Demonstrating the Effectiveness of an Aerosol Sealant to Reduce Multi-Unit Dwelling Envelope Air Leakage

Conservation Applied Research & Development (CARD)
FINAL REPORT

Prepared for: Minnesota Department of Commerce, Division of Energy Resources

Prepared by: Center for Energy and Environment

Prepared by:

David Bohac
Ben Schoenbauer
Jim Fitzgerald

Center for Energy and Environment
212 Third Avenue North, Suite 560
Minneapolis, MN, 55401
Phone: 612-335-5858
website: mncee.org
Project Contact: David Bohac

Curtis Harrington
Jose Garcia
Mark Modera

Western Cooling Efficiency Center
215 Sage Street, Suite 100
Davis, CA, 95616
Phone: 530-902-3890
website: wcec.ucdavis.edu
Project Contact: Curtis Harrington

Contract Number: 73096

Prepared for Minnesota Department of Commerce, Division of Energy Resources
Mike Rothman, Commissioner, Department of Commerce
Bill Grant, Deputy Commissioner, Department of Commerce, Division of Energy Resources
Mary Sue Lobenstein, Project Manager
Phone 651-539-1872
Email MarySue.Lobenstein@state.mn.us

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DISCLAIMER

Abstract

An innovative aerosol sealing process has been developed to significantly reduce multifamily building envelope air leakage. The technology was adapted from an established process for sealing duct leaks. For envelope sealing, an aerosol sealant is sprayed into an apartment unit that is pressurized by fans installed in a hallway or an exterior door. As the air and sealant particles are forced through leaks, the sealant sticks to the edges of the gaps and gradually fills the openings.

A field demonstration and modelled study has been conducted to measure envelope air leakage reduction and estimate energy savings for air sealing new and existing multifamily units in Minnesota buildings using the aerosol process. A total of 18 units were sealed in three new construction buildings. The sealing process typically required 60 to 90 minutes of injection and resulted in envelope leakage reductions of 67% to 94%. The envelope leakage ranged from 0.2 to 1.4 ACH50 with half of the units achieving a leakage more than 80% below the code requirement of 3.0 ACH50. EnergyPlus models for four different ventilation strategies in new and existing buildings showed space heating energy savings of 4% to 25%. Nine units were sealed in three existing multifamily buildings. Pre-seal tests showed air leakage levels two to five times greater than that for the new construction, resulting in longer sealing times. However, the air sealing still achieved similar relative leakage reductions of 39% to 89% and greater reductions in absolute leakage and energy use.

Table of Contents

List of Figures

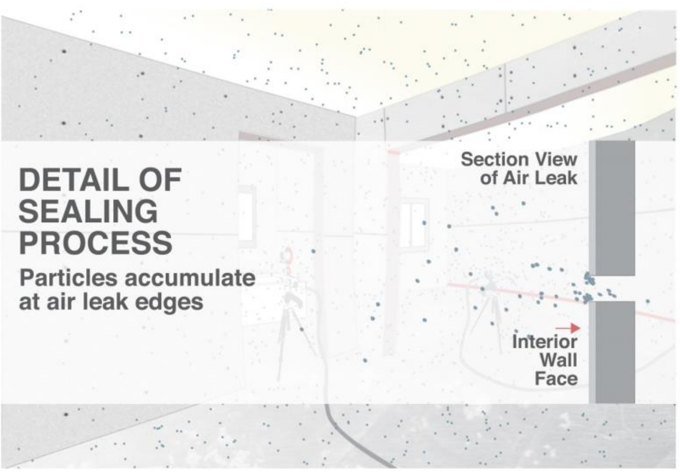
List of Tables

Executive Summary

Introduction/Background

While tight exterior envelopes have become standard for single-family homes, similar construction practices have been slow to reach the multifamily sector. Multifamily buildings have many of the same leakage paths as houses, as well as additional paths hidden in walls or other cavities that are difficult to seal with conventional methods. Researchers recently developed an aerosol sealant to seal leaks in building walls, floors, and ceilings. The process has the potential to be more effective and convenient than conventional sealing methods because it requires less time and effort, and it can seal a larger portion of a leakage area more quickly.

Figure 1. Image of particles sealing a gap



How it Works

The aerosol envelope sealing technology developed by the Western Cooling Efficiency Center at UC Davis uses an automated approach to produce extremely tight envelopes. Air is blown into a unit while an aerosol sealant "fog" is released in the interior. As air escapes the building through leaks in the envelope, the sealant particles are carried to the leaks where they impact and stick to the edges of the leaks, eventually sealing them. A standard house or duct air leakage test fan is used to pressurize the building and provide real-time feedback and a permanent record of the sealing. The technology is thus capable of simultaneously measuring, locating, and sealing leaks in a building.

Figure 2. Visual images of sealed air leaks

MN Code Envelope Air Tightness Requirements

In 2015 the State of Minnesota adopted the 2012 versions of the International Residential Building Code, International Building Code, and International Energy Conservation Code (Residential and Commercial Provisions) with state amendments. These changes require that multifamily buildings between one and three stories meet the residential energy code envelope tightness requirement of 3.0 ACH50. For multifamily buildings four stories and above, the envelope tightness requirement can be met using sufficiently tight materials, tight assemblies, or an envelope air leakage test. In Minnesota, all multifamily buildings four stories and above comply by using tight materials or assemblies and instead of tightness tests. However, some funding agencies require lenders to comply with the Minnesota Overlay and Guide to the Enterprise Green Communities Criteria. This requires that units meet the EPA ENERGY STAR Multifamily High Rise Requirements requirement for a maximum air leakage rate of 0.30 cfm50 per square feet of enclosure (EPA 2013).

Study Objectives

At the start of this project the technology was in pre-commercial development. The project team performed aerosol envelope sealing demonstrations on three new construction and three existing multifamily buildings. The objectives for the study were to:

- measure the envelope leakage reduction and final tightness
- refine the unit preparation and sealing process
- model the impact of envelope tightness on outdoor air and inter-unit air flow rates
- estimate energy savings for tighter envelopes.

Methodology

Air Sealing

Aerosol envelope air sealing was performed on nine existing and 18 new construction multifamily units to measure air leakage reductions, document labor hours required, and help identify best practices for sealing preparation and implementation.

Figure 3. Image of air sealing process in the field

The air sealing protocol was adapted based on experience with past laboratory and field projects. The type of sealant deposition protection measures, temporary seals, manual pre-sealing, and time required for all tasks were broken out for a subset of the sealed units. Multi-point, total unit air leakage tests were conducted on all units before and after sealing. The leakage test was repeated for a subset on units after the unit sealing was finished. Multiple fan, guarded air leakage tests were also performed to break out exterior and interior envelope leakage. Pre/post-acoustic tests and documentation of sealant locations using a fluorescent dye in the sealant and black-light photography were conducted for some of the units.

Airflow and Energy Modeling

The airflow and energy use modeling was performed with EnergyPlus simulations to determine building airflows from wind, stack, and mechanical effects as well as the air leakage characteristics of each unit. Whole building simulations often assume a constant air infiltration rate to represent the effects of uncontrolled infiltration driven by the natural forces of wind and stack effect and unbalanced mechanical ventilation. However, comparing the performance of different multifamily envelope tightness and ventilation strategies requires simulations that compute actual infiltration. The building airflows were computed from detailed information on the location and size of envelope air leaks along with inside air temperature/RH, outside air temperature/RH, wind speed/direction, and mechanical ventilation flow rates. The models were developed for four ventilation strategies and the energy consumption was compared for each strategy before and after sealing.

Aerosol Sealing Process

1. Pre-seal large gaps and temporary sealing — Any gaps wider than 3/8" and any leaks located where the aerosol will not stay in suspension need to be manually sealed.
2. Cover finished horizontal surfaces — Some of the sealant will settle on horizontal surfaces during the process so they should be protected with plastic, duck mask, or masking tape.

3. Setup equipment and perform sealing — One nozzle is typically placed in every bedroom and living area; the unit is then pressurized while an aerosol sealant "fog" is released in the interior.
4. Remove coverings and clean surfaces — Windows must be opened and fans set at high to purge remaining sealant; surface protection should be removed and any extra residue cleaned.
5. Post-sealing air leakage test — An air leakage test should be conducted when all penetrations in the envelope have been made.

Results

Air Sealing

Aerosol envelope sealing was performed on a convenience sample of 18 units in three new construction buildings and nine units in three existing buildings. Key characteristics and pre-sealing leakage results are listed in Table 1

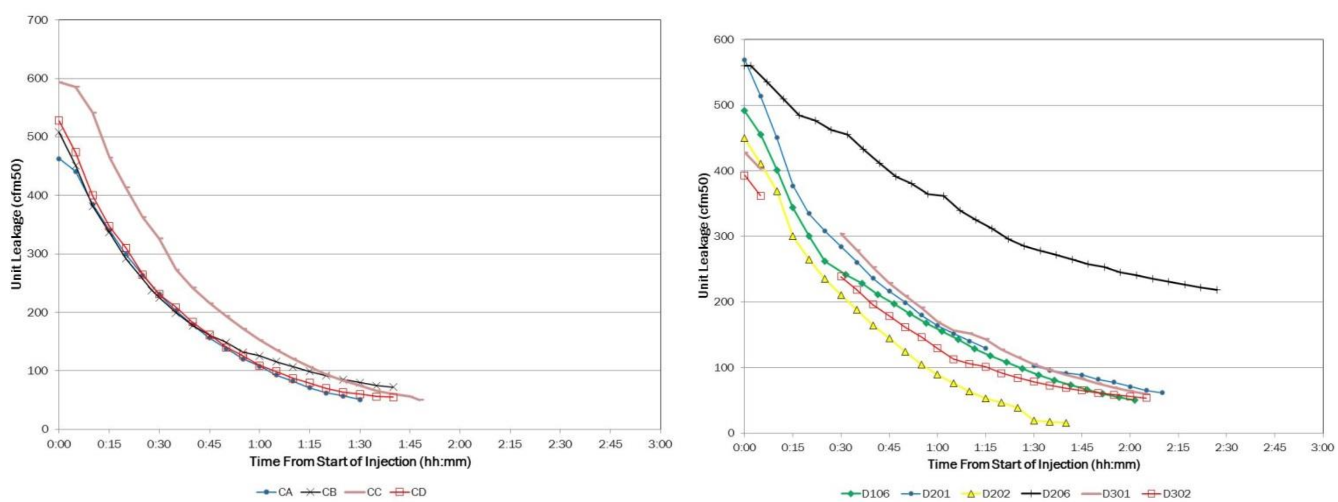
The research team conducted the sealing using an equipment design modified from previous field tests and the protocol described in the methodology section. Figure 4 displays an example of the reduction in envelope leakage through the aerosol sealing process for four new construction and six existing building units. In general, the sealing rate was greatest for the first 30 minutes and steadily decreased after that.

Table 1. Building characteristics

			# Units		Avg. Floor	Pre-Seal Leakage (ACH50)		
Type	ID	Stories	Total	Tested	Area (ft²)	Min	Max	Avg
NC	A	4	36	6	451	3.11	3.50	3.22
NC	B	4	42	8	1,044	1.98	2.85	2.39
NC	C	5	107	4	384	7.08	8.41	7.75
Ex	D	3	16	6	237	12.0	17.2	13.4
Ex	E	2	2	1	1,579			13.7
Ex	F	2	4	2	760	15.8	17.2	16.5

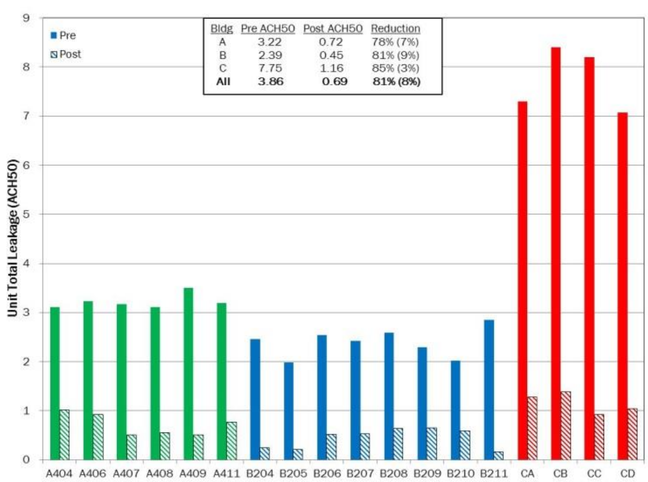
*NC = new construction, EX – existing buildings

Figure 4. Variation in unit leakage (cfm50) through aerosol sealing process for units in new construction building C (left) and existing building D (right)



The aerosol envelope sealing of new construction and existing building units successfully demonstrated high levels of air leakage reduction with no damage to the finished surfaces. For the new construction units the reduction varied from 67% to 94% with an average of 81%, as shown in Figure 5 All of the units were more than 50% tighter than the 3.0 ACH50 code requirement for low-rise residential buildings, and half of the units met the Passive House tightness requirement of 0.6 ACH50. In addition, all of the units were at least 80% tighter than the EPA ENERGY STAR Multifamily High Rise requirement of 0.3 CFM50/ft².

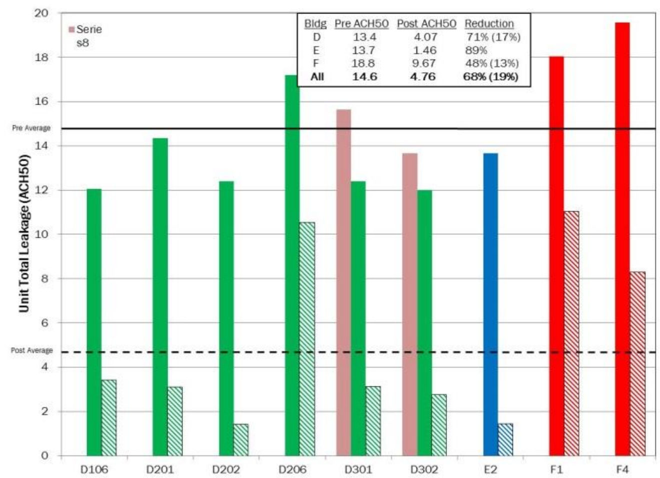
Figure 5. Pre and post sealing unit leakage and percent reduction for new construction units



As shown in Figure 6, results were equally impressive for existing buildings, sealing an average of 68% of the unit leakage. The tightness achieved was less consistent for two of the tests, where only 39% of the available leakage was sealed. In one case this was due to large unforeseen leaks behind a kitchen cabinet.

The pre-sealing results show initial leakage levels of 12.0 ACH50 to 17.0 ACH50 and post-sealing results from 1.4 ACH50 to 10.5 ACH50. This indicates that with manual pre-sealing of larger leaks, the aerosol sealing process can realistically reduce air leakage in existing apartments to meet or exceed the new construction low-rise residential code requirement of 3.0 ACH50.

Figure 6. Pre and post sealing unit leakage and percent reduction for existing units

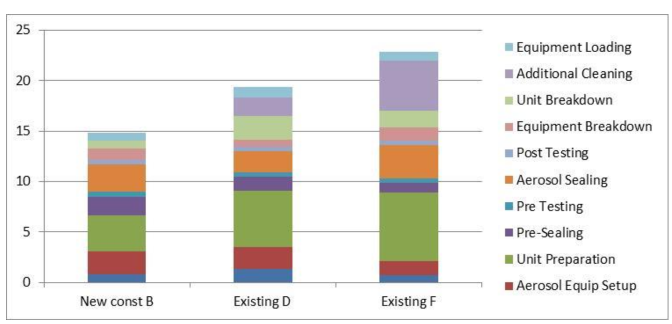


Labor Requirements

The total time required to complete the six different tasks for the air sealing process was tracked for three of the six buildings. The average task labor times for all sealed units for the three buildings are displayed in Figure 7. The total time per unit for the sealing process varied from 14 to 22 person-hours. However, this was a research project with staff that was being trained on the process and it is likely that with trained personal there would be a reduction in labor time by a factor of two or greater. There are opportunities to reduce labor time by:

- Pre-sealing large leaks;
- Performing sealing at a time when there are minimum finished surfaces to cover; and
- Using new, more portable and automated equipment.

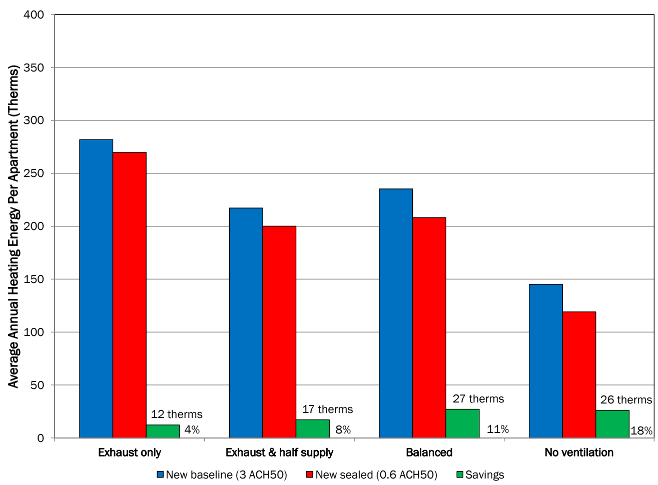
Figure 7. Average task labor times in person-hours per unit for sealed units in three existing buildings



Energy Savings Modeling — New Construction

Figure 8 shows the new construction modeling compared the energy performance for a building with units that have a total (exterior and interior) envelope leakage of 3.0 ACH50 to a building that was sealed 80% tighter (e.g. 0.6 ACH50) with the aerosol process. The 80% reduction in envelope leakage is approximately equal to the 81% average reduction for the aerosol sealing of the 18 new construction units completed for this project.

Figure 8. Modeled annual space heating energy use and savings for new construction units



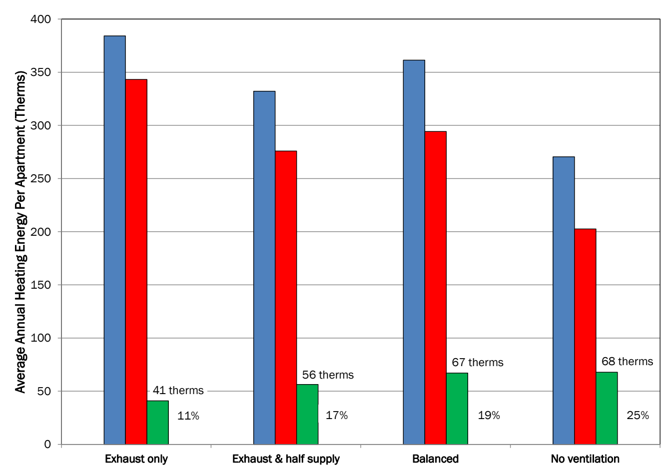
The results show an 4% to 18% reduction in heating energy use due to sealing the envelope with annual gas savings of 12 to 27 therms and cost savings from $7 to $16. An annual cost savings of $15 for a tightness reduction from 3.0 to 0.6 ACH50 and balanced ventilation indicates that the sealing cost would have to be $150 to $225 per unit for a 10 to 15 year payback, assuming that the aerosol process is an "add-on" that reduces the leakage of a unit in a low-rise multifamily building from the code required value to a very tight level. However, aerosol sealing might eliminate the need for conventional methods and the higher levels of quality control that would be necessary to achieve tighter envelopes, ultimately costing less than conventional alternatives.

When the modeling for this project was performed, it was expected that the 3.0 ACH50 code requirement would apply to the *total* unit leakage. However, Minnesota code officials have indicated that the 3.0 ACH50 requirement applies to *exterior leakage only*, which allows units to be leakier than if the requirement applied to the total leakage. Increasing the leakage of the baseline model results in higher absolute savings for the new construction sealing, which is closer to the savings reported for the sealing of existing buildings as a part of this project.

Energy Savings Modeling — Existing Buildings

The modeling for existing construction, Figure 9, focused on comparing the energy performance of an existing building that was sealed to the low-rise multifamily code requirement for new construction. The two total envelope leakage levels modeled for the existing buildings were 9.5 ACH50 and 3.0 ACH50.

Figure 9. Modeled annual space heating energy use and savings for existing building units



The results show an 11% to 25% reduction in heating energy use due to sealing the envelope with annual gas savings of 41 to 68 therms and cost savings from $24 to $39, which may not be sufficient for many building owners. However, the modeling results were based on a 68% reduction from a starting leakage of 9.5 ACH50, and the average pre-sealing leakage of the nine existing units was over 14 ACH50. A pre-sealing leakage of 15 ACH50 and a reduction of 75% would increase annual savings by about a factor of two. The simulations assumed that 43% to 47% of the total leakage was to the exterior. If the percent exterior leakage for the models was 68%, the savings would have been about 50% greater. Under certain factors, leakier units could see higher savings of three times or more (e.g. $70 to $120 per year).

Another advantage of the aerosol sealing method in both new construction and existing buildings is that it greatly reduces airflow between units and common spaces. The modeling showed that the 80% reduction in total unit leakage reduced airflows between units by 68% to 80%.

CIP Recommendations

New Construction

Xcel Energy and CenterPoint Energy offer design assistance programs for commercial and industrial new construction and major renovation, including for multifamily buildings. The program provides consulting services and energy modeling as well as electricity and natural gas efficiency implementation rebates. Although a tighter building envelope and associated air infiltration reduction is not a standard measure for the program, it can be modeled if requested by the design team. The modeled air infiltration results from this project should be used for baseline and reduced envelope tightness infiltration values for design assistance programs.

The airflow modeling conducted for this project suggests that design assistance program building energy models should use a baseline air infiltration rate of 0.16 ACH for buildings with normal wind shielding. The baseline is reduced to 0.13 ACH for well shielded buildings and increased to 0.18 ACH for exposed buildings. The percent reduction in modeled air infiltration should be the difference between the measured exterior envelope leakage and the low-rise residential code requirement of 3.0 ACH50. Given the high level of energy savings achieved in this project, aerosol envelope sealing will likely be the most cost-effective sealing method for multifamily units required to meet more stringent compartmentalization requirements.

Existing Buildings

The CenterPoint Energy/Xcel Energy Multifamily Building Efficiency program will include envelope air sealing as a custom measure beginning in 2017. The payback for the air sealing work will need to be less than the measure life of 20 years to qualify for an incentive. The Minnesota Energy Resources Multifamily Direct Install Plus program does allow envelope air sealing as one of the targeted measures for investigation, and air sealing work may qualify for a custom rebate. All Minnesota utility programs for existing multifamily buildings should include incentives for envelope air sealing.

The State of Minnesota Technical Reference Manual for Energy Conservation Improvement Programs (2016) includes an algorithm for residential and small commercial buildings, but it is not directly applicable to multifamily units and there is currently no generally accepted methodology for computing multifamily envelope air sealing savings. The current calculation includes a value for “n_heat” which is the conversion factor from leakage at 50 Pa to leakage at natural conditions, building height, and exposure level. The modeling results from this project indicate that a value of 25 should be used for n_heat of existing multifamily buildings with less than 50 cfm of continuous, unbalanced mechanical ventilation and well shielded from wind. The value should be reduced to 21 for normal wind shielding and 19 for exposed shielding.

An evaluation of the building ventilation system should be conducted and recommended upgrades completed when any significant exterior envelope air sealing is performed. Exterior air sealing is not recommended when the unit does not have a mechanical ventilation system.

Introduction

Multifamily building envelopes are notoriously leaky causing unintended outside air infiltration that increases space conditioning costs. Air leaks and flow between units increase sound transmission and often result in tenant odor complaints and other indoor air quality concerns. While voluntary standards and guidelines for envelope tightness have existed for decades, only recently have these codes become a requirement in parts of the U.S. Current methods for sealing leaks in the building envelope are all manual and, even when diligently applied, can fall short of the ultimate tightness goal due to unrecognized leakage pathways.

The aerosol envelope sealing technology developed by the Western Cooling Efficiency Center (WCEC) at UC Davis uses an automated approach to produce extremely tight envelopes. Air is blown into a unit for an hour or two while an aerosol sealant "fog" is released in the interior. As air escapes the unit through leaks in the envelope, the sealant particles are carried to the leaks where they impact and stick to the edges of the leaks, eventually sealing them. A standard house or duct air leakage test fan is used to pressurize the building, and also provide real-time feedback and a permanent record of the sealing that occurred. The technology is thus capable of simultaneously measuring, locating, and sealing leaks in a building.

At the start of this project the technology was in pre-commercial development. This project performed aerosol envelope air sealing demonstrations on three new construction and three existing multifamily buildings. The objectives were to measure the envelope leakage reduction and final tightness; refine the unit preparation and sealing process; model the impact of envelope tightness on outdoor air and inter-unit air flow rates; and estimate energy savings for tighter envelopes.

Background

Construction practices in Minnesota for multi-unit dwellings have not produced the level of air tightness that has become standard practice for single-family houses. Excessive air infiltration means unnecessarily high costs and energy use for space conditioning. In a building airflow and energy simulation analysis performed by Emmerich, McDowell, and Anis (2005), reducing infiltration for a four story Minneapolis apartment building to reasonable levels resulted in 43% gas savings and a 14% increase in space cooling electric use. The annual energy cost savings were $63/unit[1] or $0.06/ft^2. While the increased electric use may initially be a concern, the increased electric use was only 3% of the space heating savings. In addition, the electric use increases because the models assume that windows are always closed. When internal and solar gains cause the inside temperature to be greater than the outside temperature the building models assume that air infiltration helps cool the units and additional cooling is provided by air conditioning. In real buildings some occupants would avoid this air conditioning by opening their windows.

Sealing the envelope of existing structures and improving the exterior tightness of new-construction is essential for reducing the costs of excess air infiltration; however, envelope openings are often hidden, diffuse, or inaccessible, and can be difficult to address with conventional methods. CEE's staff experience from commissioning unit envelopes and attempting to reduce inter-unit air flow has shown that sealing these boundaries is challenging. For example, total unit air leakage tests on 38 units in six Minnesota multifamily buildings found median envelope leakages that ranged from 454 cfm50[2] for a 1982 11 story condominium to 2,368 cfm50 for a 1930s duplex with an overall median of 861 cfm50 (Bohac et al. 2008). Four to ten hours of caulk and foam sealing that targeted inter-unit leaks resulted in a median reduction of 139 cfm50 or 18%. While some leakage paths in multi-unit dwellings are similar to those found in single-family houses, other paths are hidden in walls and other cavities.

Current state-of-the-art methods for envelope air sealing are all manual, relying on contractor personnel to visually identify and manually seal leaks individually. The achieved air-tightness levels can be highly variable, and are based on the time allotted and the vigilance and experience of the individual contractor that performs the work. In addition, it is common for air-tightness verification to be performed by a different contractor after the sealing and most or all of the construction is complete. This provides limited opportunity for feedback on the effectiveness of the air sealing, making it difficult for the sealing contractor to assure that a specific level of tightness has been achieved. If the house tightness is greater than acceptable, additional sealing at later stages of construction is more expensive and may not be possible or effective.

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[1] Assumed cost of gas= $1.01/therm and electricity= $0.0827/kWh

[2] cfm50 = envelope leakage rate in cubic feet per minute (cfm) at a pressure difference of 50 pascals (Pa)

Development of Aerosol Envelope Sealing Method

Aerosol sealing has been used successfully for residential duct sealing for 15 years, where it has been shown to seal duct leaks with a width of up to 5/8 inch. A similar technology has been developed for sealing leaks in the walls, ceiling, etc. of buildings. Initial proof-of-concept testing of the aerosol sealing process showed excellent results, sealing 40 in^2 of leakage in a small scale enclosure in less than 10 minutes (Harrington and Modera 2012). The proof-of-concept testing also showed that higher building pressure and higher sealant injection rates led to more sealant deposited in and around leaks. Subsequent field demonstration projects showed the viability of the technology in larger spaces and practical application in real buildings.

A number of demonstrations in new construction for both multifamily and single-family homes showed the ability to seal 60% to 85% of available building leakage in less than two hours of sealant injection (Maxwell, Berger, and Harrington 2015; Harrington and Springer 2015). The homes in these demonstrations ranged in size from 600 ft^2 to 3,000 ft^2 with the estimated cost for installation well under \$0.50/ft^2. The time required for setup, sealing, and cleanup was closely tracked for installations in large new single-family homes, and determined each installation required an average of 11 person-hours to complete. It is reasonable to assume that with experienced personnel and commercialized equipment the time required could be reduced to two contractors over four hours.

Recent demonstrations of the automated aerosol envelope sealing process in both single-family and multifamily buildings, and at two different stages of construction, are described below in more detail. This work was performed for previous projects and was not part of the project described in this report.

Single-Family

Envelope sealing of Honda Smart Home in Davis, CA

The Honda Smart Home is a net-zero energy, two-story single-family home built to showcase some of the most advanced strategies to reduce the carbon footprint of U.S. homes. WCEC worked with Honda Motor Company to design the mechanical systems for the home, and to demonstrate the aerosol envelope sealing process to reduce building shell leakage for better ventilation control and lower infiltration loads.

A recent demonstration of the aerosol envelope sealing process on the Honda Smart Home achieved a reduction in building air leakage from 5.5 ACH50[3] to 1.0 ACH50. Photographs from this installation, including examples of seals formed, are shown below in Figure 10 and Figure 11. This building was initially sealed using standard methods and the photos show areas where the aerosol sealant found and sealed leaks that had not been properly sealed with foam and caulk. The ultimate goal was to meet the very aggressive Passive House standard of 0.6 ACH50, which also requires that the air barrier be applied to the external building envelope.

[3] ACH50 = measured air leakage (cubic feet per hour) at a reference pressure of 50 Pa divided by the interior volume (cubic feet)

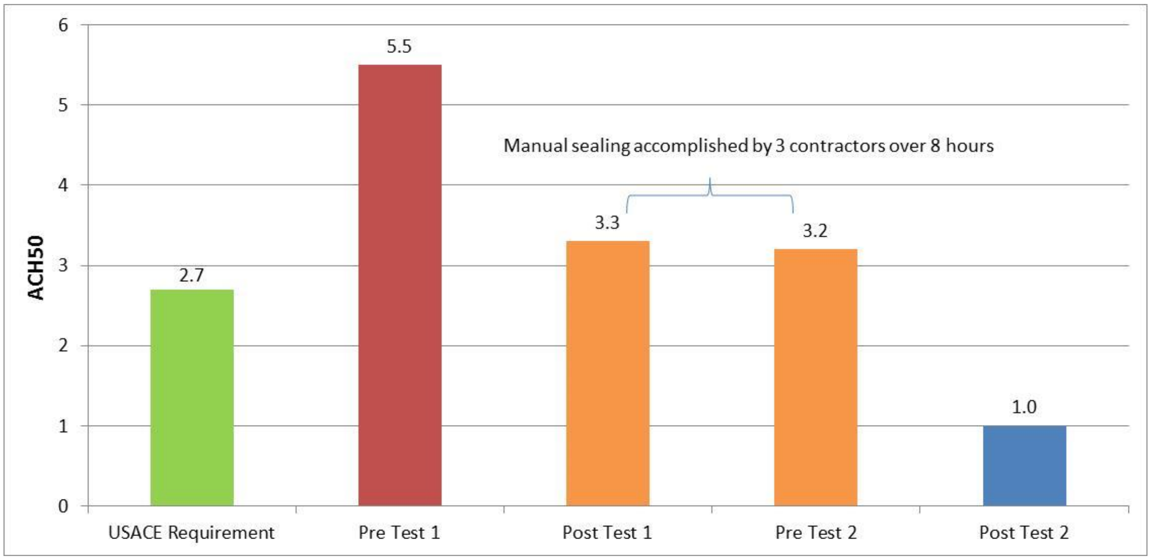
Figure 10: Photos of aerosol sealing installation on single-family home including examples of seals formed

Figure 11: Photos of Honda Smart Home before aerosol envelope sealing application

The contractor was asked to use standard methods to seal leaks with a gap width greater than 0.25 in. (smallest dimension) since the time required to aerosol seal a leak has been shown to increase with the square of the smallest dimension (length or width) of the leak (e.g. it takes four-times longer to seal a leak that is 0.5 inches across than to seal a leak that is 0.25 inches across). Figure 12 summarizes the results of the demonstration, highlighting the three discrete phases in the sealing process.

The first aerosol sealing application used an airless nozzle injection system with five injection points and without any temperature/humidity control. This injection reduced the building leakage from 5.5 ACH50 to 3.3 ACH50. After the first application, three contractors spent 24 person-hours attempting to further seal the building manually with expanding foam and caulk, resulting in an almost negligible impact on the overall tightness of the building shell. Finally, the aerosol envelope sealing process was applied again, this time using air-atomization nozzles and temperature/humidity control. That process reduced the building leakage from 3.2 ACH50 to 1.0 ACH50 in about four hours.

Figure 12: Summary of results from aerosol envelope sealing demonstration in Honda Smart Home



This demonstration provided a superb comparison of the performance difference between airless and air-atomization nozzles, as well as the impact of temperature/humidity control. WCEC staff found that while the airless atomization nozzles created a uniform particle size distribution, the air-atomization nozzles projected the aerosol with more initial momentum, allowing the aerosol to better fill the building space and promote evaporation of water from the sealant particles. However, the largest performance improvement resulted from controlling the relative humidity within the space. This was accomplished during the air-atomization application by simply heating the inlet air and controlling the liquid sealant flow rate. Evaporation of water contained in the sealant mixture is critical to allow the particles to reach the proper size and to adhere to leak sites.

In summary, this demonstration revealed the advantage of using the aerosol envelope sealing process over standard manual sealing methods. Relying on manual sealing to accomplish the level of air-tightness desired would have required a substantial amount of time and labor. To achieve relative humidity control it is more promising to use an air-atomization nozzle system than one that utilizes airless nozzles without controls. In subsequent demonstrations the performance of the air-atomization system significantly improved as WCEC staff used injection nozzles simultaneously at multiple locations , compared to the single injector nozzle that had to be moved around in the Honda Smart Home.

Envelope sealing on a production scale in Clovis, CA

Another project with the objective of sealing new single-family homes on a production scale was completed in 2015 for Building America to look at envelop sealing on a production scale in Clovis, CA. Table 2 presents the results of sealing each of the test homes.

Table 2: Summary of sealing results for six new construction houses

Test #	Sealing Time (min)	Sealing Pre-Test (CFM50)	Sealing Post-Test (CFM50)	ACH50 Pre Sealing (CFM)	ACH50 Post Sealing (CFM)	Percent Reduction
1	90	5,100	1,936	9.1	3.4	62%
2	81	4,603	1,690	13.7	5.0	63%
3	74	4,472	676	11.5	1.7	85%
4	112*	4,758	1,018	8.5	1.8	79%
5	82	4,813	969	12.4	2.5	80%
6	77	5,095	1,226	13.2	3.2	76%

* air compressor ran out of fuel causing a pause in the sealing.

Since the process was applied at a rough-in stage of construction, it would be expected that a significant amount of the leakage present in the house at that time would have been sealed in later stages of construction, the exception being duct leakage. Consequently, the percent reduction is not the reduction of house tightness of a completed house with conventional sealing compared to the tightness of a completed house with aerosol sealing. The percent reduction is the leakage reduction produced by the aerosol sealing of a house at the rough-in stage of construction. The leakage data presented in Table 2 shows the leakage measurement performed with HVAC ducts blocked and large holes covered. Test 2 indicated significantly higher air leakage at the end of sealing which was likely caused by multiple HVAC ducts becoming unblocked during pressurization.

Multifamily

Following the successful application of the aerosol envelope sealing process at the Honda Smart Home, WCEC conducted tests of a new air-atomization injection system capable of multiple injection points. Funding for this test was provided by both the California Energy Commission and the Department of Energy's Building America program. The first application using the new injection system was performed on several apartments in Queens, NY. Figure 13 shows pictures of one apartment before sealing and example seals formed around an electrical box. Figure 14 shows the software used by the contractor to track the sealing performance in real-time.

