Improving Design, Commissioning, Operation and Maintenance in New Residential Ventilation Systems

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1 ABSTRACT

Single-family and low-rise multifamily homes in the United States have become tighter to save energy and enhance comfort. To ensure acceptable indoor air quality (IAQ), mechanical ventilation is also required. As these systems become commonplace in the U.S., various improvements and updates have been made to codes, standards, and voluntary programs such as ASHRAE Standard 62.2, International Mechanical Code, International Residential Code, USEPA Energy Star Home and Indoor Air Plus, and USDOE Zero Energy Ready Homes.

This paper will summarize historical and current issues and challenges to improvement related to design, commissioning, operation, and maintenance of whole-house ventilation systems in new single-family, low-rise multifamily, and factory built dwellings. It presents findings from field research over the past 30 years on occupied dwellings. A discussion of improvements that were made, are underway, and may be coming in the future is provided. Incorporating ventilation into codes and standards is a critical path, as are the broader implementation challenges in the "real world" over the dwelling's useful life cycle. This paper will help to identify what progress has been and needs to be made.

In the U.S., the most popular ventilation system is an exhaust fan capable of continuous operation. These are often quiet, energy efficient, dual-duty fans that are also used for local exhaust in bathrooms, laundry rooms, or kitchens. Many homes use their central forced air heating and cooling systems to distribute, filter, and temper outdoor air that is ducted directly to the return side of the forced air system, either passively or sometimes with a dedicated outdoor air fan to ensure the correct air flow. These supply ventilation systems are generally harder to commission because air intakes are often not easily accessible and testing is more prone to issues of repeatability.

The introduction of variable speed blowers may increase commissioning challenges associated with flow rate measurement. Zonal ductless heat pumps may require exhaust fans or balanced dedicated outside air systems, operating in unison while maintaining interior pressure balance, typically using energy recovery ventilators or heat recovery ventilators, with pressure taps and fan calibrations and electronically commutated motors (ECMs). Systems with real time digital flow indicators will assist designers, builders, code officials, and HVAC contractors. Smarter ventilation controls may help to provide improved commissioning, operation, and maintenance, and help stakeholders from design to long-term replacement.

The paper will highlight opportunities for improvements in control labelling; optimizing designs for different climates; training of HVAC technicians and all critical stakeholders; ventilation controls; and lower-cost, reliable air quality sensors. These improvements must focus on every link in the chain to improve on "build tight, ventilate right."

2 KEYWORDS

Ventilation, Indoor Air Quality, Residential, Occupant Behavior

3 INTRODUCTION

The concept of "build tight, ventilate right" was first introduced in voluntary energy programs in the Pacific Northwest, in 1983 and later 1986 in energy codes and standards, by the Canadian R2000 program and the Northeast Power Plan Model Conservation Standards. (Hales et al., 2014) The Bonneville Power Administration (BPA) funded research demonstration programs working with the state energy offices of Washington, Oregon, Idaho, and Montana. (Lubliner et al., 1986) (Lubliner et al., 2002) These programs worked with the residential construction industry to build homes and monitor energy use and indoor air quality (IAQ). Theses RD&D programs also collected builder construction costs and occupant feedback related to the building and HVAC system installed.

The first of these RD&D market transformation efforts (1984) was called the Residential Standards Demonstration Program (RSDP), which focused on single-family, site-built dwellings. Later in the 1980s, the Residential Construction Demonstration Program (RCDP) began to focus on specific technologies to build single-family homes and low-rise (three stories or less) multi-family "garden style" units. The Model Conservation Standards (MCS) and early building science efforts (1983) targeted performance envelope tightness of roughly 2.0 air changes per hour and employed air-to-air heat exchangers. Later, non-heat recovery and less tight building envelopes were introduced as more cost-effective ventilation options. Utility programs provided financial incentives to encourage builders to build these homes. (Lubliner et al., 1988) (Lubliner et al., 1990) (Palmiter et al., 1992) (Palmiter et al., 1996) (Washington State Energy Office, 1991) (Vine et al., 1986)

In 1986, Washington state introduced many of these energy-saving technologies and building systems into the Washington State Energy Code (WSEC). These included requirements for heat and non-heat recovery whole-house ventilation systems and tighter building enclosures, with field performance testing of envelope leakage and ventilation system flow rates at completion of construction.

