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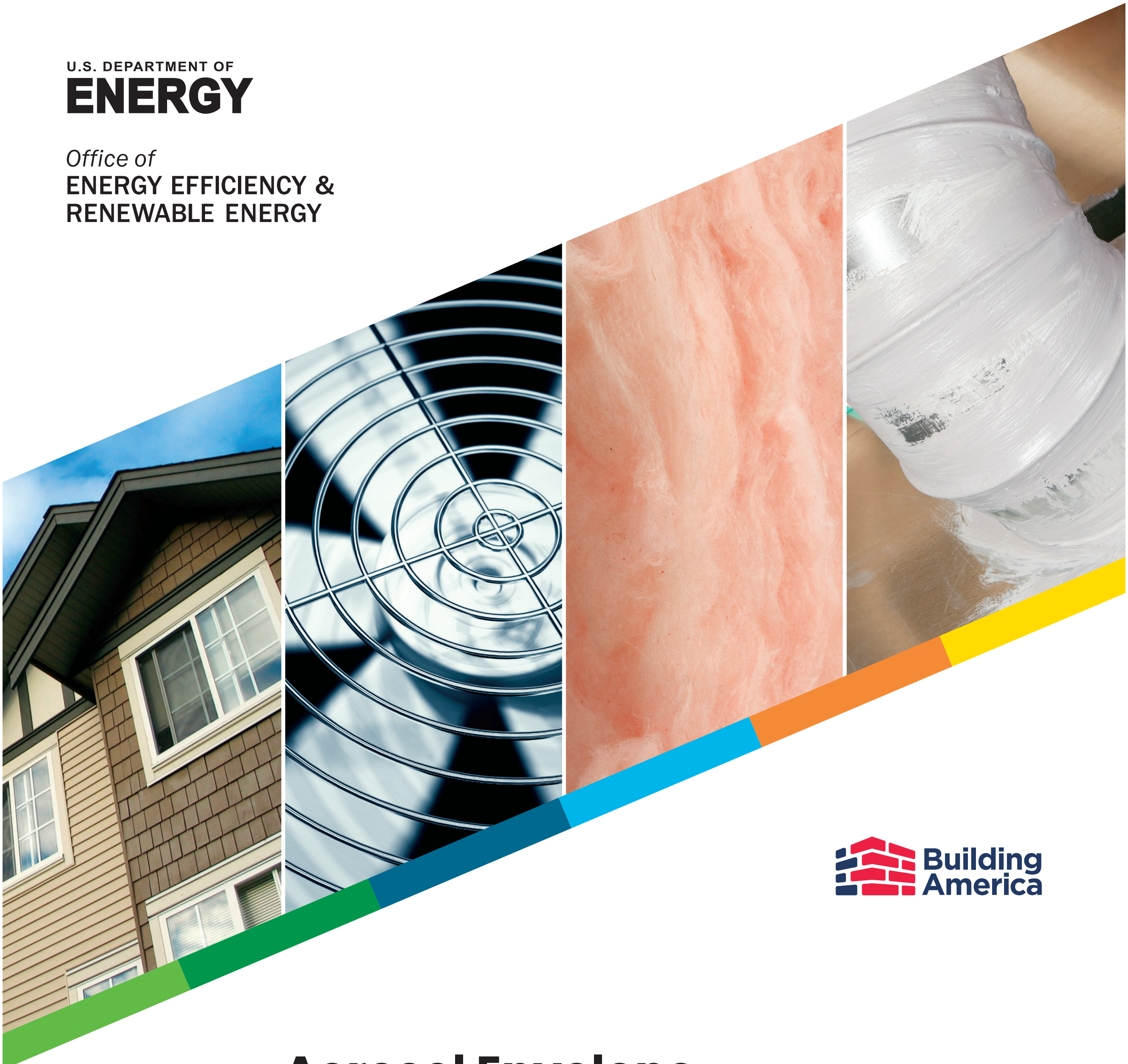

Building America

Aerosol Envelope Sealing of Existing Residences

May 2024

Notice

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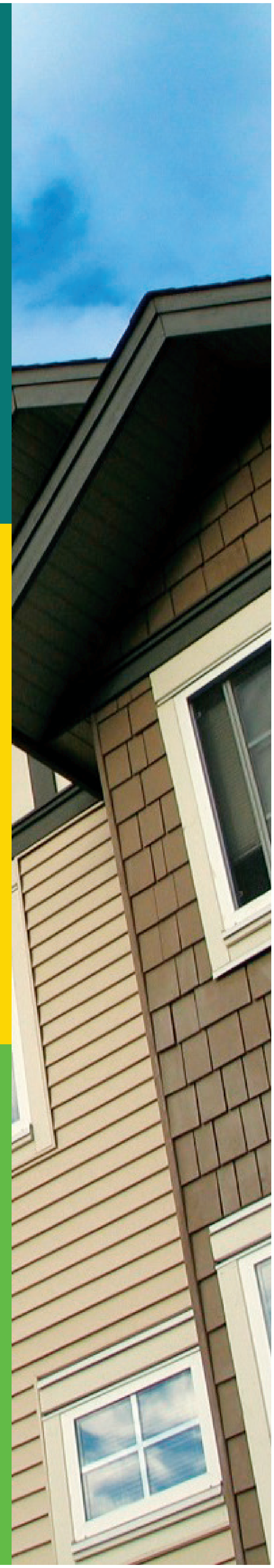

Aerosol Envelope Sealing of Existing Residences

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Office of Energy Efficiency and Renewable Energy

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May 2024

Suggested Citation
Bohac, Dave, Curtis Harrington, and Frederick Meyers. 2024. "Aerosol Envelope Sealing of Existing Residences." Minneapolis, MN. DOE/GO-102024-6121. www.nrel.gov/docs/fy24osti/85625.pdf.

This material is based upon work supported by the Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Building Technologies Office under Award Number EE0008690.

Foreword

The U.S. Department of Energy (DOE) Building America Program has spurred innovations in building efficiency, durability, and affordability for more than 25 years. Elevating a clean energy economy and skilled workforce, this world-class research program partners with industry to leverage cutting-edge science and deployment opportunities to reduce home energy use and help mitigate climate change.

In cooperation with the Building America Program, the Center for Energy and Environment is one of many **Building America teams** working to drive innovations that address the challenges identified in the Program's **Research-to-Market Plan**.

This report, *Aerosol Envelope Sealing of Existing Residences*, explores the best methods for aerosol envelope sealing of unoccupied, existing residences and documents typical leakage reductions.

As the technical monitor of the Building America research, the National Renewable Energy Laboratory encourages feedback and dialogue on the research findings in this report as well as others. Send any comments and questions to building.america@ee.doe.gov.

Acknowledgments

The work presented in this report was funded by the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy Building Technologies Office.

The research was conducted by Center for Energy and Environment's (CEE) Building America Team with guidance and support from DOE Building America staff Eric Werling, Lucas Phillips, Lena Burkett, Chris Early, and Nick Cindrich.