Figure 13: Photos of one apartment before being sealed and sealed electrical box

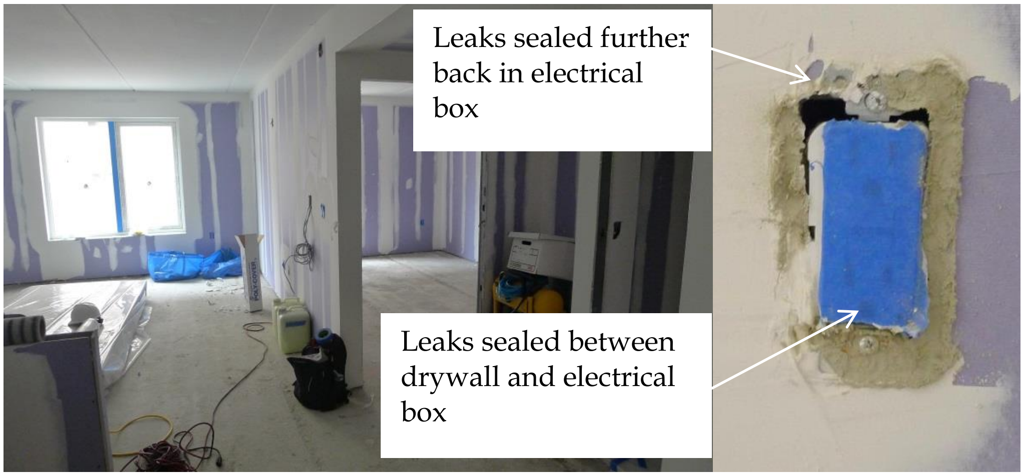


Figure 14: Photos of software used to track and record the sealing process in real-time

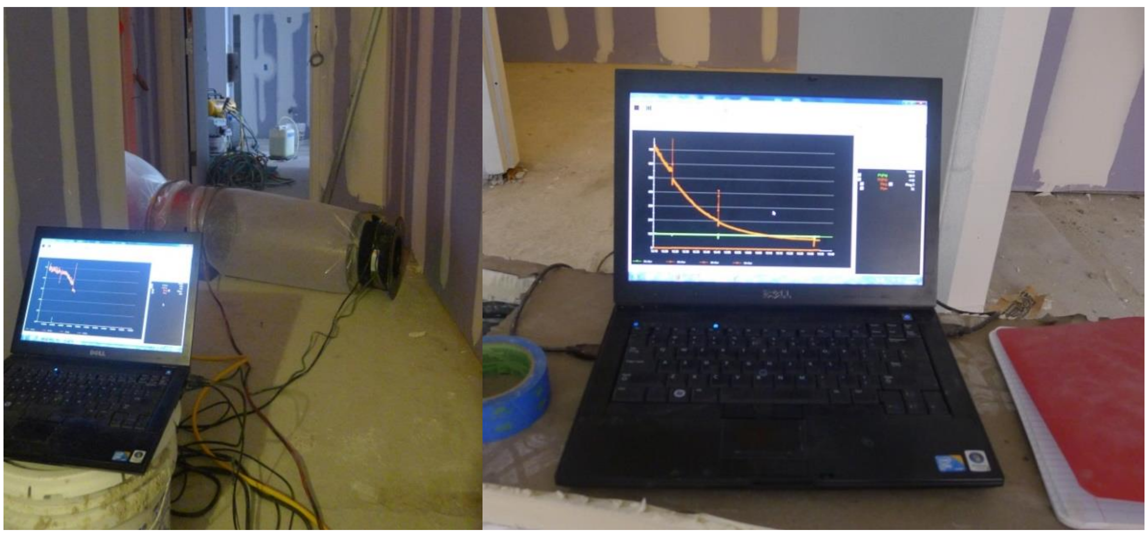
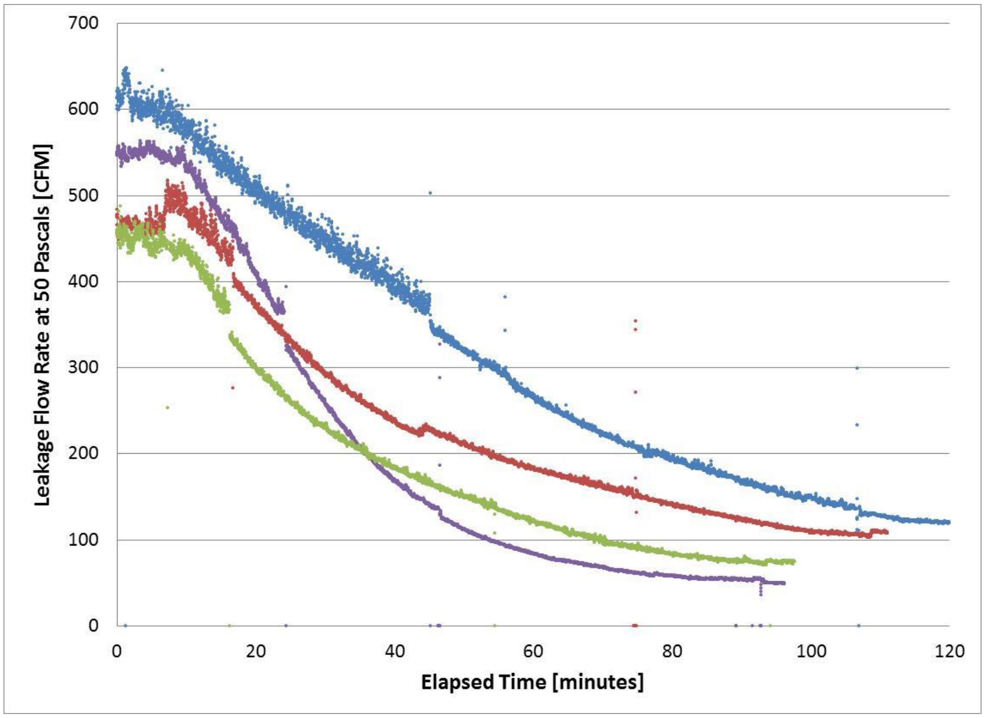


Figure 15 displays the sealing profiles for four apartments and shows that the process was capable of sealing at least 80% of the air leaks in less than two hours. The plateau in sealing rate occurs when all smaller leaks are sealed (<0.5 inch in the smallest dimension) and only large leaks that cannot be sealed by the aerosol process remain. This plateau occurs at different points depending on the building's initial bulk-sealing level.

Figure 15: Sealing profiles for demonstration of aerosol sealing process on four apartments in Queens, NY



An additional benefit of the aerosol sealing process is the ability to reduce sound transmission across a wall. A sound transmission test was developed to investigate the effects of using the aerosol sealing process to reduce sound transmission between the Queens, NY, apartments. Sound transmission is an important factor in occupant comfort, and the amplitude of transmission at higher frequencies was shown to be correlated to the tightness of the building compartment. Lower frequencies transmit across walls primarily by flanking through dense structural members, while higher frequency sounds tend to travel through cracks, and this was observed in preliminary sound tests before and after sealing the envelope (Figure 16).

Figure 16: Sound attenuation results for three apartments sealed in Queens, NY

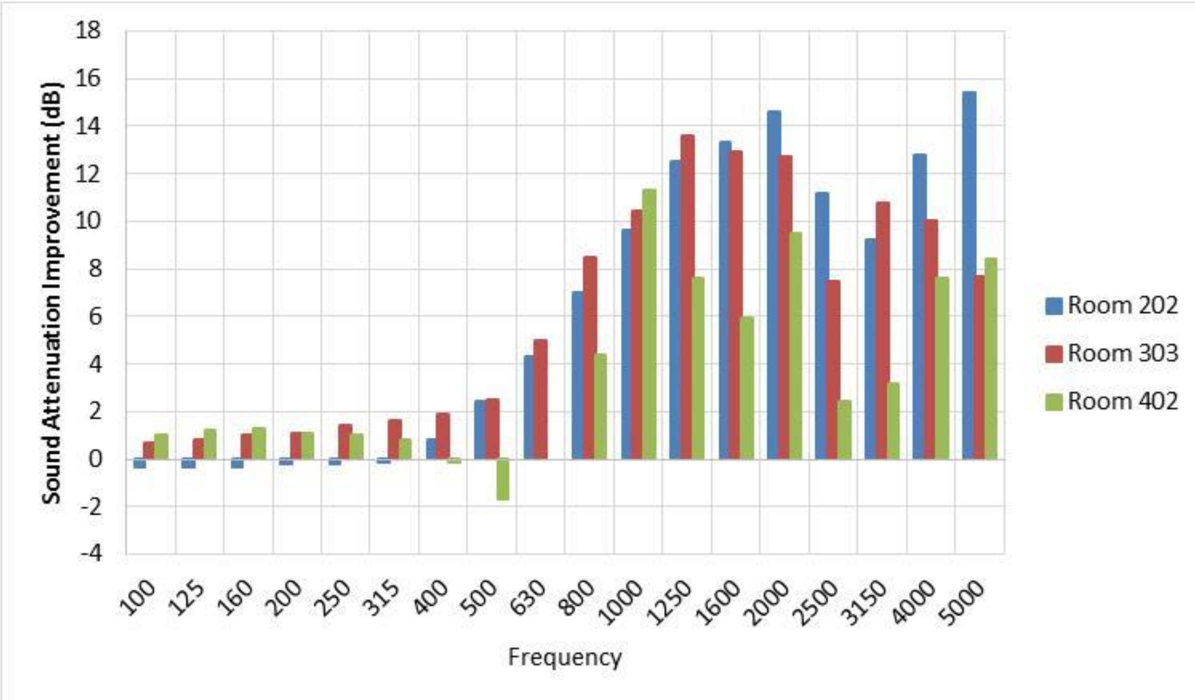


Figure 16 shows the sound attenuation improvement for 18 frequencies selected according to ASTM standards E90 and E336 that resulted from aerosol sealing. As the figure shows, there was not a significant attenuation improvement at frequencies below 500 Hz. However, at higher frequencies there was a significant sound transmission reduction. The differences in the trends between different tests may be a result of small differences in construction and sealing characteristics (i.e. one wall sealed better than another).

Envelope Air Tightness

Minnesota Code Requirements

In 2015 the State of Minnesota adopted the 2012 versions of the International Residential Building Code, International Building Code (ICC 2012b), and International Energy Conservation Code (Residential and Commercial Provisions) (ICC 2012a) with state amendments. The 2015 version of the code requires that one to three story multifamily buildings meet the residential energy code envelope tightness requirement. This specifies that the measured leakage be 3.0 ACH50 or less. The code does not specify a test method and it does not specify the portion of the envelope included in the test.

There are generally two test options: (1) an exterior leakage test that only includes leakage between the unit and outside, and (2) a total leakage test that includes leakage across the entire envelope, including demising walls, floors, and ceilings. Since the focus of this requirement is energy use, and the air flow between interior spaces has limited impact on energy use, it would be reasonable to assume that the tightness requirement applies only to the exterior portion of the unit's envelope and not the demising walls and floors/ceiling that adjoin interior spaces.

That suggests that an exterior leakage test is appropriate for the tightness requirement and is consistent with current practice. Code officials have allowed testing agencies to perform the leakage test on an entire floor or wing of an apartment building (Sivigny 2016).

For multifamily buildings four stories and above the envelope air barrier tightness requirement can be met using sufficiently tight materials, tight assemblies, or an envelope air leakage test (ICC 2012a):

- **Materials**. Materials with an air permeability no greater than 0.004 cfm/ft^2 at 75 Pa are required. Materials shall be deemed in compliance with this section provided joints are sealed and materials are installed as air barriers in accordance with the manufacturer's instructions.
- **Assemblies**. Assemblies of materials and components with an average air leakage shall not exceed 0.04 cfm/ft^2 under a pressure differential of 75 Pa.
- **Building test**. The completed building shall be tested and the air leakage rate of the building envelope shall not exceed 0.40 cfm/ft^2 at a pressure differential of at 75 Pa in accordance with ASTM E 779.

It is expected that almost all buildings four stories and above will comply with the air barrier requirement by using tight materials or assemblies and will not use the building test path.

Other Guidelines

Some funding agencies require lenders to comply with the Minnesota Overlay and Guide to the Enterprise Green Communities Criteria (MHFA 2016). This refers to portions of the EPA ENERGY STAR Multifamily High Rise (MFHR) requirements, which includes a requirement for a maximum air leakage rate of 0.30 cfm50 per square feet of enclosure (EPA 2015a). The MFHR testing and verification protocols (EPA 2015b) specify that the leakage is to be measured using either ASTM E779 or ASTM E1827 and includes other requirements relevant to multifamily unit testing. The test must be setup so that the measurement includes leakage to the entire envelope including exterior and party walls, floors, and ceilings (e.g. a total leakage test).

Ventilation

An evaluation of the impact of envelope sealing needs to consider the type and capacity of the mechanical ventilation system. First, older multifamily buildings have typically relied on air infiltration through leaky exterior envelopes and on occupants to open windows to provide sufficient ventilation. Sealing exterior leaks in older buildings requires the consideration of whether the reduction in air infiltration will require the installation of a mechanical ventilation system to assure adequate ventilation. Second, the type of mechanical system (e.g. exhaust only, supply only, or balanced) can impact building pressure differences which affects air infiltration and the energy savings from sealing leaks to reduce infiltration.

Minnesota Code Requirements

Requirement Prior to 2015

The 2015 version of the building and energy codes had not yet been implemented when the building air flow and energy modeling activities started for this project. The previous version of the code in effect at that time specified that the Commercial Energy Code applied to a multifamily residential building if any of the following were true:

- Any conditioned space is shared between units
- Dwelling units do not have a separate means of egress (independent means of egress)
- Four or more stories

Consequently, all of the multifamily buildings of interest for this project needed to comply with the Commercial Energy Code with ventilation requirements specified by the Minnesota Mechanical Code (Chapter 4, Ventilation), which includes the following section for outdoor air requirements:

> **403.2 Outdoor air required**. The minimum rate of required outdoor air shall be determined in accordance with the Ventilation Rate Procedure, Section 6.1 of ASHRAE 62.1-2004, or the Indoor Air Quality Procedure, Section 6.2 of ASHRAE 62.1-2004.

Section 6.2 of ASHRAE 62.1-2004 (2004) includes tables that specify required outdoor air ventilation rates. The rates for a subset of the area types that are relevant to multifamily buildings are shown in Table 3. In addition to outdoor air flow rates, the standard also indicates:

- Apartment unit bathroom and kitchen exhaust makeup air can be provided by air infiltration and transfer air (and is not required by corridor supply)[4].
- Living area ventilation requirement of 0.35 air changes per hour is assumed to be satisfied by air infiltration and open windows (see Table E-2a).

The information in Table E-2a suggests that it was not necessary to meet the 0.35 air changes per hour (ach) living area ventilation requirement using mechanical ventilation. However, for this project, when a mechanical ventilation system was installed for general ventilation, the capacity was sized for a ventilation rate of 0.35 ach.

[4] Note that some code officials required that supply airflow rates match the exhausted airflow from the units at each floor.

Table 3: Ventilation requirements for common multifamily building area types; ASHRAE 62.1-2004

Area type	Ventilation requirement	Notes
Living area	0.35 air changes per hour but not less than 15 cfm/person (Table E-2)	Assume #people= #bedrooms+1
Bathroom	20 cfm continuous exhaust (Table E-2)	
Kitchenette	0.3 cfm/ft² continuous exhaust (Table 6-4)	Applies to kitchens with a floor area less than 80 ft²
Kitchen	25 cfm continuous exhaust (Table E-2)	Applies to kitchens with a floor area greater than or equal to 80 ft²
Corridors, meeting rooms, community rooms	0.06 cfm/ ft² continuous supply (Table 6-1)	Main entry not required
Public toilets	50 cfm continuous exhaust (Table 6-4)	
Trash room	1 cfm/ ft² continuous exhaust (Table 6-4)	Includes janitor closets, trash and recycling rooms

2015 Requirement

The codes adopted by the State of Minnesota in 2015 specified that one to three story multifamily buildings meet the residential ventilation requirements included in section R403.5 Mechanical Ventilation (ICC 2012b). The following is a summary of the key components of R403.5:

- Balanced mechanical ventilation that is +/- 10% of design capacity, air intake within 10% of the exhaust output
- Total ventilation rate = outdoor air in each hour equal to (0.02 x floor area) + (15 x (#bedrooms + 1))
- Continuous ventilation rate = total ventilation rate/2, not less than 40cfm

Multifamily buildings greater than three stories are required to meet the ventilation requirements of the 2015 Minnesota Mechanical Code for commercial buildings (MNDLI 2015). Chapter 4 provides guidance on the envelope tightness limit for using natural ventilation:

> **401.2 Ventilation Required**. Every occupied space shall be ventilated by natural means in accordance with Section 402 or by mechanical means in accordance with Section 403. Where the air infiltration rate in a dwelling unit is less than 5 air changes per hour when tested with a blower door at a pressure of 0.2-inch water column (50 Pa) in accordance with Section 402.4.1.2 of the *International Energy Conservation Code*, the dwelling unit shall be ventilated by mechanical means in accordance with Section 403.

The test protocol specified by 402.4.1.2 allows for either a total building or an individual dwelling leakage test. Since there is a reasonable chance that new construction units will have a total leakage less than 5 ACH50, and it will not be feasible to wait until after the leakage test to install mechanical ventilation, new construction building will require mechanical ventilation. Section 403.3 includes the following minimum rates for mechanical ventilation:

- Living Spaces: 0.35 ACH but not less than 15 cfm x (1 + # bedrooms)
- Kitchens: 25 cfm continuous or 100cfm intermittent
- Bathrooms: 20 cfm continuous or 50cfm intermittent
- Corridors: 0.06 cfm/ft^2

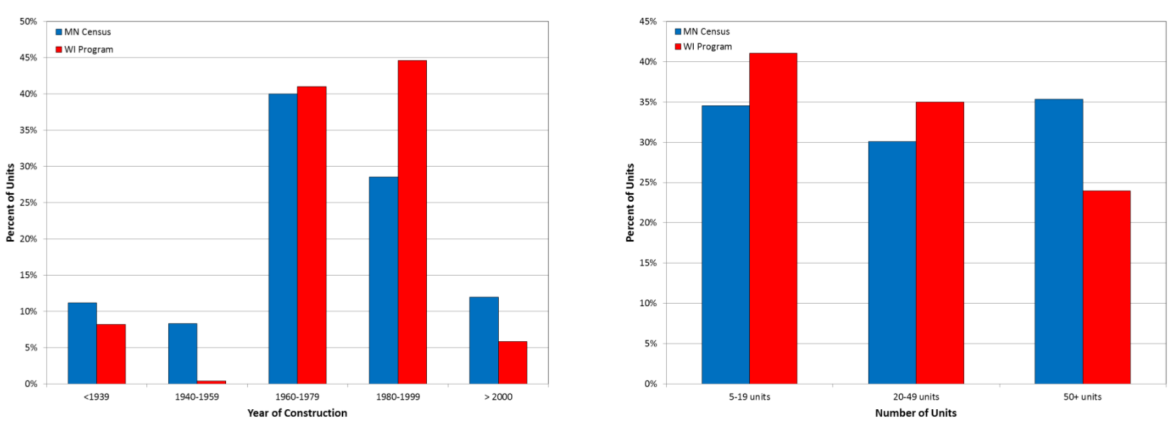
In addition, Section 403.1 indicates that the system must be balanced:

> **403.1 Ventilation system**. Mechanical ventilation shall be provided by a method of supply air and return or *exhaust air*. The amount of supply air shall be approximately equal to the amount of return and *exhaust air*. The system shall not be prohibited from producing negative or positive pressure. The system to convey *ventilation air* shall be designed and installed in accordance with Chapter 6.

Market Characteristics

A 2013 CARD funded Minnesota multifamily characterization study provided comprehensive information on building energy use and many characteristics relevant to energy use (Pigg et al 2013). Unfortunately, the project did not collect information on ventilation and there is no published information on the prevalence of mechanical ventilation in Minnesota multifamily buildings. Some insight on mechanical ventilation for existing multifamily buildings in the upper Midwest is available from data collected from 2001 to 2003 at 249 Wisconsin multifamily buildings that participated in a utility energy efficiency program. The frequency of units by building age and size is similar for both the population of Minnesota multifamily units and the Wisconsin program participants (See Figure 17). In both samples about 10% of the units are in buildings built before 1940, less than 10% in 1940 to 1959 buildings, and about 80% to 90% in buildings built after 1959. For the Wisconsin sample there are somewhat more units in smaller buildings (5 to 19 units) and less in larger buildings (50+ units). The similarity of the building stock suggests that results from the Wisconsin program should be a reasonable indicator of trends for Minnesota multifamily buildings.

Figure 17: Comparison of building age (left) and size (right) for MN and WI energy program participants



Information on common space ventilation was collected for 81% of the buildings and unit ventilation data was collected for all buildings. Overall, common space ventilation was observed for 21% of the buildings with about the same fraction for exhaust only and supply only systems (9% and 8% respectively) and with 4% having balanced systems. The results confirm that common space ventilation is most prevalent in larger buildings built after 1960 (see Table 4). The most common bathroom ventilation was a ceiling exhaust fan (83%, see Table 5) and the next most common was central exhaust (11%, see Table 6). Bathroom central exhaust ventilation was most common in buildings constructed from 1960 to 1979 although there doesn't appear to be much relationship between the frequency of central exhaust and building size. It should be noted that it is possible for a ceiling exhaust fan to be connected to a central fan. This type of system is designed to draw air from the unit continuously, with a higher flow rate when the fan is on. It is not clear whether any of the systems recorded as ceiling exhaust fans were connected to a central fan.

Table 4: Percentage of WI buildings with common area ventilation by age and size

Building Size	<1939	1940-59	1960-79	1980-99	> 2000	All
5-19 units		0%	15%	11%	0%	10%
20-49 units	17%		43%	57%		46%
50+ units	0%		86%	50%		62%
Total	13%	0%	33%	20%	0%	21%

Table 5: Percentage of WI buildings with bathroom ceiling or wall exhaust fans by age and size

Building Size	<1939	1940-59	1960-79	1980-99	> 2000	All
5-19 units			44%	98%	100%	86%
20-49 units	50%		69%	100%		69%
50+ units	100%		67%	100%		78%
Total	67%		57%	98%	100%	83%

Table 6: Percentage of WI buildings with bathroom central exhaust ventilation by age and size

Building Size	<1939	1940-59	1960-79	1980-99	> 2000	All
5-19 units			28%	0%	0%	6%
20-49 units	0%		31%	0%		25%
50+ units	0%		33%	0%		22%
Total	0%		30%	0%	0%	11%

Minnesota Code Sound Transmission Requirements

As noted previously, compartmentalizing dwelling units is expected to help reduce contaminant and sound transfer between units. The benefit for reduced sound transmission is recognized by both the codes for low-rise and high-rise residential buildings. The current Minnesota building code requires that one to three story multifamily buildings comply with the 2012 IRC Appendix K – Sound Transmission for wall and floor-ceiling assemblies between dwelling units (ICC 2012b). This specifies prescriptive requirements for sealing or treating penetrations and performance requirements for sound transmission:

> **AK101.1 General.**
> Wall and floor-ceiling assemblies separating dwelling units, including those separating adjacent townhouse units, shall provide air-borne sound insulation for walls, and both air-borne and impact sound insulation for floor-ceiling assemblies.
>
> **AK102 Air-Borne Sound**
> **AK102.1 General.**
> Air-borne sound insulation for wall and floor-ceiling assemblies shall meet a sound transmission class (STC) rating of 45 when tested in accordance with ASTM E 90. Penetrations or openings in construction assemblies for piping; electrical devices; recessed cabinets; bathtubs; soffits; or heating, ventilating or exhaust ducts shall be sealed, lined, insulated or otherwise treated to maintain the required ratings. Dwelling unit entrance doors, which share a common space, shall be tight fitting to the frame and sill.

Buildings with four or more stories must meet the 2012 International Building Code Section 1207 Sound Section (ICC 2012c). The requirements are similar to those for one to three story buildings:

> **1207.1 Scope**
> This section shall apply to common interior walls, partitions and floor/ceiling assemblies between adjacent *dwelling units* or between *dwelling units* and adjacent public areas such as halls, *corridors, stairs* or service areas.
>
> **1207.2 Air-borne sound.**
> Walls, partitions and floor/ceiling assemblies separating *dwelling units* from each other or from public or service areas shall have a sound transmission class (STC) of not less

than 50 (45 if field tested) for air-borne noise when tested in accordance with ASTM E 90. Penetrations or opening in construction assemblies for piping; electrical devices; recessed cabinets; bathtubs; soffits; or heating, ventilating or exhaust ducts shall be sealed, lined, insulated or otherwise treated to maintain the required ratings. This requirement shall not apply to dwelling unit entrance doors; however, such doors shall be tight fitting to the frame and sill.

Minnesota Utility Energy Efficiency Programs

Existing Buildings

There are currently two Minnesota utility conservation improvement programs that specifically target existing multifamily buildings. Both programs could incorporate envelope air sealing as a qualifying retrofit measure. The program services and incentives that may apply to envelope air sealing are described below.

CenterPoint Energy/Xcel Energy Multifamily Building Efficiency

This is a continuation of the existing Multifamily Building Efficiency program. The following description is included in CenterPoint Energy's Triennial CIP Plan for 2017-19:

> The Multi-Family Building Efficiency project is a joint CIP offering from CenterPoint Energy and Xcel Energy (the Companies) that is intended to help multi-family property owners understand their buildings' energy use, achieve immediate energy savings through low-cost/no-cost improvements, and move beyond initial measures to achieve deep energy savings. It will accomplish this through a combined approach of a building assessment/direct install phase to engage building owners and achieve early savings, and a performance-based component to encourage further improvements in the building. The project will provide incentives that are based on a percent of the cost of the improvements.

Buildings must have five or more units and can be either renter or owner-occupied. Eligibility is reviewed on a case by case basis considering a variety of factors.

CenterPoint Energy has indicated that envelope air sealing will be included as a custom measure for this program (Dedolph 2016). The payback would need to be less than the measure life of 20 years in order for the air sealing work to qualify for an incentive. The incentive is likely to be $3.50/Dth for market rate buildings with double the incentive for low-income qualifying buildings. The State of Minnesota Technical Reference Manual for Energy Conservation Improvement Programs (2016) includes an algorithm for residential and small commercial buildings (see Technical Reference Manual Savings Calculation section below). However, that is not directly applicable to multifamily units, and there is currently no generally accepted methodology for computing energy savings for multifamily building envelope air sealing. A methodology needs to be established that is accepted for use for utility efficiency programs.

Minnesota Energy Resources Multifamily Direct Install Plus

Minnesota Energy Resource's Multifamily Direct Install Plus (MFDI) program is targeted to multifamily buildings with five or more rental units with a central gas meter, central heating, and central or individual hot water system fueled by natural gas, on commercial rates. As noted in the Triennial CIP Plan for 2017-19:

> The MFDI project features a staged sales approach to the project design, starting with low-cost measures that are easily adoptable and building to larger actions with higher cost and impact as customers become confident in the approach and benefits.

After the direct installation of low-flow showerheads and faucet aerators, one of the program services is a targeted investigation of up to three high-value opportunities. Envelope air sealing could be included as one of the targeted measures for investigation and it may qualify for a custom rebate. All projects are individually reviewed and rebates require pre-approval. The rebate is calculated as the lesser amount of:

- A buy down to a 1 year payback,
- $1.00 per therm saved during the first year,
- Full incremental cost.

Similar to the CenterPoint Energy/Xcel Energy Multifamily Building Efficiency program, there is currently no generally approved methodology for computing multifamily envelope air sealing savings. A methodology needs to be established that is accepted for use for utility efficiency programs.

New Construction

Xcel Energy and CenterPoint Energy offer design assistance programs for commercial and industrial new construction and major renovation. Multifamily buildings can be eligible for these programs. As noted in Xcel Energy's Triennial CIP Plan for 2017-19:

> The Business New Construction program influences owners, architects, and engineers to include energy efficient systems and equipment in their designs for new construction, additions to existing buildings and/or major renovation projects. We provide consulting services and energy modeling, as well as electricity and natural gas efficiency implementation rebates.

Xcel offers two services: Energy Design Assistance (EDA) and Energy Efficient Buildings (EEB). EDA provides: (1) free computer energy modeling of the planned design, (2) funding to offset the cost of design time associated with the increased energy analysis, (3) financial incentives to improve the cost-effectiveness of a package of energy efficiency measures, and (4) field verification to ensure that the strategies are installed per the design intent. Buildings must have a floor area of 20,000 ft^2 or greater and achieve a minimum 5% demand and energy savings in order to qualify for that potion of the rebate. There is an Enhanced track for buildings that have a floor area of 50,000 ft^2 or greater for which the design teams strive to achieve a minimum demand savings of 30% and are interested in obtaining a sustainable building certification such as United States Green Building Council's Leadership in Energy and Environmental Design (LEED).

The Xcel 2017-19 CIP filing includes the following information for EEB:

- … provides a simplified approach to optimizing energy efficiency options in new construction, additions, and major renovations.

- It offers final design review, equipment recommendations, and onsite verification.
- Incentives are provided for heating, cooling, lighting, building envelope, motors, and custom opportunities.
- Any size building may participate, but this component is best suited for buildings that are greater than 5,000 ft^2.

Although a tighter building envelope and associated air infiltration reduction is not a standard measure for the program, it can be modelled if requested by the design team (Baker 2016). Increased envelope tightness is usually obtained by either choosing a liquid applied membrane or foam insulation. There are multiple options for verifying a tighter envelope: inspection before exterior cladding is applied, blower door air tightness test, or review of details and specifications. The baseline air infiltration is typically 0.1 ACH at a wind speed of 10 mph, and the increased tightness reduces the baseline infiltration by 15%. When there are operable windows, it is assumed that they are not always closed and the baseline infiltration is increased to 0.6 ACH (0.1 ACH infiltration and 0.5 ACH for open windows). The tighter envelope measure does not apply to the operable window infiltration.

Technical Reference Manual Savings Calculation

The State of Minnesota Technical Reference Manual for Energy Conservation Improvement Programs (2016) provides methods and inputs for calculating energy savings for Minnesota utility energy savings measures. The manual includes a savings calculation method for residential insulation and air sealing. It is noted that the method is applicable to existing residential and small commercial customers with natural gas space heating. The retrofit is assumed to have a measure life of 20 years. The air sealing savings are specified by the following equation:

$$E_{inf} = \left((1.08 \cdot 24 \cdot HDD65 \cdot Q_{50} \cdot CF/N\_heat)/Eff\right)/Conv \quad (1)$$

where:

E_{inf} = air infiltration energy savings, Dth

HDD65 = the heating degree days of the climate zone with a 65 degree base (7,651 for Twin Cities)

Q_{50}= Total reduction in infiltration at 50 Pa as measured by blower door, cfm

CF= Correction factor. Assumed to be 0.7[5]

N_heat = Conversion factor from leakage at 50 Pascal to leakage at natural conditions, based on climate, building height and exposure level (see Table 7)

Eff = efficiency of heating system

Conv= units conversion, 1,000,000 Btu/Dth

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[5] The correction factor corrects heating usage as building balance points are below 65F, and setback schedules are common. A typical heating degree day correction factor is 0.7. Assuming a typical building balance point temperature of 55F if was found that for a sampling of Minnesota cities HDD55 = 0.7 x HDD65.

It is important to note that the conversion of the measured building leakage (Q_{50}) to infiltration at natural conditions assumes that the building can be treated as a single zone with little or no restriction to internal air movement and that there is no impact due to mechanical ventilation. Those are not valid assumptions for multifamily buildings. More sophisticated modelling methods are required to compute air filtration and associated energy costs for multifamily buildings (see Methodology/Airflow and Energy Modelling).

Table 7: N_heat conversion factor for Minnesota

Relative Exposure	Building Height (# Stories)		
	1	2	3
Well Shielded	18.6	14.9	13.0
Normal	15.5	12.4	10.9
Exposed	14.0	11.2	9.8

Methodology

Aerosol envelope air sealing was performed on existing and new construction multifamily units to measure air leakage reductions, document labor hours required, and help identify best practices for sealing preparations and implementation. The air sealing protocol was adapted based on experience with past laboratory and field projects. The type of sealant deposition protection measures, temporary seals, manual pre-sealing, and time required for all tasks were broken out for a subset of the sealed units. Multi-point, total unit air leakage tests were conducted on all units before and after the sealing. For a subset of the units the leakage test was repeated after the unit sealing was finished. In addition, multiple fan, guarded air leakage tests were performed to break-out exterior and interior envelope leakage. Pre/post-acoustic tests and documentation of sealant locations using a fluorescent dye in the sealant and black-light photography were conducted for some of the units. The air flow and energy use modelling was performed with EnergyPlus simulations that determined building air flows from wind, stack, and mechanical effects along with the air leakage characteristics of each unit.

Site Selection

The new construction and existing buildings selected for this project were a convenience sample of Minnesota buildings and do not necessarily represent the entire Minnesota multifamily housing stock. The goal was to demonstrate the use of an innovative aerosol sealing method for tightening multifamily housing units. The objectives were to provide information on the range of sealing achieved, the type of leaks sealed, and any protocol modifications that might be necessary for large-scale adoption of this method. The only criteria were that the building be located in Minnesota; the building interior temperature be 50°F or warmer; the contractor be willing to provide access to the unit for testing and sealing; and the building be available during the appropriate stage of construction.

Our initial criteria for the stage of construction for new construction units included the following:

1. Sheet rock
    a. Installed on exterior walls, walls between units, and ceilings.
    b. At least the first coat of mud and tape applied.
    c. No paint or other finish (preferred, but not required).
2. Floors
    a. Unfinished surface in place (e.g. plywood or gypcrete).
    b. No finished material in place (e.g. no carpeting, tile, wood, etc).
3. Electrical rough-in complete with boxes installed, but no devices, and preferred that recessed light cans installed.
4. Windows installed and sealed in opening.
5. Exterior and hallway doors installed except for opening that will be used for fan to pressurize unit (can be installed and left open).
6. Mechanical penetrations (ducts, pipes, etc.) complete.

For a limited number of cases the criteria were relaxed and additional temporary sealing or surface protection was provided.

It was expected that the existing units would be either undergoing major renovation over a two to six week period or minor renovation during a two to five day period of occupant change-over. The stage of construction criteria applied to new construction was also applied to units undergoing major renovation. Minor renovations were expected to include carpet and possibly cabinet replacement. Similar to the new construction units, some criteria were relaxed for the buildings. For example, for one of the buildings the renovation work was nearly complete and the sealing work was performed with new flooring and cabinets in place.

Air Sealing Protocol

Aerosol envelope sealing had been performed previously by WCEC staff on twelve single-family houses and six multifamily units. The procedures and equipment established for that work was updated for this project. The minimum requirement for the sealing to take place is that an air barrier must be in place so that the unit can be pressurized. In general, the length of time to protect surfaces, make temporary seals, and provide access to the aerosol is reduced when the aerosol sealing is performed earlier in the construction process. For new construction the target was to perform sealing shortly after the drywall had at least a first coat of mud/tape in place and after any poured floor was in place. A greater amount of finished surfaces were in place for the existing units. The air sealing protocol is outlined below and described in greater detail in Appendix A:

- **Protection:** Some fraction of the aerosol sealant inevitably settles on the floor, window sills, ceiling fans, and the tops of other horizontal surfaces. Horizontal surfaces that cannot have sealant deposition are covered with plastic, duck mask, or masking tape.
- **Temporary Seals:** Potential leak sites where sealing is not desired should be blocked with tape or plastic. All protection needs to be able to withstand the 100 Pa pressures experienced during sealing. Sites that may require temporary seals include exterior door frame, exhaust fans, ventilation system inlets/exhausts, leaky windows, smoke detectors, and sprinkler heads. It should not be necessary to seal distribution system supply and return registers. The process may seal some exterior duct leaks, but air handlers and furnaces may need to be isolated if the registers are not sealed.
- **Open Access to Aerosol:** The aerosol sealant must stay in suspension as the air moves to the leak. Depending on the degree of finishing work completed, it may be necessary to remove electric plates, plumbing escutcheons, and ceiling fan canopies.
- **Pre-Sealing:** It is necessary to manually seal leaks with a gap width greater than about 3/8 in. or those leaks located where the aerosol will not stay in suspension when the air moves through the leak. It is best to identify the potential for such leaks early in the construction process and determine responsibilities for eliminating those leaks. However, the leaks can be sealed during a pre-inspection as long as they are still accessible. The leaks with larger gaps are often penetrations such as plumbing, duct, electric lines, AC line set, and gas pipes.
- **Spray Nozzle Placement and Operation:** In general, one nozzle is placed in every bedroom and living area of the apartment. Bathrooms and hallways may be too small to have a dedicated nozzle placed inside. In those cases, nozzles should be directed from another room toward the smaller room to help distribute the aerosol into those smaller spaces. The nozzle is directed upward from the floor and placed

so that there is at least 8 feet from the nozzle to any walls in the direction of the injection plume. This promotes suspension of the aerosol while preventing sealant deposition on walls. The compressed air lines are operated at a pressure from 60 to 90 psi with liquid injection rates from 10 to 100 ml/min per nozzle.

- **Aerosol Sealing**: The unit should be pressurized to approximately 100 Pa during the sealing. For this project the pressurization was produced with using two Energy Conservatory DuctBlaster fans installed in the hallway door with DG700 digital gauges connected to TECLOG3 software to automatically regulate, measure, and record the fan flow required to achieve the desired pressure. The nozzle liquid lines are switched from water to sealant after confirmation that the nozzles and pressurization fans are working properly. The liquid injection rate is manually varied throughout the sealing process to achieve a relative humidity of approximately 90% in the space. In-line electric duct heaters are used with the pressurization fans to allow higher sealant injection rates. Sealing typically continues until either the leakage reduction rate drops below about 1 cfm50/min or a desired tightness is achieved.
- **Clean-up**: When the sealing is complete liquid injection lines need to be purged with water, windows must be opened, and fans set at high to purge the interior of remaining sealant. Temporary seals and protection must be removed. The amount of clean-up is typically limited when preparations are properly planned and executed.

Future Equipment Development

Future commercialization of the system will include more fully automated operation of the components and reductions to equipment size to reduce setup time. The aerosol sealing process is performed at an established relative humidity to improve sealing rates and seal durability while minimizing deposition on the floor. The building interior humidity is controlled during the sealing by reducing sealant injection rates as leaks in the building seal and airflow into the building drops. The future system will have software controlled, variable rate injection pumps that are adjusted to achieve the target humidity. This improvement is expected to reduce the training required for operating the equipment and provide a more consistent application process.

In addition to the improved automation, the injection equipment will be more compact reducing the size and weight of the supplies needed for the process. The new system will have much smaller compressed air lines that are less than half the diameter of previous versions of the equipment, making it lighter and less bulky. The heater used in the process will be mounted to the blower door fan which will reduce the setup time. The compressor is being switched to a compact tankless type and the major components will be mounted to a cart for easier transport.