A variety of envelope air sealing measures were employed such as the use of 6 mil polyethylene vapor retarder with acoustic sealants which was a common practice in the early Canadian R2000 program. Dr. Joe Lstiburek's "airtight drywall approach" (ADA), was later employed, and found to be a more acceptable solution, for many energy efficient builders in Washington State. The ADA uses the continuous drywall and includes gaskets &/or caulk, to control air leakage, bulk moisture transport and moisture diffusion from the inside the home into exterior wall assemblies. The ADA uses continuous ceiling drywall over interior partition walls to limit air leakage limit bulk and diffusion moisture transport, between the attic and partition wall.

Balanced heat or energy recovery ventilation were more typically installed in tighter envelope homes (<2 ACH50PA). For other envelope tightness levels (>2-5 ACH50PA), quiet whole house exhaust fans where employed with occupant-controlled unfiltered air inlet vents in windows or filtered inlet vents in exterior walls. Often the whole house exhaust fan served "double duty" and was located in a bathroom to also provide intermittent ventilation to control moisture and odours. Furnace supply systems to a return HVAC duct was another as later found more challenging option in terms of design, commissioning and occupant maintenance and operation.

In the late 1980s, BPA expanded these RD&D efforts to include federally regulated Housing and Urban Development (HUD)-code manufactured housing, Super Good Cents, and Manufactured Housing Acquisition Program (MAP). In 1994, HUD-manufactured homes introduced whole-house ventilation system requirements as increased thermal efficiency standards were improved as part of HUDs Manufactured Housing Construction and Safety Standards (MHCSS). (Lubliner et al., 2005) (Lubliner et al., 2003) (Palmiter et al., 1992) (Stevens et al., 1996) (Zieman et al., 2003)

The site-built efforts were based in part on ASHRAE Standard 62.2, which was evolving with requirements for whole-house mechanical ventilation; better performing, quieter, and lower fan energy exhaust and balanced ventilation system; and improved occupant system control requirement and labelling. Since then, the WSEC and other energy codes such as the IECC/IRC/IMC and ASHRAE 62.2, are constantly being improved and refined per the build tight, ventilate right concept.

Research conducted in the past decade by the Northwest Energy Efficiency Alliance, Washington State University, DOE national labs, Building America, and others have continued to study and document these challenges and look for solutions that improve on design, installation, commissioning, occupant/building owner education, and operation and maintenance (O&M) as critical requirements to strengthen the weak link in the chain.

Much of this research is focused on site-built, single-family homes; however, there is a critical need to look at apartment units and factory-built homes as well because they may have higher occupancy levels per unit volume. In multifamily, there is also a need to address compartmentalization between units. As government and utility efficiency programs, ASHRAE standards, and building codes seek tighter envelope requirements, improved duct air sealing, moving leaky HVAC forced air centrally ducted systems into the conditioned space, or shifting to typical ductless from typical U.S. centrally ducted HVAC systems, less duct leakage-induced infiltration may increase challenges and opportunities, and make it even more critical to ventilate right..

4 RECENT RESEARCH BY DWELLING SECTOR

4.1 Site Built Single Family

Northwest Energy Efficiency Alliance (NEEA)/Washington State University Energy Program (WSU): This report presents the findings and conclusions of the Pacific Northwest Residential Ventilation Effectiveness Study in houses with low air leakage. NEEA commissioned WSU to conduct the study, which included a total of 29 single-family dwellings in Washington state. (Eklund et al., 2015) (HM Government, 2011)

Carbon dioxide (CO_2), relative humidity, and temperature were monitored in multiple rooms during the heating and shoulder seasons. Residents performed week-long experiments with bedroom doors open or closed and ventilation systems on or off. Residents were asked to keep journals of these actions and use of auxiliary fans. The paper also reports the results of one-day tracer gas decay tests done on 26 of these homes.

The measured effectiveness of the five types of ventilation systems are compared in terms of removing site-generated CO_2 and tracer gas. The paper also assesses the impact of house tightness on ventilation performance and the fan electricity invested in providing ventilation. Resident knowledge of their ventilation systems, maintenance of systems, and as-found control setting impact on ventilation effectiveness are also reported.