The authors thank the following people for their contributions to this effort:

- Tony Beres, Jake Selstad, and Andy Nail of CEE conducted infrared surveys, air leakage tests, and combustion safety tests of Minnesota residences. Phil Anderson of CEE recruited sites and reviewed results for the Minnesota residences. Melissa Anders assisted with testing, compiled field data, and analyzed results of Minnesota residences.
- Mike Lyon (AeroBarrier lead application engineer) recruited sites, managed the sealing process, participated in sealing work, and reviewed results for the Minnesota residences. Alex Hefflefinger and Collin Mack (Midwest AeroBarrier) conducted the aerosol sealing of the Minnesota residences.
- Micah Seierstad (CalBarrier) led the aerosol sealing work for residences in California. Micah also assisted with site recruitment and initial site assessments.
- Stephen Chally (Frontier Energy) and the Sonoma Clean Power Lead Locally program performed outreach and participant recruitment.
- The house and multifamily building owners and occupants allowed us to perform aerosol sealing work and testing of their residences.

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List of Acronyms

ACEEE	American Council for an Energy Efficient Economy
ACH50	leakage flow rate in air changes per hour at an induced pressure of 50 pascals
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
BEOpt™	Building Energy Optimization Tool
CEE	Center for Energy and Environment
CFM50	leakage flow rate in cubic feet per minute at an induced pressure of 50 pascals
DOE	U.S. Department of Energy
EIA	Energy Information Agency
EPA	U.S. Environmental Protection Agency
HVAC	heating, ventilating, and air conditioning
HRV	heat recovery ventilator
ICC	International Code Council
IECC	International Energy Conservation Code
NREL	National Renewable Energy Laboratory
$PM_{2.5}$	fine particles or droplets that are two and one half microns or less in width
RESNET	Residential Energy Services Network
WCEC	Western Cooling Efficiency Center at University of California, Davis
ZPD	zone pressure diagnostics

EXECUTIVE SUMMARY

Introduction

Residential building envelopes are notoriously leaky, with unintended flows between conditioned and unconditioned spaces that result in additional space heating and cooling equipment energy use. Retrofit air sealing methods are manual and rely on contractor personnel to visually identify and seal leaks on an individual basis. The achieved air tightness levels are highly variable based on the time allotted and the vigilance and experience of the contractor who performs the work. Aerosol envelope sealing may provide a process for existing homes and multifamily units to gain the benefits of a well-sealed residence at a reasonable cost with minimal disruption.

The general process involves pressurizing a residence while distributing an aerosol fog of sealing material inside the enclosure (see Figure ES-1). As air escapes the building through leaks in the envelope, the sealant particles are carried to the leaks, where they make contact and stick. The sealant particles adhere to surfaces that they impact, so sealant material does not deposit on walls or ceilings except for at leak sites. Sealant will settle onto horizontal surfaces due to gravity, so these surfaces should be covered to avoid unwanted deposition.

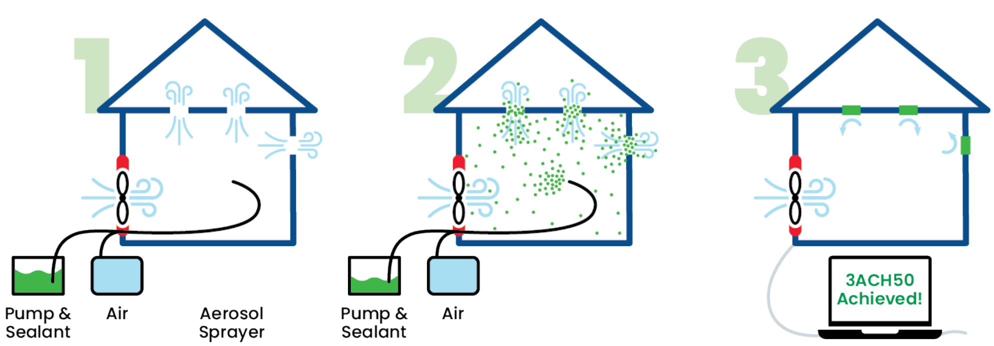

Figure ES-1. The progression of the sealing process from the start (left) to the end (right)

Front view of Minnesota residence 9. *Photo by the authors*

At the start of this project in 2019, aerosol envelope sealing was being applied to new construction, but there were only limited demonstrations and no commercialization of its application in existing residences. The initial project objective was to determine how the aerosol sealing protocol for new construction could be modified to effectively seal existing residences. One focus was to evaluate what pre-aerosol sealing assessment procedures, surface protection measures, manual sealing procedures for larger leaks, aerosol sealant modifications, and aerosol sealing procedures are necessary to establish a streamlined and cost-effective process to seal existing single-family homes and multifamily units. A variety of unoccupied single-family homes and multifamily units with various levels of remodeling were sealed to demonstrate aerosol sealing leakage reductions. Air leakage inspections and diagnostics were conducted to help identify the effectiveness of sealing common leakage paths and the types of residences that are likely to yield the greatest leakage reductions. Alternative aerosol sealing methods were considered, and a process to seal from the attic space was demonstrated. Modified sealant formulations that reduce the potential for microbial growth and improve the appearance of the seals were laboratory tested for sealing rate, leakage reduction, and seal durability. Finally, energy modeling was conducted to estimate the energy implications of the measured reductions in leakage.

Methodology

The project consisted of three distinct efforts.

1. Scaled field demonstrations of the sealing process, tracking from setup to sealing and cleanup

2. Laboratory testing of new sealants that dry clear, making them more appropriate for retrofit applications

3. BEopt™ (Building Energy Optimization Tool) (2023) modeling of the energy implications of the measured reductions in leakage.

The field demonstrations included a minimum of four measurements of the residence envelope leakage. The first occurred before any prep work or sealing, the second after all surface protection or preparations were complete and immediately prior to aerosol sealing, the third immediately after aerosol sealing was completed, and the fourth after aerosol sealing with surface preparation removed. Because temporary protection of finished surfaces and sealing of intentional openings can significantly impact the amount of leakage that is eliminated with aerosol sealing, particular attention was paid to documenting the differences between the protected and unprotected leakage. Additional diagnostics were performed as appropriate to document the impact on specific leakage paths (e.g., house/attic, house/garage, and floor/wall junction).