Air Leakage

Total Envelope Leakage

The primary measurement of envelope leakage was a total leakage test that included leakage for all portions of the unit including the exterior walls, floor, ceiling, and demising walls. The tests were conducted in accordance with ASTM E 779-10 Standard Test Method for Determining Air Leakage Rate by Fan Pressurization (2010). The test method was intended for single-zone buildings or multi-zone buildings that could be treated as a single zone. The test method was adapted for testing a single unit in a multifamily building, and temporary seals were used when construction was not complete. This included:

- Exterior windows and/or doors of adjoining units and common spaces were opened so that the pressure of those spaces was approximately equal to the outside pressure.
- The test fan was placed in the hallway door of the unit, and the hallways were well connected to other units and the outdoors so that the air flow through the test fan had no significant impact on the hallway pressure.
- The termination of the "outdoor" pressure tube was often placed in the hallway to provide a more stable pressure reference.
- Some mechanical openings were temporarily sealed (e.g. exhaust fan ducts, supply ventilation ducts, thru-wall air conditioner sleeves, plumbing waste pipes, etc.
- Exterior doorways that did not have doors installed were temporarily sealed.
- Poly sheets placed on floors during pre-sealing tests may have reduced leakage through hardwood flooring of existing units.

The primary envelope tightness value of interest was the leakage at a pressure difference of 50 Pa. The test protocol was designed to produce a reliable leakage estimate for a pressure difference of 50 Pa with a secondary goal of computing an accurate flow exponent. Typically, 30 second average measurements[6] of the unit to exterior pressure difference and fan flow rate were recorded for eight pressure differences ranging from 20 to 60 Pa. The change in pressure between points was usually 10 Pa with 5 Pa differences for measurements closer to 50 Pa and a duplicate measurement at 50 Pa. A common sequence was to record measurements at 20, 30, 40, 45, 50, 50, 55, and 60 Pa. However, values below 20 Pa were sometimes recorded for low wind conditions and measurements above 50 Pa were not performed if they required a change in the fan flow ring. The baseline pressure difference was recorded before and after the fan-on points with a typical measurement period of 60 seconds. Three quarters of the units were tested using a pressurization method, and a quarter were tested using depressurization. The same method was used for the pre and post-sealing test for individual units so that the measurement method would not impact the measured change in leakage. The elevation, inside air temperature, and outside air temperature were used to adjust for air density. The measurement and analysis were conducted using Energy Conservatory TECLOG3 software. The multi-point analysis specified by ASTM E 779-10 for a power law relationship (see equation 2) was used to report the leakage flow rate at a pressure difference of 50 Pa.

[6] A 30 second time period was used for almost all of the fan on measurements. A few measurements for a couple of units were conducted for 15 seconds and measurements were sometimes conducted for 60 seconds for windy conditions. The number of fan on measurements for a test varied from 6 to 13 with a median of 8.

$$Q = C_Q(\Delta P)^n \quad (2)$$

where:

Q = test fan flow rate, cfm

C_Q= flow coefficient, cfm/Pa^n

n= flow exponent

ΔP = inside with respect to outside pressure difference, Pa

The one second pressure and flow measurements for a typical depressurization test are displayed in Figure 18. The red line represents the fan flowrate and the green line is the unit pressure with respect to outside. The solid green vertical lines designate the nine measurement periods, and the two sets of dashed green lines designate the "baseline" measurements when the fan was turned off. The average of the two baseline measurements were used to adjust each of the "fan-on" measurements for unit/outside pressure differences due to wind and stack effects. Figure 19 displays the log-log regression plot, table of measurements, and calculated results for the nine recorded measurements.

Figure 18: One-second pressure/flow measurements for a typical test

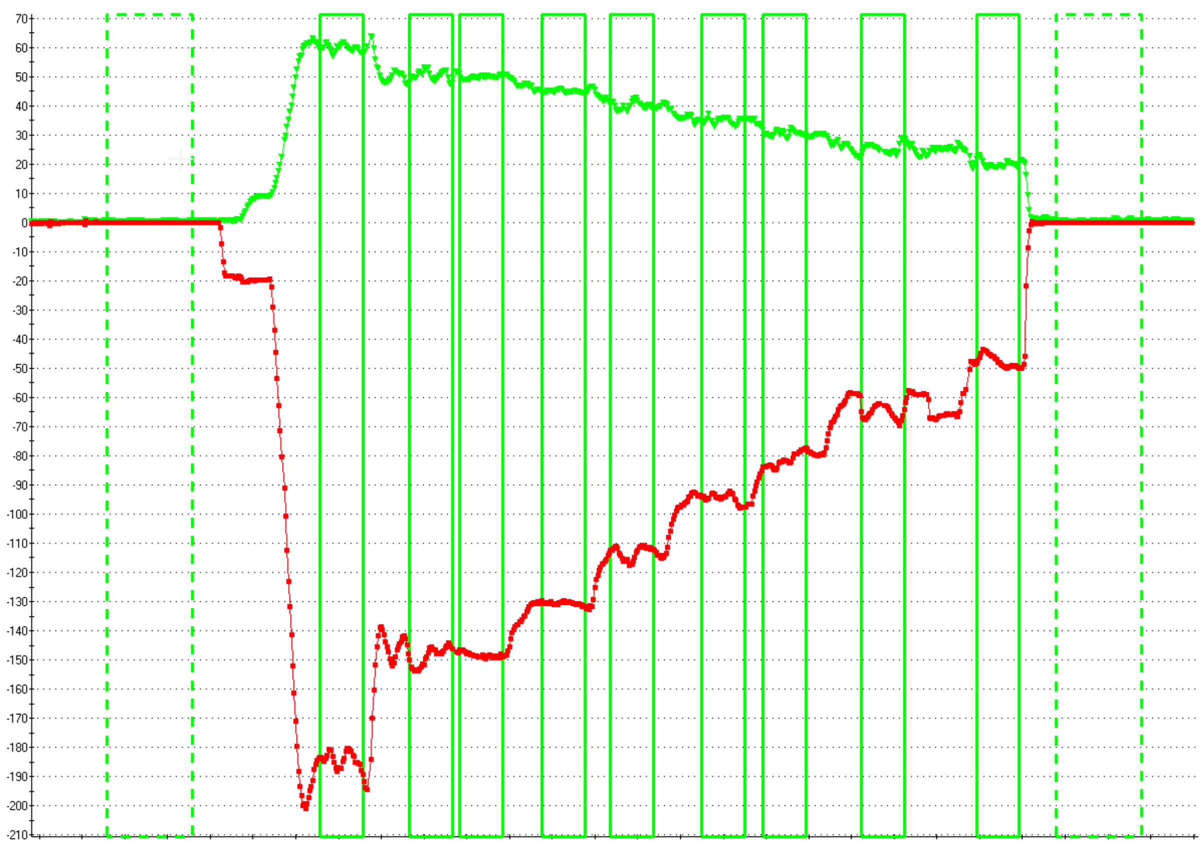
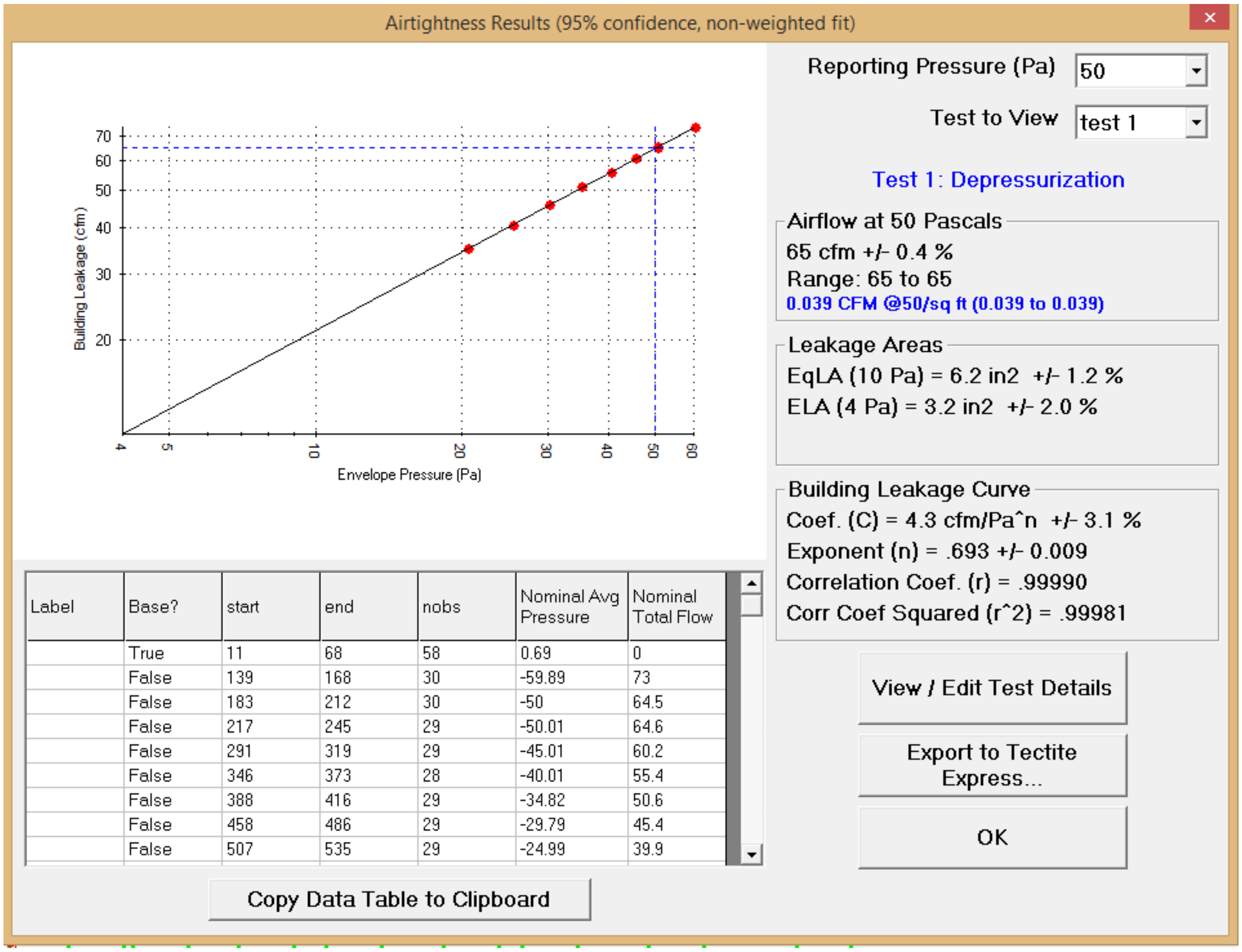


Figure 19: Regression analysis for a typical test



Label	Base?	start	end	nobs	Nominal Avg Pressure	Nominal Total Flow
	True	11	68	58	0.69	0
	False	139	168	30	-59.89	73
	False	183	212	30	-50	64.5
	False	217	245	29	-50.01	64.6
	False	291	319	29	-45.01	60.2
	False	346	373	28	-40.01	55.4
	False	388	416	29	-34.82	50.6
	False	458	486	29	-29.79	45.4
	False	507	535	29	-24.99	39.9

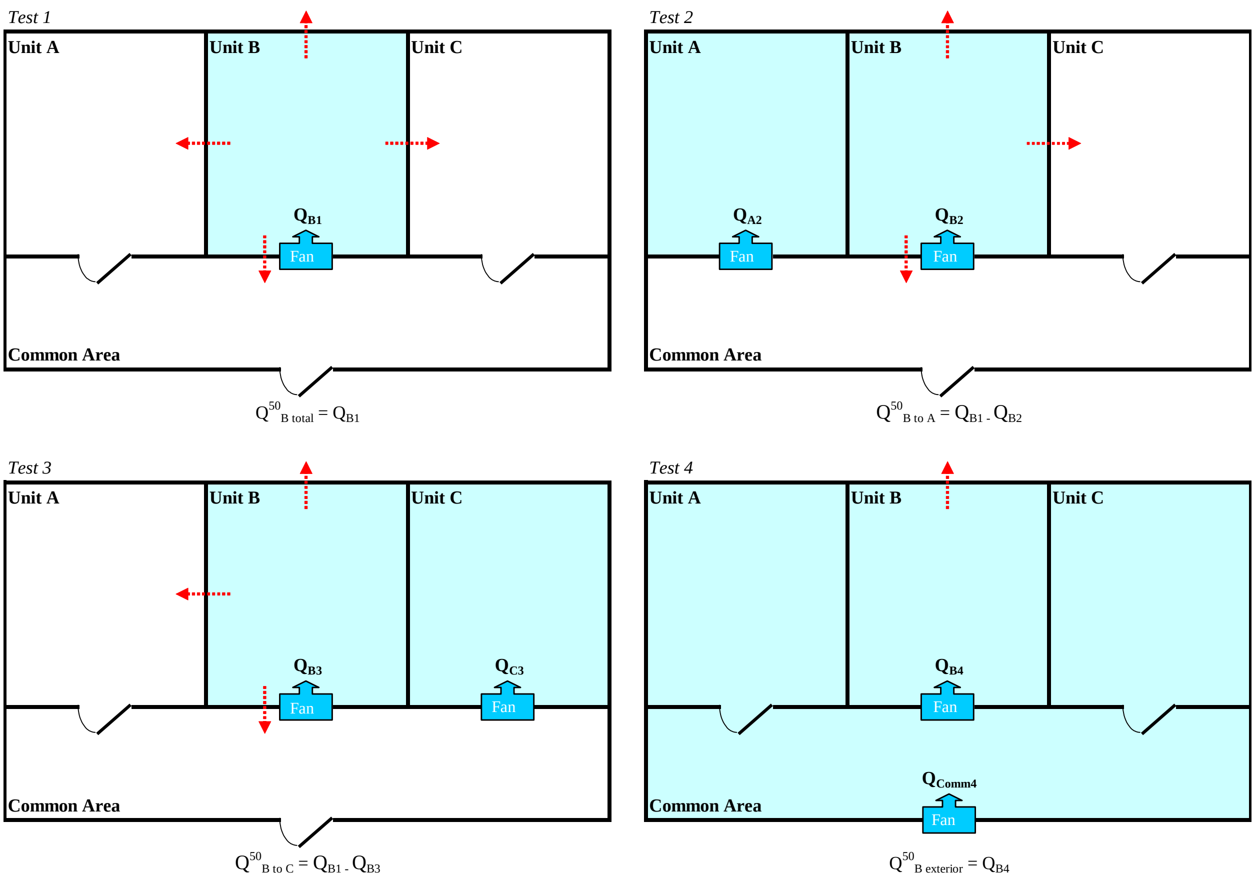
The tests were conducted using two types of variable speed, calibrated fans. The larger fan (Energy Conservatory Model 3 fan) has a capacity from approximately 300 to 6,300 cfm and the capacity of the smaller fan (Energy Conservatory Duct Blaster®) is approximately 10 to 1,500 cfm. The fans were manufacturer calibrated prior to the measurements. Flow measurements had an accuracy of 3% of the flow rate. Pressure measurements were performed using a two channel, digital micromanometer (Energy Conservatory DG-700) that was calibrated annually in accordance with manufacturer guidelines and has a specified accuracy of the greater of 0.15 Pa or 1.0% of the measurement. The pressure channels were auto-zeroed every one to two minutes to minimize zero drift errors.

Breakdown of Exterior and Interior Air Leakage

Measuring the distribution of the total leakage between the exterior and interior envelope leakage was a secondary priority. Guarded-zone measurement techniques were used to estimate the leakage for different portions of the envelope. These techniques measure the leakage of a test unit while one or more additional fans are used to pressurize some of the adjoining area to the same level as the test unit (Feustel 1989; Bohac, Dutt, and Feuermann 1987; Furbringer, Roecker, and Roulet 1988; Modera, Diamond, and Brunsell 1986; Levin 1988). Since there is no pressure and flow between the unit and the adjoining areas being pressurized, the measured flowrate of the fan in the test unit is approximately equal to the leakage for the areas that are not being pressurized. Guarded-zone measurements were conducted on a subset of the units to help determine whether the aerosol sealing method was more effective for one portion of the envelope than another. The exterior and interior envelope leakages of units were measured before and after the sealing to separately estimate the percent reduction in interior and exterior leakage.

Two different approaches were used for the guarded-zone tests. The first approach used a fan in the hallway door of the test unit and another fan in one of the adjoining apartments to eliminate the flow or indicated leakage directly between units. A typical sequence of tests for one unit in an apartment building with three units and a common area is shown in Figure 20.

Figure 20: Guarded-zone test sequence for three unit apartment building



Test 1 was used to determine the unit's total air leakage. A second fan was installed in the hallway door of unit A for the second test. The fan in unit B was adjusted to produce a 50 Pa pressure for unit B relative to outdoors and the fan in unit A was adjusted so that the pressure difference between units B and A was zero[7]. The difference in the air leakage for the first two

[7] The unit to outside pressure differences were adjusted to the specified pressure of 50 Pa relative to the measured baseline pressure differences with the fans off and sealed. Also, the pressure difference between units during fan operation was adjusted to be equal to that measured with the fans off and sealed.

tests was equal to the air leakage between unit B and A. The four tests provide a measure of the unit's total leakage, leakage to each adjoining unit, and leakage to the exterior. In addition, the leakage to the adjoining units and exterior can be subtracted from the total to obtain the leakage to the common area. Only units that were directly above, below, or to the side of each "test" unit were included. Units diagonal to or across the hall from the test unit were not included in the process. For some of the buildings there was not a complete air barrier for one or more adjoining areas. When there was not a complete air barrier those areas could not be pressurized and it was not possible to measure leakage to those areas.

The second guarded-zone approach used one fan in the test unit hallway door and a second fan in the building exterior. The fan in the building exterior was used to pressurize adjoining areas to the test unit by opening or closing hallway doors and windows. For example, the configuration of Test 4 in Figure 20 was modified to have the hallway door of unit A closed and one or more windows of unit A open so that there was no significant pressure difference between unit A and the outside. With that configuration the fan in unit B measured the sum of the leakage of unit B to outside and to unit A. The difference between that value and the leakage from Test 4 (exterior only) was used to estimate the leakage between unit B and A. The process was then repeated for other adjoining spaces. For some buildings the air barrier for the entire building was not complete. For those situations the second fan was placed in the doorway between the hallway for the test unit and the stairwell to that hallway. Doors were opened as necessary so that the stairwell was sufficiently connected to the outside. For that configuration it was possible to pressurize the areas on the same level of the test unit, but not the areas above or below the test unit.

It is important to note that the calculations for the guarded zone technique assume that there is a single leakage path between the units and that the relationship between flow and pressure for those leakage paths can be described by equation (2). In multifamily buildings the leakage from one unit to another often travels through relatively large mechanical chases or open floor joists and those areas can be open to multiple units or to the outside. Shao et al. (1992) determined that the guarded zone technique will not properly quantify air leakage paths that travel through "branched connections" or intermediate zones. They state that it appears that the guarded zone technique can significantly underestimate inter-unit leakages (by as much as 30 to 50%) when most of the leakage between two units is though large cavities that also have leaks to the outside or common area. While further work is required to better estimate errors due to intermediate zones, those errors are typically expected to be less than 25% of the measured value. Other studies have evaluated the errors that are due to wind fluctuations and non-zero pressures between the units when two fans are operating (Furbringer and Roulet 1991 and Herrlin and Modera 1988). The time averaging of pressure/flow measurements and automated fan speed controls used for this study helps significantly reduce those errors. When a two-fan test was conducted, values were only recorded when the average pressure difference between the two units being pressurized was within about 0.2 Pa of the baseline pressure difference.

Individual Leakage Sites

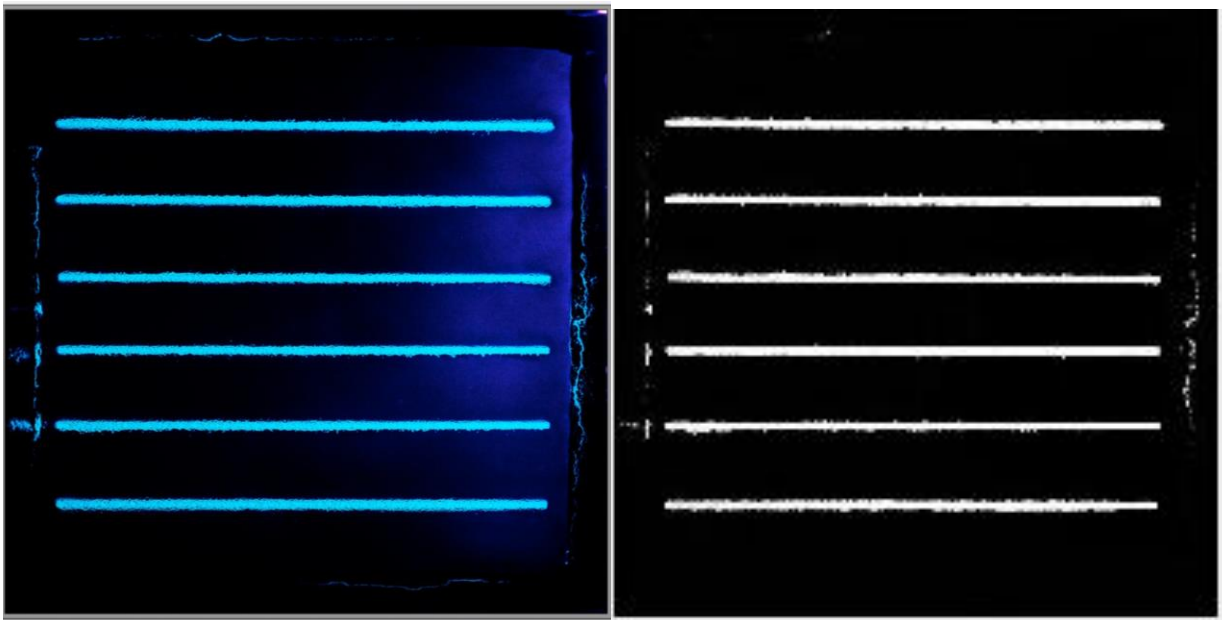
The leakage of individual sites was measured by placing an air flow metering device over a leak during a depressurization test. The test fan pulled air through the leakage site at an induced envelope pressure of 50 Pa. Leakage flow rate measurements greater than 10 cfm were conducted with an Energy Conservatory FlowBlaster® air flow device. It is a powered flow hood that creates approximately zero pressure difference across the meter during the measurement. Consequently, the measured flow rate is the flow through the leak at the induced envelope pressure. A custom calibrated Energy Conservatory Exhaust Fan Flow Meter was used for lower flow rates. The opening was replaced with a plate that had multiple 1.0 inch diameter holes. The relationship between the pressure across the plate and the flow rate was determined for one and multiple open holes. For the leakage measurement, a sufficient number of holes were opened to minimize the pressure difference across the box while still providing a reasonably accurate measurement.

Fluorescent Leak Identification

Determining the leakage distribution in a building envelope is difficult leading to a general lack of understanding of where leaks exist in a building. One method tested in this project for determining leakage distribution was to add fluorescing dye to the sealant material to highlight where the seals were formed in a building. Lab testing of the method showed some promising results. The general idea is that since the aerosol sealant only deposits in and around leaks sites, the surface area of the seals formed on a wall is directly related to the leakage area on that wall. The sealant also settles onto horizontal surfaces preventing this method from being used on floors.

The methodology was developed by sealing a known quantity of leakage with the aerosol sealing process and using image processing software to estimate the area sealed. Using image editing software, a method was developed to determine the number of pixels in the image that fluoresce in order to determine the size of the seal formed. Figure 21 shows an example of the image of the panel sealed in the laboratory before and after image processing. The results provided an estimate that ended up being twice as large as the size of the leak sealed. An overestimate was expected due to the deposition of sealant around the leak so the analysis divides the amount of sealant captured in the image by a factor of two.

Figure 21: Photo of seals under fluorescent light (Left), and photo of seals after image processing



Sound Transmission

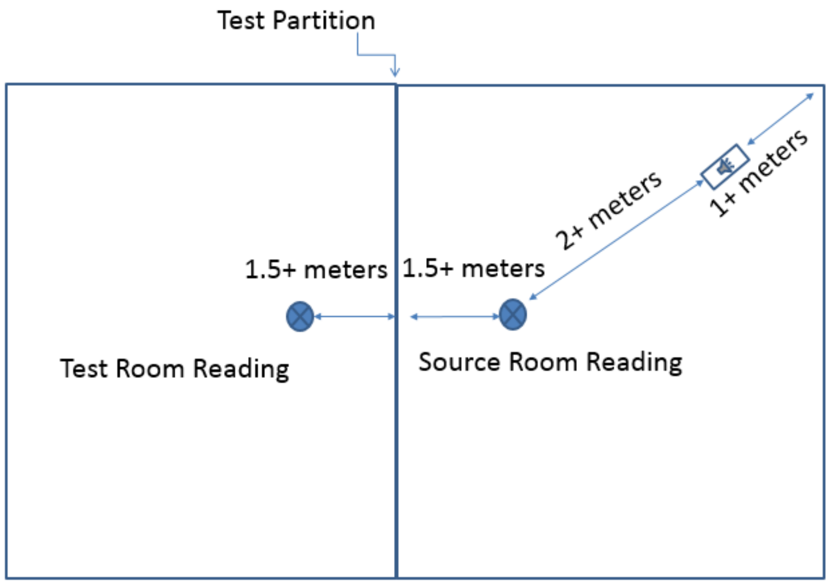
As noted in the earlier Minnesota Code Sound Transmission Requirements section, wall and floor/ceiling assemblies of Minnesota low and high rise residential buildings must comply with sound transmission requirements. The assemblies must meet an STC rating of 45 for one to three story buildings, and must not be less than 50 (45 if field tested) for buildings four stories and above. In both cases the assemblies are tested in accordance with ASTM E90. The field test protocol for this project was developed with reference to the following standards:

1. ASTM E90-2009: Laboratory Measurement of Sound Transmission Loss of Building Partitions and Elements
2. ASTM E966-2010: Field Measurements of Sound Attenuation of Building Facades
3. ASTM E336-2011: Measurements of Sound Attenuation between Rooms in Buildings

Measurement

The sound transmission tests measure sound attenuation across a test wall in a unit before and after the unit is sealed. The tests require a speaker system and recording devices. The speaker are faced into a corner of the room and directed away from the test wall during the test. Sound recording devices capable of omnidirectional sampling are used to capture the sound data in both the room with the sound source and the room across the wall being tested. The recording device is centered and placed more than 1.5 meters away from the test wall. The height of the sound measurement device is kept at or near the height of the speaker (Figure 22).

Figure 22: Sound Test Setup Diagram



A background noise measurement is recorded prior to all sound level measurements. A handheld decibel meter is used to confirm that the sound produced by the speaker is at least 10 dB above the background noise (this is especially important in the room without the sound source). If the sound produced by one speaker is too low, a second speaker is used. A total of 4 background sound level measurements are recorded per sealed unit:

1. Pre-seal Background Level Measurement, source room
2. Pre-seal Background Level Measurement, receiving room
3. Post-seal Background Level Measurement, source room
4. Post-seal Background Level Measurement, receiving room

A total of 4 measurements are recorded using the recording device. These measurements are longer than 10 seconds to meet the ASTM standards.

1. Pre-seal Sound Level Measurement, source room
2. Pre-seal Sound Level Measurement, receiving room
3. Post-seal Sound Level Measurement, source room
4. Post-seal Sound Level Measurement, receiving room

Analysis

Using the recorded data, the analysis is conducted using 18 selected frequencies within the range of 0 to 5000 Hz. These 18 frequencies are defined in ASTM E90. The sound analysis software Raven Pro was selected for the analysis. This software was selected because the interface is user friendly, and it is capable of producing sound level data for any frequency in the audible range.

Sound Transmission Reduction (STR) is defined as the reduction in sound power level across the test wall at the 18 selected frequencies (equation 3). This reduction is due to the interaction of the source sound waves with the wall as well as any sound flanking around the wall. The sound attenuation is defined as the increase in sound transmission reduction across the wall after sealing is completed (equation 4).

$$STR = SPL_{source} - SPL_{receiving} \quad (3)$$

$$Attenuation = STR_{postseal} - STR_{preseal} \quad (4)$$

A sound transmission test was developed to investigate the effects of using the aerosol sealing process on sound transmission between apartments. Sound transmission is an important factor in occupant comfort, and the amplitude of transmission at higher frequencies was shown to be correlated to the tightness of the building compartment. Lower frequencies transmit across the wall primarily by flanking through dense structural members while higher frequency sounds tend to travel through cracks. This was observed in preliminary sound tests before and after sealing the envelope (Figure 16). As noted previously (see *Minnesota Code Sound Transmission Requirements*), Minnesota code requires the use of properly sealed wall assemblies with STC ratings no less than 50 or sound transmission tests of completed demising walls with STC values no less than 45 for both low and high-rise residential buildings.

Airflow and Energy Modelling

In order to model a building using common energy simulation software such as EnergyPlus, several assumptions must be made about the construction of the building and the performance characteristics of many of the systems within the building. The value of the results obtained from such a simulation is highly dependent on the specific capabilities of the modeling software and the extent to which the software will allow dependent and independent variables to be analyzed. The independent variables include the building's physical characteristics and operating parameters of the ventilation systems. The dependent variables include building energy use, total outside air flow (e.g. infiltration and ventilation), and inter-zonal air flows (e.g. adjoining units and units to/from common spaces). Obviously, the accuracy or validity of the various inputs and assumptions has significant influence on the results.

Whole building simulations often assume a constant air infiltration rate to represent the effects of uncontrolled ventilation driven by the natural forces of wind and stack effect, as well as unbalanced mechanical ventilation. However, comparing the performance of different multifamily envelope tightness and ventilation strategies requires simulations that compute actual infiltration, which varies in a large part due to the climate of the particular location chosen for the simulation. The direction and amount of airflow into or out of a building is based on the difference in indoor and outdoor pressures, and the size and location of holes or leaks in the building envelope.

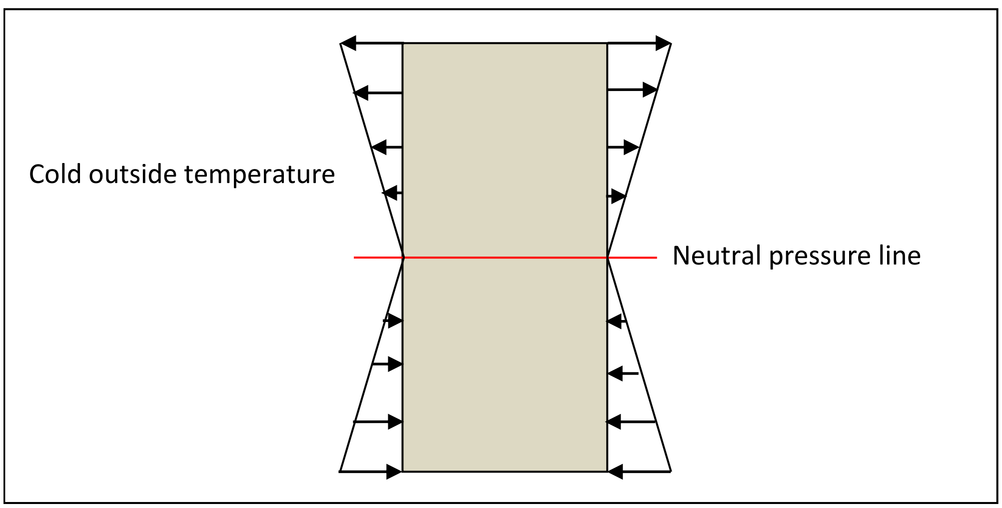
Natural Forces that Drive Air Flow

Whole building simulations often assume a constant infiltration rate to represent the effects of ventilation driven by the natural forces of wind and stack effect. However, comparing the performance of different ventilation strategies in multifamily buildings requires that simulations account for actual infiltration, which varies in a large part due to the climate of the particular location chosen for the simulation.

The direction and amount of airflow into or out of a building is based on the difference in indoor and outdoor pressures, and the size and location of holes or leaks in the building envelope. Wind striking an exterior surface of a building (the windward side) pressurizes that surface and drives airflow into the building (infiltration) through leaks and holes (i.e. windows, vents, etc.). Conversely, the exterior surfaces of the building opposite the windward side (the leeward side) experience a reduction in pressure as a result of the wind. This reduced pressure results in air flowing out of the building (exfiltration) though leaks and holes on the leeward side. It should be noted that the direction of flow, either into or out of a building, depends on more than the outside surface pressure since the driving force for flow is based on the relative pressure between inside and outside. Wind pressure can also affect relative indoor zonal air pressures, and influence airflow between interior zones.

The term "stack effect" describes the buoyancy-driven movement of air into and out of a building. Stack effect is driven by the difference in air temperature between indoors and outdoors. During the cooling season, cold air inside a building is denser than the hot air outside the building. This denser air sinks and exits the building through leaks on the lower floors, while drawing in makeup air from the outside through leaks in the upper floors. During the heating season the opposite occurs; warm air inside the building is less dense than the cold air outside the building. The warm air rises and exits the building through leaks in the upper floors, drawing in makeup air through leaks in the lower floors (Figure 23). The influence of the stack effect on infiltration and exfiltration rates is more pronounced in taller buildings and can be mitigated by air-sealing each floor, or compartmentalizing the vertical zones inside the building.

Figure 23: Illustration of stack effect during the heating season. Warm indoor air exits near the top of the building while make-up air enters from the bottom of the building



Mechanical Ventilation Systems

Mechanical ventilation provides better control of indoor-outdoor airflow and can ensure that ventilation is provided regardless of wind and stack effects. The ventilation system capacity of 70 cfm was computed from the unit floor area of 1,200 ft^2, a 10 ft height, and code required 0.35

ach ventilation rate[8]. Four types of continuous ventilation schemes were modeled using a combination of individual unit exhaust fans and/or a balanced ventilator integrated into the air conditioner of each apartment:

- **Exhaust Only**: Exhaust fan in each unit with no direct supply of outdoor air. This imposes a negative pressure on the apartment that is intended to draw outside air from outside the unit in for ventilation. The air can enter the unit both directly from outdoors and from adjoining interior areas (e.g. other units and the hallway).
- **Exhaust and Half Supply**: Full capacity exhaust fan in each unit with supply ventilation to the unit that is half the exhaust capacity. This system results in slightly lower negative pressures in the apartment than what occurs for exhaust only ventilation. The EnergyPlus model included both a half capacity balanced ventilation system integrated with the window air conditioner and a half capacity exhaust fan. This ventilation scheme was intended to show the impact of having both exhaust and supply ventilation systems without perfect balance of the two.
- **Balanced**: The balanced models do not use the exhaust fans at all, instead using a ventilation object built-in to EnergyPlus that allows the window air conditioner in each apartment to supply a specified amount of ventilation while also exhausting the same amount. While such perfectly balanced ventilation systems are not often achieved in multifamily buildings, it is common for this to be the ultimate design goal.
- **No Ventilation**: No continuous or intermittent mechanical ventilation, which is common in existing multifamily buildings.

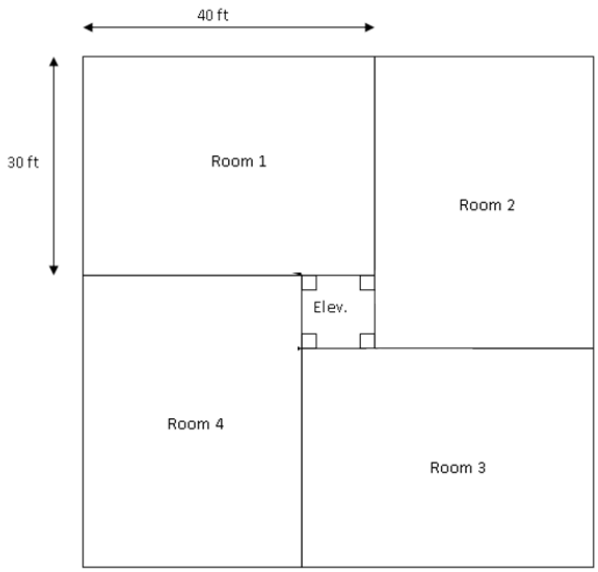
The mechanical ventilation systems were operated continuously. None of the schemes included intermittent operation of additional bathroom or kitchen exhaust fans. The electricity input of the 325 watt air handlers used for the balanced and exhaust/half supply systems was absorbed as heat in the apartment units. The heat from the lower power exhaust fans was exhausted outside and was not absorbed in the units.

Building Geometry

The floor plan was the same for each of the six floors (Figure 24) in the modeled building and was symmetric to minimize the effects of building orientation on the simulation results. For example, the magnitude of the effect due to wind on the building is independent of the direction, which allows for a more general result. In addition, symmetry is computationally less cumbersome. Each unit was 30 ft wide and 40 ft long with a floor area of 1,200 ft^2 and interior volume of 12,000 ft^3. The length of the exterior wall perimeter was 70 ft and the exterior wall surface area was 700 ft^2. The total envelope surface areas were: interior walls= 700 ft^2, exterior walls= 700 ft^2, floor= 1,200 ft^2, ceiling= 1,200 ft^2, total= 3,800 ft^2. For the first and sixth floor units the exterior surface area was 1,900 ft^2 and for the second to fifth floor units the exterior surface area was 700 ft^2.

