Using an Aerosol Sealant to Reduce Multifamily Envelope Leakage

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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.

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 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 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 electric use. The annual energy cost savings were \$63/unit[1] or \$0.06/ft^2.

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. Our 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 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.

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". A similar technology has been developed for sealing leaks in the walls, ceiling, etc. of buildings. Initial proof-of-concept testing of the aerosol envelope 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

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

of demonstrations in single-family new construction homes showed the ability to seal 60% to 85% of available building leakage in less than two hours of sealant injection (Harrington and Springer 2015). The homes ranged in size from 600 ft^2 to 3,000 ft^2 with the estimated cost for installation well under $0.50 per square foot. The time required for setup, sealing, and cleanup was closely tracked for installations in large new single-family homes, and it was determined that 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.

A demonstration sealing project of four multifamily new construction units showed that the process was capable of sealing at least 80% of the air leaks in less than two hours (Maxwell, Burger, and Harrington 2015). Sound transmission tests on three units showed little change in attenuation after sealing for low frequencies, but the attenuation was typically 4 to 12 dB for frequencies above 500 Hz. This shows another benefit of reduced inter-unit air leakage – reduced noise transmission which produces improved occupant comfort.

Minnesota 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 required that one to three story multifamily buildings meet the residential energy code envelope tightness requirement of 3.0 ACH50. For multifamily building four stories and above the envelope tightness requirement can be met using sufficiently tight materials, tight assemblies, or an envelope air leakage test. It is expected that most buildings will comply by using tight materials or assemblies and will not conduct tightness tests. However, some funding agencies require lenders to comply with the Minnesota Overlay and Guide to the Enterprise Green Communities Criteria. This refers to portions of the EPA ENERGY STAR Multifamily High Rise requirements including a requirement for a maximum air leakage rate of 0.30 cfm50 per square feet of enclosure (EPA 2013).

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 from 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. Those results are included in this paper. For a subset of the units the leakage test was also conducted after the unit was finished and 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 also conducted for some of the units. Those results are not included here, but will be presented in the project final report. 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.

Air Sealing Protocol

Aerosol envelope sealing had been performed 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:

- **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" 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 commercialization of the system is expected to include separate compressors and liquid pumps for the spray nozzles to make them easier to deploy and modifications to existing duct sealing software, which will more thoroughly automate the envelope sealing process.

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.

The heating and cooling equipment was chosen based on a 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).

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. The modeling for this project was based on a similar approach used to evaluate multifamily ventilation options (Markley and Harrington 2014).

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. 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 in for ventilation.
- **Exhaust and Half Supply**: Full capacity exhaust fan in each unit with supply ventilation to the unit that is half the exhaust capacity. This results in slightly lower negative pressures in the apartment. 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.

Building Geometry

The floor plan was the same for each of the six floors (Figure 1) 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.

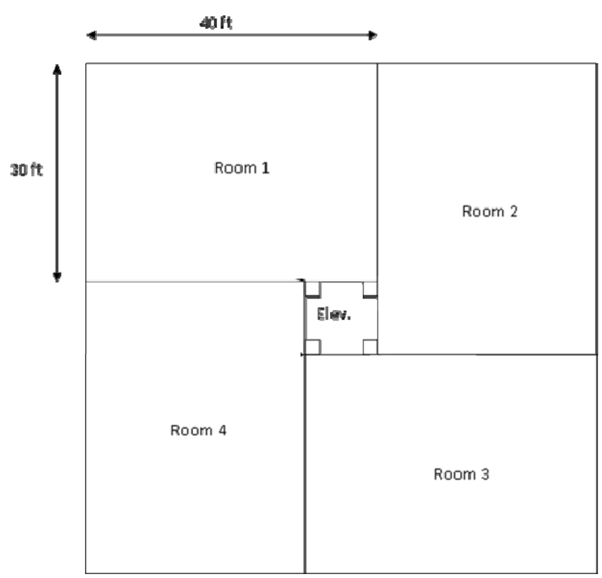

Figure 1: Floor plan of building model, all four floors are identical

Building Leakage

Leaks in the building surfaces and exhaust registers were modeled as crack leaks. 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. 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.