Leakage measurement tool used to measure leakage around a light switch. *Photo by the authors*

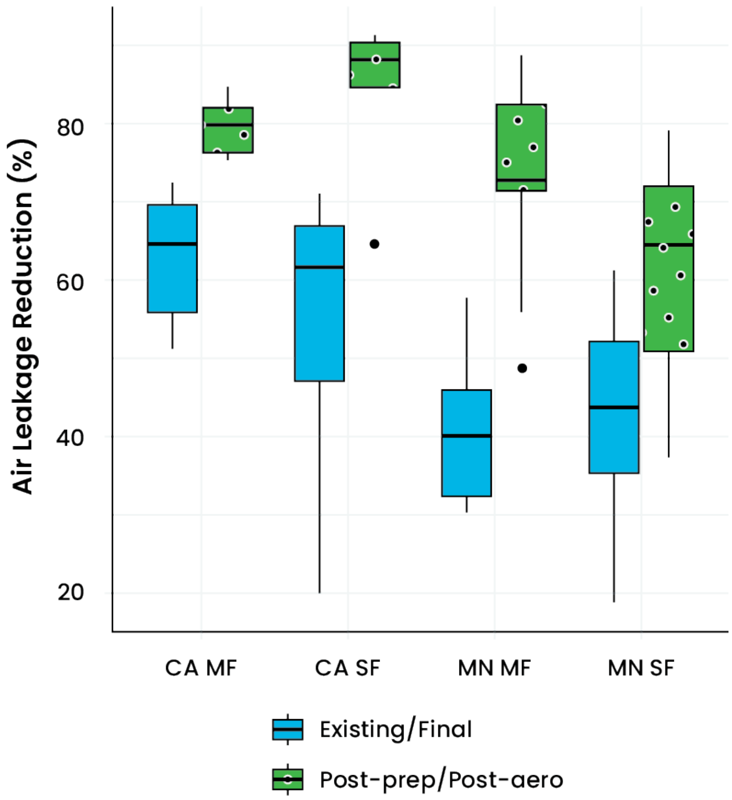

Figure ES-2. Air leakage results summary for all residences

The appearance, durability, and strength of the new sealant were each measured and then compared to the current market sealant. The process used to form seals was meant to simulate the sealing process used in a residential building. This includes controlling differential pressure across the leak, application humidity, and nozzle conditions. Seals were formed at different application humidities to determine sensitivity, which can fluctuate in field applications. The testing focused on failure pressure of seals formed using the aerosol sealing process.

BEopt (2023) was used to model energy savings when sealing homes to different leakage levels in several climate zones. BEopt is a parametric analysis tool that allows multiple building configurations to be compared using EnergyPlus (Crawley et al. 2001) as the simulation engine. The reference model used for the baseline was a modified version of the existing single-family home model in BEopt. The envelope leakage varied between 3 and 15 ACH_{50} to determine the impact of air sealing on building energy use. The simulations were conducted in each of the International Energy Conservation Code (IECC) climate zones to determine how climate conditions impact the results.

Results

Interior Sealed Residences

A total of 5 California and 12 Minnesota single-family houses and 6 California and 9 Minnesota multifamily units were sealed for this project. The average leakage reduction was 47%, with somewhat higher reductions for the California residences (Figure ES-2 – blue boxes). The California homes were 19% leakier than Minnesota residences, which could be due to differences in construction between the regions or differences in how the contractors prepared the homes. It was thought that higher leakage reductions could be the result of higher initial leakage; however, there is almost no correlation between the existing air leakage and the percent leakage reduction with an R^2 of 0.05 for both the multifamily and single-family residences.

Figure ES-2 also shows the percent reduction immediately before and after the aerosol sealing when the preparations were in place (green boxes). With preparations in place, the aerosol process reduced leakage by an average of 72%. This indicates that the aerosol process sealed almost three quarters of the leaks that were not covered by preparations.

The lower reduction when the preparations were not in place was due to the percentage of leaks that were covered by the preparation process and the aerosol seals that were disturbed when the preparations were removed. For the California single-family residences, an average of 25% of the existing leakage was covered by the preparations and the average was 19% for the multifamily units. For the Minnesota residences, the averages were 5% and 8% for the single-family and multifamily residences respectively. Across all the residences, the average amount of existing leakage covered by the preparations was 11%. The amount of aerosol seals that were disturbed for each residence was estimated by subtracting the amount of leakage covered by preparations from the increase in leakage when the preparations were removed. For all residences, the average amount of aerosol seals disturbed was 27%. It appears that improved methods for applying surface protection could increase leakage reduction by 10 or more percentage points.

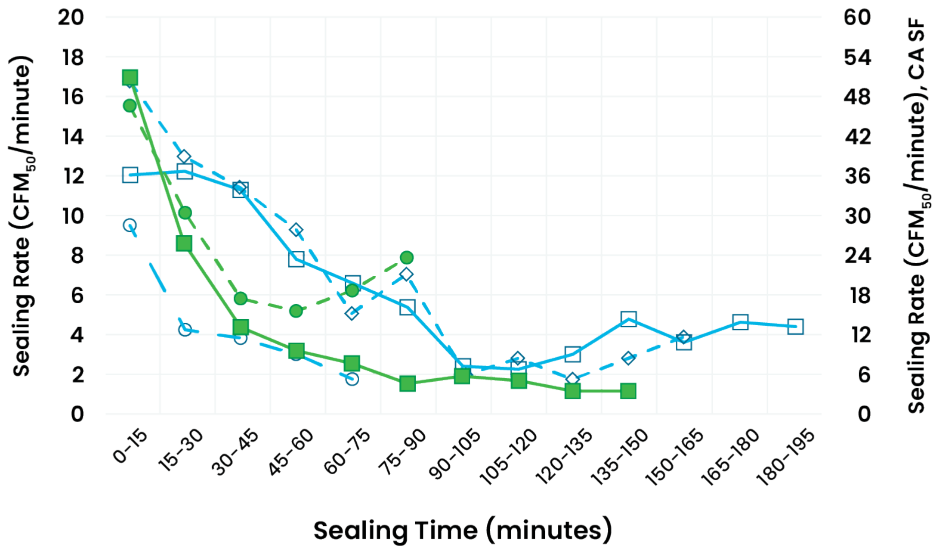

Figure ES-3. Median air sealing rate for five groups of residences (CFM_{50}/min)
Results for California single-family (CA SF) houses are plotted on right vertical axis; all others are plotted on left axis.

One-minute average data from the AeroBarrier equipment were used to evaluate the aerosol sealing rates. The median sealing rate for the first 15 minutes of aerosol sealing ranged from 9.6 CFM_{50}/min for Minnesota multifamily units to 51 CFM_{50}/min for California houses (see Figure ES-3). For most residences, the rate of sealing was greatest at the start of the sealing and gradually decreased over time. The greater rate of sealing at the start of the process suggests that the houses had a large length of narrow gap leaks that seal faster than wider leaks. The California and Minnesota apartment units had the lowest initial sealing rates of 15.6 and 9.6 CFM_{50}/min, respectively.

Volume-normalized sealing rates of 9.8 and 13.9 ACH_{50}/h for the California and Minnesota apartment units, respectively, were higher than the other groups of residences except California houses. Also, the sealing times were shorter for the apartment units than for the houses and townhouses. The median sealing time for the apartment units was 56 minutes, while it was 95 and 171 for the California and Minnesota single-family houses, respectively. The sealing times for these residences are likely longer than would be typical for market-based sealing, as it was often extended by 15 to 30 minutes to evaluate the impact of extended sealing. Sealing periods of 45 to 60 minutes for apartments, and 90 to 120 minutes for houses, are more typical for AeroBarrier contractors (Lyon 2023).