[8] See section Background/Ventilation/Minnesota Requirements for further information on ventilation requirements for Minnesota multifamily buildings.

Figure 24: Floor plan of building model, all four floors are identical



Building Leakage

Leaks in the building surfaces and exhaust registers were modeled as crack leaks as specified by the power law flow equation given by equation 1. Because wind- and stack-driven pressures vary with building height, the locations of building envelope leaks affect airflow rates for both infiltration and exfiltration. Under some conditions air can flow in opposite directions through leaks at different heights in the same wall. To capture the effects of distributed leak heights on airflow, all exterior walls for each apartment were modeled with three leaks evenly spaced along the height of the walls. The building was modelled for "City" terrain that assumes a well shielded wind condition. Interior walls, which are not directly impacted by wind or stack effect (because temperature differences between indoor zones are small), were modeled with a single leak between each adjoining zone. Floors or ceilings were also modeled with a single leak, since height is not a factor in horizontal surfaces. It was assumed that there was no significant restriction to air movement between rooms within a unit. Each unit was modeled as a single, well-mixed zone.

A primary path for vertical air movement in a building is through vertical shafts that run the entire height of the building; examples of this include elevator shafts, exhaust ducts, plumbing chases, and garbage chutes. To account for such vertical air movement the model included an elevator shaft in the common space between apartments. Each apartment was modeled with a leak through the apartment door and another leak through the elevator door.

The impact of using aerosol sealing in ***new construction*** was evaluated by comparing a building with the Minnesota residential code required leakage of 3.0 ACH50 to a building that was sealed 80% tighter (e.g. 0.6 ACH50). That level of sealing is about equal to the average sealing of 81% for the 18 new construction units sealed for this project (see Results and Discussion/Air Sealing/New Construction/Aerosol Sealing). The specified leakage values are for the total unit leakage (not just the exterior leakage). Table 8 lists the leakage values in units of CFM50 and CFM50/ft2.

The impact of using aerosol sealing for ***existing buildings*** was evaluated by comparing a building with a leakage of 9.5 ACH50 to a building with a leakage of 3.0 ACH50. The 68% leakage reduction is equal to the average sealing for the nine existing units sealed for this project. The pre-existing leakage of 9.5 ACH50 is consistent with the average pre-existing total leakage of 31 units from five Minnesota buildings included in a secondhand smoke study (Bohac et al., 2008) and 44 units from ten Minnesota buildings undergoing major renovations.

Table 8: Unit total and exterior air leakage rates for energy models

New Construction	Existing Buildings	Total Leakage*			Exterior Leakage*		
		(ACH50)	(CFM50)	(CFM50/ft^2)*	(ACH50)	(CFM50)	(CFM50/ft^2)*
Sealed		0.6	120	0.032	0.28	56	0.081
Baseline	Sealed	3.0	600	0.158	1.41	282	0.403
	Baseline	9.5	1900	0.500	4.09	817	1.17

* Leakage of first and top floor units differ slightly due to the difference in floor leakage for first floor units and ceiling leakage for top floor units.

The distribution of leaks was determined using various sources. For the model with a total leakage of 3.0 ACH50, the floor/ceiling leakage was calculated based on typical leakage for floors of commercial buildings, assuming that high-rise multifamily buildings have similar floor construction to commercial buildings. The hallway door leakage was based on typical leakage for an entry door with no undercut. The remaining leakage needed for the unit to meet the total specified envelope leakage area was distributed between interior and exterior walls so that the exterior leakage was 47% of the total (see Table 9). While the fraction of total leakage to the exterior can vary greatly, results from both previous studies and this study (see Breakdown of Exterior and Interior Air Leakage for New Construction and Breakdown of Exterior and Interior Air Leakage for Existing Building Results) suggest that exterior leakage of 50% is typical. For the pre-sealing, existing building model (9.5 ACH50) hallway door leakage stayed the same, and the remaining interior and exterior leaks increased proportionally to keep about the same faction of exterior leakage (43%). For the post-sealing, new construction model (0.6 ACH50) it was not reasonable to keep the hallway door leakage the same so all of the leakages were reduced proportionally (see Table 9).

Table 9: Distribution of envelope leakage rates for energy models

Total Leakage (ACH50)	Exterior	Floor & Ceiling	Hallway Door	Unit to Unit
0.6	47%	5%	29%	18%
3.0	47%	5%	29%	18%
9.5	43%	13%	9%	34%

The size of the model air leaks were selected to produce a total envelope leakage of 3.0 ACH50 for the new construction baseline conditions. When the modeling for this project was performed, there was uncertainty as to how the code would be interpreted. The most common expectation was that the 3.0 ACH50 code requirement would apply to the total unit leakage. More recently, code officials have specified that they will allow the exterior leakage to be no greater than 3.0 ACH50. As shown in Table 8, the exterior leakage for the new construction baseline model is 1.41 ACH50, which is 53% below the code requirement. Using a baseline exterior leakage of 3.0 ACH50 would approximately double the absolute energy savings produced by an 80% leakage reduction.

Heating and Cooling

The heating and cooling equipment was chosen based on a recent market characterization report by Pigg et al (2013). The heating system consisted of a central boiler that served baseboard radiators in each apartment. The boiler system operated with a 75% seasonal efficiency. Cooling was provided by window air conditioners, and the performance of the air conditioner was based on a report by Winkler et al (2013).

Building Construction

Building materials were chosen primarily from the National Renewable Energy Laboratory's (NREL) Building Component Library, which provides physical properties for a range of construction types. The external wall assemblies were based on DOE reference models for a pre-1980's and new midrise apartment. Interior walls were not insulated and interior doors are not designed to seal individual rooms in an apartment. Therefore, individual rooms in each apartment are not significantly isolated from each other and were considered to be part of one well-mixed thermal zone.

Results and Discussion

Aerosol envelope sealing was performed on a convenience sample of 18 units in three new construction buildings and nine units in three existing buildings. The buildings are located in the Twin Cities metropolitan area, which is in the northern portion of International Energy Conservation Code climate zone 6. All of the buildings are affordable housing except for new construction building C which is an extended stay hotel[9]. Key characteristics and pre-sealing leakage results are listed in Table 10.

None of the buildings except B were required to meet an envelope tightness criterion. Building B was required to meet the EPA ENERGY STAR Multifamily High Rise tightness criterion of 0.3 cfm50 per square foot of envelope area. This was one of the first buildings that the architect and general contractor had built to this standard. In order to produce tight units, they included a comprehensive set of air sealing details and hired a third-party envelope quality control consultant to help assure that the details were properly implemented. Their efforts were successful. Even before the aerosol sealing, all of the units exceeded the tightness criteria by more than 50% and all had a tightness of less than 3 ACH50.

New construction building A did not have to meet a tightness standard, but the architect anticipated that they would have to for future projects and had started to incorporate more extensive air sealing measures in their design. The average pre-seal leakage for those six units was 3.22 ACH50 and they would have met the 0.3 cfm50/ft^2 standard.

The average air leakage of 7.75 ACH50 for the four hotel units are likely more representative of the leakage for Minnesota multifamily units when an envelope tightness standard is not enforced. The three existing buildings were pre-1940s construction that were undergoing major renovation which included air sealing and other energy efficiency improvements. The average pre-seal unit tightness by building ranged from 13.4 to 16.5 ACH50 which was slightly higher than the average of 11.8 ACH50 for 37 units from 8 buildings tested for a previous renovation project.

Table 10: Building characteristics

Type	ID	Stories	# Units		Avg. Floor	Pre-Seal Leakage (ACH50)		
			Total	Tested	Area (ft^2)	Min	Max	Avg
NC	A	4	36	6	451	3.11	3.50	3.22
NC	B	4	42	8	1,044	1.98	2.85	2.39
NC	C	5	107	4	384	7.08	8.41	7.75
Ex	D	3	16	6	237	12.0	17.2	13.4
Ex	E	2	2	1	1,579			13.7
Ex	F	2	4	2	760	15.8	17.2	16.5

NC= new construction, Ex= existing building

[9] The residential floors of hotels have similar layouts and code requirements as multifamily buildings with the same concerns for increased space conditioning energy use for uncontrolled air infiltration.

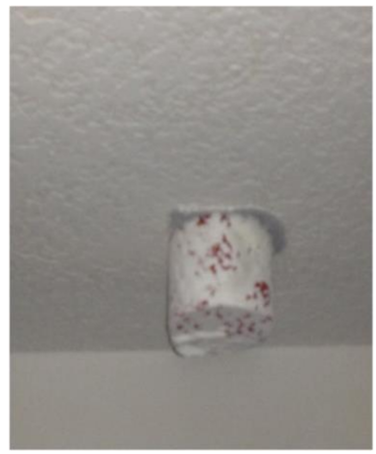
Air Sealing Locations

The aerosol sealing process causes sealant particles to attach to edges of the leakage opening as the pressurized air/sealant fog flows through envelope leaks. Leak gaps of about 3/8 inch will be closed for sealing durations of 45 minutes or greater. It is expected that most of the sealing will occur at the interior surface of the envelope. However, when the interior gap is large and the path from the interior to the exterior surface is fairly direct, the sealing can occur beyond the interior surface (see section Air Sealing/New Construction/Identified Air Leakage). Figure 25 displays visual light images of typical leakage sites at the surface of the interior envelope and the build-up of aerosol sealant after sealing was complete. Figure 26 displays ultra violet light images of typical leakages sites after sealing was completed using the fluorescent sealant.

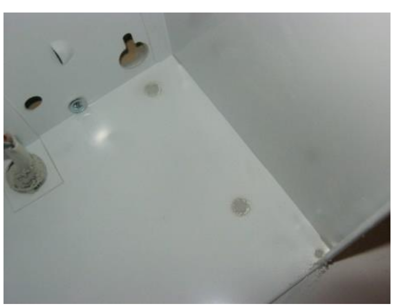
Figure 25: Visual images of sealed air leaks

Water supply and waste pipes

Plastic pipe through ceiling



Sprinkler pipe

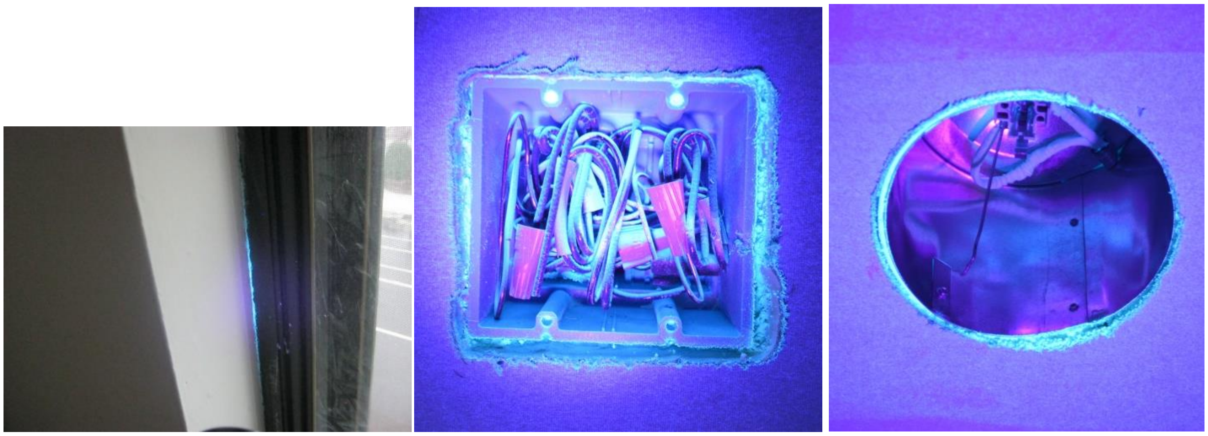


Kitchen fan housing interior

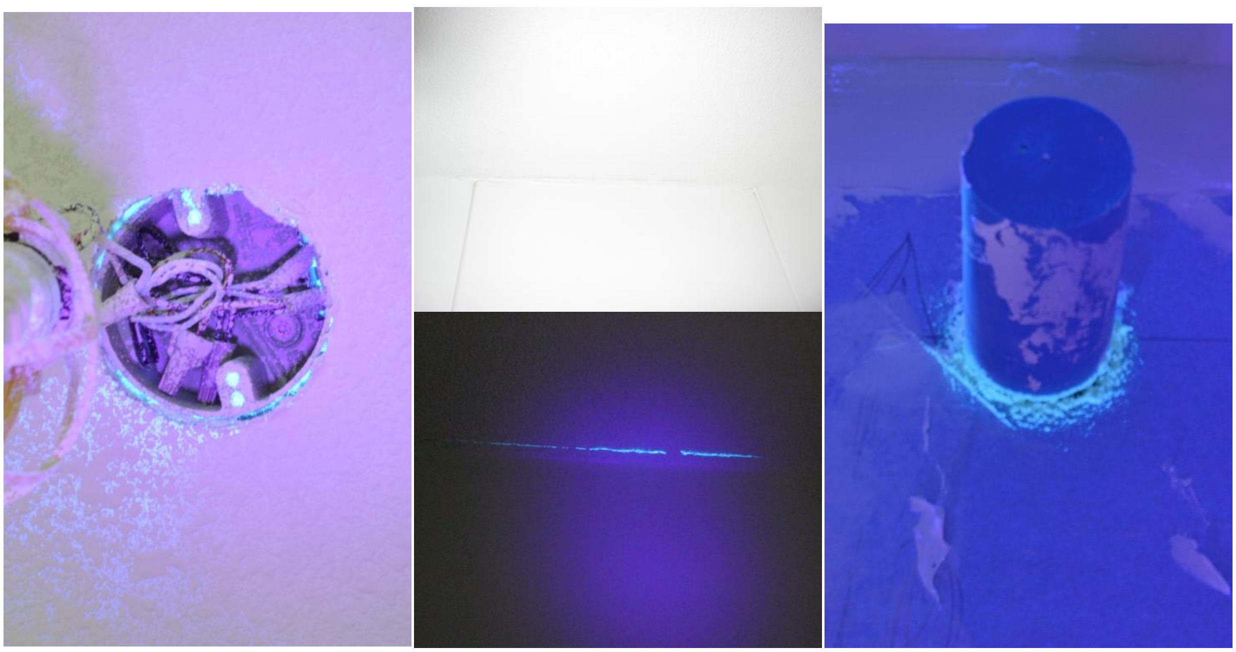
Cabinet/wall joint

Electric outlet box

Figure 26: UV images of sealed air leaks



Window | Double electric box | Ceiling recessive light can



Ceiling electric box | Ceiling/wall joint (visual on top) | Sprinkler pipe

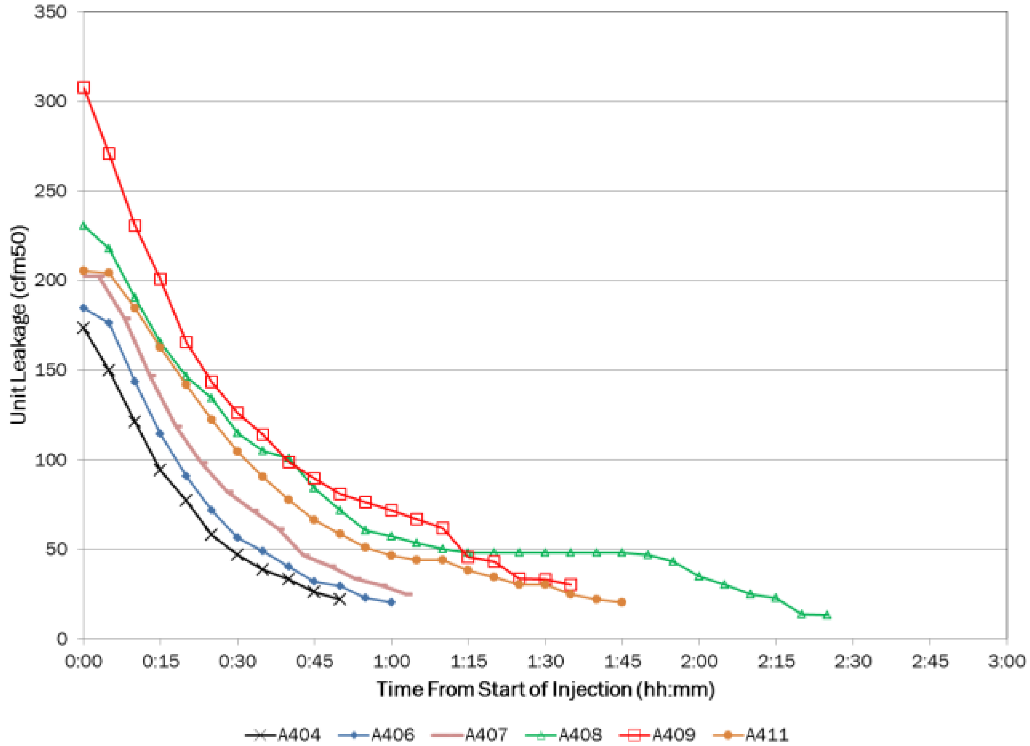
Air Sealing

New Construction

Sealing Rate

Air sealing was performed using an equipment design modified from previous field tests and the protocol described in the Methodology/Air Sealing Protocol section. Figure 27 to Figure 29 displays the reduction in envelope total leakage and the variation in the aerosol sealing rate for each of the units in buildings A, B, and C respectively.

Figure 27: Variation in unit leakage (top) and sealing rate (bottom): Building A



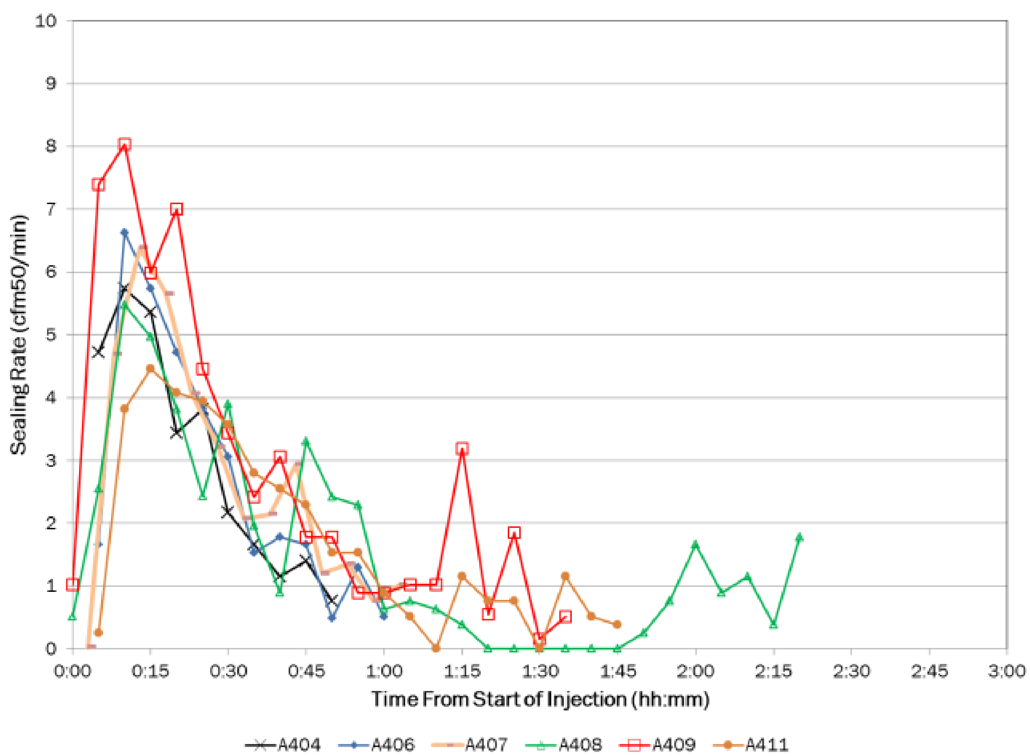
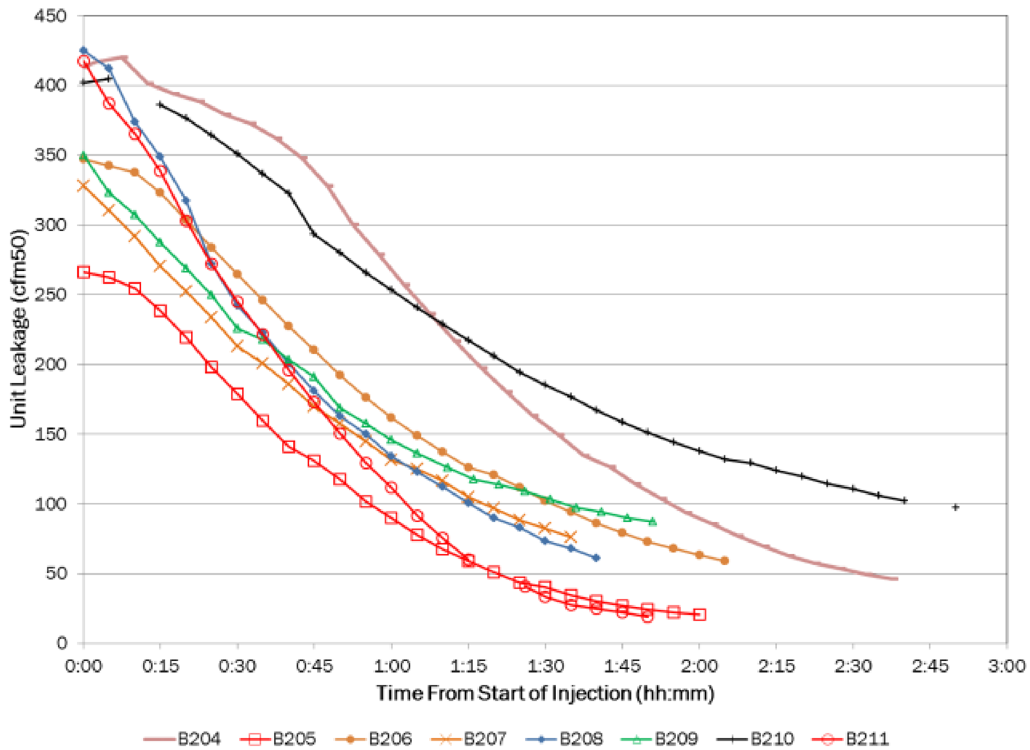


Figure 28: Variation in unit leakage (top) and sealing rate (bottom): Building B



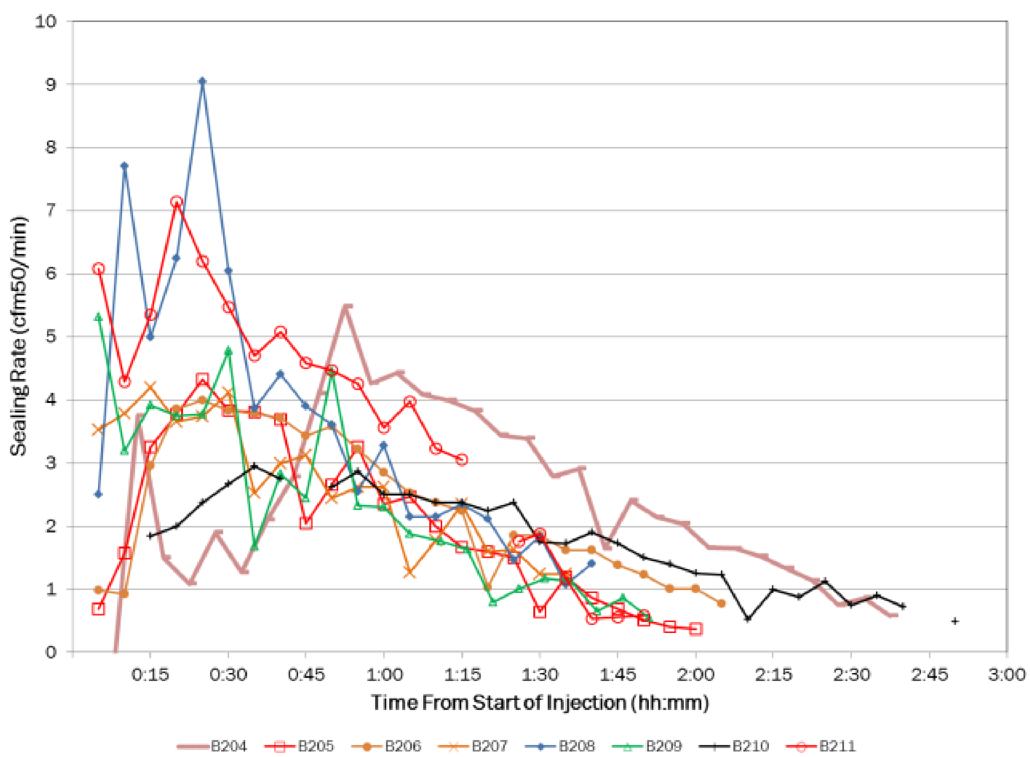
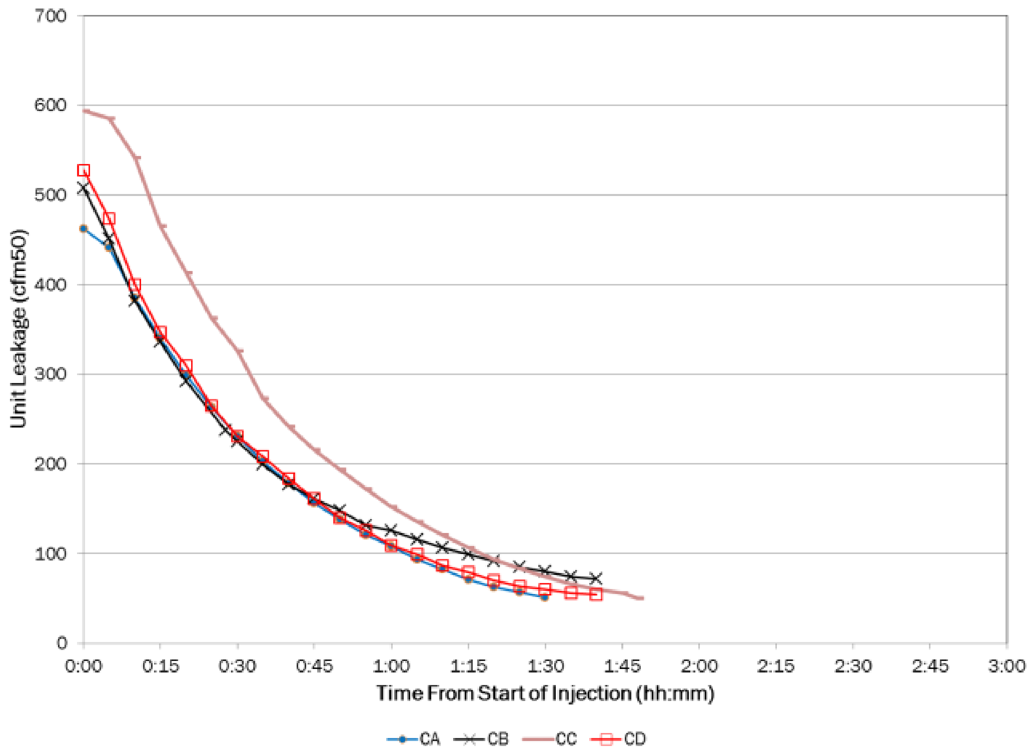
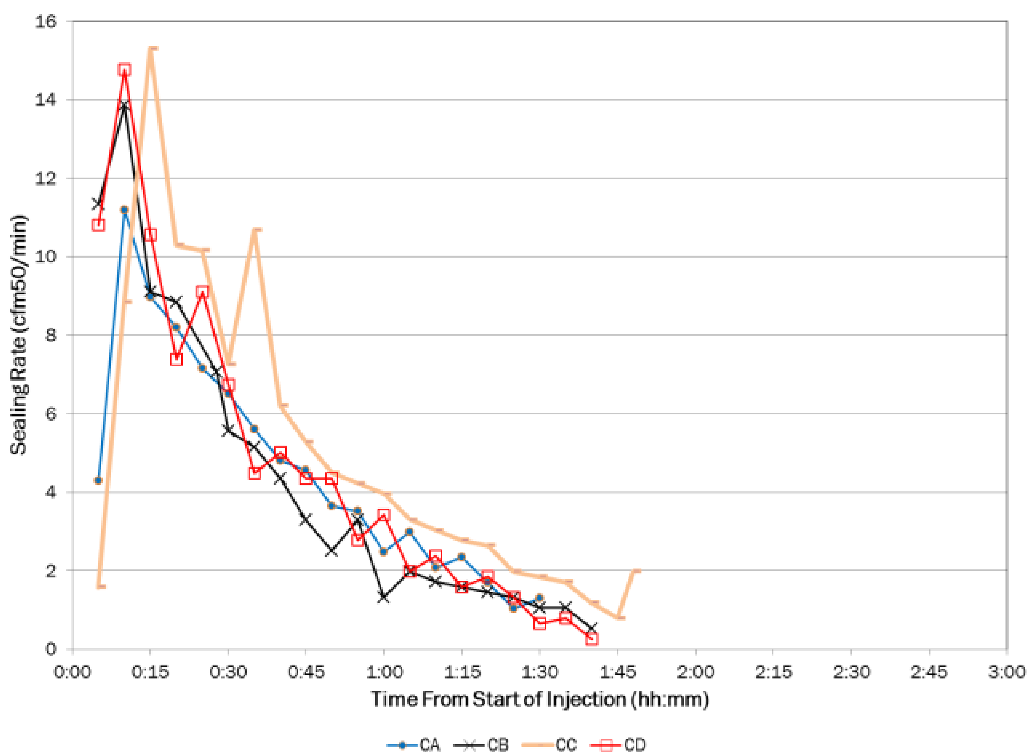


Figure 29: Variation in unit leakage (top) and sealing rate (bottom): Building C

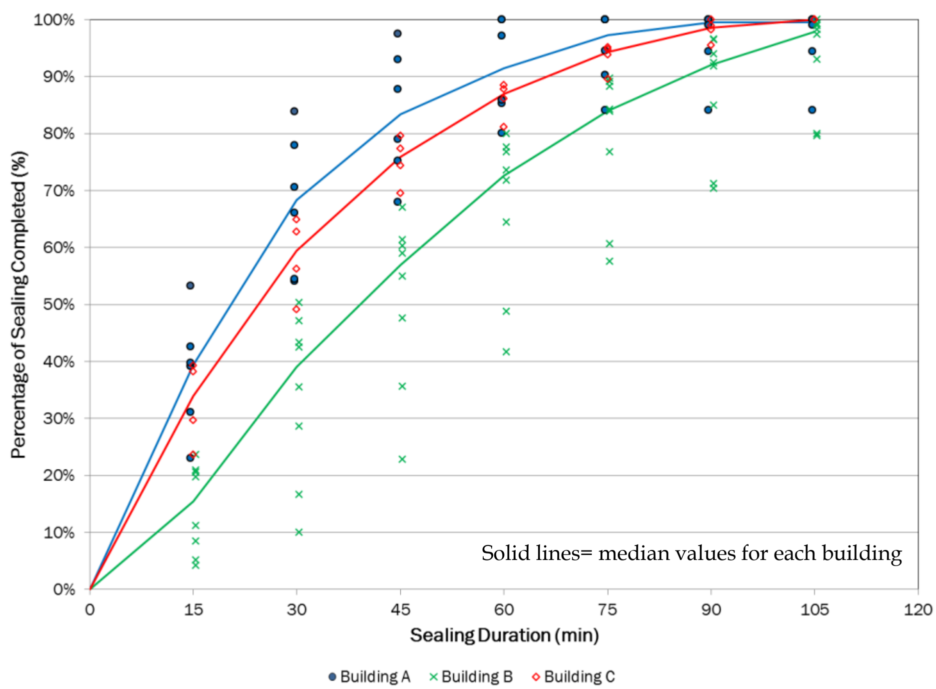




For almost all of the units the sealing rate peaked in the first 15 minutes and then steadily decreased. The pattern of leakage reduction was consistent for five of the six units in building A and for all four units in building C. The reduction pattern was more variable for the units in building B, the first building sealed for this project. There were more equipment malfunctions and other issues for those units than for those in the latter buildings when the field staff was more experienced. For example, for unit B204 some of the nozzles were not spraying properly for the first 35 minutes[10], for unit B210 one of the pressurization fans lost power at the start of sealing, and for unit B209 the fan circuit breaker was tripped by other workers in the building after about 70 minutes of sealing. One unit in building A (A408) also had an atypical sealing pattern. After about an hour of typical sealing performance, the leakage reduction stopped when air was drawn into the sealant tubes, and after the air was purged some of the nozzles did not spray properly. The leakage reduction resumed about a half hour later after the nozzles were replaced.

The sealing was quicker for the units in buildings A and C than those in building B. After 30 minutes of sealing, the median percent sealing completed[11] for building A, B, and C was 68%, 39%, and 60% respectively (see solid lines Figure 30).

Figure 30: Percent of sealing completed over time



The slower sealing for some of the units in building B was caused by equipment malfunctions that were partially due to the inexperience of some of the field staff. In addition, for some of the building B units the time required for the sealant to travel from the pump to the nozzles was included in the sealing time. For the latter buildings a higher initial sealant flow rate was used

[10] The nozzles used for sealing earlier in the day were used again for unit B204. After that experience it was decided that the nozzles needed to be cleaned between uses.

[11] % sealing completed= (leakage reduction from start to specified time)/(total leakage reduction for entire aerosol sealing process)

to reduce the delay for the sealant to be sprayed into the units. Also, the length of time for the sealant to reach the desired concentration and the water vapor to reach the desired relative humidity in the unit is inversely proportional to the normalized leakage rate (e.g. ACH50)[12]. The building B units had the lowest ACH50 values and the longest time to reach the desired sealant and moisture concentration. Compared to the units in building A, the units in building B would have taken about five to ten minutes longer for the relative humidity and sealant concentration to increase from the initial values to the desired values. The extra time would have been about 15 to 25 minutes for the units in building B compared to building C. A lower air relative humidity and sealant concentration impact the sealing rate to some degree. Consequently, the delay in the sealing at startup will be a fraction of the time required to achieve the desired concentrations.

The sealing in buildings A and C started at a faster rate and was completed quicker than the units in building B. After 30 minutes, over half of the sealing was complete for all except one of the ten units in buildings A and C, and over 60% of the sealing was complete for six of the ten units. After an hour the sealing was more than 80% complete for all of the units and over 95% complete for three of the ten units. The average sealing duration was 86, 127, and 99 minutes for buildings A, B, and C respectively, and the maximum times were 145, 172, and 108 minutes respectively.

The sealing times were longer than likely would have occurred if these units were being sealed for production purposes. In general, the sealing was stopped when the rate of leakage reduction dropped below 1 cfm50/min for at least 5 to 10 minutes[13]. However, the sealing was sometimes continued for over a half hour after the rate of leakage reduction was below 1 cfm50/min. The longer sealing was performed to evaluate the sealing rate over extended periods and to measure the tightness levels that could be achieved with extended sealing. For production based air sealing, the aerosol sealing would likely be stopped either after an envelope tightness standard is reached or if the rate of sealing does not justify the expected energy savings for the cost of additional sealing. If the sealing had been stopped in each unit when the rate of reduction was below 2 cfm50/min, the average sealing durations would have been 46, 84, and 79 minutes for buildings A, B, and C respectively.

It might be helpful to be able to predict the sealing duration based on information from visual inspections or air leakage tests. In general, the aerosol sealing process takes longer to seal wider gaps so a qualitative assessment of gap widths of observed leaks may help predict sealing times. Alternatively, the flow exponent determined from the power law relationship (see equation 1) is related to the type of air leaks. Leaks similar to an orifice produce an exponent closer to 0.5 and leaks through narrow/long openings produce an exponent closer to 1.0. An exponent of 0.65 is most common for residential buildings. No information was collected on

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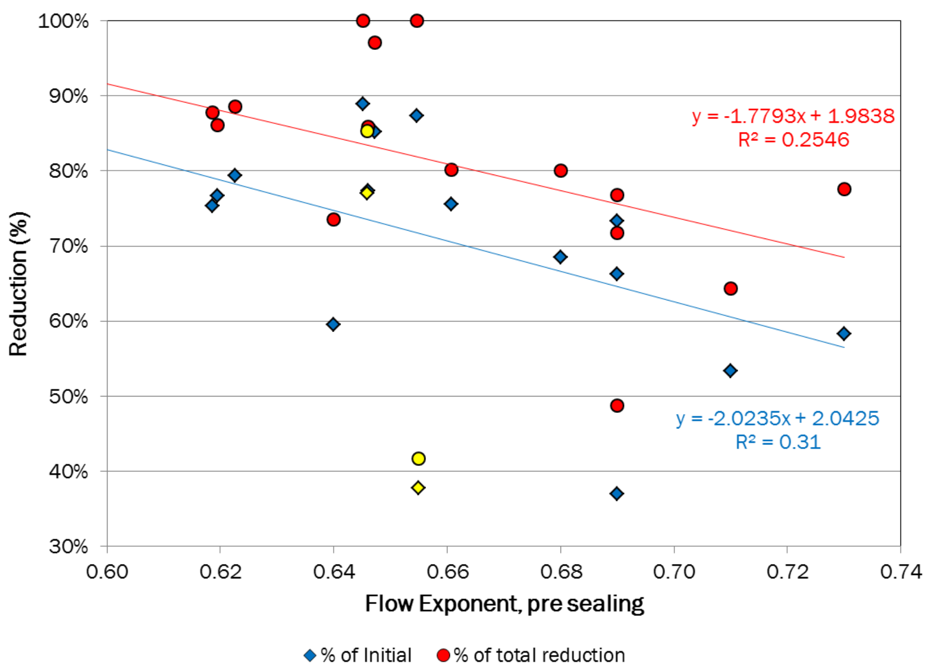
[12] The algorithm for computing the sealant injection rate to produce the desired relative humidity in the unit is based on steady-state conditions. From the start of sealant injection the time required to reach 95% of the desired humidity is three times the inverse of the ACH50.