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 effect of aerosol envelope sealing was modeled by tightening the exterior and unit-to-unit leaks by 80% from a baseline leakage of 3 ACH50 and 0.6 ACH50 sealed for new construction, and by about 70% from 9.5 to 3 ACH50 for existing construction. The level of sealing chosen was based on an estimate of the tightness observed during demonstrations of the aerosol sealing technology. The distribution of leaks was determined using various sources. 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 remaining leakage needed for the unit to meet the total specified envelope leakage area was distributed between interior and exterior walls. The door leak was subtracted from the previously determined total interior leakage, and the remaining interior leakage was distributed among interior wall surfaces. The unit leakage distribution for each model was: hall=51%, exterior=18%, adjoining unit=16%, and ceiling/floor =5%.

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. All of the buildings are affordable housing except for new construction building C which is an extended stay hotel[2]. Key characteristics and pre-sealing leakage results are listed in Table 1. 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

[2] 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

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 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 1: Building characteristics

			# Units		Avg. Floor	Pre-Seal Leakage (ACH50)		
Type	ID	Stories	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		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

Air Sealing

The research team conducted the sealing using an equipment design modified from previous field tests and the protocol described in the methodology section. Figure 2 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 then steadily decreased. The sealing patterns for the four new construction units were very consistent and each unit reached a tightness of less than 1.4 ACH50 (less than 0.06 cfm50/ft^2) for about 100 minutes of sealing. All of the units would have met a 3 ACH50 criterion in about 60 minutes, but the sealing time was extended in order to study the sealing rate over longer sealing periods. The sealing pattern was consistent for four of the six existing building D units with leakage reductions for those four units ranging from 72% to 78% (see chart on right side of Figure 2). The low final leakage of 1.4 ACH50 (52 cfm50) for unit 202 (lowest curve) is an example of the tightness that can be achieved when almost all large leaks are sealed before the aerosol process. Alternatively, unit 206 only had a 39% leakage reduction. All of the building D units were nearly finished and ready for occupancy when the aerosol sealing was performed. After the unit 206 aerosol sealing was complete, a hidden leak that was too large to be sealed by the aerosol was detected behind a kitchen cabinet. This illustrates the challenge of identifying all large gaps leaks in finished residences.

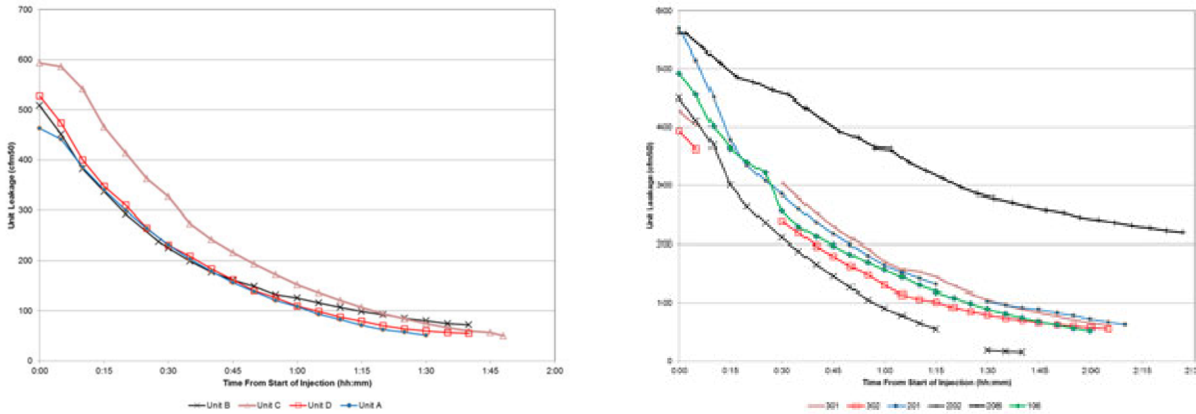

Figure 2: Variation in unit leakage (cfm50) through aerosol sealing process for units in new construction building C (left) and existing building D (right)

The aerosol envelope sealing produced consistently high leakage reductions for the 18 new construction units (Table 2). 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 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/ft^2. 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.