Attic Air Sealing

A new attic air sealing strategy for occupied residences was investigated. The residence is depressurized to 100 Pa while applying the aerosol fog of sealant material in the ventilated attic space. The sealant particles deposit on leaks as the particles are drawn into the home. The attic insulation is removed beforehand to give the sealant a path to the leaks on the attic floor. This approach was applied to three California townhouses and one house in Minnesota. The California townhouses included 938- and 764-square-foot single-story units built on slabs with ventilated attics. The aerosol sealing reduced the townhomes' total envelope leakage by an average of 4.4 ACH_{50} or 55%, from an average initial leakage of 8.0 ACH_{50} to a final leakage of 3.6 ACH_{50}. The average reduction was 0.59 CFM_{50} per square foot of ceiling area. By contrast, the conventionally sealed attics reduced the homes' leakage by an average of only 14%, from an initial leakage of 7.2 ACH_{50} to a final leakage of 6.2 ACH_{50}.

The planned work at the Minnesota three-story house included removing the attic insulation, using can foam to manually seal large house-to-attic air leakage, aerosol envelope sealing from the attic, spraying two-inch-thick two-part foam over the attic floor, and blowing insulation over the foam. The goal of this demonstration was to see if the aerosol sealant could be used instead of the foam. The house started with an air leakage of 1,756 CFM_{50}. Removing the attic insulation increased the leakage by 293 CFM_{50} (17%), and the manual sealing reduced it by 231 CFM_{50} (11%). The aerosol attic sealing reduced the house leakage by 387 CFM_{50} (21%) to achieve an overall reduction of 325 CFM_{50} (19%) from the existing condition. The smaller percent reduction is partially due to the greater exterior wall surface area of the house—the top-level ceiling area was a lower fraction of the total surface area. The reduction of 387 CFM_{50} from aerosol sealing is equal to a ceiling-surface-area-normalized leakage of 0.27 CFM_{50}/ft^2. This is 55% less than the average normalized leakage obtained for the three California apartments. Because most gaps sealed by the can foam were narrow, it is expected that a high fraction of the manual can foam sealing could have been achieved with aerosol sealing. A combination of the manual and aerosol sealing is equal to a normalized leakage reduction of 0.42 CFM_{50}/ft^2, which is only 28% less than the average for the California apartments.

Alternative Sealant Testing

Our team sought a new sealant with little or no tack after drying and good sealing performance. Evaluations were conducted on three sealant formulations: (1) the current sealant used in AeroBarrier applications (ABX1), (2) a modified version of the AeroBarrier sealant with the addition of an antimicrobial additive (ABX2), and (3) a new formulation using a different polymer that is more translucent when dry (ABF23). ABX1 is a commercially available product that dries white and is non-tacky. In liquid form, it is like a very thin paint, and after sealing it resembles flexible calking. The ABX2 formulation is a modification of ABX1 with 0.1% wt/wt formulation ratio of fungicide and was observed to be visually identical to ABX1, both before and after application. In addition, ABX2 sealant performance was similar to that of ABX1. Given the similarity in performance demonstrated in these tests by ABX1 and ABX2 and the added benefit of a mold growth inhibiter, it would be appropriate to move forward with testing the ABX2 in whole-building applications. The ABF23 sealant is not recommended for further testing in its current formulation. This sealant did display some good qualities such as low leakage through the seal and improved transparency. However, the low sealing rates, difficulty forming complete seals on test leaks, and residual tack would limit the success of this sealant in building applications.

Energy Modeling

BEopt modeling of source energy savings was conducted for various levels of sealing in 16 U.S. locations across 16 climate zones. The results showed that reducing the leakage of a 2,400-ft^2 single-family home from 15 ACH_{50} to 10 ACH_{50} would save between 3% and 15% of the source energy use for a home depending on the climate zone. Sealing a home to reduce leakage from 15 ACH_{50} to 7 ACH_{50} would achieve 5% to 23% savings, and sealing a home from 15 ACH_{50} to 3 ACH_{50} would achieve 8% to 35% source energy savings. Colder climates benefited the most from air sealing, with climate zones 5A, 6A, 7, and 8 showing the largest savings.

Conclusions

Aerosol sealing performance in existing homes was effective with an average leakage reduction of 47% across all 34 sites. This is in comparison to leakage reductions of 25% to 30% shown in a review of the national weatherization programs (Blasnik et al. 2015). The surface preparation for homes undergoing occupancy change is extensive, requiring an average of 23 person-hours for a single-family home. This work can be significantly reduced when aerosol sealing is incorporated into a renovation project. The materials used for protecting surfaces in the home during the sealing process prevented the sealant from reaching some leaks. For homes on raised foundations, the amount of leakage made inaccessible in the process of protecting floors was significant and reduced the achievable air tightness. This leakage could be addressed using the attic sealing method, with the sealant applied to the crawl space.

The sealing of occupied slab-on-grade apartments from the ventilated attic space showed very encouraging results, with these homes achieving a 52% to 57% leakage reduction while requiring no protection of the interior of the residence. In these cases, the attic insulation would need to be removed and the sealing could be included as part of an overall attic insulation and air sealing upgrade package. A similar approach could be evaluated for use in crawl spaces in homes on raised foundations to address floor leakage that would otherwise be covered by surface preparation when applying the aerosol from inside the home.

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1 Introduction

Problem Statement

Residential building envelopes are notoriously leaky, with unintended flows between conditioned and unconditioned spaces that result in additional space heating and cooling equipment loads. Retrofit air sealing methods are manual, relying on contractor personnel to visually identify and manually seal leaks, one at a time. The achieved air-tightness levels are highly variable based on the time allotted and the vigilance and experience of the contractor who performs the work. Conventional approaches typically only produce leakage reductions of 25%–30% (Blasnik et al. 2015; Bohac and Cheple 2002). The aerosol sealing technology could provide a process for existing residences to gain the benefits of a well-sealed home at a reasonable cost with minimal disruption. At the start of this project, aerosol envelope sealing was being applied to new construction, but there had only been limited demonstrations and no commercialization of the technology for existing residences.

Objectives

The initial project objective was to determine how the aerosol sealing protocol for new construction could be modified for effective sealing of existing residences. A variety of unoccupied single-family homes and multifamily units with various levels of remodeling were sealed to demonstrate aerosol sealing leakage reductions. Air leakage inspections and diagnostics were conducted to help identify the effectiveness of sealing common leakage paths and the types of residences likely to yield the greatest leakage reductions. Alternative aerosol sealing methods were considered and demonstrated. Finally, improved sealant formulations were laboratory tested for leakage reduction and seal durability. The desired outcome was to demonstrate an aerosol sealing process for widespread application in unoccupied, existing residences that could dramatically improve the current housing stock's energy performance.

Research Questions

What pre-aerosol sealing assessment procedures, surface protection measures, manual sealing of larger leaks, aerosol sealant modifications, and aerosol sealing procedures are necessary to establish a streamlined and cost-effective process to seal existing single-family homes and multifamily units? What level of air leakage reduction can be achieved with aerosol envelope sealing and what house or unit characteristics can be used to help predict percentage reductions? Can aerosol sealant be applied to portions of the interior or at the exterior of the occupied space? Can a modified sealant formulation be developed that reduces the potential for microbial growth and improves the appearance of the seals, while still providing the same sealing rate and seal durability?