[13] The unit leakage values displayed in the charts for the end of the sealing sometimes differ from the post-sealing test values due to: (1) large difference between sealing pressure (100 Pa) and test reference pressure (50 Pa) and assumed flow exponent, added compressed air flow into unit, and high back pressure on DuctBlaster during sealing.

typical gap widths from visual inspections. However, pre-sealing flow exponents were computed from the multi-point air leakage tests on all of the units.

Figure 31 displays the percent leakage reduction (blue diamonds) and percent of sealing completed (red circles) versus the flow exponent. The color coded regression lines for the two relationships are provided in Figure 31 along with the regression equation. For both cases the slopes are negative and statistically significantly different from zero ($p < 0.05$). This suggests that units with lower flow exponents (e.g. leaks more similar to orifices) seal quicker than those with higher exponents. However, further results are required in order to confirm that the relationship with flow exponent and the sealing rate is valid for a wide range of buildings.

Figure 31: Variation of first hour sealing rate with leakage flow exponent



Aerosol Sealing Leakage Reduction

The aerosol envelope sealing produced consistently high leakage reductions for the 18 new construction units Figure 32 and Table 11). All units had a reduction of at least 67%, the average was 81%, and maximum was 94%. There was only a weak correlation between the percent reduction and initial leakage (R^2= 0.09, slope= 0.01 %/ACH50) which confirms that the sealing was highly effective for both tight and leaky units.

After the sealing, the units were extremely tight. All of the units were more than 50% tighter than the 3 ACH50 requirement for low-rise residential buildings and half of the units met the Passive House tightness requirement of 0.6 ACH50. In addition, all of the units were at least 80% tighter than the EPA ENERGY STAR Multifamily High Rise requirement of 0.3 CFM50/ft². These results suggest that a unit that might otherwise have a leakage of 15 ACH50, could use aerosol sealing to reduce the leakage by 80% to achieve a leakage of 3 ACH50. Or a unit that might meet the code required standard of 3 ACH50 could use aerosol sealing to achieve the Passive House standard of 0.6 ACH50.

Figure 32: Pre and post sealing unit leakage and percent reduction for new construction units

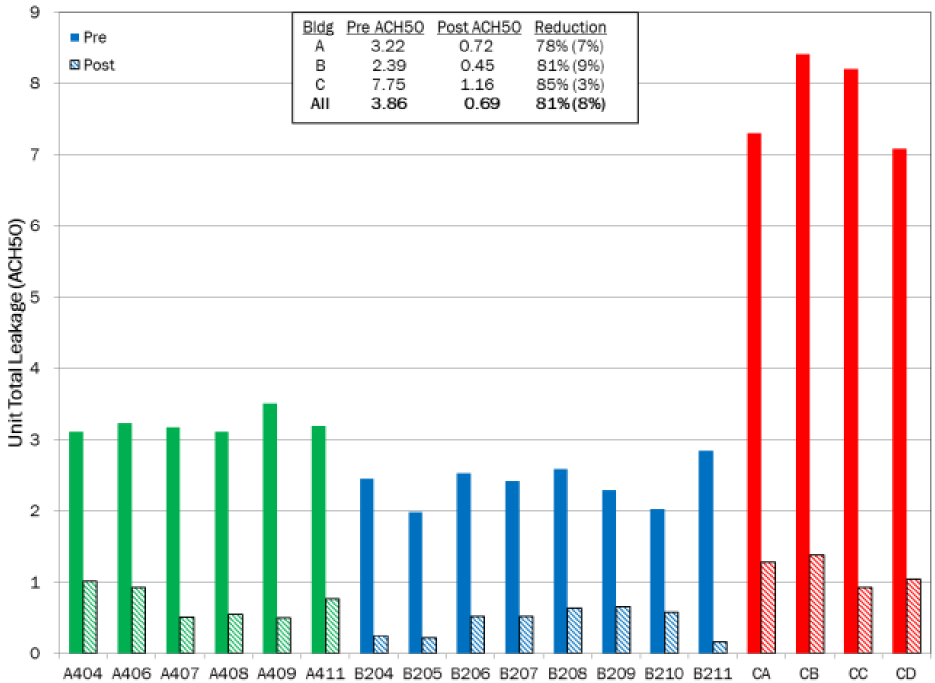


Table 11: New construction building pre/post aerosol sealing leakage test results

ID	Floor Area (ft^2)	Envel Area (ft^2)	Total Leakage (cfm50)		Total Leakage (ACH50)		Total Leakage (cfm50/ft^2)		Reduction	
			Pre	Post	Pre	Post	Pre	Post	(cfm50)	(%)
A404	455	1,667	198	65	3.11	1.02	0.12	0.039	133	67%
A406	455	1,667	206	59	3.23	0.93	0.12	0.036	147	71%
A407	447	1,644	199	32	3.17	0.51	0.12	0.020	167	84%
A408	455	1,667	199	35	3.11	0.55	0.12	0.021	163	82%
A409	447	1,644	220	32	3.50	0.51	0.13	0.019	188	86%
A411	447	1,644	200	48	3.19	0.77	0.12	0.029	152	76%
B204	1,136	3,746	418	43	2.45	0.25	0.11	0.011	375	90%
B205	915	2,933	272	30	1.98	0.22	0.09	0.010	242	89%
B206	920	2,936	350	72	2.54	0.52	0.12	0.025	278	79%
B207	918	2,929	333	73	2.42	0.53	0.11	0.025	260	78%
B208	1,069	3,529	415	103	2.59	0.64	0.12	0.029	312	75%
B209	1,088	3,445	375	107	2.30	0.66	0.11	0.031	268	71%
B210	1,294	3,917	393	114	2.02	0.59	0.10	0.029	279	71%
B211	1,014	3,176	433	25	2.85	0.16	0.14	0.008	408	94%
CA	348	1,590	462	81	7.30	1.28	0.29	0.051	381	82%
CB	348	1,590	531	88	8.41	1.39	0.33	0.055	444	84%
CC	420	1,865	626	71	8.20	0.93	0.34	0.038	555	89%
CD	420	1,865	540	80	7.08	1.05	0.29	0.043	460	85%
Min	348	1,590	198	25	1.98	0.16	0.09	0.008	133	67%
Max	1,294	3,917	626	114	8.41	1.39	0.34	0.055	555	94%
Avg	700	2,414	354	64	3.86	0.69	0.16	0.029	290	81%
Median	455	1,865	375	71	3.11	0.59	0.12	0.029	278	82%

Breakdown of Exterior and Interior Air Leakage

Guarded-zone air leakage tests were conducted to determine the breakdown of total envelope leakage to the portions that are to the exterior and interior of the building. The test method varied for each building depending on which areas adjoining the test units could be pressurized and the time available to conduct the tests. The following summarizes the breakdown of envelope leakage generated by the guarded-zone measurements conducted for the three new construction buildings:

- Building A: (1) exterior & third floor, (2) adjoining units on same floor, and (3) common area.
- Building B: (1) exterior, (2) adjoining units on same floor, (3) adjoining units above and below, and (4) common area. Not available immediately prior to aerosol sealing. Conducted before gypcrete floor poured which had large impact on unit leakage.
- Building C: (1) adjoining unit on same floor.

The measurements were only conducted before the aerosol sealing. Since the post-sealing average leakage rates for buildings A, B, and C were 45, 71, and 80 cfm50 respectively, the breakdown of such low envelope leakage did not justify the staff time required to perform the post-sealing guarded-zone tests.

The fourth floor of building A where the test units were located was depressurized to measure the leakage to the common areas and the other units on the same floor as the test unit. The third floor air barrier was not sufficiently in-tact to allow the third floor to be depressurized, and therefore it was not possible to measure the leakage to the lower floor. Consequently, the exterior leakage could not be measured separately from the interior leakage to the lower floor.

The total leakage was separated between: (1) exterior & third floor, (2) adjoining units on same floor, and (3) common area. The leakage results were fairly consistent between the six units (see Table 12).

Table 12: Breakdown of interior and exterior leakage for building A: pre-sealing

	(cfm50)			($cfm50/ft^2$)			Percent of Total		
ID	**Ext&B**	**Adj U**	**Comm**	**Ext&B**	**Adj U**	**Comm**	**Ext&B**	**Adj U**	**Comm**
A404	93	42	63	0.09	0.08	0.49	47%	21%	32%
A406	94	30	83	0.09	0.06	0.64	45%	15%	40%
A407	88	48	63	0.09	0.10	0.49	44%	24%	32%
A408	98	53	47	0.09	0.11	0.37	49%	27%	24%
A409	87	47	86	0.09	0.10	0.67	40%	21%	39%
A411	105	58	38	0.10	0.12	0.29	52%	29%	19%
Min	87	30	38	0.09	0.06	0.29	40%	15%	19%
Max	105	58	86	0.10	0.12	0.67	52%	29%	40%
Average	94	46	63	0.09	0.09	0.49	46%	23%	31%
Median	93	47	63	0.09	0.10	0.49	46%	23%	32%
CV%	7%	21%	30%						

Key: Ext&B = exterior and floor below; Adj U= adjacent units on same floor; Comm= common space

The average leakage to the exterior and to the third floor was 2.0 and 1.5 times greater than the leakage to the adjoining units and common space respectively. The percent leakage to the exterior and third floor was an average of 46% of the total leakage, while the leakage to the fourth floor adjoining units and common space was 23% and 31% respectively. For all of the units the pre-sealing total envelope leakage was greater than the low-rise residential requirement of 3.0 ACH50 (see Table 13). However, all of the units would have been at least 44% below the 3.0 ACH50 requirement using the sum of the leakage to the exterior and third floor. After the aerosol sealing even the total envelope tightness complied with the code requirement.

Table 13: Volume normalized envelope leakage for building A (ACH50)

	Total		Ext. & Below
ID	**Pre**	**Post**	**Pre**
A404	3.11	1.02	1.46
A406	3.23	0.93	1.47
A407	3.17	0.51	1.41
A408	3.11	0.55	1.54
A409	3.50	0.51	1.39
A411	3.19	0.77	1.67
Min	3.11	0.51	1.39
Max	3.50	1.02	1.67
Average	3.22	0.72	1.49
Median	3.18	0.66	1.46

While on an absolute basis the greatest leakage was to the exterior and third floor, the results in Table 12 show that the average leakage normalized by the surface area was about the same for the sum of the exterior and the third floor, and the sum of the leakage to the adjoining areas (0.09 cfm50/ft^2). However, those were about five times tighter than the leakage to the common spaces (0.49 cfm50/ft^2). The relative uncertainty of the leakage to the common space is quite high since it is computed from the total minus (exterior + 3rd floor) + (adjoining units). However, the large and consistent difference of the common space normalized leakage compared to that of the other surfaces indicates that the higher normalized common space leakage is significant. These results suggest that any additional efforts for manual air sealing to improve the total envelope leakage should have focused on the demising walls between the unit and common space.

All of the adjoining areas of the second floor test units of building B were pressurized to measure the leakage to each type of surrounding space. These tests were completed on six of the eight units sealed and were conducted prior to the aerosol sealing. Unfortunately, the tests were conducted prior to the installation of the gypcrete floor and that work reduced the leakage by an average of 44% (a range of 29% to 57%, see Table 14).

Table 14: Breakdown of interior and exterior leakage for building B: pre-gypcrete floor

	Total	(ACH50)		Percentage of Total Leakage						Floor
ID	**(cfm50)**	**Total**	**Exter**	**Exter**	**Comm**	**Left**	**Right**	**Up**	**Down**	**Red.**
B206	494	3.58	0.28	8%	46%	19%	9%	12%	7%	29%
B207	580	4.21	0.73	17%	51%	12%	2%	12%	6%	43%
B208	957	5.97	0.46	8%	76%	4%	5%	4%	3%	57%
B209	648	3.97	0.99	25%	58%	2%	0%	11%	5%	42%
B210	784	4.04	0.33	8%	58%	7%	9%	12%	6%	50%
B211	757	4.98	1.07	22%	45%	9%	0%	13%	11%	43%
Min	494	3.58	0.28	8%	45%	2%	0%	4%	3%	29%
Max	957	5.97	1.07	25%	76%	19%	9%	13%	11%	57%
Average	703	4.46	0.64	15%	56%	9%	4%	11%	6%	44%
Median	703	4.13	0.59	13%	54%	8%	4%	12%	6%	43%

The significant sealing from the gypcrete made it impossible to determine the breakdown of the leakage immediately prior to the aerosol sealing, and the results are not representative of "completely sealed" new construction units. However, the measurements provide some interesting information.

- First, the leakage to the floor below averaged only 6% of the total. This indicates that a large portion of the average leakage reduction of 44% from the gypcrete was to areas on the same (e.g. second) floor and not to the first floor. Second, the leakage to the common space was relatively large. The average sum of the leakage to the units on the left and right sides was only 13% of the total, while the leakage to the common space was an average of 56% of the total.
- Second, the average normalized leakage to the adjacent units was 0.20 cfm50/ft^2 compared to 1.59 cfm50/ft^2 for the common space (see Table 15). This suggests that there was significant leakage at the interface between the common space wall and unit subfloor that was greatly reduced by the gypcrete.
- Third, the percent leakage to the exterior after the gypcrete was installed and prior to the aerosol sealing was between 15% to 26%. The percent leakage to the exterior averaged 15% before the floor was installed. If the floor did not seal any of the leakage to the exterior, the percent leakage would have increased to 26% (range of 11% to 43%). This indicates that the percentage of leakage to the exterior is a half or less of that for building A.
- Finally, the average volume weighted total leakage before sealing was 4.46 ACH50 and none of the units were below 3.0 ACH50. However, even before the gypcrete floor was poured the average exterior leakage was 0.64 ACH50 and all of the units were at least 64% below 3.0 ACH50.

Table 15: Normalized leakage for building B: pre-gypcrete floor

	Surface Area Normalized Leakage (cfm50/ft²)				
ID	**Total**	**Exterior**	**Common**	**Left/Right**	**Up/Down**
B206	0.12	0.13	0.77	0.27	0.049
B207	0.11	0.34	1.01	0.16	0.056
B208	0.12	0.19	1.44	0.17	0.030
B209	0.11	0.42	1.29	0.02	0.047
B210	0.10	0.10	3.86	0.38	0.055
B211	0.14	0.29	1.19	0.21	0.091
Min	0.10	0.10	0.77	0.02	0.030
Max	0.14	0.42	3.86	0.38	0.091
Average	0.12	0.25	1.59	0.20	0.055
Median	0.12	0.24	1.24	0.19	0.052

It was not possible to pressurize any of the building C hallways. Only the adjacent units on the same floor were pressurized for the guarded-zone tests. This provided a breakdown of the leakage to two areas: (1) an adjacent unit and (2) the remainder of the adjoining interior space and the exterior. Both the percentage and surface area normalized leakage to the adjacent unit were consistent between the four test units (see Table 16). The average percent leakage to the adjacent unit was 8% and the normalized leakage was 0.12. The normalized leakage to the remaining areas was three times higher (0.36 cfm50/ft²) than that for the adjoining unit.

Table 16: Breakdown of adjacent unit and remaining leakage for building C

	Total	Adjacent Unit		Remainder	
ID	**(cfm50/ft²)**	**(cfm50/ft²)**	**(%)**	**(cfm50/ft²)**	**(%)**
CA	0.29	0.12	8%	0.33	92%
CB	0.33	0.12	7%	0.39	93%
CC	0.34	0.12	7%	0.39	93%
CD	0.29	0.12	8%	0.33	92%
Min	0.29	0.12	7%	0.33	92%
Max	0.34	0.12	8%	0.39	93%
Average	0.31	0.12	8%	0.36	92%
Median	0.29	0.12	8%	0.33	92%

The breakdown of the total envelope leakage to the exterior and interior portions was only completed for six units in one of the three buildings. This limited sample does not allow for any definitive conclusions for the leakage breakdown for the population of Minnesota multifamily buildings. However, it is interesting that even though the leakage to adjoining units on the same floor was only being sealed to reduce sound transmission and air transfer, the normalized leakage to adjoining units was only 0.09, 0.20, and 0.12 cfm50/ft^2 for buildings A, B, and C respectively. That was lower than the typical normalized leakage to other areas of the building and the exterior. Also, the average leakage to the exterior was less than half of the total for buildings A and B. The percent of leakage to the exterior was 46% of the total for building A and was between 15% to 26% for building B. Total and guarded-zone leakage tests would need to be conducted on a greater number of buildings in order to confirm these trends.

Identified Air Leakage

The leakage of individual locations was measured before and after the sealing of two units (A407 and A409) in building A. Of the nine sites in unit A407 where leakage was measured, four of the sites had no measurable leakage. Three had leakage between 2 to 13 cfm50 and combined for only 21 cfm50 of leakage (see Table 17), which was about 10% of the total pre-sealing leakage of 199 cfm50 in the unit. The three leaks were narrow and left to be sealed by the aerosol process. Two of the sites had leakage of 30 cfm50 or greater. Both leaks were expected to be sealed later in the construction process and were temporarily sealed for the aerosol sealing. One was a large opening around the tub spout and handle that would eventually be covered by a plate. The other site was several openings through the hall door metal frame and it was expected that most or all of these would be sealed when the locks were installed. After the aerosol sealing was finished, the leakage of the three sites with pre-sealing leakage greater than 1 cfm50 had each been reduced to less than 1 cfm50. Since the overall leakage was reduced by so much more than the sum of the individual site leaks identified, this suggests that almost all of the envelope leakage was diffuse and not easily identified.

Table 17: Leakage measurements of individual sites for units A407 and A409

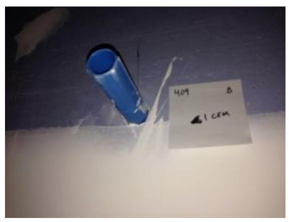
	Leakage (CFM50)			Leakage (CFM50)	
Description (Unit A407)	**Pre**	**Post**	**Description (Unit A409)**	**Pre**	**Post**
Tub spout and handle*	63	< 1	Tub spout and handle*	63	< 1
Bathroom recessed light can	13	< 1	Bathroom recessed light can**	11	< 1
Kitchen ventilation duct	< 1	< 1	Kitchen ventilation duct	3.5	< 1
Bathroom sink penetrations	< 1	< 1	Bathroom sink penetrations	< 1	< 1
Electric outlet box	< 1	< 1	Electric outlet box	< 1	< 1
Living room double electric outlet	2	< 1	Two electric outlet boxes	1	< 1
Supply ventilation duct	6	< 1	Toilet water supply pipe	< 1	< 1
Kitchen electric outlet box	< 1	< 1	Sprinkler pipe	< 1	< 1
Hall door frame openings*	30	< 1	Shower head pipe	< 1	< 1
			Sprinkler pipe (living room)	< 1	< 1
			Electric panel and low voltage outlet	< 1	< 1

* - temporarily sealed
**- manually sealed

The leakage of 11 sites in unit A409 was measured before sealing was conducted. Figure 33 includes photos of each location before it was sealed. The measurement results were very similar to those obtained for the leakage locations in unit A407 (see Table 17). There was no measureable leakage for 7 of the 11 locations. The leakage for the tub spout/handle was 63 cfm50 and this area was temporarily sealed. The bathroom recessed light can leakage was about the same as that for unit A407 (11 cfm50). However, there were some larger gaps between the can and the sheetrock that were sealed manually instead of being left for the aerosol process. There were only two locations with measurable leakage and the sum of the leakage for those sites was only 4.5 cfm50. The aerosol sealing reduced the envelope leakage by 84% from 220 to 32 cfm50, and all of the locations had a leakage less than 1 cfm50. Again, this suggests that almost all of the envelope leakage was diffuse and not easily identified.

Figure 33: Photos of unit A409 sites with pre-sealing measured leakage


Tub spout & handle


Shower head


Recessed light can


Bathroom sink pipes


Toiler water line


Sprinkler pipe


Kitchen ventilation


Electric outlet box


2 electric outlet boxes


Sprinkler pipe


Electric panel & low voltage outlet

Envelope total air leakage tests were conducted just prior to occupancy for the four aerosol sealed units in building C and for five units in the same building which were not aerosol sealed. The tests were conducted with and without the opening to the pocket door temporarily sealed. The result with the pocket door open was based on a multi-point leakage test and regression analysis. The result with the pocket door sealed was based on a single measurement at an induced pressure difference of 50 Pa. The difference in leakage results provided an estimate the leakage through the pocket door opening. For the three units that were aerosol sealed, the envelope leakages through the pocket door opening were 20, 27, and 31 cfm50 with an uncertainty of about 5 cfm50 for each value and an overall average of 26 cfm50. For the five units that were not aerosol sealed, the envelope leakages through the pocket door opening were 156, 134, 87, 96, and 110 cfm50 with an overall average of 117 cfm50. This suggests that about three quarters of the leakage through the pocket door opening was eliminated by the aerosol sealing. This is a situation where the aerosol did not create a seal at the inner surface of the unit. The aerosol would have had to be carried through the pocket door cavity to the leaks in that cavity.

Existing Buildings

Sealing Rate

The sealing pattern was consistent for five of the six units in building D. The leakage of the sixth unit (D206) was only reduced by 39%. The leakage reduction of the other five units ranged from 72% to 88% (see upper chart of Figure 34). Three of the five units had valid flow measurements over the first 30 minutes[14]. For those three units the maximum sealing rate over the first 30 minutes was greater than 10 cfm50/min and occurred about 15 minutes after sealing started. The total sealing time ranged from 100 to 130 minutes with an average of 120 minutes.

For all of the units except D202, sealing was continued beyond an hour and 45 minutes in order to evaluate the sealing rate over extended periods and to measure the tightness levels that could be achieved with extended sealing. If the sealing had been stopped when the sealing rate decreased to 2.0 cfm50/min, the duration would have been reduced to an average of 81 minutes with a range of 70 to 95 minutes for the five units. That is similar to the average time for the sealing to decrease to 2 cfm50/min for the new construction buildings B and C. Also, an average of 88% of the sealing had been completed when the sealing rate dropped to 2 cfm50/min. For unit D106 the sealing rate dropped to 2.0 cfm50/min after 80 minutes of sealing, and at that time the envelope leakage had been reduced from 491 to 108 cfm50, which was a 78% leakage reduction. The sealing continued for another 40 minutes, further reducing the leakage to 50 cfm50 for a final leakage reduction of 90%. In this unit 87% of the final leakage reduction was achieved in the first 80 minutes of sealing.

The low final leakage of 1.4 ACH50 (52 cfm50) for unit D202 (yellow line with black triangles in Figure 34 is an example of the high level of tightness that can be achieved when almost all leaks with a gap width of less than 3/8 inch are sealed before the aerosol process. On the other hand, there was only a 39% leakage reduction for D206 (black line with black crosses Figure 34). All of the building D units were nearly finished and ready for occupancy when the aerosol sealing was performed. After the unit D206 aerosol sealing was finished, a hidden leak around the plumbing penetrations was detected behind a kitchen cabinet. The leak was in a location where most of the aerosol sealant attached to other cabinet surfaces before going through the leak and the leak was too wide to be sealed by the aerosol. This illustrates the challenge of identifying all of the large gap leaks in finished residences.

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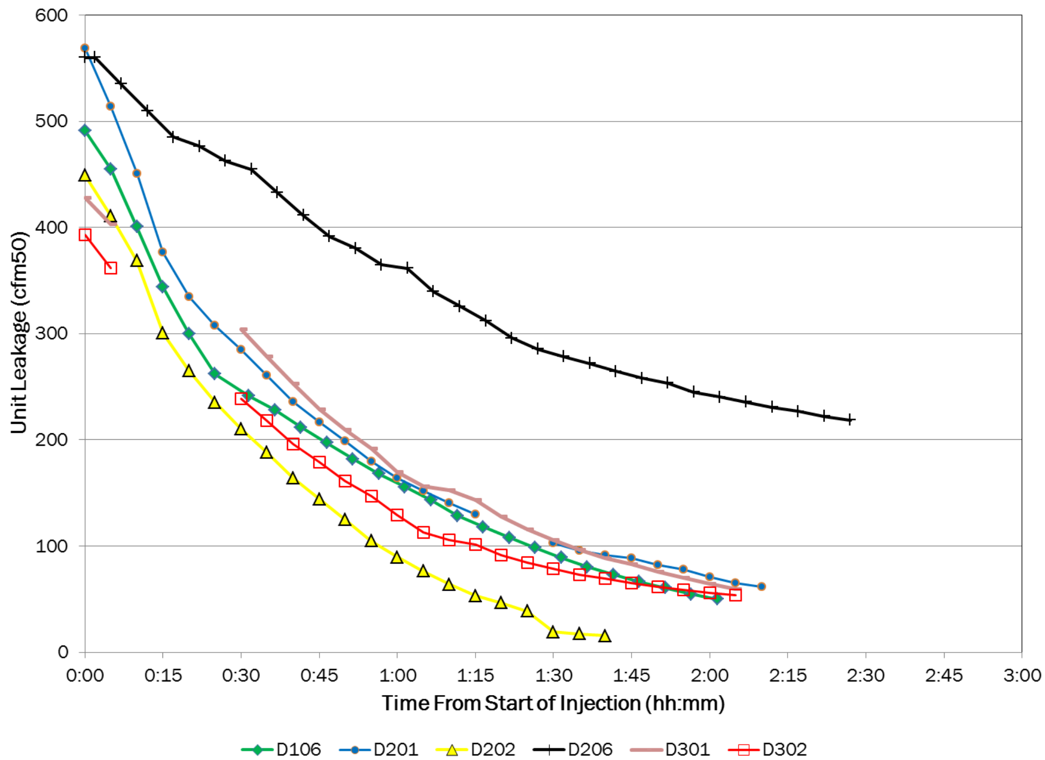
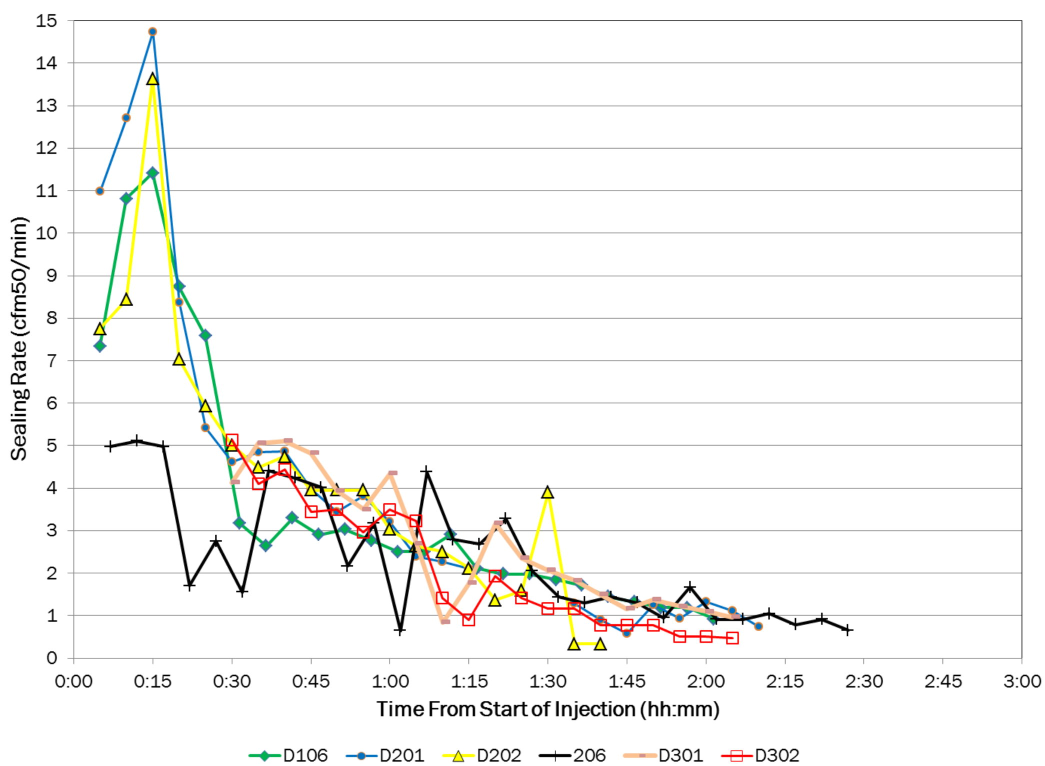
[14] Units D301 and D302 were sealed at the same time using one pressurization fan in each unit. The fan flow measurements were not valid for the first 25 minutes of sealing.

Figure 34: Variation in unit leakage (top) and sealing rate (bottom): Building D





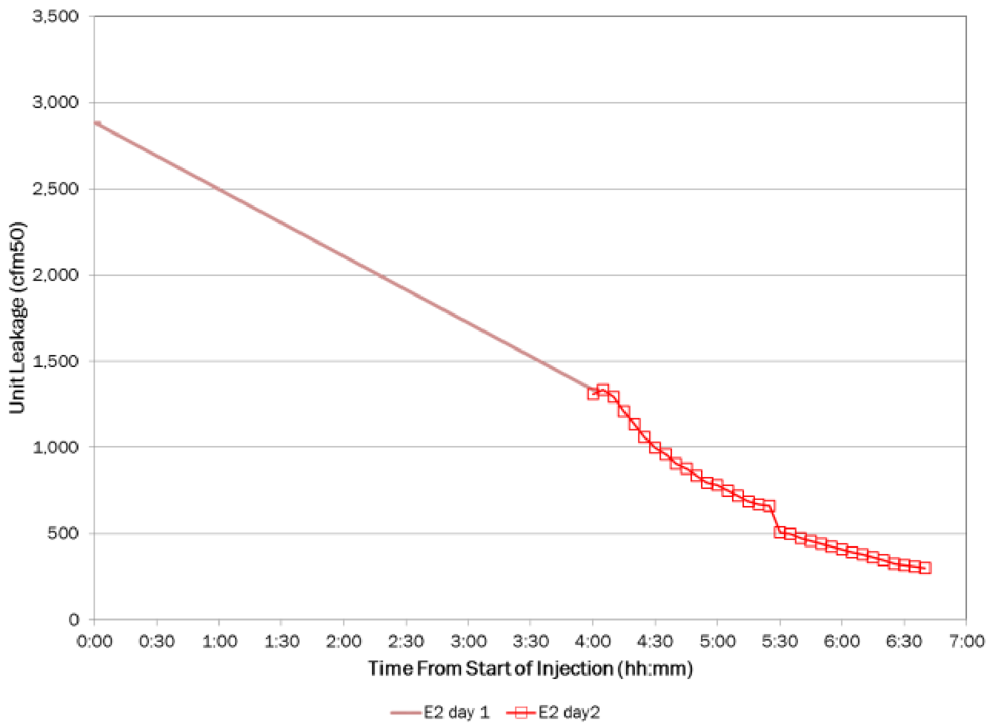
Unit 2 of building E is the second floor unit of an up/down duplex with a full basement under the first floor unit. Unit 2 is the largest (1,579 ft^2 floor area) of all of the units sealed for this project and had the highest air leakage (2,884 cfm50) with a high normalized leakage of 13.7 ACH50. The capacity of the two Duct Blasters[15] would have only pressurized the unit to 15 Pa, and it was not possible to reconfigure the equipment setup to use larger pressurization fans. Instead, an additional fan was installed to "guard" a portion of the space that adjoined unit 2. An Energy Conservatory Minneapolis Blower Door™ was installed to blow outside air into the basement so that the basement pressure was higher than the unit 2 pressure. That configuration produced an initial pressurization of 41 Pa for unit 2 relative to outdoors.

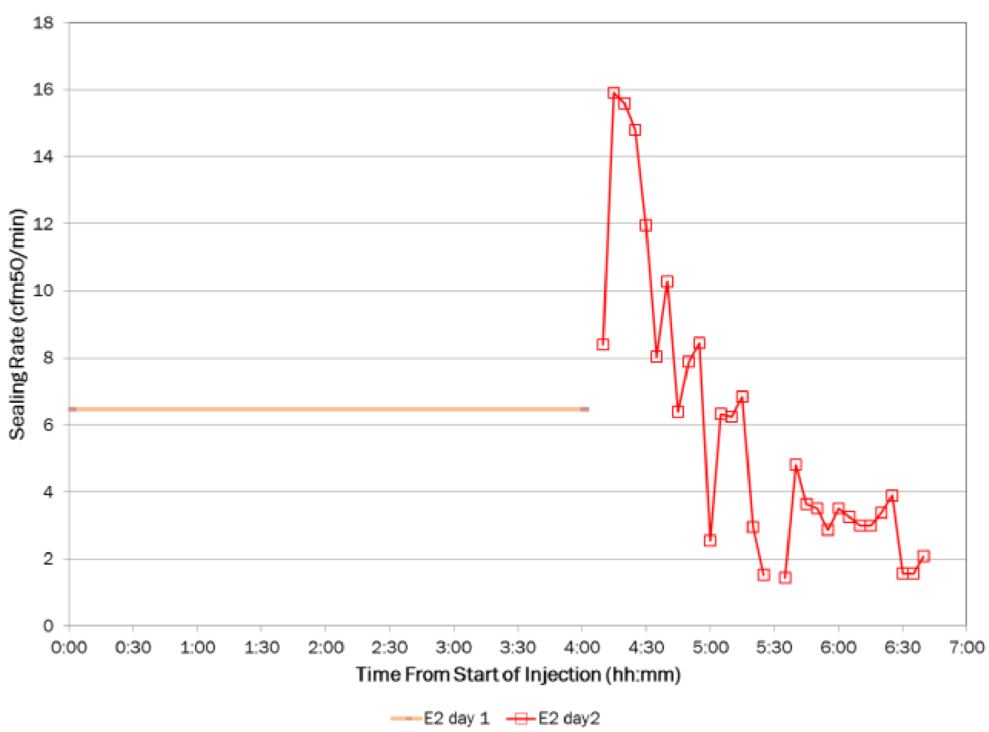
Four hours of sealing reduced the total leakage to about 1,400 cfm50 (see Figure 35). The reduced leakage allowed the unit pressure to increase to 65 Pa, which was still below the 100 Pa target pressure. Also, since no air (e.g. sealant fog) was flowing from unit 2 to the basement, no leaks were sealed between unit 2 and the basement. The sealing was stopped after four hours and started again the following day using the normal configuration of two Duct Blaster® fans in the unit with no other fans anywhere else in the building. This produced an initial pressurization of 46 Pa that increased to 100 Pa over the next 65 minutes. The second day of sealing was stopped after about 2.5 hours.

The total 6.5 hours of sealing reduced the envelope leakage by 2,576 cfm50 (89%) for an average sealing rate of 6.6 cfm50/min. However, the sealing for unit 2 of building E was not typical. First, the pressurization was below the 100 Pa target for the first five hours of sealing. Second, the pressurization of the basement did not allow the leaks between the unit and basement to be sealed during the first four hours. Finally, there were problems with the uniformity of the sealant concentration in the unit. The interior was compartmentalized and this did not allow for good mixing within the interior. The six nozzles were distributed throughout the ten rooms so that each nozzle covered an approximately equal floor area (see Figure 36). This created a lower concentration of sealant in the rooms closest to the pressurization fans and a saturated concentration of sealant in the rooms furthest from the fans. In addition, the high velocity of air blowing against the living room wall opposite from the fans caused sealant deposition on that wall. Higher capacity fans, higher capacity heaters, and the introduction of pressurization airflow at two different locations would have greatly reduced the sealing duration for unit 2. Two pressurization fan locations and the use of fan ducting in the unit to reduce the air velocity at walls would likely have eliminated significant sealant deposition on walls.