Table 2: New construction building pre/post aerosol sealing leakage test results

	Floor Area	Envel Area	Leakage (CFM50)		Leakage (ACH50)		Leakage (CFM50/ft^2)		Reduction	
ID	(ft^2)	(ft^2)	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%

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 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.

Table 3: Existing building pre/post aerosol sealing leakage test results

	Floor Area	Envel Area	Leakage (CFM50)		Leakage (ACH50)		Leakage (CFM50/ft^2)		Reduction	
ID	(ft^2)	(ft^2)	Pre	Post	Pre	Post	Pre	Post	(CFM50)	(%)
D 106	228	1,079	433	123	12.05	3.43	0.40	0.11	310	72%
D 201	253	1,074	568	123	14.35	3.10	0.53	0.11	445	78%
D 202	235	1,178	454	52	12.40	1.43	0.38	0.04	401	88%
D 206	230	1,062	615	377	17.19	10.53	0.58	0.36	238	39%
D 301	245	1,070	428	109	12.40	3.15	0.40	0.10	319	75%
D 302	233	1,055	393	91	12.01	2.77	0.37	0.09	302	77%
E 2	1,579		2,884	308	13.70	1.46			2,576	89%
F 1	760		1,603	982	15.83	9.69			622	39%
F 4	760		1,740	738	17.18	7.29			1,002	58%
Min	228	1,055	393	52	12.01	1.43	0.37	0.044	238	39%
Max	1,579	1,178	2,884	982	17.19	10.53	0.58	0.355	2,576	89%
Avg	502	1,086	1,013	322	14.12	4.76	0.44	0.136	691	68%
Median	245	1,072	568	123	13.70	3.15	0.40	0.108	401	75%

Labor Requirements

The labor time required to complete the six different tasks for the air sealing process were tracked for three of the six buildings. The average task labor times for all sealed units for the three buildings are displayed in Figure 3. The values include the number of staff multiplied by the time required for each person. The total time varied from about 14 person-hours for the new construction units to slightly over 22 person-hours for existing building F. The sealing time was consistently 6 to 7 person-hours for the three buildings, but generally should only require less than 2 person-hours since the process can be managed by one contractor. However, there was larger variation in the unit preparation (3.6 to 6.8 person-hours) and additional clean-up (0 to 5 person-hours). 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. Also, the 14 person-hours for building B is likely a high value 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
- **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