2 Background

The existing residential building stock was responsible for 21% of primary energy use in the United States in 2021 (EIA 2022), and it is estimated that about 51% of site energy use is for heating and cooling (EIA 2018). A significant fraction of heating and cooling loads is a result of infiltration; prior estimates show infiltration accounts for 29% of residential conditioning loads, or 2.24 quads annually (DOE 2014). Of this infiltration-related energy use, heating accounted for the majority at 79%; cooling accounted for the remaining 21% (DOE 2014). Assuming natural gas is used for space heating and electricity for cooling, the U.S. Environmental Protection Agency (EPA) estimates infiltration-related energy use contributes 153 million metric tons in greenhouse gas emissions annually (EPA 2022).

In many parts of the United States, this unintended air infiltration results in excess space heating and cooling equipment energy consumption. For example, the 135,000 U.S. single-family houses in Lawrence Berkeley National Laboratory's Residential Leakage Database had a geometric mean leakage of 11 air changes per hour at a pressure difference of 50 pascals (ACH_{50}) (Chan, Joh, and Sherman 2013). Although voluntary standards for measured envelope tightness have existed for decades, these have only recently become a code requirement in some states, and tightness requirements are typically moderate. The 2009 International Energy Conservation Code (ICC 2009) included an option for measured envelope air leakage testing to achieve leakage of less than 7.0 ACH_{50}. The 2012 version of the code changed to a mandatory testing requirement with leakage less than 3.0 or 5.0 ACH_{50} depending on climate zone (ICC 2012).

The high level of envelope leakage in most U.S. houses indicates that there is a significant need to seal these residences. Air sealing the existing U.S. housing stock has been a major priority for weatherization programs (Blasnik et al. 2015). The national Weatherization Assistance Program is funded by the Department of Energy (DOE) to provide grants to local agencies to administer efficiency upgrades to homes. A review of the impact of those programs conducted by Oak Ridge National Laboratory showed that envelope sealing measures could reduce leakage by 800–1,100 CFM at 50 Pa (CFM_{50}), or 25%–30% over pre-retrofit leakage (Blasnik et al. 2015). This is consistent with the average leakage reduction of 27% seen in a study of 1,427 houses that underwent weatherization improvements for a sound insulation program (Bohac and Cheple 2002). The improvements included attic air sealing, wall insulation, attic insulation, and storm or full window replacement. Leakier houses had a greater percentage reduction. Houses with a leakage greater than 7.5 ACH_{50} had an average reduction of 43%, and the average reduction was 20% for houses with leakage of less than 7.5 ACH_{50}.

Similar levels of air leakage reduction have been reported for existing multifamily units. Envelope leakage measurements on a sample of 21 units in seven buildings showed that sealing penetrations and crawlspaces reduced existing leakage from an average of 9.2 ACH_{50} to 6.7 ACH_{50} (Im et al. 2012). The reduction for individual units varied from 0.0% to 50.7% and averaged 24.1%. Guarded leakage tests of one building resulted in an average reduction in exterior leakage of 19.8%. A Center for Energy and

Environment (CEE) study of air sealing and ventilation improvements to reduce secondhand smoke transfer produced similar results (Bohac et al. 2008). Total unit air leakage tests on 32 units in six Minnesota multifamily buildings found an average of 7.2 ACH_{50}. The median envelope leakages for individual buildings ranged from 3.3 ACH_{50} for a 1982 11-story condominium to 15.6 ACH_{50} for a 1930s duplex. Four to ten hours of caulk and foam sealing that targeted inter-unit leaks resulted in leakage reductions from 0% to 41% with an average of 18% or 1.3 ACH_{50}. While some leakage paths in multi-unit dwellings are like those found in single-family houses, other paths are hidden in walls and other cavities.

One challenge for aerosol envelope sealing of existing residences is that the residences must be unoccupied. However, targeting existing residences at the time of occupancy change can increase the potential market for aerosol sealing by 10 times compared to new construction. In addition, because older buildings are leakier than new construction buildings, the energy savings potential is even larger. Targeting time of sale provides an opportunity to seal thousands of houses each year. The Mortgage Bankers Association reports a nationwide average turnover rate of 7% to 7.5%, or 13 to 14 years, as the average duration of occupancy by one family or owner. In the 13-county Twin Cities metro area, 56,930 homes were sold in 2015 (for comparison, 6,925 new home construction permits were issued in that same period). Sealing 5% of those houses would result in reduced air infiltration and energy waste for 2,500+ houses. There are also thousands of rental houses and apartment units that are unoccupied during tenant turnover. The project team focused on working with housing providers to seal their residences during times of tenant change over and when there are minor or major renovations. This provides much greater energy use reductions than can be achieved with current low-income weatherization programs.

2.1 Aerosol Envelope Sealing Research and Development

Aerosol sealing has been used as a strategy for sealing air leaks in a variety of ways and has seen significant development over the last 25 years since it was first applied in residential air ducts. The general process involves pressurizing an enclosure (e.g., duct system, building) while distributing an aerosol fog of sealing material inside the enclosure (see Figure 1). As air escapes the building through leaks in the envelope, the sealant particles are carried to the leaks where they make contact and stick, sealing the leaks. The sealant particles require an impact to adhere to a surface, so sealant material does not deposit on walls or ceilings except at leak sites. Sealant will settle onto horizontal surfaces due to gravity, so these surfaces should be covered to avoid unwanted deposition. This process was first used to seal ducts in the 1990s (Modera et al. 1996) and later adapted for whole building envelopes in the 2010s (Harrington and Modera 2012).

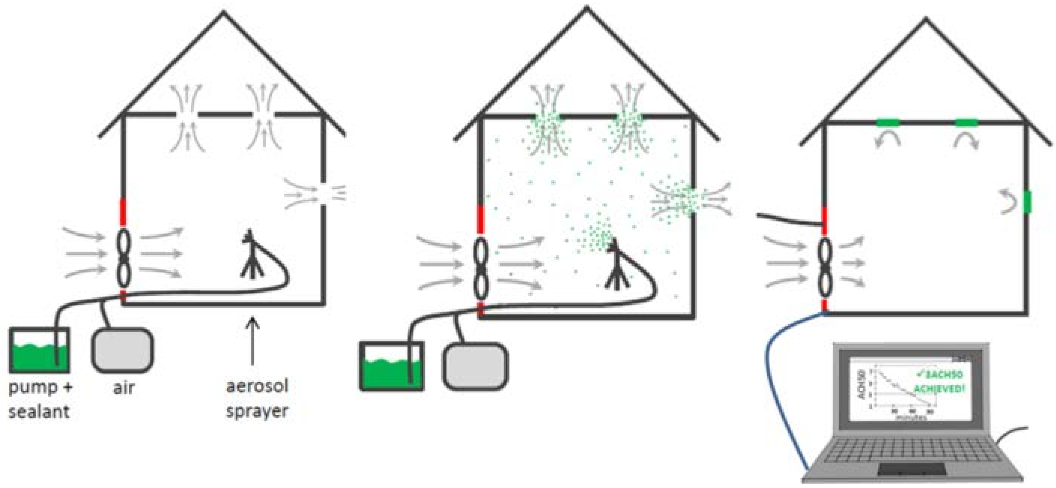


Figure 1. The progression of the sealing process from the start (left) to the end (right)

