system.

The system in Figure D1 is all-electric and provides an economic transition pathway to non-fossil fuel operation of school buildings. This concept can be installed on a room-by-room basis such that a rolling installation process can be developed. The Empire State Building renovation used a floor-by-floor renovation process that allowed the building to function. The Empire State Building was converted from one of the least efficient buildings to one of the most efficient.

Estimated cost for the Figure D1 concept is $40,000 per classroom with $20,000 for equipment cost and $20,000 for <u>local</u> HVAC installation labor. The smart ventilation system (CERV2 by Build Equinox, Urbana Illinois) monitors classroom IAQ and comfort, and controls operation of a bulk fresh air energy recovery unit (used during high occupancy) and four ducted heat pump conditioning units. The CERV2 has integrated CO_2 and VOC sensors for IAQ management, and integrated temperature/humidity sensors for comfort conditioning control.

An array of additional capabilities (see Figure D3), such as wireless open-window, open-door, occupancy, and remote IAQ sensors can be paired with the CERV2 unit. When windows are opened, for example, window sensors send a wireless signal to the CERV2, prompting the CERV2 to alter operation mode if necessary (eg, turning off heat pump conditioners). The CERV2 can also report window and door status to a central control dashboard monitored by Facility and Administration personnel.

Figure D4 shows smart phone and smart device ("Alexa") control of a classroom's IAQ and comfort. Varying levels of authorization allow teachers to manage individual classrooms, and authorized facilities personnel and administration to have access to dashboards for overall school facility management. The system includes local wireless control which is not dependent on WiFi internet operation. WiFi connectivity is also built into the system, providing remote access by authorized personnel from anywhere in the world to monitor and control building operations.

A ventilation supply duct fabricated from Koolduct (low GWP, UL listed foam duct board) integrates 3 one ton, ducted minisplit heads for distributed comfort across a classroom. A fourth ducted minisplit heat pump is directly integrated into the CERV2's output, and provides conditioning needs for low occupancy periods (80% of the year). The CERV2 and commercial ERV have MERV13 filtration for filtration of indoor air and outdoor air flows. UVGI (either in-duct or upper room) can be integrated into the system.

Maintenance efficiency is improved by automated scheduling. Reminders for filter replacement, remote diagnostics, and online troubleshooting provide local maintenance staff with access to information and expertise when needed. Each classroom's IAQ-comfort components (CERV2, ERV, and minisplit heat pumps) can be operated through a sequence of operations to identify problems.

The CERV2 unit includes OTA (Over-the-Air) upgrading that allows CERV2 to automatically upgrade its capabilities as new control options and features become available. The CERV2 archives all operational data, which is downloadable by building supervision into csv spreadsheet format. The archive includes all operational settings, sensor readings, and operation modes.

A primary difficulty with rooms that have large variations in occupancy is efficient operation during both low and high occupancy periods. The concept described includes multiple heat pump comfort conditioning units, and a variable speed fresh air energy recovery unit. Today's low temperature minisplit heat pumps (high capacity at -13F and lower outdoor temperatures) have the highest performance efficiencies (HSPF, Heating Season Performance Factor =10, and SEER, Seasonal Energy Efficiency Rating > 20) and are rapidly growing throughout North American buildings in all climate zones.

During low occupancy periods (0 to 7 people), the CERV2 supplies fresh air at 40cfm per person. A single minisplit heat pump supplies heating and cooling during low occupancy periods. The CERV2's internal CO2/VOC/T/RH sensors determine when additional fresh air is required and when heating or cooling are required. The CERV2 also recognizes when outdoor air is "nicer" than indoor air, automatically bringing in fresh, filtered air to the classroom.

As occupancy increases above 7 or 8 people, the CERV2 senses the need for additional fresh air, and begins operating the bulk fresh air ERV, energy recovery unit. Figure D7 shows a Renewaire unit with up to 1100cfm of air flow capacity. Combined with the CERV2's 300cfm air flow, a classroom would have the capability of accommodating up to 32 people (students, teacher and visitors) while maintaining 800ppm carbon dioxide concentration. High occupancy requires increased comfort conditioning due to both human loads and increased fresh air flow demand during extreme weather. Computer simulation of energy loads described below show that an unoccupied classroom in central Illinois needs 10,000Btu/h while a fully occupied classroom requires 40,000Btu/h during winter design day conditions. At less extreme conditions, the minisplit heat pumps can be efficiently modulated by the CERV2 to very low capacity levels.

The following discusses results of an energy analysis for an example classroom.

A typical classroom is assumed to be 30ft^2 per student plus 150ft^2 for teacher. A 20 student classroom would total 750ft^2. An exterior wall area of 250ft^2 (R9 insulation) with 100ft^2 of conventional, double glazed windows and 750ft^2 of roof area (R12 insulation) are assumed.

The classroom is assumed to be in Urbana IL and simulated with ZEROs building simulation model (see BuildEquinox.com/ZEROs).

Healthy indoor environments require 40cfm per person of fresh air to maintain indoor carbon dioxide concentration below 800ppm, for a total of 840cfm for 20 students plus 1 teacher. A 180 day school year would have approximately 1800hours of occupancy, assuming 10 hours per day of full operation. The remaining hours are unoccupied. Overall, a classroom is fully occupied 20% of the year, and unoccupied for 80% of the year.