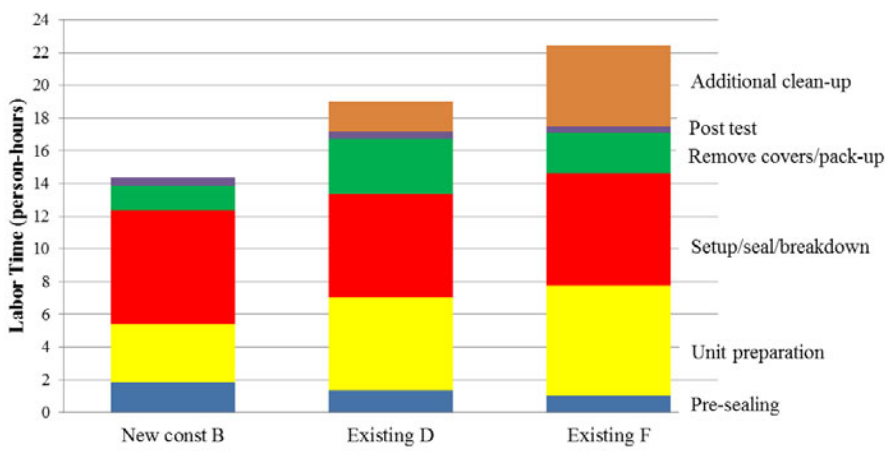

Figure 3: Breakdown of labor in person-hours for six sealing tasks

Energy Savings

New Construction

The modeling for new construction compared the energy performance for a building that complies with the Minnesota residential code requirement of 3 ACH50 to a building that was sealed 80% tighter (e.g. 0.6 ACH50) with the aerosol process. The change in heating energy consumption after sealing is the most significant change, and is a result of the reduced infiltration of outdoor air. Figure 4 shows that the heating energy is reduced for all ventilation types. 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. The results show a 4% to 18% reduction in heating energy use due to envelope sealing with annual cost savings of $7 to $15[3].

Another trend that can be seen in Figure 4 is the overall magnitude of the heating energy use linked to the ventilation system type. The model with no mechanical ventilation has significantly lower ventilation related loads, and therefore the lowest heat requirement. In addition, ventilation systems that use more fan energy require less heating due to the added fan heat. For example, the model with exhaust and supply ventilation has the most fan energy use and the lowest heating requirement of the models with mechanical ventilation.

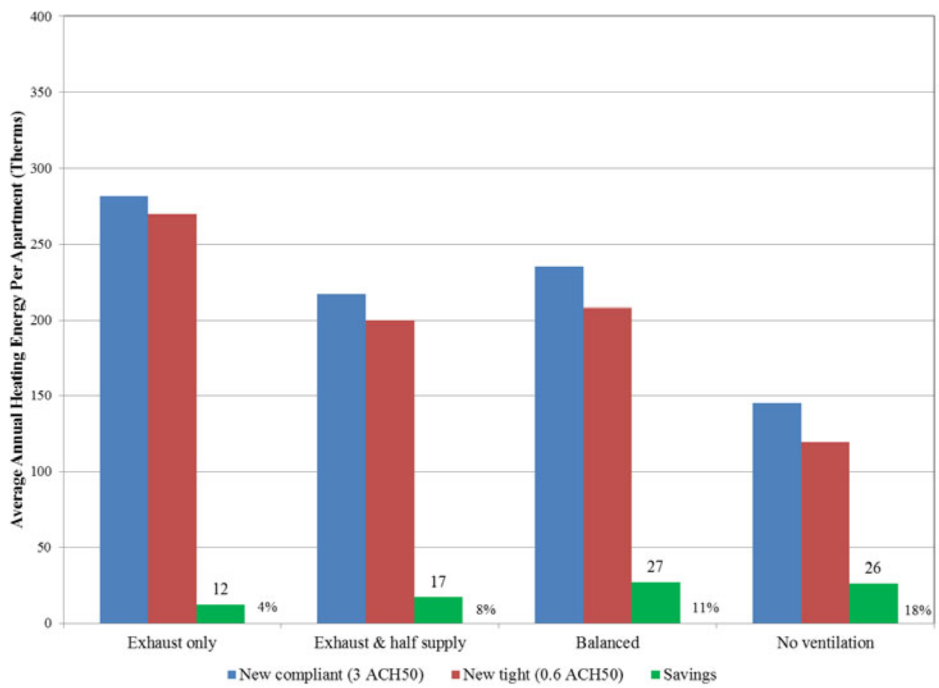

Figure 4: Modelled annual space heating energy use and savings for new construction units

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 is not considered to be significant. The results showed between a 1% reduction and a 4% increase in cooling energy use. Again, the magnitude of cooling energy is linked to the ventilation type, with higher cooling needs for models with ventilation systems that use more fan energy.