When the process is applied to envelopes, all openings not intended to be sealed (e.g., exhaust ducts, gaps around doors, open plumbing connections) are blocked with tape or plastic. Depending on the condition of the house during application, horizontal surfaces such as floors and countertops may need to be covered with plastic to protect them from sealant that settles during the process. There is usually no noticeable deposition on vertical surfaces or on the underside of horizontal surfaces. A standard blower door fan is used to pressurize the house and provides real-time feedback and a permanent record of the sealing that occurred.

The sealant used for this project is a diluted version of a synthetic acrylic elastomeric material used as a spray or roll-on exterior air barrier. The sealant is tested according to various standards of the American Society for Testing and Materials (ASTM); however, because the sealant is atomized, the contractor should wear appropriate personal protective equipment and avoid entering the building during installation if possible. If entering the building is necessary, the contractor should wear a fitted respirator to avoid breathing the aerosol. No one else should be in the building during the sealing. When the installation is complete, the remaining aerosol is flushed out of the home by continuing to pressurize the space for several minutes after stopping the sealant injection.

Field demonstration projects showed the viability of the technology in larger spaces and its practical application in real buildings (Harrington and Springer 2015). There have been demonstrations of the technology for multifamily applications (Bohac et al. 2016; Maxwell, Berger, and Harrington 2015), showing the potential to apply the technology more broadly to different building types, and modifying the process to isolate individual compartments within a building. More recently, a project was completed to identify ways to streamline the aerosol envelope sealing process in new homes and evaluate ways to improve air sealing outcomes at lower cost. The results of this project are described in more detail below.

2.1.1 Building America New Home Study

This DOE Building America project investigated the use of an aerosol-based sealing method to reduce air leakage of new homes in Minnesota and California (Bohac and Harrington 2020). The project team worked directly with builders to identify the best stages to incorporate aerosol sealing from the perspectives of cost, performance, and seamless integration with construction. Eight builders in Minnesota and California participated in the research, providing homes for testing and feedback on appropriate stages of construction during which to apply the sealing. The tightness of the aerosol-sealed houses was compared to that of a similar group of houses that used conventional sealing methods. Aerosol sealing produced tighter houses overall. Researchers also evaluated conventional sealing methods to determine whether they can be eliminated or reduced to improve cost-effectiveness.

The builders who participated in this study were interviewed after the project's completion to collect their feedback on aerosol sealing's advantages and disadvantages, as well as how it might best be incorporated into the construction process. The builders in Minnesota generally saw the value in using an aerosol sealing service to get their homes well below code. Additionally, they identified sealing processes and materials that could potentially be removed when applying aerosol sealing, but they were hesitant to change their construction methods for a small number of their production houses. The primary concern was around vapor intrusion, which has been mitigated in part by using polyethylene sheeting on the interior of the home. Removing poly wrap was suggested, but one builder mentioned that they already deal with many warranty issues that include moisture intrusion, and they would be concerned about removing that product.

The California builders had a different perspective, as the California Building Energy Efficiency Standards do not require a specific level of measured air leakage. Instead, there is a process through which the state inspects air sealing processes in the home. Based on that process, it is assumed that the builders achieve an air leakage rate of 5.0 ACH_{50} or lower for their homes. There are performance credits and utility incentives for verifying that their homes achieve leakage rates below 5.0 ACH_{50}; however, the builders perceived that these benefits did not justify the additional cost of air sealing. If the models used to evaluate the performance of a home design attributed more energy savings to building envelope sealing, then there could be cost-effective tradeoffs that builders could use to justify the additional cost (e.g., downsized heating, ventilating, and air-conditioning [HVAC] equipment).

Aerosol sealing was performed on 11 homes in California and 15 homes in Minnesota. The method was very effective at sealing air leaks in the homes. Many of the demonstrations resulted in a tightness below 1.0 ACH_{50}, which is well below the California Building Energy Efficiency Standards target of 5.0 ACH_{50} and Minnesota Energy Code requirement of 3.0 ACH_{50}. Further, low air leakage was often achieved at an early stage of construction before much of the manual sealing was performed. This project demonstrated the ability to seal homes at various stages of construction, including before and after drywall is installed. Even with changes to installation protocols, the process consistently reduced envelope leakage by 70% or more when evaluating leakage before and after sealing.

The aerosol envelope sealing process produced tighter homes and demonstrated a potential opportunity for cost savings in the construction process. A review of the standard air sealing efforts performed by U.S. builders shows several areas where efforts can be reduced or eliminated by applying aerosol sealing. By reducing other sealing work, builders can (1) minimize material used for sealing a building because aerosol sealing only applies material where leaks are present; (2) reduce the possibility of redundant sealing (e.g., sealing on both external and internal wall surfaces) while ensuring a continuous air barrier is applied; and (3) reduce the number of trades involved in the air sealing process and clearly define the responsibility for creating a successful air barrier, so that fewer trades need to be trained and supervised and less time is wasted sealing leaks that do not impact envelope leakage.

This research demonstrated that builders can use the aerosol sealing technology to meet their air leakage targets without requiring close attention to detailed air sealing work. The technology seals smaller, distributed leaks in a home very efficiently; these leaks are harder to address with conventional sealing techniques. Builders are still concerned about cost and hesitant to reduce current sealing efforts, but the aerosol sealing process’ ability to meet even the most stringent leakage targets gives builders confidence that their air leakage goals can be met without fundamental changes to their regular construction practices. As codes become more stringent, builders may be more likely to adopt the aerosol sealing technology as a cost-effective tool to meet future air leakage goals.

2.1.2 Aerosol Sealing Commercialization

The aerosol duct sealing technology was developed by Lawrence Berkeley National Laboratory researchers in the 1990s. There are now over 1,000 Aeroseal machines in 17 countries that have been used to seal ducts in over 100,000 homes. Following the success of initial demonstrations of the aerosol envelope sealing process, the Western Cooling Efficiency Center (WCEC) at University of California, Davis pursued a licensing agreement with the sealing company Aeroseal. In 2014, University of California, Davis’s intellectual property office marketed the process to identify companies interested in licensing the technology. Aeroseal beat out several other entities based on their proposed business model for the technology. The aerosol envelope sealing technology was officially licensed to Aeroseal in 2016. The technology is being commercialized under the name AeroBarrier.