All ventilation system flow rates were measured during initial field visits, occupants surveyed reported run-time systems and ventilation and O&M, IAQ perspectives were identified in these homes. Field technicians attempted to adjust run time and flow rates to bring the homes into compliance with ASHRAE 62.2, and identify root causes of non-compliance issues when possible.

Some dwelling used centrally ducted HVAC (typically condensing gas furnaces or air source heat pumps). Other dwellings used non-ducted zonal heating. Dwellings were selected to represent five ventilation system types typical in the PNW new construction energy efficiency program, where targeted envelope leakage was 2 to 5 air changes per hour at 50 PA. System types included heat and non-heat recovery systems. Heat recovery ventilation (HRV) systems were either Dedicated Outside Air Systems (DOA)or connected to the central HVAC. Exhaust-only whole-house fans were typically located in bathrooms. Some had occupant-operated unfiltered window inlets to provide outside air; others had larger openings through the wall for filtered inlets that are more typically used in Europe.

The analysis provides an initial response to the research questions by summarizing the results of the short-term analysis, considering the energy use of the ventilation systems, conducting an analysis of the long-term data for the primary bedroom for six night hours (midnight to 6 a.m.), and summarizing the field work to ascertain occupants' knowledge of their ventilation systems. The initial findings related to O&M and commissioning include:

- Measurements show the natural ventilation is inadequate when the ventilation systems are off and that the ventilation systems provide a clear benefit when they are turned on.
- The field work provides evidence that lack of occupant knowledge about the proper operation and maintenance of the ventilation systems can negatively influence ventilation system effectiveness. Over time, this could result in significant deterioration in system performance.
- There is a fairly wide variation of ventilation fan electricity use both within and across ventilation system types. The exhaust systems have the lowest direct energy use followed by the energy recovery ventilator (ERV) or HRV systems. The ventilation systems integrated with central forced air systems have the highest use though there is wide variation.
- The fact that over 90% of the occupants were satisfied with their system performance and IAQ even though over half of them did not have enough knowledge to operate or maintain the system is troubling, especially where the lack of knowledge correlates with unresolved O&M issues found. It means that occupant satisfaction is not a good indicator of ventilation system performance. Further, if something was seriously wrong with the system, the home occupant would probably not be able to recognize it or take appropriate action. (Figure 1) provides some indication of the O&M issues related to the occupants' understanding of the system in their dwellings.
- Problems found on initial audit include controls not set to deliver sufficient ventilation to meet standards, inaccessible controls, filters and fan housings jammed with dust and

lint, disconnected ducts, HRV operation wired backwards, and ductwork never completed. Complexity of controls was also often problematic.

- The use of air inlet vents provides greater spatial (space distribution) and temporal (time distribution) ventilation effectiveness benefits only if they are left opened by occupants (most were found closed). Air inlet vents were not required in ASHRAE Standard 62.2; however, they had been required prior to 2012 in the WA state energy and IAQ codes for homes without central HVAC systems.

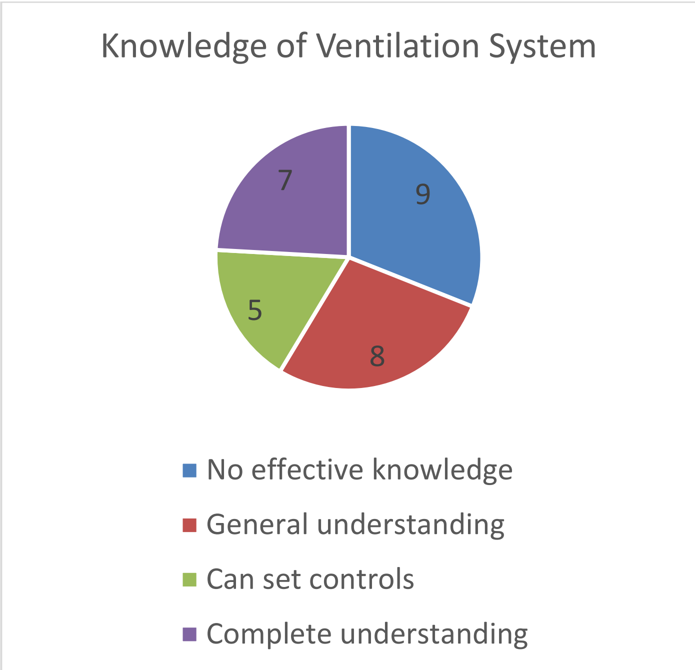

Figure 1: Occupant Ventilation Knowledge Groups (Eklund et al., 2015)