[15] Capacity= 1,300 cfm with restrictions from in-line heaters and flex duct

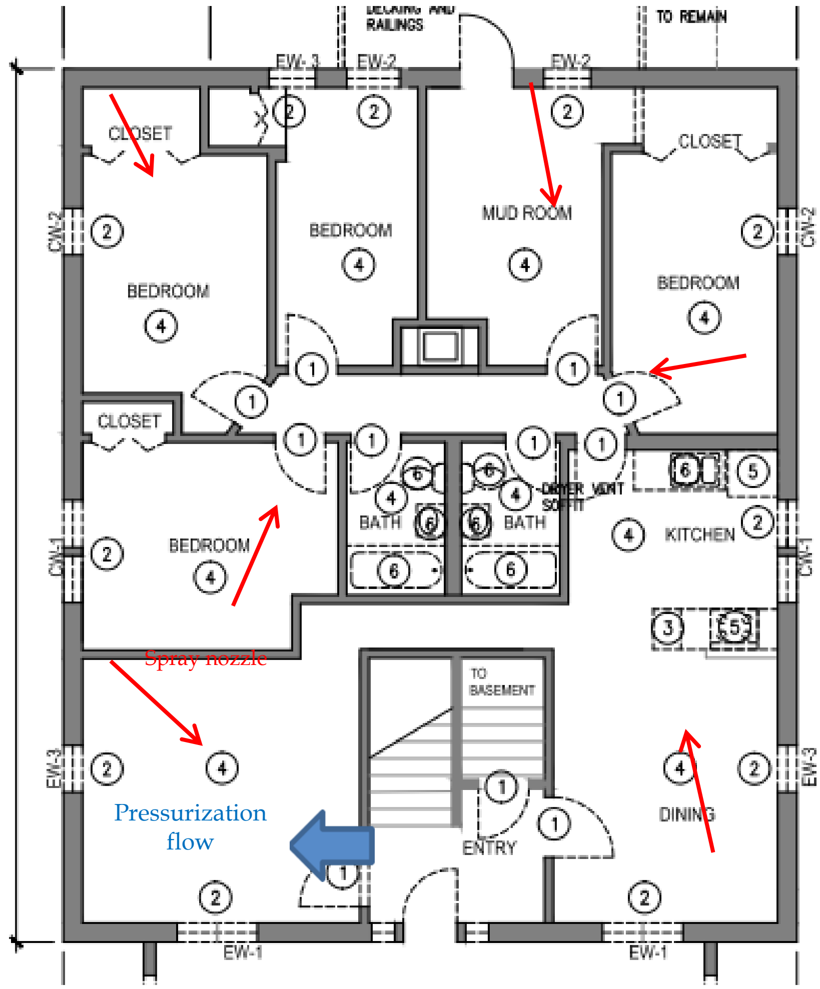
Figure 35: Variation in unit leakage (top) and sealing rate (bottom): Building E[16]





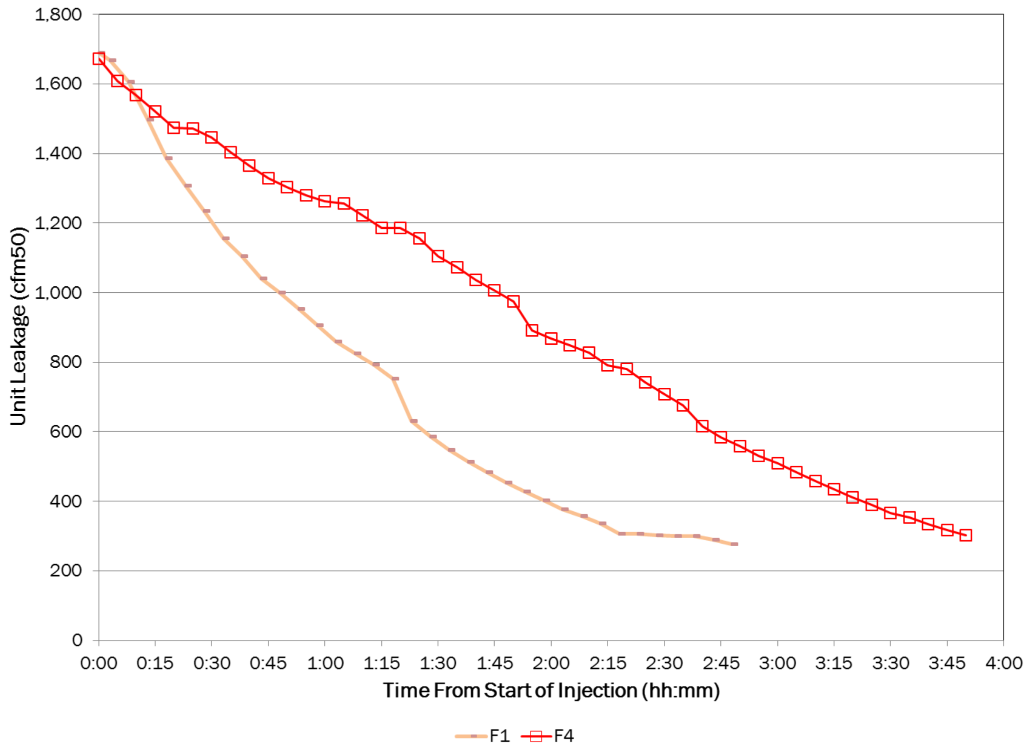
[16] The sealing was performed over two days. The envelope leakage was only available for the start and end of day 1 sealing. The day 1 solid line represents the average of the day 1 sealing.

Figure 36: Unit 2 floor plan with nozzle and fan locations



Units 1 and 4 in building F are located on the first and second floors respectively of a two story four-plex with a full basement below the first floor. The sealing of unit 1 proceeded smoothly. Due to the limited fan flowrate capacity the unit pressure started at 50 Pa and reached the target of 100 Pa after 50 minutes of sealing. It was held at 100 Pa for the remainder of the sealing. The sealing rate reached a peak of 22 cfm50/min after 15 minutes and dropped to 10 cfm50/min after 45 minutes (see Figure 37). Over the first two hours and 15 minutes the sealing rate averaged 10 cfm50/min. The sealing was continued for another 30 minutes to evaluate the effect of extended sealing.

Figure 37: Variation in unit leakage (top) and sealing rate (bottom): Building F



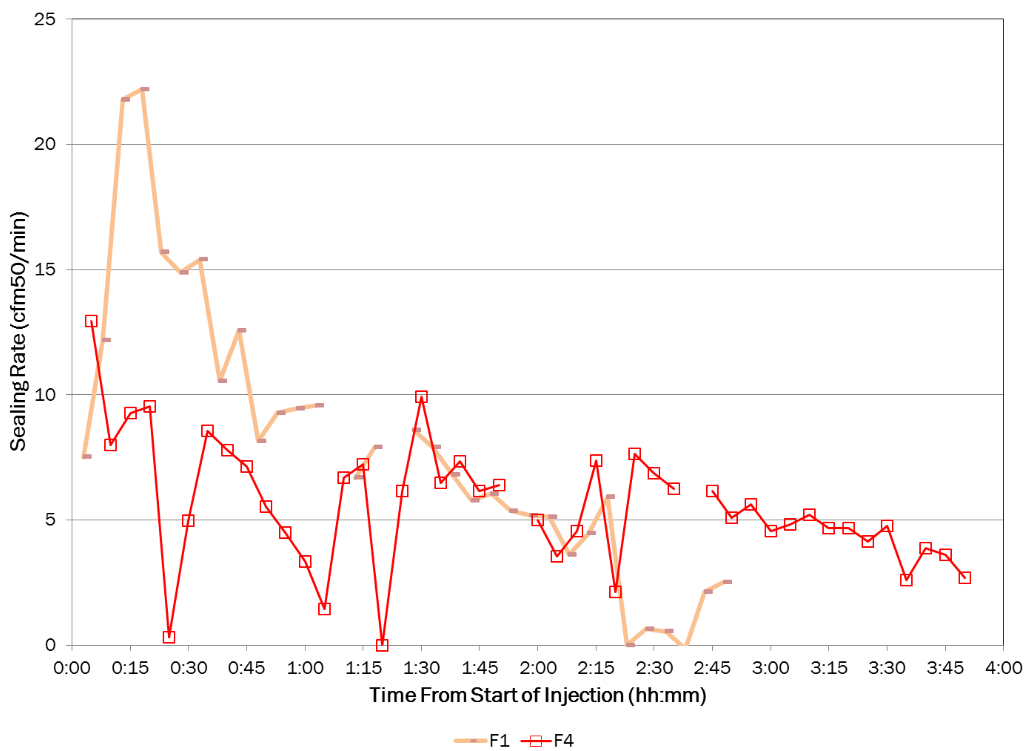
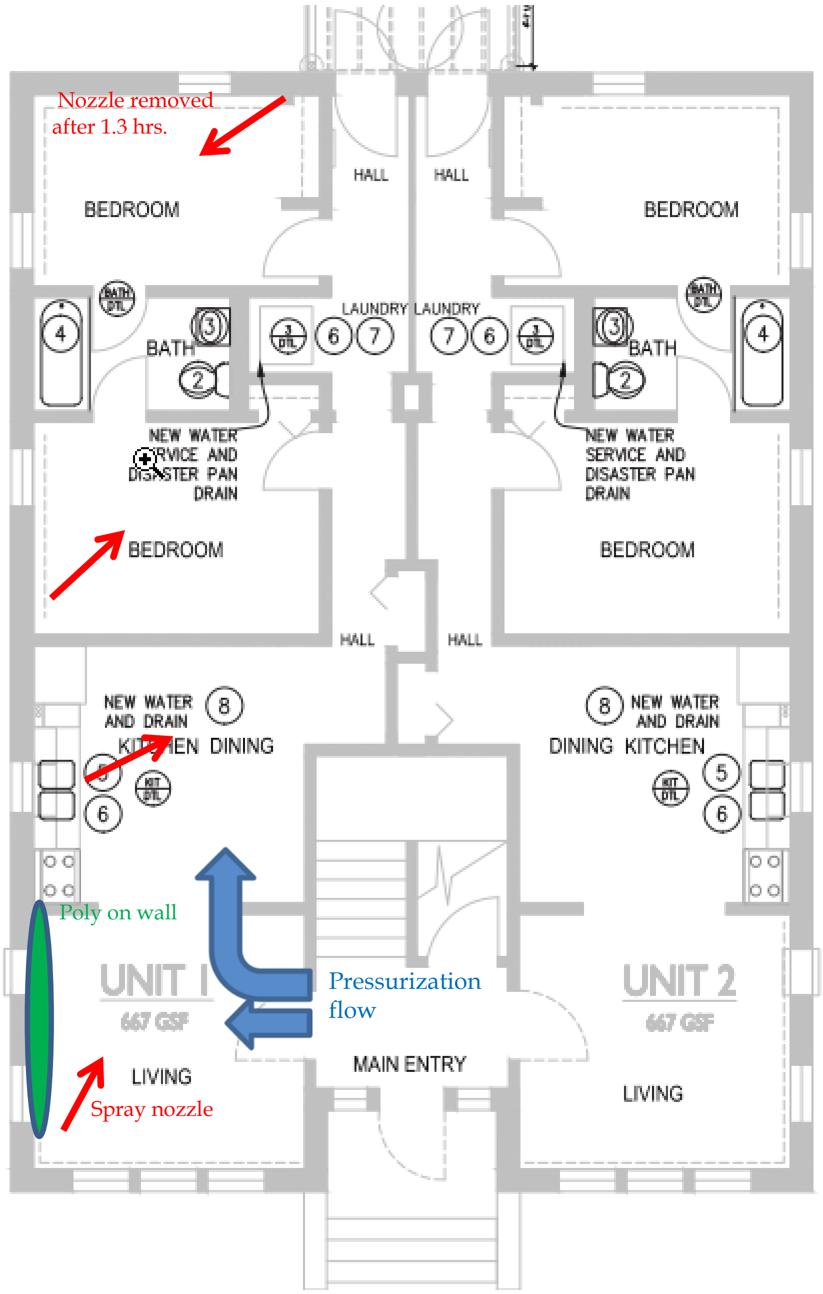


Figure 38: Unit 1 floor plan with nozzle and fan locations[17]



Aerosol Sealing Leakage Reduction

The aerosol sealing demonstrations on existing buildings were equally impressive sealing an average of 68% of the unit leakage (see Figure 39 and Table 18).

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[17] The unit 4 configuration was a mirror image of that for unit 1 except the fourth nozzle in the far back bedroom was not used for unit 4 sealing.

Figure 39: Pre and post sealing unit leakage and percent reduction for existing units

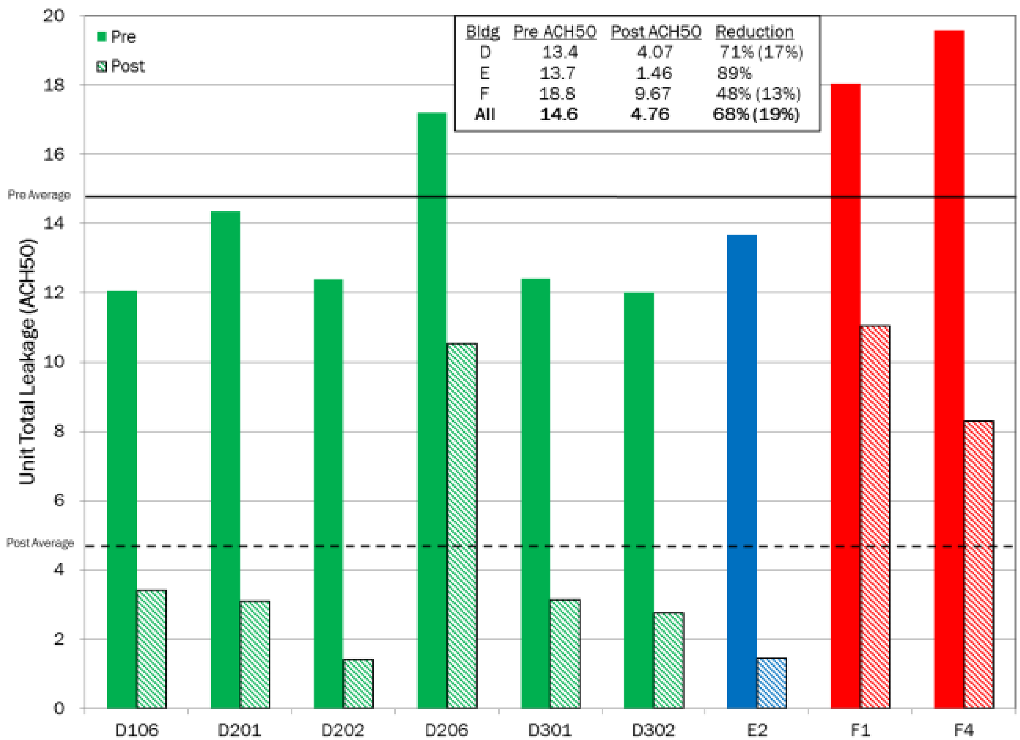


Table 18: Existing building pre/post aerosol sealing leakage test results

ID	Floor Area (ft²)	Envel Area (ft²)	Leakage (CFM50) Pre	Leakage (CFM50) Post	Leakage (ACH50) Pre	Leakage (ACH50) Post	Leakage (CFM50/ft²) Pre	Leakage (CFM50/ft²) Post	Reduction (CFM50)	Reduction (%)
D 106	228	1,079	433	123	12.05	3.43	0.401	0.114	310	72%
D 201	253	1,074	568	123	14.35	3.10	0.529	0.114	445	78%
D 202	235	1,178	454	52	12.40	1.43	0.385	0.044	401	88%
D 206	230	1,062	615	377	17.19	10.53	0.579	0.355	238	39%
D 301	245	1,070	428	109	12.40	3.15	0.400	0.102	319	75%
D 302	233	1,055	393	91	12.01	2.77	0.373	0.086	302	77%
E 2	1,582	4,677	2,884	308	13.70	1.46	0.617	0.066	2,576	89%
F 1	667	2,379	1,603	982	18.03	11.04	0.674	0.413	622	39%
F 4	667	2,387	1,740	738	19.56	8.30	0.729	0.309	1,002	58%
Min	228	1,055	393	52	12.01	1.43	0.373	0.044	238	39%
Max	1,579	1,178	2,884	982	19.56	11.04	0.729	0.413	2,576	89%
Avg	502	1,086	1,013	322	14.63	5.02	0.521	0.136	691	68%
Median	245	1,072	568	123	13.67	3.15	0.529	0.108	401	75%

The ultimate apartment tightness achieved was less consistent than that for the new construction units. For example, the reduction for unit D206 was only 39% due to large unforeseen leaks behind the kitchen cabinet. The pre-seal results show initial leakage levels of

12 ACH50 to 17 ACH50 and post-seal results from 1.4 ACH50 to 10.5 ACH50. This indicates that with proper preparation of the building, including manual sealing of larger leaks, the aerosol sealing process can realistically reduce air leakage in existing apartments to meet or exceed the State of Minnesota's new construction requirement of 3 ACH50. Given the current state of the technology, existing building sealing should occur when contents are removed from the space at time of tenant changeover or during building renovation. It is also not clear whether carpets can be protected from sealant deposition which should be considered for further research.

Breakdown of Exterior and Interior Air Leakage

Guarded-zone leakage tests were conducted on all six units of building D before and after the aerosol sealing was performed. One fan was installed in the hallway door of the unit being tested, a second fan was installed in the main entrance of the building, and the hallway doors to all the other units were opened. After an initial baseline pressure measurement, the fan in the main entrance was adjusted to create an increase of 50Pa for the pressure between the hallway adjacent to the test unit and outdoors. The fan in the hallway door of the test unit was adjusted to create a unit to hallway pressure difference equal to the baseline pressure difference. For this procedure test unit fan flow rate is approximately equal to the exterior envelope leakage rate for a pressure difference of 50 Pa. The interior leakage is computed from the difference between the total and exterior leakage.

Before sealing all of the units had more leakage to the exterior than to the interior (see Table 19). The exterior leakage ranged from 55% to 84% of the total with a median of 64%. When the leakages are normalized by the surface areas, the exterior leakage is five to six times greater than the interior leakage. The average interior leakage of 0.20 cfm50/ft^2 is similar to the 0.09, 0.20, and 0.12 cfm50/ft^2 values for the new construction buildings A, B, and C respectively. However, the average normalized exterior leakage of 1.10 cfm50/ft^2 is much greater than the pre-sealing values of 0.09 and 0.20 cfm50/ft^2 for buildings A and B[18] respectively. This was a major renovation project of an early 1900s masonry building. The results suggest that the air sealing methods were successful in achieving relatively tight demising walls, but the exterior walls were still leaky. Consequently, the exterior leakage was a much higher percentage of the total (average 68%) compared to the exterior percentages of 46% and between 15% to 26% for the new construction buildings A and B.

The average total envelope leakage was 13.4 ACH50 which was greater than the average of 11.8 ACH50 for 37 units in eight similar age and construction buildings prior to them being renovated. One of the six units in building D (D301) was tested before the major renovation work. After the renovation and prior to the aerosol sealing, the leakage for unit D301 had only been reduced by 13%. This illustrates the challenge of sealing existing buildings, even when they are undergoing major renovation.

[18] Building A area includes the exterior wall and floor. The building B leakage was measured before the gypcrete floor was poured.

Table 19: Breakdown of interior and exterior leakage for building D: pre-sealing

	(cfm50)			(ACH50)			($cfm50/ft^2$)			% of Total	
ID	**Total**	**Ext.**	**Int.**	**Total**	**Ext.**	**Int.**	**Total**	**Ext.**	**Int.**	**Ext.**	**Int.**
D 106	433	263	171	12.1	7.3	4.7	0.40	1.10	0.20	61%	39%
D 201	568	384	184	14.4	9.7	4.6	0.53	1.37	0.23	68%	32%
D 202	454	248	206	12.4	6.8	5.6	0.38	1.25	0.21	55%	45%
D 206	615	364	252	17.2	10.2	7.0	0.58	1.53	0.31	59%	41%
D 301	428	358	70	12.4	10.4	2.0	0.40	0.67	0.13	84%	16%
D 302	393	323	70	12.0	9.9	2.2	0.37	0.67	0.12	82%	18%
Min	393	248	70	12.0	6.8	2.0	0.37	0.67	0.12	55%	16%
Max	615	384	252	17.2	10.4	7.0	0.58	1.53	0.31	84%	45%
Average	482	323	159	13.4	9.0	4.4	0.44	1.10	0.20	68%	32%
Median	443	340	177	12.4	9.8	4.7	0.40	1.17	0.21	64%	36%

For all of the units the total envelope leakage was more than 4.0 times greater than the code required 3.0 ACH50 for low-rise multifamily buildings. Also, the exterior leakage values for the units were at least 2.3 times greater than 3.0 ACH50, with an average of 3.0 times greater. Moreover, the average total leakage is 3.5 times greater than the average for all of the new construction units in this project. This suggests that conventional sealing methods cannot tighten existing units to the level that can be achieved for new construction.

The guarded-zone tests were repeated after the aerosol sealing was complete. Table 20 displays the post sealing results and Table 21 displays the sealing reductions. As noted previously, unit D206 had a large, hidden leak behind a cabinet that was not able to be sealed by the aerosol method. For the other five units the aerosol sealing resulted in an average exterior leakage of 1.62 ACH50 and for all of the units the exterior leakage was at least 30% below the code required value of 3.0 ACH50. The average surface area normalized exterior leakage decreased to 0.18 $cfm50/ft^2$, which is consistent with the pre-sealing values for the new construction buildings. The percent leakage to the exterior dropped from 70% before sealing to 57% after sealing. This was the result in a greater reduction in the exterior leakage (82% decrease) than the interior leakage (64% decrease).

The relationship between the percent leakage reduction and the pre-sealing normalized leakage was inconsistent. There was a strong relationship for the interior leakage with larger percent reductions for greater normalized leakage (see upper right chart of Figure 40), but no significant relationship for either the exterior or total leakage. It might be expected that leakier surfaces have a greater potential for leakage reduction. However, the impact of the aerosol sealing varies with the gap width of the leakage. Leaks with smaller gaps are almost completely sealed while the aerosol method will have little impact on the leaks with wider gaps. So it is likely that the percent leakage reduction is mainly a function of the distribution of the gap width for the leaks and not as dependent on the overall leakiness of the area.

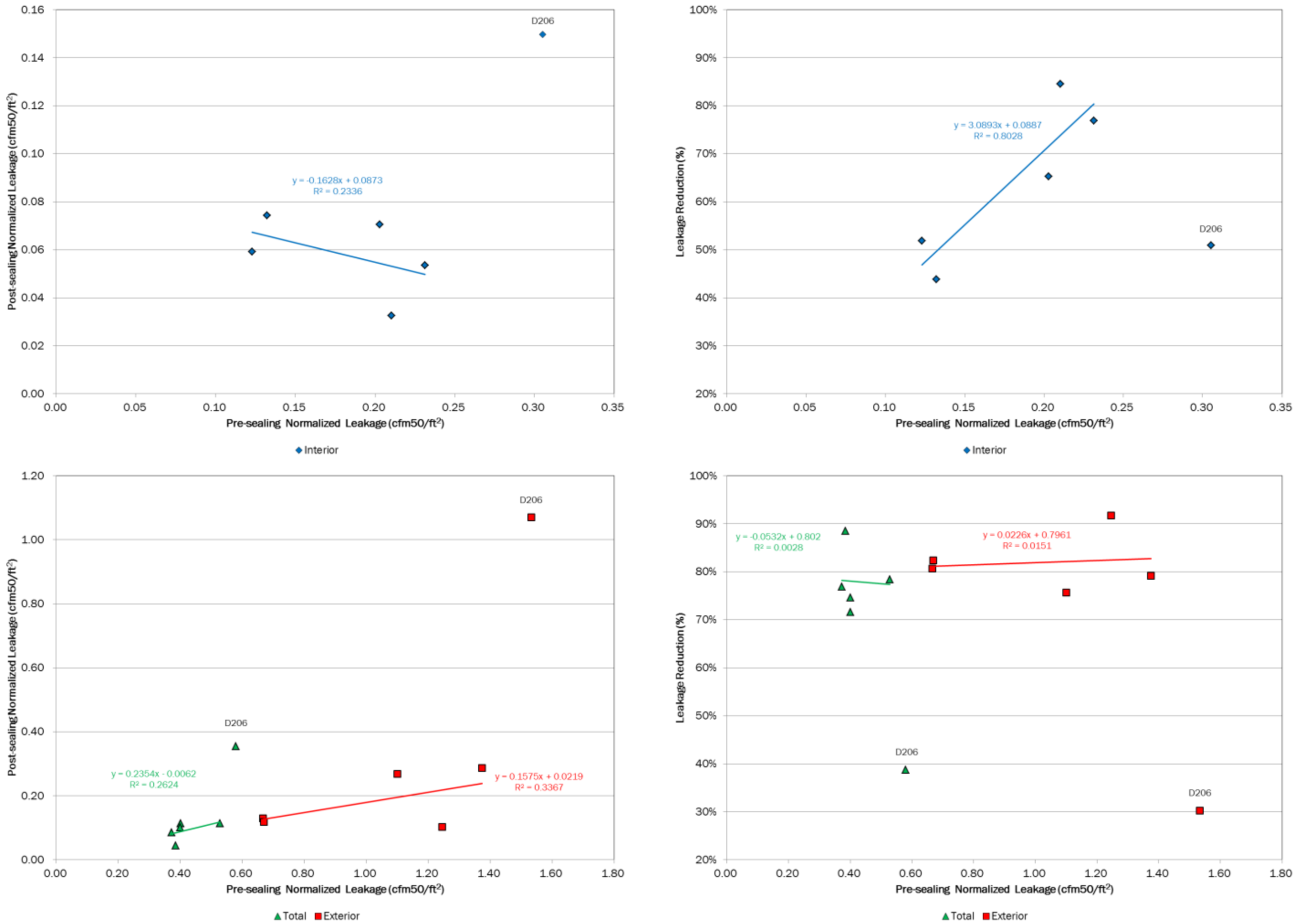
Table 20: Breakdown of interior and exterior leakage for building D: post-sealing

	(cfm50)			(ACH50)			(cfm50/ft²)			% of Total	
ID	**Total**	**Ext.**	**Int.**	**Total**	**Ext.**	**Int.**	**Total**	**Ext.**	**Int.**	**Ext.**	**Int.**
D 106	123	64	59	3.43	1.78	1.65	0.11	0.27	0.07	52%	48%
D 201	123	80	43	3.10	2.03	1.07	0.11	0.29	0.05	65%	35%
D 202	52	21	32	1.43	0.56	0.87	0.04	0.10	0.03	39%	61%
D 206	377	254	123	10.53	7.08	3.45	0.36	1.07	0.15	67%	33%
D 301	109	69	40	3.15	2.00	1.15	0.10	0.13	0.07	64%	36%
D 302	91	57	34	2.77	1.74	1.04	0.09	0.12	0.06	63%	37%
Min	52	21	32	1.43	0.56	0.87	0.04	0.10	0.03	39%	33%
Max	377	254	123	10.53	7.08	3.45	0.36	1.07	0.15	67%	61%
Average	146	91	55	4.07	2.53	1.54	0.14	0.33	0.07	58%	42%
Median	116	67	41	3.13	1.89	1.11	0.11	0.20	0.06	63%	37%

Table 21: Sealing reduction of interior and exterior leakage for building D

	(cfm50)			(ACH50)			(cfm50/ft²)			% Reduction	
ID	**Total**	**Ext.**	**Int.**	**Total**	**Ext.**	**Int.**	**Total**	**Ext.**	**Int.**	**Ext.**	**Int.**
D 106	310	199	111	8.62	5.52	3.10	0.29	0.83	0.13	76%	65%
D 201	445	304	141	11.25	7.68	3.57	0.41	1.09	0.18	79%	77%
D 202	401	227	174	10.96	6.20	4.76	0.34	1.14	0.18	92%	85%
D 206	238	110	128	6.66	3.07	3.58	0.22	0.46	0.16	30%	51%
D 301	319	288	31	9.25	8.36	0.89	0.30	0.54	0.06	81%	44%
D 302	302	266	37	9.24	8.12	1.12	0.29	0.55	0.06	82%	52%
Min	238	110	31	6.66	3.07	0.89	0.22	0.46	0.06	30%	44%
Max	445	304	174	11.25	8.36	4.76	0.41	1.14	0.18	92%	85%
Average	336	232	104	9.33	6.49	2.84	0.31	0.77	0.13	73%	62%
Median	315	246	120	9.24	6.94	3.34	0.29	0.69	0.14	80%	59%

Figure 40: Pre and post sealing unit leakage and percent reduction for existing units



Fluorescent Leak Identification

The fluorescent marking of the seals did not produce a reliable measurement of the distribution of leakage sealing. This was most likely due to insufficient lighting, which was needed to illuminate the small areas of sealant for an entire wall section. A better protocol to increase consistent camera lens focus for non-photographers may have produced a sharper image and better data as a result. For example, setting the camera focus with room lights on, as opposed to attempting to focus under such low light, could improve image sharpness. Another potential solution would be to take photos of smaller sections of the wall in order to improve image resolution. That method would require a standard protocol for marking the boundary of the image so that the images could be stitched together for post processing. Further investigation is needed to determine if this method could be useful.

Figure 41 shows two sample black light images of fluorescent-marked seals. These images demonstrate that the seals successfully illuminated under black light for smaller wall sections. However, Figure 42 shows much less contrast between sealed areas versus those areas not sealed. The quantitative analysis method was not capable of distinguishing the areas that were sealed with the fluorescent dyed sealant.

Figure 41: Sample black light images of fluorescent-marked seals photographed close-up

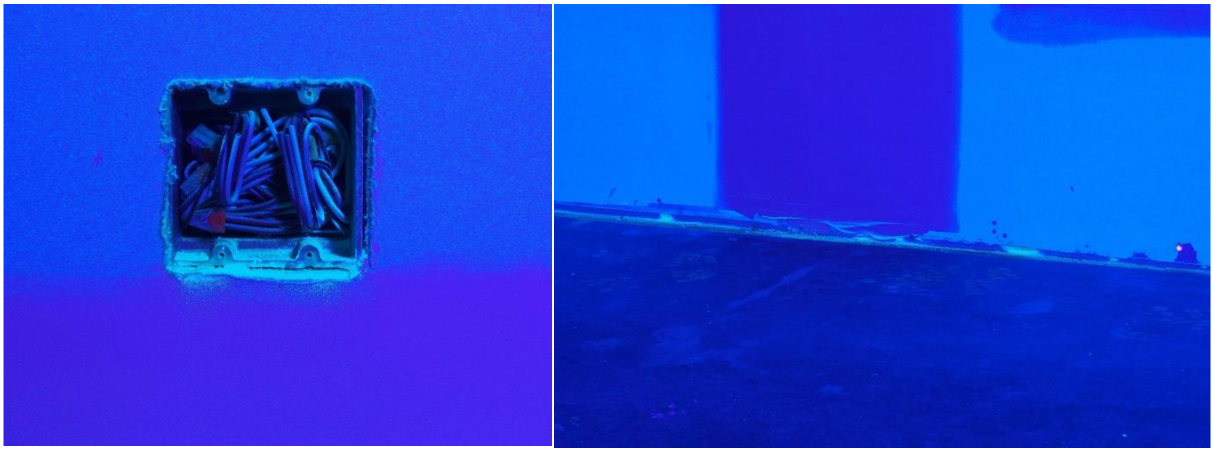


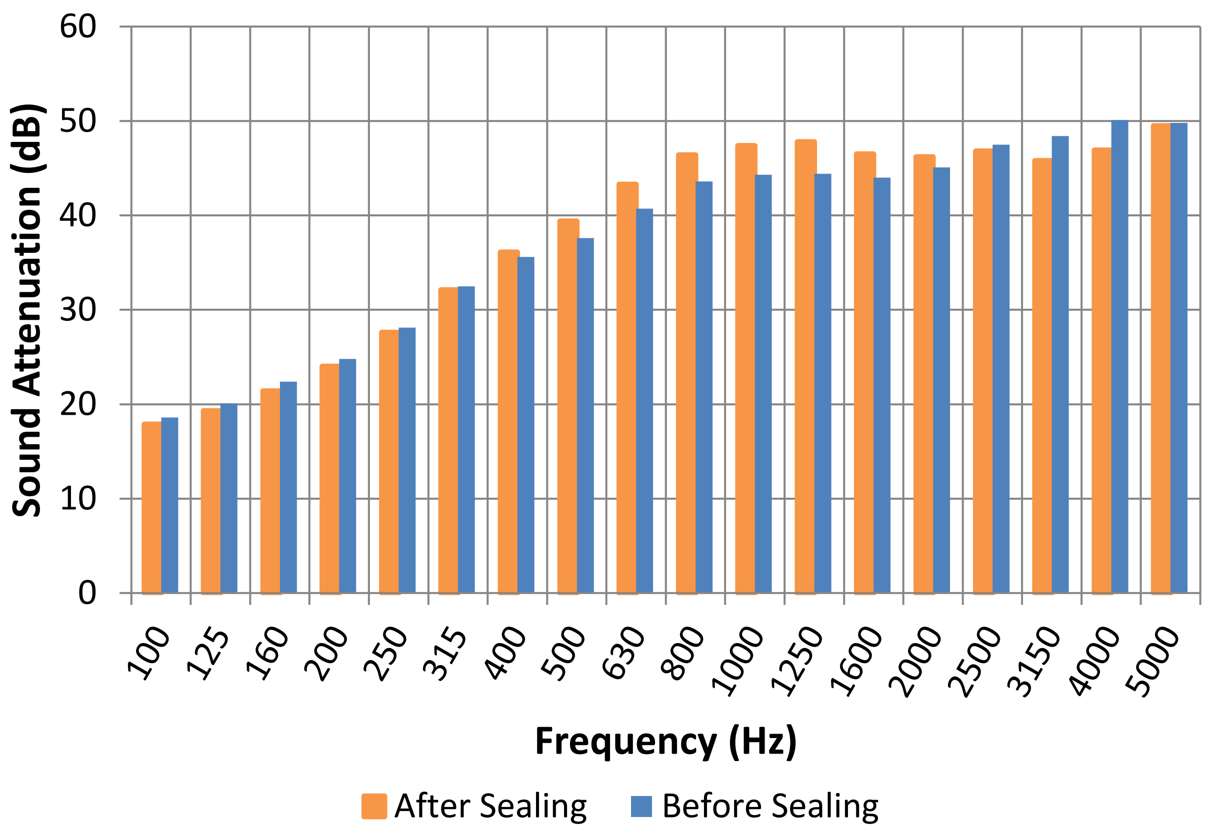
Figure 42: Sample black light image of entire wall after aerosol sealing

Sound Transmission

Sound transmission testing was performed on 13 different walls in the three new construction buildings (building A: 4, building B: 6, and building C: 3) and three walls in the existing building D. The results showed the aerosol sealing had little to no impact on wall sound transmission. Figure 43 presents the sound attenuation across a wall before and after sealing for one of the tests.

The data shows that the pre and post sound attenuation were relatively consistent across all frequencies analyzed. While there does appear to be some minor differences between the tests performed before and after sealing, it is believed that this is within the uncertainty of the test protocol. Since the testing was not performed in a controlled environment, background noise or noise flanking through the hallway into the measurement room could have led to slight variations in results. This variation is apparent in the data that shows sound attenuation of the wall decreasing due to the sealing, which was not expected.

Figure 43: Sound attenuation across a wall before and after sealing with aerosol technology



Due to Minnesota code requirements for sound transmission, interior walls between apartments are designed and constructed to reduce sound transfer. It is likely that the level of wall air tightness was already sufficient to effectively eliminate air leaks as a significant sound transmission pathway so that further sealing had little or no impact. The guarded-zone leakage tests estimated that the normalized leakage to adjoining units was only 0.09, 0.20, and 0.12 cfm50/ft^2 for buildings A, B, and C respectively. Those levels are significantly less than the 0.30 cfm50/ft^2 compartmentalization requirement for the EPA ENERGY STAR Multifamily High Rise program. The apartments tested in New York had no insulation in the walls separating apartments and had several penetrations that allowed sound to travel between units. Sealing those penetrations led to significant changes in sound transfer across the wall. Sound tests were conducted across three walls of the existing building D which was built before the sound transmission requirement went into effect. However, the units were small (e.g. average floor area of 237 ft^2) with limited opportunities for sound transmission tests. Two of the wall sections tested were the back of closets that had few penetrations and the third was the adjoining wall to a stairwell. Also, it is likely that for this major renovation the builder was required to meet the new sound transmission requirements.

The sound transfer testing performed in this project suggests that aerosol sealing does not appear to impact walls that are already reasonably sound-proofed. The testing in New York showed that the initial sound attenuation across the walls was less than 40 dB for nearly all frequencies analyzed, and aerosol sealing improved the sound attenuation by about 4-15 dB for frequencies above 500 Hz. By contrast, the initial sound attenuation measurements performed in Minnesota exceeded 40 dB at most of the higher frequencies above 500 Hz that are impacted most by aerosol sealing. Future testing should focus on walls that do not attenuate higher frequency sounds more than 40 dB.

Labor Requirements

Labor for the air sealing process can be divided into ten discreet tasks:

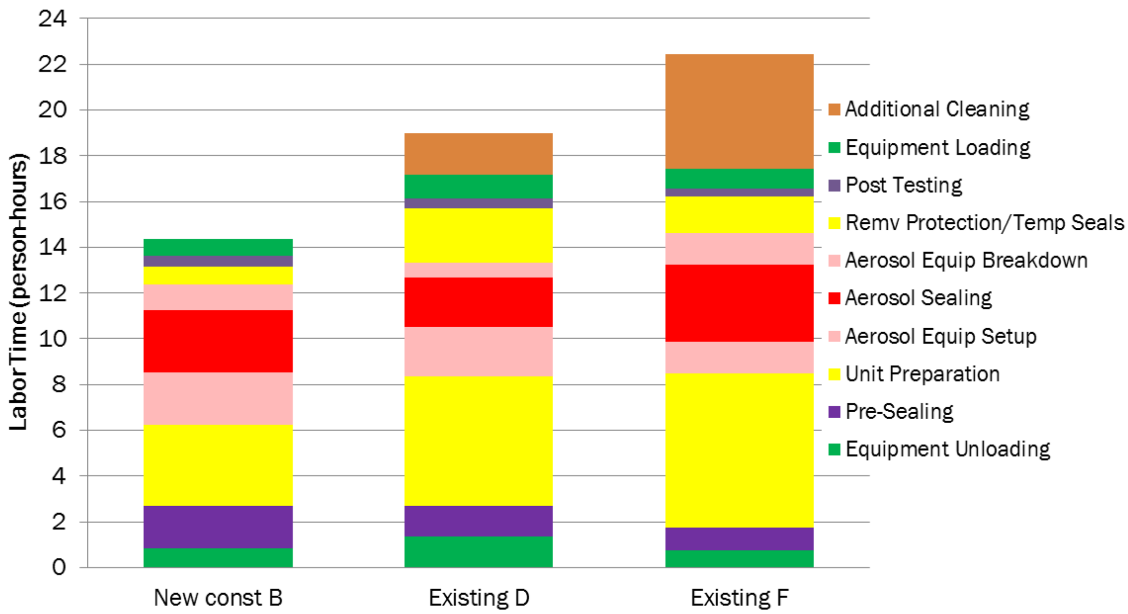
1. Equipment unloading
2. Pre-sealing
3. Unit preparation
4. Aerosol equipment setup
5. Aerosol sealing
6. Aerosol equipment breakdown
7. Removal of protective sheeting and temporary seals
8. Post testing
9. Equipment loading
10. Additional Cleaning

The labor time required to complete these ten different tasks for the air sealing process were tracked for the units in three of the six buildings. The tracking included eight units in new construction building B, six units in existing building D, and two units in existing building F. The labor times were averaged over all of the units in each building to generate the person-hours by task per unit for the three buildings that are displayed in Figure 44. The values include the number of staff multiplied by the time required for each person. The average total time for the entire process varied from about 14 person-hours per unit for the new construction units to slightly over 22 person-hours per unit for existing building F.