An annual cost savings of $15 for a tightness reduction from 3 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. However, this assumes 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. The method might also be used to reduce the leakage of somewhat leaky units, like those in building C, from 7.75 to 1.55 ACH50 which would produce higher absolute energy

[3] Assumes gas cost of $0.58/therm

savings (as will be shown in the following section). In addition, the aerosol sealing might eliminate the need for conventional 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.

Another advantage of the aerosol sealing method is that it not only reduces exterior leakage, but also helps compartmentalize the units by sealing leaks between units. This greatly reduces air flow between units and common spaces which reduces the transfer of contaminants between units. The modelling showed that the 80% reduction in total unit leakage reduced air flows between units by 68 to 80%. However, for very tight envelopes exhaust and/or supply only ventilation is not a feasible option and balanced ventilation is required.

Existing Buildings

The modeling for existing construction focused on comparing the energy performance of an existing building that had been sealed to meet compliance for new construction. Previous research suggests that existing apartments in Minnesota have an average leakage around 9.5 ACH50. The two 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.

The change in heating energy consumption after the envelope sealing is more pronounced in an existing apartment than in new construction. Figure 5 shows 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 reduction of 75% would increase annual savings by about a factor of 2. Also, the simulations assumed that 18% 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 for every unit with an average exterior leakage fraction of 68%. If the models assigned twice or three times as much of the total leakage to the exterior (e.g. 36% or 54%), the savings would have been almost two or three times greater. 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).

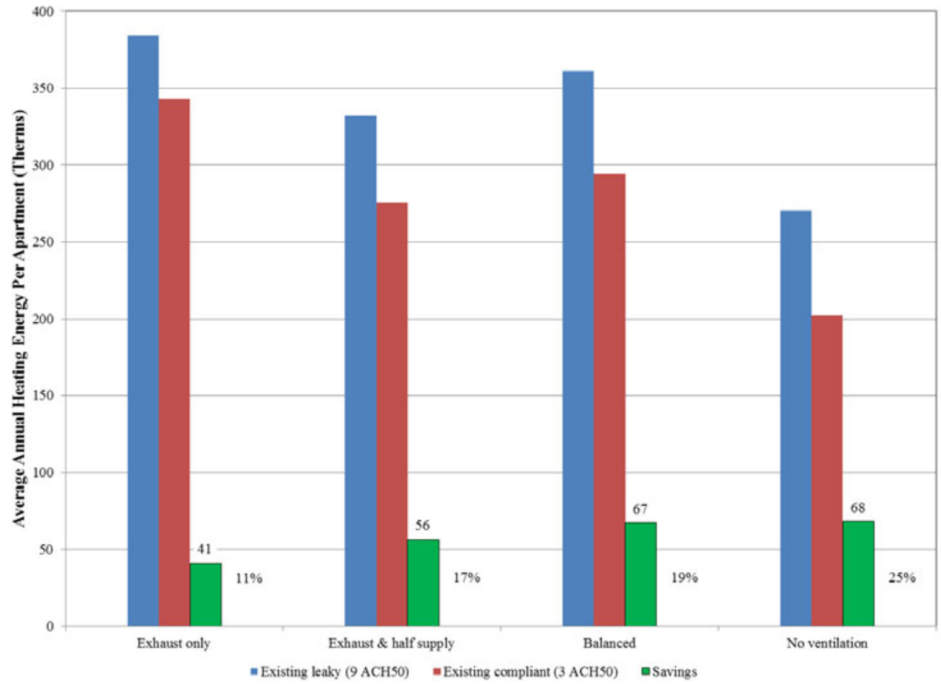

Figure 5: Modelled annual space heating energy use and savings for existing building units

In all cases, existing building 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.

Conclusions

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/ft^2. 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. In addition to energy savings, aerosol sealing also helps compartmentalize units which reduces contaminant transfer between units. The modelling showed that the 80% reduction in total unit leakage reduced air flows between units by 68 to 80%. 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).

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