The technology received the International Air-Conditioning, Heating, Refrigerating Exposition Product of the Year award. It is the only product to win four categories across three different International Builders Show events, including Best in Show and Most Innovative Building Product awards in 2018, Best Green Product in 2020, and Most Innovative Software in 2021. There are currently more than 138 dealers in the United States and Canada, with 22 dealers added in the first nine months of 2022. Work prices are set by each dealer, and they compete separately for work.

2.2 Surface Protection for Aerosol Sealing

The surface protection activities performed (also referred to as masking) attempt to balance the time required for preparation and clean up while avoiding covering potential leak sites. For example, attempts should be made to avoid blocking leaks under baseboards when applying floor protection; this level of detail adds to preparation time when placing covering. The bullet list below provides brief descriptions of standard surface preparation methods for common items. Appendix A provides more detailed descriptions and pictures of the preparation methods for each item.

- For finished flooring (carpeted and uncarpeted) that will not be replaced (Figure 2):
    - Place plastic sheet over the flooring.
    - For floors that are part of the exterior air barrier (e.g., over a crawlspace or unfinished basement), attach duct tape around the perimeter adjacent to the baseboard and use painters' tape to attach the plastic to the top of the duct tape. Ensure that the tape is applied continuously to prevent aerosol from finding gaps leading under the plastic.
    - For floors that are NOT part of the exterior air barrier, painter's tape is spaced every few feet to keep plastic from pulling back from baseboard. This does not provide a continuous seal between the plastic and the baseboard.

Figure 2. Duct tape is used at the perimeter of carpeted rooms as a base for attaching the plastic covering (left). Plastic covering on carpeted floor (right)

Photos by the authors

- For stairways:
    - Place plastic sheet over the treads and risers.
    - See instructions for finished flooring. If the cavity under the stairs is adjacent to the exterior, secure the edges of the plastic to the treads and risers. If the cavity is not adjacent to the exterior, use painter's tape spaced as necessary to keep the plastic in place.

- For windows:
    - Tape sliding components of operable windows.
    - Tape over weep holes from the exterior if possible (if window is located on the second floor, try to reach out and block weep hole).
    - For permanent window fixtures, protect horizontal, finished surfaces with plastic, duct mask, or tape.
    - For skylights, make sure to cover operable components with painter’s tape.
- For kitchen/bathroom counters, cabinets, and appliances (Figure 3):
    - Drape plastic over the items. Alternatively, apply cleaning solution to these surfaces prior to sealing, which will prevent sealant from adhering and allow for easy cleanup after sealing.
    - Leave cabinets with plumbing or electrical penetrations open to allow sealant to reach those leaks.

Figure 3. Kitchen appliances and cabinets are covered for sealing. The photo on right shows cabinets opened to allow aerosol to seal plumbing penetrations and outlets below the sink

- For bathroom showers, tubs, and toilets:
    - Cover fixtures, shower head, and railing with plastic and/or painter’s tape on top of surface.
    - Fill p-traps and toilets with water.
- Electric outlets and switches: remove plates. Tape over outlet plugs to avoid allowing sealant to flow into electrical box.

- Smoke detectors, chandeliers, sprinkler heads, ceiling light fixtures, and ceiling fans: cover with plastic and/or painter’s tape.
- Interior doors, closet doors, and shelving: leave in place and cover with plastic or remove and place under plastic floor covering.
- Exterior doors: tape seams.
- Cover tops of horizontal surfaces or apply cleaning solution. This includes:
    - Doorknobs
    - Switches
    - Windowsills
    - Door hinges
    - Shelves
- Cover HVAC equipment including supply and return grilles, bathroom/kitchen exhaust grilles, exhaust fans, and dryer exhaust ensuring that sealant cannot make its way into the supply and exhaust ducts.
- Window air-conditioning units: seal with plastic and tape or duct mask so that there is no air movement through the unit.
- For furnace and boiler, natural draft and induced draft:
    - Remove vent pipe. Seal vent pipe to exterior with duct mask or plastic and tape.
    - Drape plastic over the unit. Use plastic to cover the opening where the vent pipe was removed and secure in place with painter’s tape.
- For power-vent furnaces, boilers, water heaters, and other vented appliances:
    - Seal combustion air inlet to the appliance with duct mask or plastic and tape. This should be an airtight seal so that air and sealant is not forced through the appliance during sealing.
    - Drape plastic over the appliance to protect against surface deposition.
- For direct-vent furnaces, boilers, water heaters, and other vented appliances:
    - No vent sealing is required. Combustion air comes directly from the outside to the unit and exhaust gases go from the unit to outside.
    - Drape plastic over the appliance to protect against surface deposition.
- For natural draft water heaters or other vented combustion equipment in the living space:

  - Remove the vent pipe. Seal the vent pipe to the exterior with duct mask or plastic and tape.
  - Use plastic to loosely cover the top of the water heater exhaust flue and the combustion intake at bottom of the heater. The plastic should NOT allow sealant to settle in the water heater.
- Combustion air duct: seal the open end in the house with duct mask or plastic and tape.
- Heat recovery ventilator (HRV): remove ducts to the exterior. Seal two openings to the HRV and end of ducts inside the house.
- Radiators or baseboard: use painter's tape to secure the plastic sheet over the top of the radiator or baseboard. Leave open at the bottom and side. Pipe penetrations into walls and floors should be left open/accessible.

2.3 Non-Energy Impacts

In addition to lower energy costs from reduced heating and cooling loads, a tighter envelope has other effects. As noted in the recent project demonstrating aerosol sealing of new homes, a tighter envelope is necessary for proper moisture control, improves occupant comfort, and reduces the intrusion of outdoor air particulate matter into the residence (Bohac and Harrington 2020). A tighter interior envelope also has many advantages for multi-unit dwellings:

- Lower interior envelope leakage reduces airflow between units, also reducing transferred odor and contaminants. Numerous studies show that there can be significant secondhand smoke transfer between adjacent units in multi-dwelling buildings (Licht et al. 2012; Dacunto et al. 2013; Kraev et al. 2009). Improved compartmentalization reduces air and contaminant transfer to improve indoor air quality and occupant comfort. For example, multizone modeling of a three-story multifamily building with continuous exhaust ventilation showed that reducing interior envelope leakage from 7 ACH_{50} to 1 ACH_{50} reduced annual average airflow from other units and the common area by a factor of almost three, from 34 CFM to 12 CFM (Bohac et al. 2020).
- Inter-unit airflow is also an indication of air leakage that provides a sound transfer path between units. Improved compartmentalization reduces sound transfer. Lower frequencies transmit across walls primarily by flanking through dense structural members, while higher frequency sounds tend to travel through cracks. The benefit of reduced sound transmission is recognized by the codes for both low-rise and high-rise residential buildings. The 2021 International Residential Code Appendix AK – Sound Transmission for wall and floor-ceiling assemblies between dwelling units (ICC 2021) specifies prescriptive requirements for sealing

or treating penetrations and performance requirements for sound transmission. A DOE Building America project that performed aerosol envelope sealing of several apartment units in Queens, New York included sound transmission tests. There was not a significant attenuation improvement at frequencies below 500 Hz, but there was a significant sound transmission reduction at higher frequencies (Bohac et al. 2016).