U.S. DOE Building America and California Energy: Similar results were found in two other field studies conducted to gather information regarding measured IAQ in occupied, new U.S. homes built after 2013. The ongoing Building America New Home IAQ study is collecting data from 20 to 30 homes in each major climate zone in the U.S. California's Healthy Efficient New Gas Homes (HENGH) project analysed 70 homes in California. Ventilation system data from both studies are presented here to provide insight into residential mechanical ventilation system operation and maintenance, and associated pollutant concentrations associated with envelope, duct tightness, HVAC operation, and occupant activities associated with the generation of IAQ pollutants.

In these studies, the most popular approach to providing whole-house ventilation is to use an exhaust fan capable of continuous operation. These are often dual-duty fans that are also used to provide local exhaust in bathrooms, laundry rooms, or kitchens. New, quieter, (low sone) and better-performing exhaust fans employing ECM blowers are generally more energy efficient than traditional exhaust fans.   They are often as the easiest way to add ventilation to a home whether for new construction or in retrofit situations. They are also easier to commission with readily available, inexpensive measurement equipment because the air intake is readily accessible in most applications.

Some homes use their central forced air heating and cooling systems to distribute, filter, and temper outdoor air that is ducted directly to the return side of the forced air system. This is done passively or sometimes with a dedicated outdoor air fan to ensure the correct air flow. These supply ventilation systems are generally harder to commission than exhaust ventilation

systems because air inlets and associated ducting are usually not easily accessible. An advantage of these systems is that there deliver relatively high air flow rates to all typically occupied rooms that may include HVAC system filtration. If the HVAC system is properly balanced this can result in greater spatial ventilation effectiveness “distribution” of outdoor air to all occupiable zones. When the HVAC system thermostat is not calling for heating a reduction in temporal ventilation “run-time” effectiveness can result. When registers deliver too cold supply air, it may can cause greater thermal discomfort to occupants from cold drafts, who may then curtail the use of the ventilation system during colder weather.
There is some regional variability in the use of exhaust and supply systems, with supply systems being more common in southern/humid climates. The introduction of variable speed blowers may increase commissioning challenges associated with flow rate measurement and may require additional HVAC manufacturer guidance.

Balanced ventilation systems combine supply and exhaust fans that are set to operate in simultaneously, maintaining interior pressure balance. Many combinations of exhaust and supply fans can be commissioned to be balanced, along with fully integrated systems such as HRVs or ERVs. Balanced ventilation, including HRVs and ERVs, are installed less frequently than exhaust or supply systems, mostly due to added cost and complexity. Balanced ventilation systems are more common in colder climates where there are more energy-related advantages to using heat recovery. There is a further divide about when to specify HRVs for sensible energy savings and ERVs that also exchange moisture between incoming and exhausting airstreams.

For the HENGH study, all but two of the 55 exhaust systems (96%) were in compliance when operating. The other 15 systems in the study were either supply ventilation systems that could not be measured or were intermittently used exhaust systems whose operating times were not known. In these California homes, only a quarter of the systems were operating as intended when technicians first arrived at the homes; most were turned off, primarily due to poor labelling. When operating, the systems moved 50% more air than the minimum requirements, and IAQ was acceptable in these homes. In addition, homes with mechanical ventilation systems operating have higher IAQ satisfaction.

In the Building America study, the preliminary total compliance rate for all homes was only 48%, but significant differences existed among regions. Compliance rates were 64% in Colorado, 57% in Oregon, and only 15% in the southern states. Noncompliance was primarily due to installation or operation errors, especially for ventilation systems connected to central HVAC ductwork. Balanced supply intake systems with exhaust non-heat recovery ventilation typically met ASHRAE Standard 62.2 compliance because of exhaust fan operation and adequate run time. Similar to the California HENGH study, in the southern states most systems were not operating upon arrival to the homes for the inspection visit. The exceptions were ERVs, which were always operating. There were some installation and maintenance issues, but the ERVs were on. Exhaust fans were always found off, with no switch labelling. The few ventilating dehumidifiers encountered were also switched off. Central fan integrated systems (CFIS) with fan controllers tended to not function due to component failure, while CFIS systems without controllers typically did function. These baseline research projects currently underway identify challenges and opportunities with regard to residential mechanical ventilation systems in the U.S. (Lubliner et al., 2020) (Sonne et al., 2015)