The following summarizes results:

Occupied electrical energy = 3845kWh/y (20% of year)

Unoccupied electrical energy = 3000kWh/y (80% of year)

Total annual electrical energy usage = 6845kWh/y; estimated utility cost = $820/y ($0.12/kWh)

Winter Design Day capacity = 40,000Btu/h (occupied); 12,000Btu/h (unoccupied)

Summer Design Day capacity = 20,000Btu/h (sensible, occupied); 12,000Btu/h (latent, occupied)

= 12,000Btu/h (sensible, unoccupied); 800Btu/h (latent, unoccupied)

The annual predicted energy load is composed of 60% energy usage during high occupancy loading and 40% energy usage during low occupancy loading. Annual estimated utility cost per classroom is $820, or approximately $40 per student per year.

A 5000 to 6000Watt solar system could supply annual energy requirements for the above classroom. Estimated installed cost would be $10,000 to 12,0000 per classroom and require 500sqft of roof space (relative to 750sqft classroom). Note that non-profit institutions would be unable to take advantage of tax credits, SRECs (Solar Energy Renewable Credits), depreciation, and other financial tools to further enhance installation value of solar energy. Third party or a “power purchase providers” can capitalize solar projects for school districts, providing school districts with stable, discounted renewable energy electric rates.

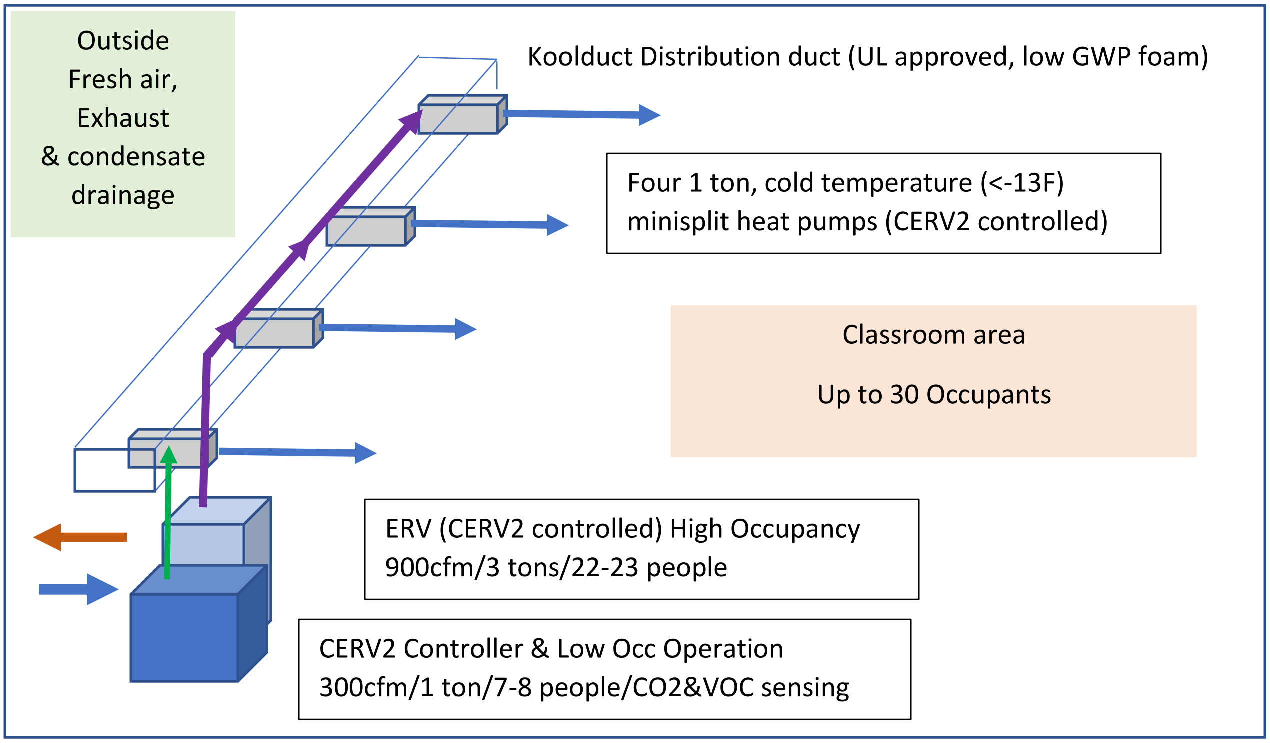


Figure D1 Schematic of classroom ventilation and comfort conditioning concept consisting of a smart ventilation unit, bulk fresh air energy recovery unit, and discrete heat pump ("minisplit") comfort conditioning units.

Figure D2 CERV2 smart ventilation and energy recovery unit.

Figure D3 Smart wireless sensors communicate with CERV2 to activate operational modes. Battery-free wireless wall switch, ACT (active circuit transmitters, low and high voltage), occupancy sensor, CO2/T/RH sensor, T/RH sensor, CERV-IR (interface relay and thermostat interface), and window/door sensor are a few of the sensors and actuators that communicate with the CERV2.

Figure D4 System control (by authorized users) for all rooms with local controls, administration dashboard, smart phone app, and smart devices (eg, Alexa).

M-SERIES | **SUBMITTAL DATA: PEAD-A12AA7 & SUZ-KA12NAHZ**
12,000 BTU/H HORIZONTAL-DUCTED HEAT PUMP SYSTEM | MITSUBISHI ELECTRIC

Job Name:	
System Reference:	Date:

Indoor Unit: PEAD-A12AA7	Outdoor Unit: SUZ-KA12NAHZ
	

Figure D6 Mitsubishi “hyperheat” ducted 1 ton, low temperature minisplit heat pump.

Figure D7 Renewaire HE1XINV energy recovery unit with 250 to 1100cfm air flow range. Unit dimensions 50” high by 36” wide by 24” depth.