The portion of the process required for the task of sealing (which includes the tasks of equipment setup, aerosol sealing, and equipment breakdown) was consistently 5 to 6 person-hours per unit for the three buildings. However, in the research project there were two people doing this job to assure that the equipment was operating properly and to make adjustments to the sealant injection rate as necessary. Going forward, once the initial equipment setup and startup are completed, the sealing process typically can be managed by one person. As a result, this task should only require about half the time as required by the research project.

There was larger variation in the unit preparation (3.6 to 6.8 person-hours/unit) and additional clean-up (0 to 5 person-hours/unit). That was expected since the units in building F were nearly finished with flooring, cabinets, ceiling fans, and plumbing fixtures that required protection from sealant deposition.

Figure 44: Breakdown of labor per unit in person-hours for 10 sealing tasks



The labor hours for all of the buildings is high since this was a limited quantity research application with staff who were learning the process and trying various methods for unit preparation and clean-up. The commercial application of this technology should result in a number of time saving measures including:

- **Pre-sealing**: for new construction – coordinate with subcontractors so that large leaks are sealed
- **Unit preparation**: for new construction - select time during construction when there are minimal horizontal surfaces to protect, leaks are accessible, and sealant is not likely to be disturbed
- **Efficiency of Scale**: for most multifamily applications the crew would be asked to seal more than one unit so that during the sealing of one unit, the crew could be doing the prep work for the next unit with only one person needing to check periodically on the unit being sealed
- **Sealing time**: new generation of more portable and reliable equipment is being developed and sealing will stop sooner when no longer cost effective or target reached
- **Breakdown/clean-up**: minimize surfaces to cover and better positioning of spray nozzles

Energy Savings

New Construction

The modeling for new construction compared the energy performance for a building with units that have a total (exterior and interior) envelope leakage of 3 ACH50[19] to a building that was sealed 80% tighter (e.g. 0.6 ACH50) with the aerosol process. The 80% reduction in envelope leakage is approximately equal to the 81% average reduction for the aerosol sealing of the 18 new construction units completed for this project. The change in heating energy consumption after sealing is the most significant change, and is a result of the reduced infiltration of outdoor air.

Table 22 and Figure 45 show that the heating energy is reduced for all four ventilation types. The results show a 4% to 18% reduction in heating energy use due to envelope sealing with annual cost savings of $7 to $15[20]. It is apparent that buildings with ventilation strategies that are pressure neutral (i.e. balanced and no ventilation) gain the most from the envelope sealing. This trend is due to the increased sensitivity pressure-neutral buildings have to natural forces causing infiltration.

Table 22: Modeled space conditioning annual energy use - new construction

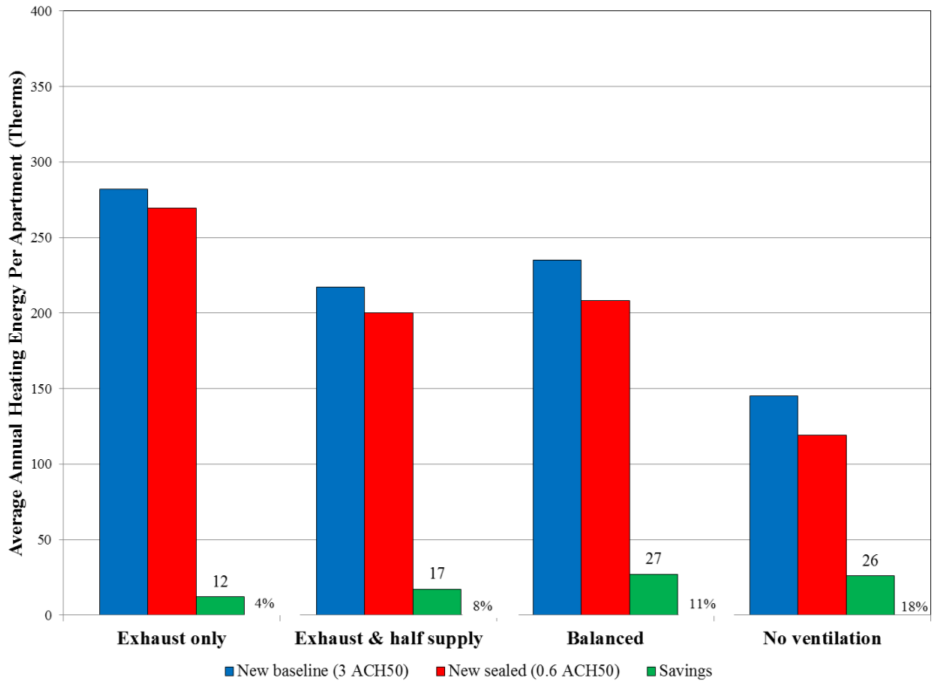
Ventilation Type	Space Heating (Therm/unit)				Space Cooling (MWh/unit)			
	3.0 ACH50	0.6 ACH50	Savings	% Savings	3.0 ACH50	0.6 ACH50	Savings	% Savings
Exhaust Only	282	270	12	4%	517	513	4	1%
Exh & ½ Supply	217	200	17	8%	847	852	-5	-1%
Balanced	235	208	27	11%	818	837	-19	-2%
No Ventilation	145	119	26	18%	668	697	-29	-4%

Another trend that can be seen in Figure 45 is that the overall magnitude of the heating energy use is linked to the ventilation system type. For units with a leakage of 3.0 ACH50, the model with no mechanical ventilation has significantly lower space heating energy use (145 therm/unit) compared to exhaust only, balanced, and exhaust/half supply ventilation (282, 235, and 217 therm/unit respectively). In addition, the mechanical ventilation systems with supply air operate the air handler fans continuously requiring less space heating due to the 325 watts of fan electric use that help heat the unit. For example, the two buildings with supply air (e.g. balanced and exhaust and half supply ventilation) have lower space heating loads than the building with exhaust ventilation, even though the average rate of outdoor air entering the apartment is higher for the buildings with supply ventilation (see the air flow results in the next section).

[19] The 2nd to 5th floor units have an exterior leakage of 1.41 ACH50.

[20] Assumes gas cost of $0.58/therm

Figure 45: Modeled annual space heating energy use and savings for new construction units

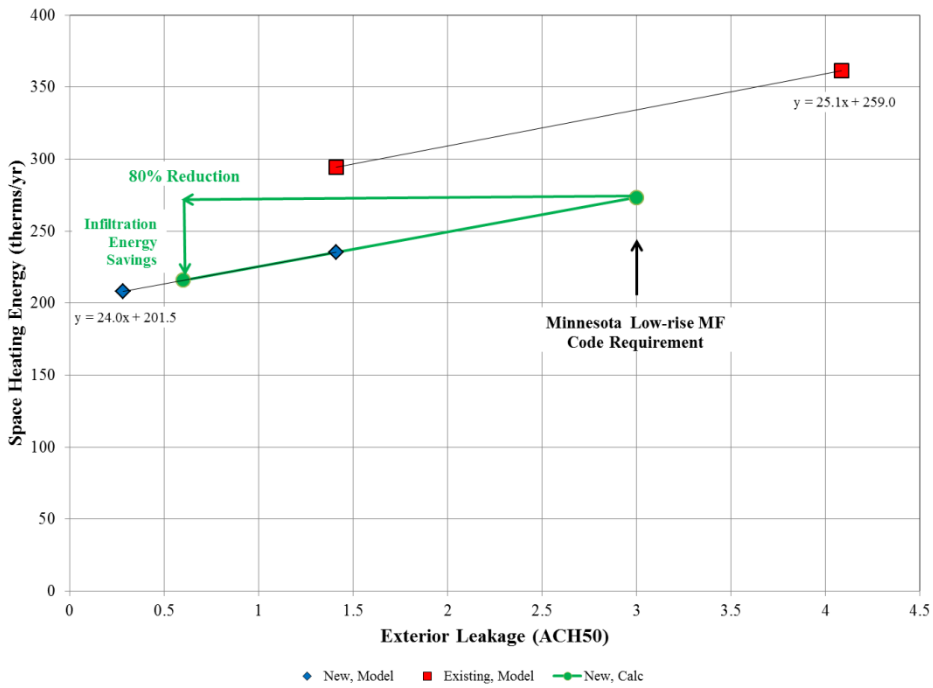


In general, there was a very small impact on the cooling energy required. In most cases the cooling energy increased slightly after sealing due to the reduction in ventilation cooling that occurred with additional infiltration. Due to the relatively small amount of energy required for cooling this change is not considered to be significant. The results showed between a 1% reduction and a 4% increase in cooling energy use (see Table 22). Again, the magnitude of cooling energy is linked to the ventilation type, with higher cooling needs for models with air handler ventilation systems that create space heating from fan operation.

As noted previously, the size of the model air leaks were selected to produce a total (exterior and interior) envelope leakage of 3.0 ACH50 for the new construction baseline conditions. When the modeling for this project was performed, it was expected that the 3.0 ACH50 code requirement would apply to the total unit leakage. More recently, Minnesota code officials have indicated that the 3.0 ACH50 requirement applies to the exterior leakage. This allows the units to be leakier than if the requirement applied to the total leakage. Increasing the leakage of the baseline model results in higher absolute savings for the new construction sealing. The exterior leakage for the new construction baseline model is 1.41 ACH50, which is 53% below the code requirement.

The blue diamonds in Figure 46 display the space heating energy use for the two levels of modeled exterior leakage for balanced ventilation. The green circles indicate the energy use for exterior leakage of 3.0s and 0.6 ACH50 (80% reduction). These values assume that the relationship between space heating energy use and envelope tightness is linear for leakage up to 3.0 ACH50. This seems reasonable since the slope of the change in space heating energy with envelope leakage is only 4% greater for the existing building models (red squares) that span the higher leakage levels[21]. For a reduction in exterior leakage from 3.0 to 0.6 ACH50 the calculated savings in space heating energy is 58 therms ($33) per year per unit. The savings would increase to 69 therms ($40) and 76 therms ($44) for a building with normal and exposed wind shielding respectively[22].

Figure 46: Annual space heating energy use for balanced ventilation



An annual cost savings of $33 for an exterior tightness reduction from 3.0 to 0.6 ACH50 and balanced ventilation indicates that the sealing cost would need to be $330 to $500 per unit for a 10 to 15 year payback. However, the 3.0 ACH50 code tightness and testing requirement only applies to one- to three-story low-rise multifamily buildings. For four-story and higher high-rise buildings the envelope tightness requirement can be met through the materials or assembly prescriptive tightness requirements and no performance test is required. If joints between assemblies and penetrations are not properly sealed, the envelope leakage can be greater than 3.0 ACH50. The sealing of the four units in building C showed that aerosol sealing can produce high relative leakage reduction (total leakage reduced 7.75 to 1.55 ACH50, average = 85%) and that applying aerosol sealing to leakier units can produce greater absolute energy savings and shorter paybacks. This suggests that aerosol sealing energy savings could be even greater for four-story and higher buildings that do not need to comply with an envelope leakage performance test and tightness level.

[21] There is an offset between the new and existing space heating energy use because of the higher insulation levels for the envelope of the new building models.

[22] Results from house infiltration modeling suggest that the infiltration rate will be 17% greater for normal and 25% greater for exposed wind shielding respectively (see Table 7).

For both low and high-rise buildings aerosol sealing could eliminate the need for some conventional sealing methods and higher levels of quality control that would be necessary to achieve tighter envelopes. There may be cases where the cost of aerosol sealing is lower than the conventional alternatives. For example, the air sealing work for building B included caulking base plates, top plates and a quarter inch gap that was purposely left between the bottom and corner joints of sheetrock. They also foamed gaps between framing and spray foamed the interior surface of the exterior sheathing. Much or all of that may have been eliminated through the use of the Aerosol sealing process. That could reduce the net cost of envelope sealing while still producing a below-code exterior envelope tightness. Replacing some conventional sealing with aerosol sealing was not assessed for this project, but is the subject of a future Department of Energy Building America study for Minnesota and California single family houses. Some of the results of that study will apply to multifamily buildings.

Existing Buildings

The modeling for existing construction focused on comparing the energy performance of an existing building that was sealed to meet the low-rise multifamily code requirement for new construction. Previous research suggests that existing apartments in Minnesota have an average leakage around 9.5 ACH50. The two total envelope leakage levels modeled for the existing buildings were 9.5 ACH50 and 3 ACH50. The models were developed for four ventilation strategies, and the energy consumption is compared for each strategy before and after sealing.

Table 23: Annual space heating gas use by number of units for Minnesota multifamily buildings

# Units	Floor Area (ft^2)	Gas Use (therms/unit)	Gas Use (therms/ft^2)
5 - 9	950 ±160	440 ±60	0.46
10 - 19	1070 ±90	470 ±60	0.44
20 - 49	980 ±100	320 ±40	0.33
50+	910 ±150	380 ±110	0.42
Overall	1000 ±70	410 ±30	0.41

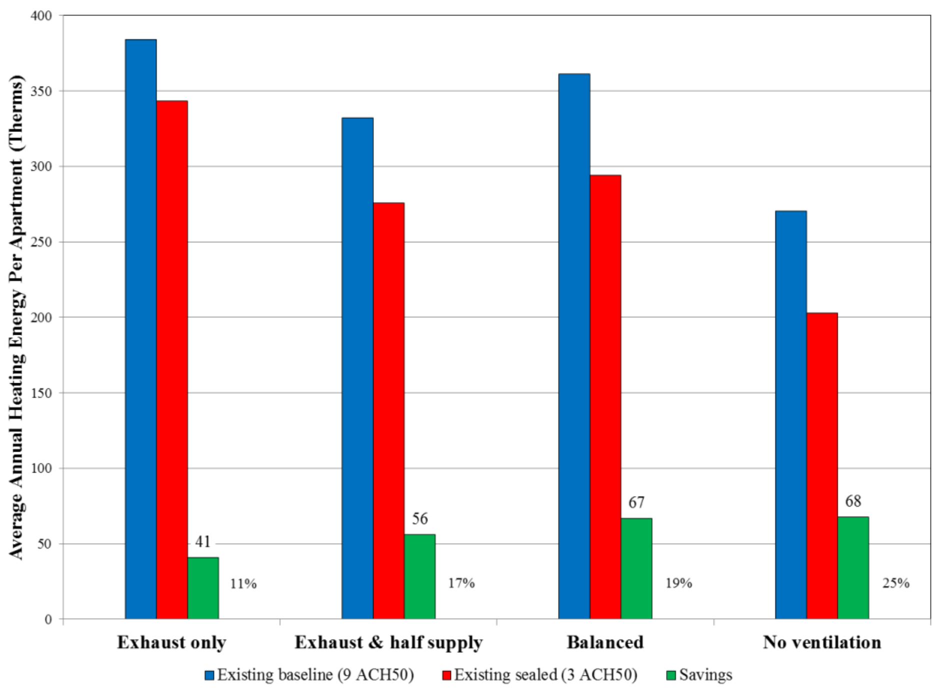
Pigg et al 2013. Includes building of all ages that use gas heat.
± values are approximate 95% confidence intervals

The modeled annual space heating energy usages were somewhat lower than the values reported for a recent Minnesota multifamily market characterization study (see Table 23, Pigg et al 2013). The annual gas space heating use for the 9.5 ACH50 tightness building ranged from 271 therm/unit (0.23 therm/ft^2) for the model with no mechanical ventilation to 384 therm/unit (0.32 therm/ft^2) for exhaust only ventilation (see Table 24). The market characterization study reported annual gas use values from 320 to 470 therm/unit (0.33 to 0.46 therm/ft^2) depending on the building size. The study included buildings of all ages and only 16% of the buildings were built since the 1980s. The energy models for existing buildings were based on wall and roof thermal characteristics for 1980s construction. It is reasonable that a model based on newer construction would result in lower energy use than the average use for a sample of buildings that has a high fraction of older buildings. This suggests that the modeled energy use is representative of a 1980s Minnesota multifamily building. In addition, for the Minnesota climate the modeled space heating energy use for air infiltration and the reduction in energy use for a tighter envelope is not highly sensitive to the thermal characteristics of the building envelope.

Table 24: Modeled space conditioning annual energy use – existing buildings

Ventilation Type	Space Heating (Therm/unit)				Space Cooling (MWh/unit)			
	9.5 ACH50	3.0 ACH50	Savings	% Savings	9.5 ACH50	3.0 ACH50	Savings	% Savings
Exhaust Only	384	343	41	11%	566	574	-8	-1%
Exh & ½ Supply	332	276	56	17%	865	892	-26	-3%
Balanced	361	294	67	19%	827	864	-38	-5%
No Ventilation	271	203	68	25%	664	711	-47	-7%

Figure 47: Modeled annual space heating energy use and savings for existing building units



The change in heating energy consumption after the envelope sealing is more pronounced in an existing apartment than in new construction. Table 24 and Figure 47 show that the heating energy is reduced for all ventilation types. Like the new construction results, the figure shows that pressure neutral (i.e. balanced and no ventilation) ventilation strategies gain the most from the envelope sealing due to the increased sensitivity pressure-neutral buildings have to natural forces causing infiltration. The results show an 11% to 25% reduction in heating energy use due to sealing the envelope with annual gas savings of 41 to 68 therms and cost savings from $24 to $39. Like the new construction model, ventilation system type used in the existing models affect the magnitude of the heating load due to the heat added by fans; however, the relative impact on the overall heating energy use is smaller.

Depending on the cost of a commercialized aerosol envelope sealing service, annual savings from $24 to $39 per unit may not be sufficient for many apartment building owners to pay for the service. However, the modeling results were based on a 68% reduction from a starting leakage of 9.5 ACH50. The average pre-sealing leakage of the nine existing units was over 14 ACH50 and the average was 11.8 ACH50 for 37 units from 8 buildings tested for a previous renovation project. A pre-sealing leakage of 15 ACH50 and a reduction of 75% would increase annual savings by about a factor of 2. The simulations assumed that 43% to 47% of the total leakage was to the exterior. Guarded tests of the six units in building D found that before sealing the exterior leakage was more than 50% of the total leakage for every unit with an average exterior leakage fraction of 68%. If the percent exterior leakage for the models was 68%, the savings would have been about 50% greater. Combined factors of leakier units, slightly higher percent leakage reduction, and a greater portion of leakage assigned to the exterior would result in higher savings of three times or more (e.g. $70 to $120 per year).

In all cases, existing building cooling energy use increases slightly after sealing the envelope due to reduced infiltration when it is cooler inside than it is outside. The impact was generally small with a 1% to 7% increase in cooling energy. It is expected that some occupants would open windows and reduce air conditioning use when conditions outside are cooler, but that was not modeled for this study.

Air Flow Modeling

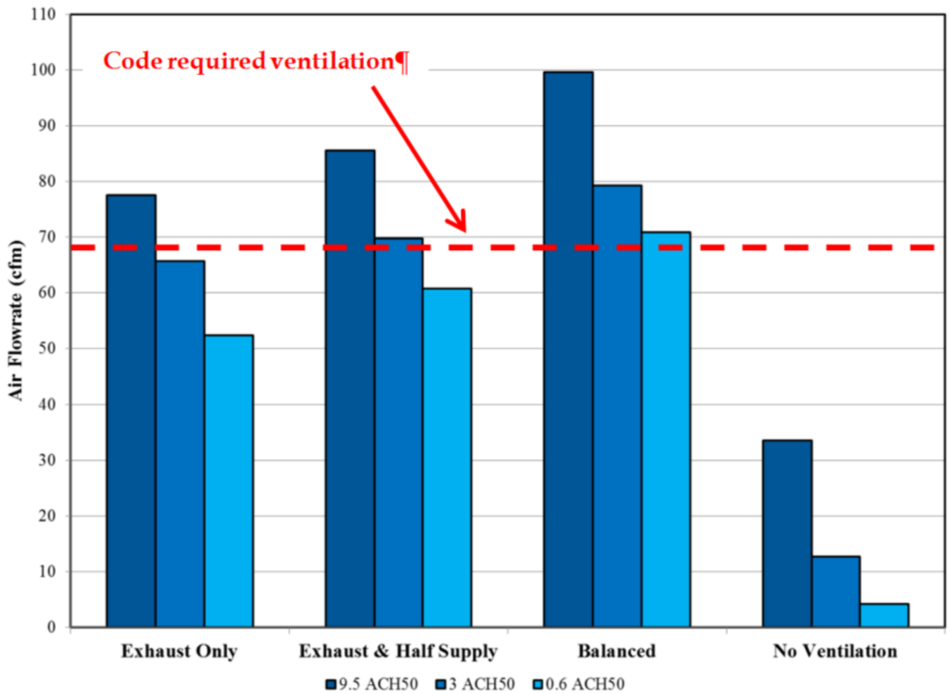
The model developed for this study was specifically designed to quantify air movement across internal and external surfaces. Analyzing airflow through a building provides details about space conditioning loads from air infiltration, ventilation compared to specified guidelines, and potential contaminant transfer between units. This section summarizes ventilation, infiltration, and inter-unit flowrates for the three envelope tightness levels: 9.5, 3.0, and 0.6 ACH50. There is no distinction between new construction and existing buildings since the envelope thermal properties do not affect air movement.

Ventilation

The level of ventilation has an important impact on proper indoor air quality. Figure 48 shows the average flow[23] that enters each unit from outside, and therefore it can be considered useful ventilation. This includes wind and stack driven infiltration along with supply air from the ventilator.

[23] The values are the average over all of the units in the building. Infiltration varies from floor to floor with generally higher infiltration for the lower levels.

Figure 48: Modeled annual average ventilation flowrate for three tightness scenarios



For each apartment with an active ventilation system the exhaust flowrate was equal to the code requirement of 0.35 ACH or 70 cfm. The balanced system had an equal supply air flowrate of 70 cfm and the "exhaust with half supply" system had a supply flowrate of 35 cfm. The type of ventilation system that most closely provides the required ventilation varies by envelope tightness and even relatively leaky units without mechanical ventilation have average ventilation that is about half the required amount.

For units with an envelope tightness of 9.5 ACH50, all three mechanical ventilation systems provided an average ventilation rate greater than the code requirement of 70 cfm. However, the average ventilation rate for the balanced system was 42% greater than the 70 cfm requirement. For the balanced ventilation system the supply air provides the required level of outdoor ventilation and no infiltration air through the building exterior is required for ventilation. Consequently, infiltration air causes the ventilation rate to be greater than the required amount. These results suggest that an exhaust ventilation system can be acceptable for leakier units and that a costlier balanced system will over ventilate.

The recommended type of mechanical ventilation changes for tighter units. Figure 48 illustrates that the exhaust ventilation system did not bring in 70 cfm of outside ventilation air into the tighter units. This shows that while an exhaust ventilation system can be measured to remove 70 cfm of air from an apartment, the source of make-up air that replaces the air removed by an exhaust fan does not necessarily come from outside and may not be appropriate for ventilation purposes. In addition, tightening the building envelope exacerbates this issue by forcing more air to come from other parts of the building (primarily the corridor in this model) as opposed to the outside. It is clear that supplying ventilation to each apartment becomes more important as the building become tighter. Only the balanced ventilation system achieved the required outdoor air for ventilation in the model with a very tight envelope of 0.6 ACH50.

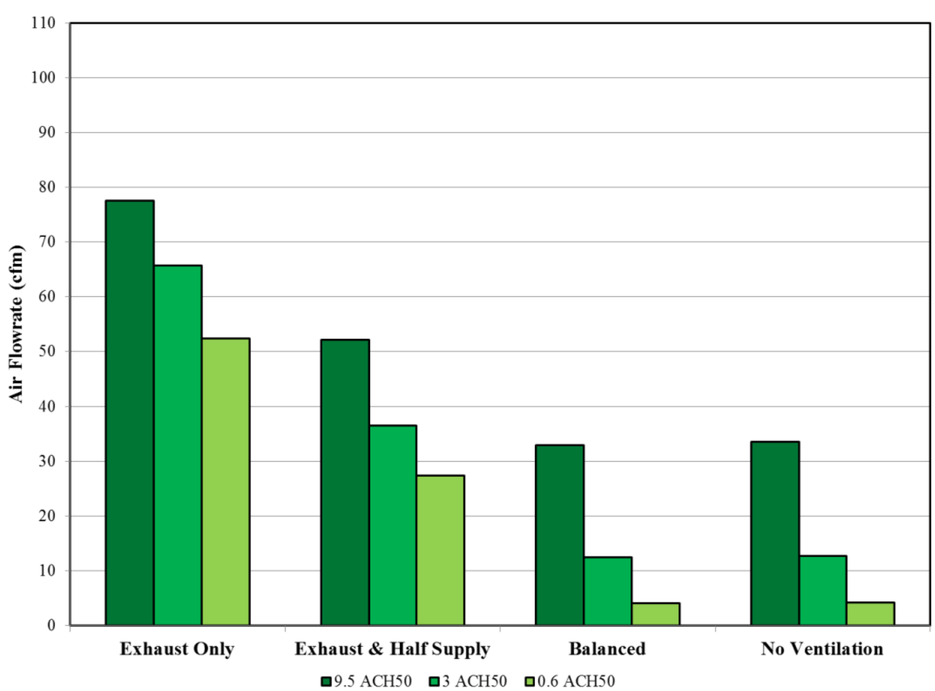
For moderately leaky units with a tightness of 9.5 ACH50 and no mechanical ventilation system, the average ventilation rate was less than half the required level. In warmer weather and calm wind conditions, occupants may need to open windows (e.g. natural ventilation) for adequate indoor air quality (IAQ). The average ventilation drops to 13 cfm for units with a tightness of 3.0 ACH50 and about 5 cfm for 0.6 ACH50. For those tighter units opening windows would typically not be acceptable and mechanical ventilation would be required for adequate IAQ.

In summary, even moderately leaky units with a total leakage of 9.5 ACH50 need mechanical ventilation or natural ventilation to achieve the code required ventilation rate. An exhaust only system is acceptable for leakier units (greater than 3.0 ACH50), and balanced ventilation is required for tighter units. However, a balanced system will over ventilate a leaky unit.

Infiltration

Air infiltration through the exterior envelope has an impact on building space heating and cooling loads. While reducing exterior envelope leakage will reduce air infiltration and conditioning loads, it can also restrict make-up air for imbalanced mechanical ventilation systems (e.g. exhaust only or exhaust with half supply). Figure 49 displays the annual average infiltration rates for the three levels of unit tightness and four types of ventilation. The infiltration rates are highest for the exhaust ventilation system that relies on air flow through the envelope for the make-up air. Infiltration is 25 to 29 cfm lower for the exhaust and half supply system that is partially balanced. The infiltration rates for the balanced and no ventilation systems are lowest and essentially the same for the two systems. There is no mechanical ventilation imbalance that forces air into or out of the envelope.

Figure 49: Modeled annual average air infiltration for three tightness scenarios



Reasonable estimates of energy savings from tighter envelopes require a reliable method for computing the relationship between envelope tightness and air infiltration that is based on building science principles. Early weatherization studies produced the “divide by 20” rule of thumb that divided the house envelope leakage[24] by 20 to compute average infiltration. This method has been refined over time to include the impact of wind exposure, building height, and climate (e.g. outside air temperature and wind speed). The State of Minnesota Technical Reference Manual (2016) provides a method for computing single family house heating season infiltration based on envelope tightness, wind exposure, and heating climate (see equation 1 and Table 7). A coefficient of 13 is used for well shielded, three-story houses and 18.6 for one-story houses.

Relating envelope leakage to infiltration is more complicated for multifamily buildings than it is for single family houses. First, the demising walls between units restrict air movement, which reduces the impact of thermal buoyancy forces or the stack effect. Second, unbalanced mechanical ventilation produces pressure differences between units and adjoining spaces, including the outdoors. Some of the interactions of these affects are nonlinear and can lead to non-intuitive results. For example, sealing the interior and exterior of an already tight unit with exhaust ventilation may have much less impact on infiltration than expected.

The airflow modeling for this project was not intended to provide a comprehensive method for computing air infiltration from envelope tightness and other parameters. However, the results provide some guidance on the relationship between infiltration and envelope leakage along with the impact of mechanical ventilation. Table 25 displays the heating season average air infiltration rate for the three levels of unit tightness and four ventilation strategies.

Table 25: Relationship between modeled space heating season infiltration rate and exterior leakage

Type of Ventilation System	Average Infiltration (cfm)			Exterior Leakage/Infiltration		
	9.5*	3*	0.6*	9.5*	3*	0.6*
Exhaust Only	79.7	66.7	52.9	10.3	4.2	1.1
Exhaust & Half Supply	54.9	37.5	27.9	14.9	7.5	2.0
Balanced	35.3	13.6	4.7	23.1	20.8	12.0
No Ventilation	36.1	13.9	4.9	22.6	20.3	11.6
		Exterior Leakage (CFM50)		817	282	56.4

* Unit tightness (ACH50)

The three columns on the right side of the table display the “divide by” coefficients computed from the exterior envelope leakage[25] divided by the infiltration rate. The coefficients vary by envelope tightness and ventilation system type. The coefficients are extremely small for units

[24] Measured at an induced pressure difference of 50 Pa.

[25] The exterior, and not total unit, envelope leakage was used because the exterior leakage has the most direct impact on air infiltration. Similar coefficients could be computed for total leakage, but the coefficients would be more dependent on interior leakage.

with tighter envelopes that have unbalanced mechanical ventilation. This occurs because, as the units become tighter, the exhaust ventilation system produces more depressurization and pulls almost the same amount of air infiltration through the exterior envelope. For example, there is a 65% reduction in exterior leakage as the unit leakage is reduced from 9.5 to 3.0 ACH50, but for exhaust ventilation systems the infiltration only is reduced by 16%. The flow imbalance for the exhaust with half supply system is half of the exhaust only system. The coefficients are somewhat higher, but still very low, for the 3.0 and 0.6 ACH50 units. This indicates that it may not be possible to generate a leakage/infiltration coefficient for units with significant exhaust or supply only ventilation that applies over a wide range of envelope tightness.

Since balanced mechanical ventilation has no impact on building pressures[26], the infiltration levels are nearly identical for the no ventilation and balanced ventilation strategies. The coefficients for the units with leakages of 3.0 and 9.5 ACH50 range from 20.3 to 23.1 and are higher than the values provided in the TRM for single-story (18.6) and three-story (13) houses. The compartmentalization of the multifamily units restricts interior air movement and reduces thermal buoyancy and wind effects. Consequently, the equivalent stack effect for multifamily buildings is less than when computed for an open six-floor building with no restrictions between floors. The sum of the ceiling and floor leakage for these models was only 5% to 13% of the total, which creates significant floor to floor restriction. It is expected that infiltration will be more similar to a one- to three-story open building than a six-story open building. The remaining discrepancy between the coefficients for the multifamily units and those reported for single family houses could be due to differences in the model configurations (e.g. wind pressure coefficients) and specific weather data selected for the model runs.

The coefficient for the balanced and no ventilation models decreases by 42% for a tighter (0.6 ACH50) envelope. This suggests that the relationship between envelope leakage and infiltration may not be linear for lower envelope leakage. Based on these limited modeling results, it appears that a coefficient of approximately 20 to 23 is appropriate for multifamily units with a total leakage of 3.0 ACH50 or greater that do not have significant, imbalanced mechanical ventilation. A high fraction of existing multifamily units would comply with those conditions. The results were generated for buildings that are well shielded from wind. The modeling was not performed for other wind shielding conditions. Based on results from house infiltration modeling, the coefficients should be reduced by 17% (e.g. 17 to 19) for normal wind shielding and by 25% (e.g. 15 to 17) for exposed multifamily buildings.

Since the coefficients for these models are generally consistent with values reported for single family houses and follow expected trends, it is reasonable to apply these values to energy studies of multifamily buildings. However, the results have been produced for a narrow set of conditions that did not consider effects of building height, wind shielding, level of imbalanced ventilation, and degree of unit compartmentalization. Further modeling is necessary to fully evaluate the impact of these effects on the relationship between exterior envelope leakage and average air infiltration.

Often the primary objective for a building energy evaluation is to estimate the reduction in annual or heating season infiltration for a reduction in envelope leakage. The right two columns

[26] The balanced ventilation systems have been modeled to have exactly equal supply and exhaust flowrates. In practice, there would be some level of imbalance in the systems.

of Table 26 display the coefficients for envelope leakage reduction divided by heating season infiltration reduction. These coefficients are more consistent than those for the direct relationship between envelope leakage and heating season infiltration.

Table 26: Relationship between reduction of modeled space heating season infiltration rate and exterior leakage

Type of Ventilation System	Infiltration Reduction (cfm)		Reduction Leakage/Infiltration	
	9.5 to 3*	3 to 0.6	9.5 to 3	3 to 0.6
Exhaust Only	13.0	13.8	41.1	16.4
Exhaust & Half Supply	17.4	9.7	30.8	23.3
Balanced	21.8	8.9	24.6	25.4
No Ventilation	22.2	9.0	24.0	25.0
	Exterior Leakage Reduction (CFM50)		535	225.6

* Reduction in unit tightness (ACH50)

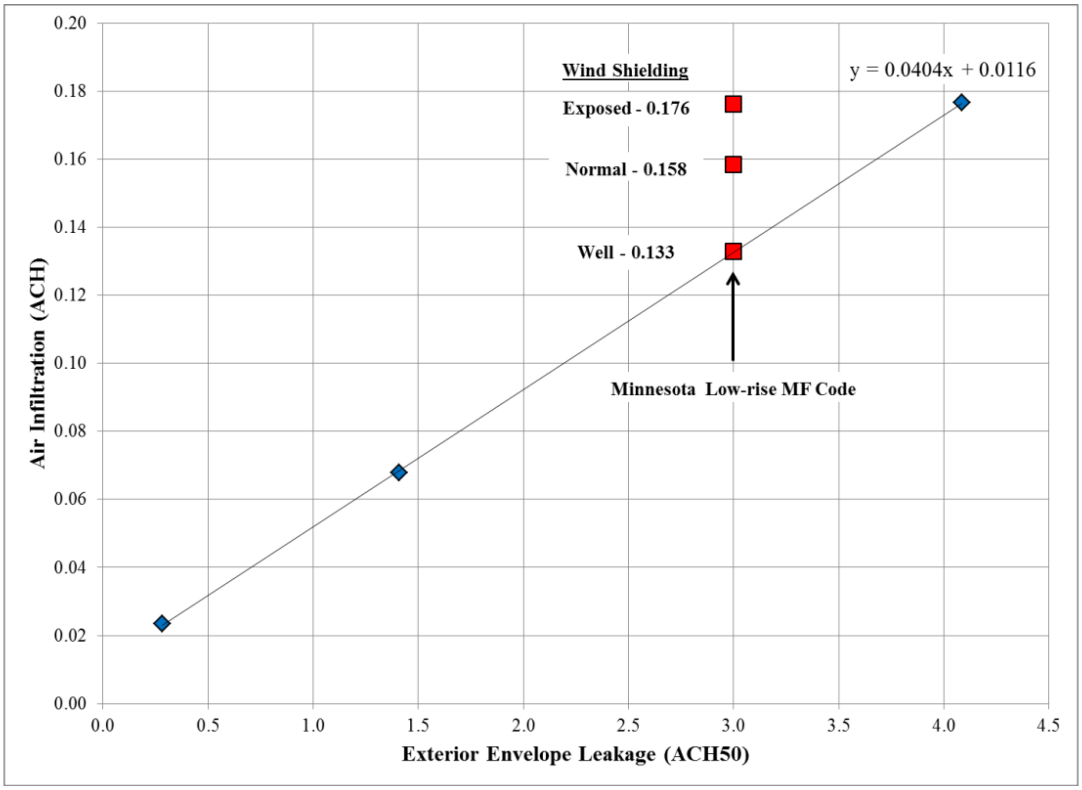
The average of the coefficients for balanced and no ventilation is 24.8, and all four values are within 4% of 25. In addition, the two coefficients for exhaust and half supply ventilation are 23% greater and 7% less than 25. This suggests that dividing the change in envelope exterior leakage by 25 should provide a reasonable estimate for the change in heating season infiltration. As noted previously, these results have been produced for a narrow range of building conditions. Further analysis should be performed for a greater range of conditions to better determine the relationship between the change in envelope leakage and the change in air infiltration.