4.2 Low-Rise, Site-Built Multifamily

Recent communication with a large public housing authority (PHA) located in Washington state responsible for the HVAC commissioning, maintenance, and operation of thousands of low-income dwelling units provides useful real-world insights related to whole-house mechanical ventilation systems. Due to COVID-19, the PHA was unable to conduct their normal annual operational inspection and fan housing cleaning and filter servicing for almost three years. These systems are single zone ERVs or whole-house/bathroom exhaust ventilation systems, designed to operate continuously to ASHRAE Standard 62.2. The operational controls are located within the fan housing, requiring the removal of a grill to shut them off. The occupants are instructed to "let it run" as part of move-in orientation and after servicing visits, as required. Recent visits to 450 to 500 of the 1,500 low-rise, multi-family, and town home dwelling units identified the following:

- Roughly 5-10% of the systems encountered were off or inoperable. This is a positive outcome when compared to occupant-controlled systems, and suggests opportunities for improvement within the low-rise, multifamily public sector, and wherever there are regular maintenance and occupant outreach programs.
- Resource conservation specialists sometimes receive complaints regarding poor outdoor air introduced, especially in areas with localized sources of outdoor pollutants.
- Areas with larger sources of pollutants tend to have higher filter and core cleaning maintenance needs for ERVs. No ERV cores were found to be significantly plugged.
- Both insert screens and foam, sponge-type filters tend to load up larger air and duct particles, and are designed to protect the equipment, not filter fine particles.
- Higher filtration systems require additional servicing costs and frequencies.
- Servicing visits do not include measurement of air flow to verify correct operation,
- ERV systems were shut off more often by occupants due to cold air blowing out of the outside preheated air supply grill located in the ceiling of the main living area.
- Both systems were shut off due to noise or occupant concern about wasting energy from the system operation (typically by seniors).
- Many occupants do not look at any of the educational information provided related to the reasons for O&M.
- Less than 5% actively clean their systems or replace filters on their own.
- A variety of non-English-speaking occupants encounter more operational and educational challenges.
- O&M issues are greater with the ERVs compared to exhaust fans, due to more complex operation and filter/core servicing requirements.
- Replacement parts when needed continue to be hard to procure. Replacement parts and new units are rarely, but sometimes, required when occupants interact with the equipment and damage the inexpensive plastic components. Although this repair situation is not very typical (estimated less than 2%), it is challenging and expensive in terms of materials and labor, typically requiring a re-visit to repair. Better quality system components help reduce costly repairs and servicing delays.

4.3 Manufactured HUD-Code: (USDOE EIS)

Manufactured HUD-code homes are regulated at the federal level by HUD's Manufactured Home Construction and Safety Standards (MHCSS). The MHSCC pre-empts local governments and states from changing these requirements. The energy standards have not been revised since 1994, and ventilation requirements remain largely unchanged in code and practice. Recently, Manufactured Housing Construction Safety Standards (MHCSS) allowed ASHRAE Standard 62.2 to be used for compliance but this an option and not typically selected by manufactures desiring to minimize the selling price of their homes to retailers. In the past few years, over 100,000 HUD-code homes have been produced by roughly 120 factories. Three major corporations own the majority the factories. Many research projects recommend improvements to help built tight, ventilate right. In the previous presidential administration, DOE rulemaking (Anast et al., 2022) was stalled by controversy associated with build-tight requirements because of issues with the minimum HUD MHCSS requirements to ventilate right, as noted in the following references. (Lubliner et al., 2000) (Lubliner et al., 2005) (Lubliner et al., 2003) (Palmiter et al., 1992) (Persily et al., 2003) (Stevens et al., 1996) (Zieman et al., 2003)

5 DIRECTIONS TOWARD IMPROVEMENT

5.1 ASHRAE and the Home Ventilation Institute

ASHRAE Standard 62.2 is improving O&M and installation best practices. The standard already includes an equivalent ventilation compliance approach that allows for the broader use of smarter ventilation controls. These controls may take into account dynamic interaction of stack effect and occupancy levels. The newly formed 62.2 best practice working group is looking to improve installation as well as O&M labelling and education.

Two recent proposals from Dr. Max Sherman are currently under discussion. These efforts will look at more specific O&M requirements and variation of outside air minimum flow rates based on source control with respect to pollutants of most concern.

There is a history of controversy within ASHRAE Standard 62.2 about the goal to just provide equipment performance capability to meet the intent of the standard vs. helping to ensure it is operated and maintained by the dwelling occupant and/or building owner with performance commissioning and greater O&M requirements.
https://www.ashrae.org/technical-resources/bookstore/standards-62-1-62-2

Members of the Home Ventilation Institute (HVI) continue to improve industry installation practices with improved installation manuals and occupant operation guidance. Labelling education efforts are also underway to meet installation and O&M challenges. These efforts specify that residential ventilation systems are provided with an on-off switch accessible to occupants, yet in both the Building America and HENGH studies, field technicians found that these switches are often unlabelled or poorly labelled, and that occupants did not know what the function of the switch was. Many systems were turned off, and in one case the field team could not find a switch although an exhaust fan was installed. These operation and labelling deficiencies lead to most systems being inoperative. This is another area that urgently needs improvement, either by changing access to switches or much better labelling requirements.
https://www.hvi.org/newsroom/press-releases/home-ventilating-institute-launches-new-label/

5.2 Washington State Energy Code

The Compliance Certificate for the 2018 Washington State Energy Code─Residential (WSEC-R) or something similar is required to be completed and signed off before issuing a certificate of occupancy at the final inspection. A correctly completed Compliance Certificate is designed to be permanently affixed in the home, typically near or on the load canter box. A correctly completed certificate provides significant assurances by documenting how to ventilate right when the occupant moves into the dwelling. Included in that certificate is commissioning documentation of the whole-house ventilation system. This includes the installer and builder document and sign off on measured flow rates and control strategies, and verification that the O&M instructions have been provided to the building occupant. It is not known to what extent builders, HVAC subcontractors, and others responsible for the installation and/or testing are correctly completing this certificate. It is also not known the extent to which the Authority Having Jurisdiction is requiring its completion and reviewing the results at the final inspection. A copy of the WSEC-R Compliance Certificate and instructions for completing the certificate are available at:

- https://www.energy.wsu.edu/Documents/Certificate%202018%20WSEC_rev%207-21-21.pdf

- https://www.energy.wsu.edu/Documents/Compliance%20Certificate%20Instructions%202018%20WSEC_rev%2007-21-21.pdf

The new proposed WSEC-R to become effective in 2023, seeks to:

1) not specifically require the currently employed compliance certificate shown in Figure 2.

2) Require tighter envelopes moving the minimum leakage rates from 5 Air changes per hour at 50 pascals (ACH@50PA) to 3 ACH 50PA).

3) Explicitly allow for the use ASHRAE standard 62.2 2019 as an alternate compliance approach to WA state modification based on I-codes.

The current WA minimum ventilation rates are based on the IRC and can be typically lower than ASHRAE 62.2-2019 because they a whole house minimum flow rate I-codes sizing criterion of 1% or the floor area instead of 3% as required in 62.2-2019. Unlike ASHRAE-62.2, the current minimum ventilation rates also do not explicitly allow for equivalent ventilation strategies, such as smart ventilation control that seek equivalent ventilation by adjusting the flow rates based on occupancy or natural stack leakage. This proposal to explicitly allow for the use of 62.2-2019 as an option was also accepted for the 2023 WSEC-R. The author believes that the Compliance Certificate and allowing the 62.2-2019 option will help improve IAQ and support the “build tight and ventilate right” philosophy in homes built under the WSEC-R