The model results from this project can also be used for building energy model default air infiltration. Most building energy models do not compute air infiltration from envelope leakage values and driving forces. The models typically use a default value for air infiltration that may be adjusted for hourly outside air temperature and wind speed. Since there is only limited published data on airflow modeled or measured multifamily air infiltration, the infiltration assumed for multifamily energy models is typically based on broad generalizations and not on specific information on envelope tightness for the modeled building. The airflow model results from this project that vary with envelope tightness should be representative of a high fraction of Minnesota new construction multifamily buildings.

Figure 50 displays the variation of air infiltration[27] with exterior envelope tightness for balanced ventilation.

[27] Infiltration is displayed for the heating season average for Minneapolis typical meteorological year (TMY) weather. The annual average values are about 10% lower than those for the heating season.

Figure 50: Modeled heating season air infiltration for three tightness scenarios and balanced ventilation

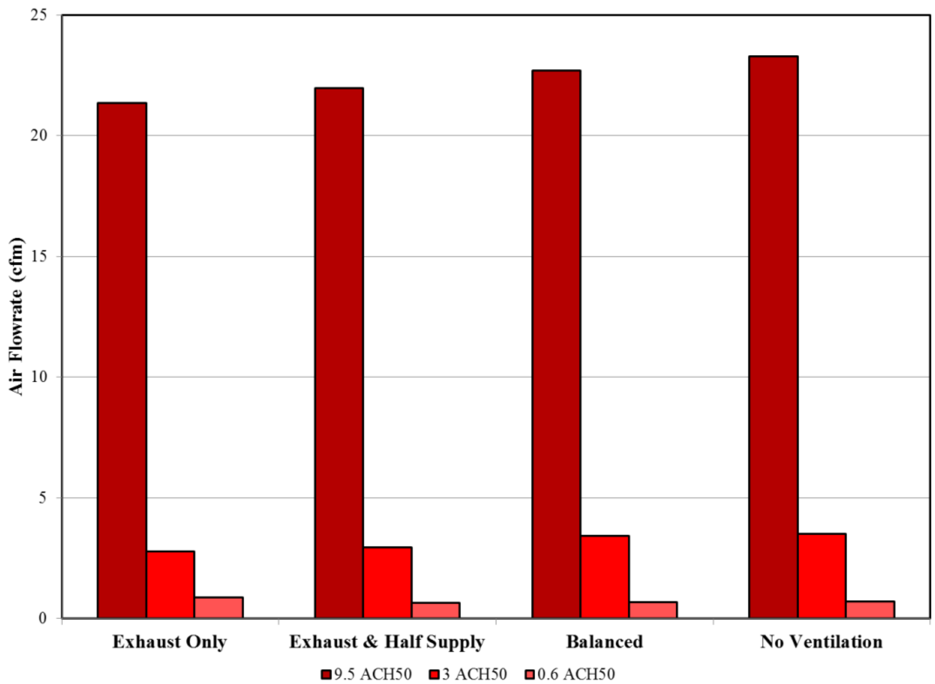


The regression line indicates that an infiltration rate of 0.13 ACH is appropriate for well shielded buildings that have a tightness level that complies with the Minnesota code requirement of 3.0 ACH50. The infiltration should be increased to 0.16 and 0.18 ACH for buildings with normal the exposed shielding. The regression equation displayed on the chart can be used to estimate the infiltration rate for variations in exterior envelope tightness. For example, a 1.5 ACH50 tightness that is 50% below code required reduces the infiltration to 0.072 ACH for a 46% infiltration reduction. Given the other uncertainties in the airflow model, it would be reasonable to assume that the percent reduction in exterior envelope leakage is equal to the percent reduction in air infiltration.

Airflow Between Units

Airflow between units transfers odors and contaminants between units. Inter-unit airflow is also an indication of air leakage that provides a sound transfer path between units. Improved compartmentalization will reduce air and sound transfer to improve IAQ and occupant comfort. Figure 51 illustrates the average amount of flow that enters an apartment from adjacent apartments in the building. For the leakiest units (9.5 ACH50), the average inter-unit airflow rate for all four ventilation strategies is 22.3 cfm, and all four values are within 4% of the average. For the units with mechanical ventilation the inter-unit air flow is about 25% of the ventilation flow. This indicates that there is significant air and contaminant transfer between units with about 20%of the air that enters the units coming from neighboring units. For the building without ventilation the inter-unit airflow is slightly higher than for the other ventilation strategies, but because of the lower ventilation flow the inter-unit flow is a high 41% of the total.

Figure 51: Modeled annual average flowrate from adjoining units



Reduced envelope leakage significantly reduces inter-unit airflow. The 65% leakage reduction from 9.5 to 3.0 ACH50 results in an average reduction in inter-unit airflow of 86%. For the units with a leakage of 3.0 ACH50 and mechanical ventilation the inter-unit air flow is only 4% of the total incoming airflow. The inter-unit flow is 22% of the total incoming flow for the building with no ventilation. The additional envelope leakage reduction of 80% to 0.6 ACH50 reduces the inter-unit flowrates by an average of 77%. For the buildings with mechanical ventilation, the inter-unit flow averages 1.2% of the total incoming flow, and it is 14% for the building with no ventilation.

Conclusions and Recommendations

The aerosol envelope sealing of 18 new construction and nine existing building units successfully demonstrated high levels of air leakage reduction with no damage to the finished surfaces. For the new construction units the reduction varied from 67% to 94% with an average of 81%. The reduction was almost as great for relatively tight units as those that were somewhat leaky. All of the units were more than 50% tighter than the 3 ACH50 code requirement for low-rise residential buildings and half of the units met the Passive House tightness requirement of 0.6 ACH50. In addition, all of the units were at least 80% tighter than the EPA ENERGY STAR Multifamily High Rise requirement of 0.3 CFM50/ft2. The aerosol sealing demonstrations on existing buildings were equally impressive sealing an average of 68% of the unit leakage. The ultimate apartment tightness achieved was less consistent with two of the tests sealing only 39% of the available leakage which in one case was due to large unforeseen leaks behind the kitchen cabinet. The pre-seal results show initial leakage levels of 12 ACH50 to 17 ACH50 and post-seal results from 1.4 ACH50 to 10.5 ACH50. This indicates that with manual pre-sealing of larger leaks, the aerosol sealing process can realistically reduce air leakage in existing apartments to meet or exceed the new construction low rise residential code requirement of 3 ACH50.

The total time per unit for the sealing process varied from about 14 person-hours for one of the new construction buildings to slightly over 22 person-hours for an existing building that was nearly finished and ready for occupancy. However, this was a research project with staff who were being trained on the process. It is likely that trained personnel, with more portable and automated equipment, utilizing a process that is better integrated into the construction process will result in a factor of two or greater reduction in labor time.

The building air flow and energy simulations showed that an envelope air leakage reduction from 3 to 0.6 ACH50 would result in space heating savings 11% or $15 per year for a unit with balanced ventilation. It might be difficult to justify the cost of aerosol envelope sealing as an add-on service to reduce unit leakage from 3 ACH50. However, the savings would be about double for units with a pre-sealing leakage greater than 6 ACH50 and the final leakage would easily exceed the tightness criterion. Ultimately the most likely benefit of aerosol sealing for new construction units is the cost savings from eliminating conventional sealing measures that can be replaced by the aerosol sealing. Currently, achieving tighter envelopes requires manual caulking and foaming of gaps and joints that can be labor intensive and require more extensive quality control to assure it is completed properly. It is possible that eliminating that the cost savings from eliminating that work could offset a large fraction of the cost of a more reliable aerosol sealing method.

The simulations for existing buildings showed savings from 11% to 25% and annual gas savings from 41 to 68 therms ($24 to $39) for an air leakage reduction from 9.5 to 3.0 ACH50. The ventilation strategies that are pressure neutral (i.e. balanced and no ventilation) save the most from envelope sealing. Many factors could contribute to higher savings. Many older buildings have a leakage greater than 9.5 ACH50 and the median leakage reduction was greater than that assumed for the models. Most importantly, the simulations assumed that 18% of the total leakage was to the exterior while guarded tests of the units showed that over 50% of the leakage was to the exterior for building D. The combined factors of leakier units, slightly higher percent leakage reduction, and a greater portion of leakage assigned to the exterior would result in four times or more higher savings (e.g. $100 to $160 per year).

CIP Recommendations

Existing Buildings

There are currently two Minnesota utility programs for existing multifamily buildings. The CenterPoint Energy/Xcel Energy Multifamily Building Efficiency program will include envelope air sealing as a custom measure beginning in 2017. The payback would need to be less than the measure life of 20 years in order for the air sealing work to qualify for an incentive. The Minnesota Energy Resources Multifamily Direct Install Plus program could include envelope air sealing as one of the targeted measures for investigation, and it may qualify for a custom rebate. All Minnesota utility programs for existing multifamily buildings should include incentives for envelope air sealing.

The State of Minnesota Technical Reference Manual for Energy Conservation Improvement Programs (2016) includes an algorithm for residential and small commercial buildings (see equation 1). However, the values shown in Table 7 of n_heat that are used to convert envelope leakage reduction to infiltration reduction are not directly applicable to multifamily units, and there is currently no generally accepted methodology for computing energy savings for multifamily building envelope air sealing. The limited energy and airflow modeling completed for this project indicate that a value of 25 should be used for n_heat. This would apply to existing multifamily buildings that have less than about 50 cfm of continuous, unbalanced mechanical ventilation and are well shielded from wind. The value should be reduced to 21 for normal wind shielding and 19 for exposed shielding[28]. It would be best to use a direct measurement of the reduction in exterior envelope leakage for the savings calculation. However, that measurement may not be feasible and can be expensive. The change in total leakage would be acceptable for air sealing that targets only exterior envelope leaks. For sealing that is expected to reduce both the exterior and interior leakage, multiplying the change in total leakage by 0.5 would typically provide a conservative estimate of the change in exterior leakage.

Air infiltration through envelope leaks does not typically provide adequate ventilation. Even for relatively leaky multifamily buildings, occupants must open windows for most weather conditions in order to provide adequate ventilation. An evaluation of the building ventilation system should be conducted and recommended upgrades should be completed when any significant exterior envelope air sealing is performed. Exterior air sealing is not recommended when the unit does not have a mechanical ventilation system.

New Construction

The modeled air infiltration results from this project should be used for baseline and reduced envelope tightness infiltration values for design assistance programs. Multifamily buildings can be eligible for the Xcel Energy and CenterPoint Energy design assistance programs for commercial and industrial new construction and major renovation. Although a tighter building envelope and associated air infiltration reduction is not a standard measure for the programs, it

[28] This is based on the variation in n_heat with wind shielding for single family houses (see Table 7).

can be modeled if requested by the design team (Baker 2016). Air leakage testing is an acceptable method for verifying a tighter envelope.

The airflow modeling conducted for this project suggests that design assistance program building energy models should use a baseline air infiltration rate of 0.16 ACH for buildings with normal wind shielding. The baseline is reduced to 0.13 ACH for well shielded buildings and increased to 0.18 ACH for exposed buildings. The percent reduction in modeled air infiltration should be the percent difference between the measured exterior envelope leakage and the low-rise residential code requirement of 3.0 ACH50. The project results indicate that aerosol sealing can produce an 80% reduction in envelope leakage which saves 58 therms/year in heating energy savings for a 1,200 ft^2 unit. An 80% reduction in envelope leakage and air infiltration is significantly greater than the 15% reduction in infiltration that is typically applied by the design assistance program when there are additional design and construction quality control measures to reduce envelope leakage.

As the aerosol sealing technology becomes more available, aerosol sealing would be a more common recommendation for new construction projects. Aerosol envelope sealing will likely be the most cost-effective sealing method for multifamily units that are required to meet more stringent compartmentalization requirements for programs such as Minnesota Housing Finance Agency's Enterprise Green Communities Criteria and Leadership in Energy and Environmental Design Multifamily Midrise.

It is likely that the baseline envelope leakage should be higher than 3.0 ACH50 for multifamily buildings four stories and higher since air tightness performance tests are not required by code for those buildings. Envelope air leakage tests of recently constructed high-rise multifamily units that did not need to comply with a compartmentalization requirement should be performed to establish a valid baseline.

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Appendix A. Detailed Air Sealing Protocol

Installation Protocol

The general process for performing aerosol sealing on multifamily buildings is presented below. The steps are broken into three main categories: setup, sealing, and cleanup. The framework is as follows:

Setup

1. Setup the blower door and run combo cords through the doorway.
2. Run a single point test at 50 Pa manually (depressurization).
3. Turn the fan around and connect it to the blank fan housing for pressurization.
4. Identify any leaks that are larger than the sealing capabilities of the aerosol process (leaks > 3/8 in.).
   a. See Checklist — Pre Sealing.
5. Temporarily seal any known intentional leaks with duct mask, tape, or other means.
   a. See Checklist — Temporary Sealing.
6. Cover anything that should not have sealant deposition on it with plastic or tape.
   a. See Checklist — Protection.
7. Place the aerosol injection nozzles in the unit using these guidelines (see Nozzle Placement for more information):
   a. Nozzles should be distributed throughout the unit.
   b. Any room with a floor area greater than 150 ft^2 should have a nozzle and larger than 500 ft^2 may need a second nozzle.
   c. Nozzles should be oriented such that the spray is
      i) NOT directed into the pressurization air flow stream.
      ii) NOT directed onto walls or other vertical surfaces.
      iii) Aerosol fog is distributed throughout the unit.
8. Spray water from the nozzles to determine final orientation.

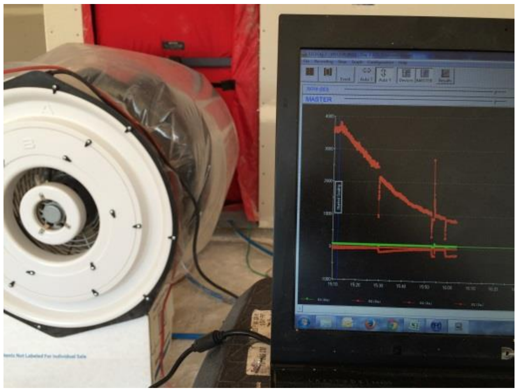
Figure 52: Sprayer direction checked before sealing starts

9. Measure the temperature and relative humidity of the air source.
10. Control the blower door to maintain 100 Pa inside the unit.
11. Set the injection rate to achieve a calculated 90% relative humidity.
12. Start sealing.

Sealing

1. Monitor the sealing profile.

Figure 53: TECLOG3 application used to monitor sealing



2. Monitor the calculated indoor relative humidity and/or compute the required sealant injection rate. Adjust the sealant injection rate to achieve a relative humidity of about 90%.
3. Seal until the leakage rate has been reduced by 85%, the sealing rate drops below 1 CFM50/minute, or another established metric has been met.
4. Purge liquid sealant lines with water either by
   a. Switching the liquid source to water when the sealing is near completion and finishing sealing with sealant in the lines until water has purged through the system, or
   b. Placing the liquid sealant lines in a bucket and purging water through the lines after the sealing is complete.

Cleanup

1. Purge the unit of aerosol by opening exterior doors/windows and running the pressurization fan(s) at high speed. Depending on the fan capacity, unit volume, and configuration of interior walls, this usually takes five to ten minutes.
2. Remove the nozzles, take them apart, and rinse with water to begin cleaning.
3. Coil up the liquid sealant and compressed air lines.
4. Remove any of the plastic or tape that was used to block the known leaks and protect surfaces.
5. Turn fan around and mount it in the door for a single point test at 50 Pa (depressurization).
6. Remove the blower door.

Unit Preparation

Protection

The aerosol envelope sealing process applies an aerosol fog to the entire apartment, some fraction of which inevitably settles out on the floor and the tops of other horizontal surfaces. As part of the preparation for the installation, any horizontal surface that cannot have sealant deposition on it should be covered with plastic or masking tape. Plastic placed on the floor should be held in place with tape or weighted ballast in case the installers must to enter the apartment during the test to access the equipment. If some sealant deposition on a surface is acceptable (i.e. on unfinished floors), plastic covering is not necessary. All protection needs to be able to withstand the pressures experienced during the installation (typically 100 Pa).

Existing multiunit dwellings and homes need more attention to detail during preparation compared to new multiunit dwellings. Although the sealant used in the process is easily cleanable from most surfaces, it is usually easier to prevent deposition in unwanted places rather than clean each surface after the sealing is complete. Figure 54 shows two images of an existing unit that is being prepared for a retrofit aerosol envelope sealing installation. The table below lists the items that should be masked off (if present) when preparing a multiunit dwelling for retrofit sealing.

Table 27: Items to consider for temporary protection from sealant deposition

Construction	Plumbing	Electrical	Mechanical
Floors (Figure 54 and Figure 55)	Tub or shower surrounds and floors	Ceiling Fans (Figure 55)	Top surface of baseboard heating
Window sills	Toilets, sinks, other bathroom pieces	Light switches (Figure 63)	
Window meeting rail and muntins	Plumbing fixtures	Light fixtures	
Door tops and hardware			
Top surface of baseboards, trims, and molding			
Horizontal surfaces of cabinets and built-ins (Figure 54)			

Figure 54: Existing unit getting prepped for a retrofit aerosol envelope sealing installation

Figure 55: Protection applied to a ceiling fan prior to air sealing work

Temporary seals

Due to the nature of the aerosol sealing process, any potential leak site where sealing is not desired should be blocked with tape or plastic. All protection needs to be able to withstand the pressures experienced during the installation which is typically 100 Pa. It is important to know what mechanical systems are installed in the building to assure that they are properly protected. While the sealant is not expected to move through conditioned air ducts that are entirely within the apartment, it is best to take precautions and block conditioned air registers during installation. Figure 3, Figure 4, and Figure 5 all show examples of temporary sealing. The table below lists items that should be considered for temporary sealing.

Table 28: Items to consider for temporary sealing

Construction	Plumbing	Electrical	Mechanical
Door frames	Bathroom Handles (Figure 58)	Intercom	Bath fan (Figure 57)
Floors (i.e. finished hardwood)	Drains	Low voltage outlets	Kitchen fan
Exterior doors (not used for fan frame)	Waste lines	Smoke detectors	Additional ventilation
Large holes/openings in the envelope		Alarms	Heating baseboards
Windows		Sprinkler heads	P-Tak openings
			Outdoor air intakes
			Combustion and exhaust air (Figure 56)
			Forced air registers
			Forced air returns

Figure 56: Temporary sealing of HVAC combustion air and exhaust penetrations

Figure 57: Temporary seal on a bathroom exhaust fan

Figure 58: Shower handle temporarily sealed to protect moving parts and intentional leaks from being sealed

Pre Sealing

Due to the nature of the aerosol sealing process, some air leakage paths are not sealable because of their size (typically leaks greater than 3/8"). If possible these leaks should be identified before sealing begins. Left unidentified and untreated, large leaks can increase the time and cost of sealing. As the unit is pressurized for sealing, large leaks can create a significant airflow path out of the unit, allowing sealant to escape. The exiting sealant can then build up on the surface around the leak, generating addition clean up and increasing the amount of sealant needed to seal the unit.

Two strategies can be used to avoid the penalties of large leaks. The first is to add a backing material to the leak to create a surface for the sealant to adhere to. Figure 59 shows a plumbing penetration where a mineral wool was used to reduce the size of the leak so that it can be sealed with the aerosol. Figure 60 shows the same method applied to a gap in the quarter round in an existing apartment unit. A backing material with structural support creates a stronger seal than one without structural support.

The second method is to permanently seal the large holes with caulk, mastic, or another permanent air sealing product. Figure 61 shows a HVAC system line set sealed with an air and fire barrier sealant caulk prior to air sealing. The table below lists items to consider for manual sealing prior to the aerosol process.

Table 29: Items to consider for manual sealing prior to Aerosol

Construction	Plumbing	Electrical	Mechanical
Floor wall connection	Showerhead penetration	Range plug	Line sets for HVAC
Sprinkler penetration	Sink penetrations	Electric baseboards	Vent duct penetrations
	Waste line penetrations	Low voltage wiring	Fresh air duct penetration
	Clothes washer connections	Additional wiring penetrations	Combustion and exhaust air penetrations
	Toilet water connection		PTAC wall penetration
	Kitchen water connection		Gas line penetrations (range, HVAC, laundry)

Figure 59: Plumbing penetrations for a bathroom sink prior to pre-sealing work (left) and after a backing material was applied (right)

Figure 60: A gap in the floor to wall detail too large for aerosol to seal before pre-sealing work (left) and after a mineral wool backing material was applied (right)

Figure 61: HVAC line set prior to any pre-sealing work (left) and after a manually applied permanent seal (right)

Access for Aerosol

The aerosol sealant must have access to leaks in order to seal them. To ensure that all leaks are accessible, the unit should be inspected for any potential leaks that are inaccessible, such as leaks enclosed in a cabinet or behind escutcheons. All electrical outlet, light switch, cable, and network plates should be removed to allow for sealing between the outside of the electrical box and the drywall (Figure 63). Plumbing penetrations enclosed in cabinets should also be exposed. The work to expose all leaks may create additional preparation needs. For example, exposing plumbing penetrations within a cabinet also exposes horizontal cabinet shelf surface that requires additional protection (Figure 62).

Table 30: Items to consider preparing to allow access for aerosol sealing

Construction	Plumbing	Electrical
Window blinds	Plumbing escutcheons	Electrical outlets
	Penetrations concealed by cabinets (i.e. sink water hook-ups)	Low voltage outlets (cable, telephone, smoke detectors, etc.)
		Ceiling fan canopy

Figure 62: Exposing the under sink cabinet and wall plumbing penetrations

Figure 63: Outlet covers were removed from electrical outlets to allow aerosol sealant better access to leaks inside the electrical boxes

Nozzle Placement

While each installation requires unique consideration as to where to place the nozzles for maximum performance, the following general guidelines for nozzle placement should be followed when possible.

The most appropriate stage of construction to install the aerosol sealing depends on the type of building and the extent to which vertical chases and penetrations are sealed prior to aerosol envelope sealing. Nozzle placement also depends on the stage of construction during which the sealing takes place. When installing the aerosol envelope sealing in a multiunit dwelling after the drywall phase of construction when internal walls are in place, at a minimum, nozzles should be placed in every bedroom and living area of the apartment. It is possible to move nozzles during the installation of the aerosol sealant, but it can be difficult if there is only one entrance into the apartment and, in general, entering the apartment during the process should be avoided whenever possible. Rooms such as bathrooms and hallways may be too small to have a dedicated nozzle placed inside. In these cases and if possible, nozzles should be directed from another room toward the smaller rooms to help distribute the aerosol into those smaller spaces. This protocol is most often used for retrofit air sealing with aerosols.

When installing the aerosol envelope sealing before interior walls are in place the nozzles should be distributed around the outside envelope of the apartment, and should be directed to spray along the wall to concentrate the aerosol on the exterior of the compartment. This should maximize the efficiency of the process and lower the amount of deposition on the floor of the apartment.

The injector nozzles generate a spray jet that travels about 8 feet before losing momentum. Deposition on vertical surfaces or on the ceiling is likely to occur if the nozzle is directed toward and within 8 feet of these surfaces. It is recommended that the aerosol plume be directed at an angle upward from the floor to promote suspension of the aerosol while preventing sealant deposition on walls.

Nozzle Operating Parameters

Air-atomization nozzles use compressed air to aerosolize a liquid stream. The ratio of compressed air flow to liquid flow largely determines the particle size produced by a nozzle. In general, the nozzles used for aerosol envelope sealing operate at an air pressure between 60 psi and 90 psi and at liquid flow rates between 20 ml/min and 50 ml/min. The maximum liquid flow rate for all of the nozzles in use should never exceed the theoretical limit on the amount of water that can be evaporated into the air entering the building through the pressurization fan. The air pressure is set by the regulator on the compressor and the liquid flow rate is set by the speed of the peristaltic pump.

A psychometric calculator should be used to determine an appropriate sealant injection rate, and it should be periodically updated during the sealing process to prevent saturating the room with water. Heating the air in the dwelling increases the water carrying capacity of the air, allowing for higher sealant injection rates and reduced sealing times. The target building relative humidity is 90%. The sealant flow rate is reduced as the leakage flow rate of the building reduces.

Pressurization Operating Parameters

To pressurize the space a fan must be installed in a hallway or exterior door, with the fan ducted into the blower door frame using a section of duct to prevent sealant from fouling the blower door fan (Figure 64). This duct section should be at least 3 feet in length and can be a flexible or rigid duct. The Energy Conservatory's TECLOG3 application records test conditions and the cruise control feature automatically adjusts the fan speed to maintain a positive 100 Pa pressure difference between the unit and the outside (or hallway). The fan flow rate and unit pressure are logged and monitored during the installation. The aerosol injection nozzles are activated after the building reaches the desired pressure. A final blower door post-test should be conducted after the building is adequately sealed.

Figure 64: Photo showing flexible duct used to separate blower door fan from the frame

Appendix B. Sealant Material Safety Data Sheet

Material Safety Data Sheet

TREMCO

EXOAIR 230 20A (Water Ver.) Limestone

Version *1.0*
REVISION DATE: 08/08/2014

Print Date 08/11/2014

SECTION 1 - PRODUCT IDENTIFICATION

Trade name	:	**EXOAIR 230 20A (Water Ver.) Limestone**
Product code	:	DEV1667
COMPANY	:	Tremco Incorporated 3735 Green Road Cleveland, OH 44122
Telephone	:	(216) 292-5000 8:30 - 5:00 EST
Emergency Phone	:	(216) 765-6727 8:30 - 5:00 EST After Hours: Chemtrec 1-800-424-9300
Product use	:	Coating

SECTION 2 - HAZARDS IDENTIFICATION

Emergency Overview

Limestone. Liquid. No serious effects anticipated under normal conditions of use. Leave area to breathe fresh air. Avoid further overexposure. If symptoms persist, get medical attention.

Acute Potential Health Effects/ Routes of Entry

Inhalation	:	No serious effects anticipated under normal conditions of use.
Eyes	:	Direct contact may cause mild irritation.
Ingestion	:	May cause gastrointestinal irritation, nausea, and vomiting.
Skin	:	May cause mild irritation.

Aggravated Medical Conditions

Pre-existing eye, skin and respiratory disorders may be aggravated by exposure.

Chronic Health Effects

Fillers are encapsulated and not expected to be released from product under normal conditions of use.

SECTION 3 - PRODUCT COMPOSITION

Chemical Name	CAS-No.	Weight %
Water	7732-18-5	> 60.0
Acrylic polymer	NJ TSRN# 51721300-5277P	15.0 - 40.0
White mineral oil	8042-47-5	1.0 - 5.0
Amorphous silica	7631-86-9	1.0 - 5.0
Titanium dioxide	13463-67-7	0.5 - 1.5

SECTION 4 - FIRST AID MEASURES

Get immediate medical attention for any significant overexposure.

Inhalation	:	Leave area to breathe fresh air. Avoid further overexposure. If symptoms persist, get medical attention.

An RPM Company 1/6 DEV1667

Material Safety Data Sheet

TREMCO

EXOAIR 230 20A (Water Ver.) Limestone

Version *1.0*
REVISION DATE: 08/08/2014

Print Date 08/11/2014

Eye contact	:	Flush with water for 15 minutes. If irritation persists, get medical attention.
Skin contact	:	Wash area of contact thoroughly with hand cleaner followed by soap and water. If irritation, rash or other disorders develop, get medical attention immediately.
Ingestion	:	Get medical attention. Do not induce vomiting.
Notes to physician	:	Not applicable.

SECTION 5 - FIRE FIGHTING MEASURES

Flash point	:	Not available.
Method	:	Not applicable.
Burning rate	:	Non-Flammable Liquid
Lower explosion limit	:	Not available.
Upper explosion limit	:	Not available.
Autoignition temperature	:	Not available.
Extinguishing media	:	This product is not expected to burn under normal conditions of use.
Hazardous combustion products	:	Carbon monoxide and carbon dioxide can form.Smoke, fumes.
Protective equipment for firefighters	:	Use accepted fire fighting techniques. Wear full firefighting protective clothing, including self-contained breathing apparatus (SCBA).
Fire and explosion conditions	:	This product not expected to ignite under normal conditions of use.

SECTION 6 - ACCIDENTAL RELEASE MEASURES

Transfer to appropriate container for disposal. Stop flow. Contain spill. Keep out of water courses. Absorb spill in sand, earth or other suitable material. Transfer to appropriate container for disposal. Use appropriate protective equipment. Avoid contact with material.

SECTION 7 - HANDLING AND STORAGE

Handle in compliance with common hygienic practices. Clean hands thoroughly after handling. Keep from freezing. Do not use in confined or poorly ventilated areas. Prevent inhalation of vapor, ingestion, and contact with skin eyes and clothing. Keep container closed when not in use. Precautions also apply to emptied containers. Store in sealed containers in a dry, ventilated warehouse location above freezing.

SECTION 8 - EXPOSURE CONTROLS / PERSONAL PROTECTION

Personal protection equipment

Respiratory protection	:	Not required under normal conditions of use.Wear appropriate, NIOSH/MSHA approved respirator with combination particulate filter and vapor/gas removing cartridge when the ventilation is not adequate or if it is necessary to abrade or grind surfaces coated with this product.
Hand protection	:	Use suitable impervious rubber or vinyl gloves and protective apparel to reduce exposure.

An RPM Company 2/6 DEV1667

Material Safety Data Sheet

TREMCO

EXOAIR 230 20A (Water Ver.) Limestone

Version *1.0*
REVISION DATE: 08/08/2014

Print Date 08/11/2014

Eye protection : Wear appropriate eye protection.Wear chemical safety goggles and/or face shield to prevent eye contact. Do not wear contact lenses. Do not touch eyes with contaminated body parts or materials. Have eye washing facilities readily available.

Skin and body protection : Prevent contact with shoes and clothing. Use rubber apron and overshoes.

Protective measures : Other equipment not normally required.Use professional judgment in the selection, care, and use.

Engineering measures : Not required under normal conditions of use.Use local exhaust when the general ventilation is inadequate.

Exposure Limits

Chemical Name	CAS Number	Regulation	Limit	Form
White mineral oil	8042-47-5	OSHA PEL: ACGIH TWA:	5 mg/m3 5 mg/m3	Mist. Inhalable fraction.
Amorphous silica	7631-86-9	ACGIH TWA: ACGIH TWA: OSHA PEL: OSHA PEL: OSHA TWA:	3 mg/m3 10 mg/m3 15 mg/m3 5 mg/m3 0.8 mg/m3	Respirable particles. Inhalable particles. Total dust. Respirable fraction.
Titanium dioxide	13463-67-7	ACGIH TWA: OSHA PEL: OSHA TWA: OSHA TWA:	10 mg/m3 15 mg/m3 15 mg/m3 5 mg/m3	 Total dust. Total dust. Respirable fraction.

SECTION 9 - PHYSICAL AND CHEMICAL PROPERTIES

Form : Liquid

Color : Limestone

pH : Not available.

Vapour pressure : Not available.

Vapor density : Heavier than air

Melting point/range : Not available.

Freezing point : Not available.

Boiling point/range : Not available.

Water solubility : Soluble

Specific Gravity : 1.023

% Volatile Weight : 78 %

SECTION 10 - REACTIVITY / STABILITY

Substances to avoid : Strong acids.Strong bases.

Stability : Stable

An RPM Company 3/6 DEV1667

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Hazardous polymerization : Will not occur.

SECTION 11 - TOXICOLOGICAL INFORMATION

Amorphous silica, CAS-No.: 7631-86-9
Acute oral toxicity (LD-50 oral) 22,500 mg/kg (Rat) 15,000 mg/kg (Mouse)

Titanium dioxide, CAS-No.: 13463-67-7
Acute oral toxicity (LD-50 oral) 25,000 mg/kg (Rat) 5,000 mg/kg (Rat) 5,000 mg/kg (Rat) 2,000 mg/kg (Rat) 11,000 mg/kg (Rat)
Acute inhalation toxicity (LC-50) > 6.82 mg/l for 4 h (Rat) 3.43 mg/l for 4 h (Rat) 5.09 mg/l for 4 h (Rat) > 2.28 mg/l for 4 h (Rat) > 3.56 mg/l for 4 h (Rat)

SECTION 12 - ECOLOGICAL INFORMATION

No Data Available

SECTION 13 - DISPOSAL CONSIDERATIONS

Disposal Method : Waste not regulated under RCRA. Dispose of in compliance with state and local regulations.

SECTION 14 - TRANSPORTATION / SHIPPING DATA

CFR / DOT:

Not Regulated

TDG:

Not Regulated

IMDG:

Not Regulated

SECTION 15 - REGULATORY INFORMATION

North American Inventories:

All components are listed or exempt from the TSCA inventory.
This product or its components are listed on, or exempt from the Canadian Domestic Substances List.

U.S. Federal Regulations:

An RPM Company 4/6 DEV1667

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SARA 313 Components : None present or none present in regulated quantities.

SARA 311/312 Hazards : Acute Health Hazard

OSHA Hazardous Components :

White mineral oil	8042-47-5
Amorphous silica	7631-86-9
Titanium dioxide	13463-67-7

OSHA Status: Considered hazardous based on the following criteria: : Irritant

OSHA Flammability : Not Regulated

Regulatory VOC (less water and exempt solvent) : 18 g/l

VOC Method 310 : 0.35 %

U.S. State Regulations:

MASS RTK Components :	White mineral oil	8042-47-5
	Amorphous silica	7631-86-9
Penn RTK Components :	Water	7732-18-5
	Acrylic polymer	NJ TSRN# 51721300-5277P
	White mineral oil	8042-47-5
	Amorphous silica	7631-86-9
NJ RTK Components :	Water	7732-18-5
	Acrylic polymer	NJ TSRN# 51721300-5277P
	White mineral oil	8042-47-5
	Amorphous silica	7631-86-9

Components under California Proposition 65:
WARNING! Contains chemicals known to the State of California to cause cancer, birth defects and/or other reproductive harm

SECTION 16 - OTHER INFORMATION

HMIS Rating :

Health	1
Flammability	0
Reactivity	0
PPE	

0 = Minimum
1 = Slight
2 = Moderate
3 = Serious
4 = Severe

Further information:

For Industrial Use Only. Keep out of Reach of Children. The hazard information herein is offered solely for the consideration of the user, subject to their own investigation of compliance with applicable regulations, including the safe use of the product under every foreseeable condition.

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Prepared by: Rich Mikol

Legend

ACGIH - American Conference of Governmental Hygienists
CERCLA - Comprehensive Environmental Response, Compensation, and Liability Act
DOT - Department of Transportation
DSL - Domestic Substance List
EPA - Environmental Protection Agency
HMIS - Hazardous Materials Information System
IARC - International Agency for Research on Cancer
MSHA - Mine Safety Health Administration
NDSL - Non-Domestic Substance List
NIOSH - National Institute for Occupational Safety and Health
NTP - National Toxicology Program
OSHA - Occupational Safety and Health Administration
PEL - Permissible Exposure Limit
RCRA - Resource Conservation and Recovery Act
RTK - Right To Know
SARA - Superfund Amendments and Reauthorization Act
STEL - Short Term Exposure Limit
TLV - Threshold Limit Value
TSCA - Toxic Substances Control Act
TWA - Time Weighted Average
V - Volume
VOC - Volatile Organic Compound
WHMIS - Workplace Hazardous Materials Information System

DEV1667 US Label

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CAUTION! May cause temporary irritation to eyes, skin and respiratory tract. Avoid ingestion or inhalation of vapors and contact with skin, eyes, and clothing. Do not inhale vapors or spray mist. Use only in well ventilated areas. Wear suitable protective clothing if indicated by conditions and other protective apparel. Observe precautions for empty containers. Wear NIOSH/MSHA certified respirator. Close containers when not in use. Handle in compliance with common hygienic practices.

For additional health and safety information, read the current MSDS carefully before using this product.

First Aid: Get medical attention immediately for any significant overexposure. INHALATION: Leave area to breathe fresh air. Avoid further overexposure. EYES: Flush with running water for 15 minutes and get medical attention. SKIN: Wash thoroughly with hand cleaner followed by soap and water. Get medical attention immediately if rash or other disorders develop. INGESTION: Call nearest Poison Control Center or physician. Do not induce vomiting.

MADE IN CANADA

NAME	CAS or TRADE Secret NO
Water	7732-18-5
Acrylic polymer	TSRN# 51721300-5277P
White mineral oil	8042-47-5
Amorphous silica	7631-86-9
Titanium dioxide	13463-67-7

WARNING! Contains chemicals known to the State of California to cause cancer, birth defects and/or other reproductive harm

Waste not regulated under RCRA. Dispose of in compliance with state and local regulations.

Contains less than 18 grams of VOC per liter less water and less exempt solvent

DO NOT THIN.

FOR INDUSTRIAL USE ONLY. KEEP OUT OF THE REACH OF CHILDREN.

Information: 216-292-5000 (U.S.)
Emergencies: 216-765-6727 (U.S.)

TDG / DOT Shipping Description:

Go to the Material Master (transaction: MM03) to determine the proper shipping description.

If the DG Profile is set to ZNR (in the Basic Data 2 tab) then the Shipping Description is "NOT REGULATED".

If the DG Profile is set to GPP then refer to the DG Master (transaction: DGP3), regulation CFR, for details.

If the DG Profile is blank, contact the EHS Group for assistance.

COMPANY IDENTIFIER / LOGO