Building Leakage Testing (R402.4.1.2)	
Dwelling unit leakage test calculated design target:	___________ ACH @ 50 Pa
Dwelling unit leakage test, measured results:	___________ ACH @ 50 Pa
Whole Building Leakage test (R2 non-corridor only) design target:	_________ CFM/sf @ 50 Pa
Whole Building Leakage test (R2 non-corridor only) measured:	_________ CFM/sf @ 50 Pa
Do building leakage tests include GPS and time stamp verification?	Y or N
Whole House Ventilation System Measured Flow Rates (M1505.4 IRC-WA)	*Circle one*
Are the system controls correctly labeled?	Y or N
The Whole House Ventilation (WHV) system operation and maintenance (O&M) instructions were provided to the building owner?	Y or N
Provided to: ____________________________________ on _________________(date)	
Whole House Ventilation System Type: (Circle one) (1) Whole house exhaust fan, location _______________________________ (2) Balanced HRV/ ERV, location ___________________________________ For R2 low-rise, serves more than one unit? (3) Supply or HRV WHV integral to the air handler. Describe system control sequence of operations or reference to design submittal: ______________________________ ____	 Y or N
Specify run-time: _______ hours per day	_____________ CFM
WHV calculated design minimum flow rate per plan submittal:	
WHV measured min flow rate at commissioning: Exhaust _______CFM, Supply _______CFM	
Do WHV flow tests include GPS & time stamp verification?	Y or N
HRV/ERV sensible heat recovery efficiency: __________	
Commissioning Notes:	
Other Mandatory Requirements	*Circle one*
All other mandatory requirements of WSEC-R have been met?	Y or N

Figure 2: 2018 WSEC-R Compliance Certificate, "Build Tight, Ventilate Right" Section

5.3 Smart Ventilation Control (SVC) Systems and IAQ Monitors

SVC research continues to provide opportunities to save energy, improve the indoor environment, and build tight and ventilate right. (Less et al., 2016) (Less et al., 2014) (Lubliner, 2013) (Lubliner et al., 2016) (Martin et al., 2018) (Sherman et al., 2011) (Turner et al., 2012) (Walker et al., 2014)
Some concepts are being developed using the Internet of Things (IoT) and less sophisticated non-IoT controls.

Listed here are some of the concepts that may improve the value proposition for SVC:

- Furnace run time (considers parasitic fan energy, central filtration, supply ventilation)
- Indoor/outdoor temperature (stack and potential site-modified wind impacts)
- Occupancy density levels (typical normal and special occupant events)
- IAQ sensors (based on IAQ pollutants of concern: PM2.5, formaldehyde, acrolien etc.)
- Commissioning, O&M (flow rates, flow balance, parasitic fans)
- IAQ sensor integration, (happy vs. Mr. Yuk icon for simple occupant education)
- Outdoor operation curtailment (wildfires, pollen, ozone, toxic plumes, etc.)
- Operation for medical needs (asthma, chronic obstructive pulmonary disease, COVID, etc.)
- Moisture and relative humidity (optimizes diurnal and/or seasonal operation in different climates.
- Demand control (managing utility time-of-day rates and electric grid loads)
- Energy saving (parasitic fan energy optimized and other strategies reduce energy use)

- Window state monitoring (advises when to open for IAQ, humidity, and diurnal cooling)
- Algorithms that integrate some of these ideas into simple home automation platforms or a series of interactive control learning algorithms

6 CONCLUSIONS

Ventilating right will continue to be challenging; however, codes, standards, and energy efficiency program opportunities will continue to improve commissioning protocol/documentation, equipment labelling, occupant/builder owner education, smarter ventilation controls, and IAQ sensors.

One hypothesis that has developed over the past 30 years was shared with this author by friends and pioneers in residential ventilation research: As homes get tighter (<2.0 ACH 50), occupants will begin to see the need to ensure that their ventilation systems are correctly installed, commissioned, operated, and maintained. However, the perception of IAQ issues and the desire to understand and correct O&M ventilation systems by dwelling occupants is even more challenging. Many recognize poor IAQ when they enter a “built tight and ventilated wrong” dwelling with pollutants of concern, while occupants are more de-sensitized and/or do not understand the need to ventilate right.

It took over 60 years of evolving standards, laws, and technologies to get occupants of cars to recognise the clear health and safety implications of using seat belts. The health and safety implications of the more complex topic of “build tight, ventilate right” will also take time before it becomes standard practice in the construction industry. Larry Palmiter, Principal and Senior Scientist with Ecotope, once said, “You can do a half-assed job of ventilation if you have a half-assed leaky envelope, but that’s not where we need to go if we want to ‘build tight, ventilate right.’” Building tight and ventilating right in single-family and low-rise multifamily site-built and factory-built dwellings will continue to evolve as equipment, design, installation, maintenance, and operation continue evolve to address this need. Wisdom is gained from real world experiences, data and good engineering and from making real world mistakes and fixing them,

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