3 Methodology

The project conducted research on aerosol envelope sealing in existing, unoccupied single-family houses and multifamily units. The project consisted of three distinct efforts: (1) scaled field testing of the sealing process, tracking from setup to sealing and cleanup; (2) laboratory testing of new sealants that dry clear, making them more appropriate for retrofit applications; and (3) Building Energy Optimization Tool™ (BEopt) modeling of the energy implications of the measured reductions in leakage. The change in house envelope tightness was measured for all residences and additional diagnostics were performed as appropriate to document the impact on specific leakage paths (e.g., house/attic, house/garage, floor/wall junction). House and multifamily unit selection considered variables impacting the sealing process including envelope tightness, construction type, ductwork location, garage type, and foundation type. Several recruitment targets were used, including: (1) residences undergoing major or minor renovation; (2) time of turnover or change of occupancy in rental housing; and (3) time of home or condominium sale. Residences were also recruited from other local energy efficiency research projects.

3.1 Field Demonstrations

The sealing work was typically scheduled for a two-day period to account for any delays in preparation. The first step was to identify any manual sealing and surface protection that would be required. The manual sealing was aimed at leaks larger than one-half inch to reduce the overall aerosol injection time required, therefore reducing the potential for unwanted sealant deposition on building materials. Significant preparation and attention to detail were required to install appropriate protection on finished surfaces.

A baseline air leakage test was performed by the project team prior to surface preparation and manual sealing. A local AeroBarrier dealer was contracted to provide the aerosol sealing service. The AeroBarrier sealing process included a pressurization leakage test of the residence before and after the aerosol sealing process. The temporary coverings in the home were then removed and the home was cleaned. Lastly, the project team performed a final leakage test to determine the overall impact of the sealing effort. If additional work was conducted that might impact the envelope leakage, another leakage test was conducted after that work was complete.

This methodology was consistent except in the case of residences where aerosol sealing was applied from the attic. For those sites, the existing attic insulation was removed prior to the aerosol sealing and new insulation was installed after the sealing process. There was no surface preparation inside the residences. Additionally, WCEC—rather than a local AeroBarrier dealer—conducted the sealing for the California residences with attic sealing.

3.1.1 Combustion Safety Tests and Ventilation Requirement

A tighter envelope can create greater house depressurization when exhaust fans and appliances are operated. This can lead to combustion spillage issues for naturally vented and induced draft combustion appliances. When envelope air sealing existing residences with naturally vented and induced draft combustion appliances, contractors must evaluate the potential for sealing to create or exacerbate combustion spillage issues, and then conduct appropriate tests when the sealing is complete. This project targeted residences that did not have naturally vented or induced draft gas space heating (i.e., furnaces and boilers) and water heaters within the conditioned space. For residences with susceptible appliances, the owners were informed that they may need to replace those appliances.

Combustion safety tests for combustion gas spillage and flue carbon monoxide of induced draft and naturally vented gas space heating (i.e., furnaces and boilers) and water heaters were completed using protocols specified by section 7.9 of ANSI/BPI-1200-S-2017 (ANSI/BPI 2017). Ventilation requirements were determined from local code and ASHRAE 62.2 (ASHRAE 62.2 2022) requirements. The owner was notified of any combustion safety failures, and their residence was disqualified from participation until failures are addressed. The owner was also notified whether the expected level of air sealing may require additional combustion appliance or mechanical ventilation upgrades after the sealing was completed. Most residences were expected to become tight enough to require mechanical ventilation that could be satisfied with a quiet, continuously operating exhaust fan. Balanced ventilation was not expected to be required, but was recommended as a more robust option. Combustion safety tests were repeated after air sealing was complete, and information was provided to the owner regarding combustion safety failures and recommendations for mechanical ventilation.

3.1.2 Quantitative Envelope Leakage Assessment

A whole-house or unit envelope leakage test (i.e., blower door test) was the primary method for quantifying the impact of air sealing on the envelope leakage. An issue with the aerosol sealing method is that the poly sheets, tape, mask, and other materials used to protect surfaces from aerosol sealant deposition on finished surfaces can limit the sealant fog from reaching envelope leaks. In addition, removing the materials after the sealing can disturb the aerosol seals. To evaluate this issue, house leakage measurements were made before and after the materials were put in place. A minimum of four measurements were conducted for each residence.

1. Existing. A multipoint depressurization[1] test before any prep work or sealing.
2. Post-prep. A single-point pressurization test with AeroBarrier equipment after all surface preparations were complete and immediately prior to aerosol sealing.
3. Post-aero. A single-point pressurization test with AeroBarrier equipment immediately after aerosol sealing was completed.
4. Final. Multipoint depressurization test after aerosol sealing, removal of surface preparation, and cleanup was completed.

Because the aerosol sealing process records air leakage data in real-time, this data was used to calculate the sealing rate at different points during the sealing process and record the total sealant injection time. Most existing and post-aero tests conducted were multipoint measurements with uncertainties between 1% and 3%.

The following additional envelope leakage tests were included when it was appropriate and feasible to work them into the sealing process:

- Single-point pressurization tests when portions of the surface preparation were in place or removed, to measure the envelope leakage reduction for different types of surface preparation
- Single-point pressurization tests when temporary seals of HVAC penetrations were installed or removed, to help establish the typical leakage and ranges of leakage for common HVAC penetrations
- When the aerosol sealing was performed prior to the end of renovation or remodeling, a multipoint depressurization test was conducted after all other renovation work was complete. Compared to the final measurement (measurement 4 above), the leakage could increase due to the disturbance of seals or creation of additional leakage. Leakage could also decrease following additional weatherization measures.

Leakage from individual openings or sections of the envelope was sometimes measured using zone pressure diagnostics, guarded leakage tests, or individual leakage site tests. These additional measurements were conducted when conditions allowed and more detailed information offered significant value.

Envelope Leakage Test

Multipoint envelope leakage tests were performed in accordance with the RESNET 380-2016 Standard of Testing Airtightness of Building Enclosures (RESNET/ICC 380). In

[1] Pressurization tests were conducted for a residence with vermiculite in the attic.

general, it was not necessary to temporarily seal any openings for the leakage tests. For residences undergoing renovation or remodeling where HVAC or plumbing systems were not complete, openings such as exhaust fan ducts, supply ventilation ducts, thru-wall air conditioner sleeves, plumbing waste pipes, and disconnected clothes dryer vent pipes were temporarily sealed. For those situations, the same temporary seals were applied for the pre- and post-sealing leakage measurements (i.e., measurements 1 and 4 listed above) so that the test procedure did not bias the reported changes in the house leakage. Leakage values and uncertainties were calculated using equations from Section 9 of ASTM E779-10 (ASTM E779-19). The envelope leakage is reported as the leakage rate at a pressure difference of 50 Pa (CFM_{50}) and divided by the residence volume to generate a normalized house leakage in units of air changes per hour at 50 Pa (ACH_{50}).

Zone Pressure Diagnostics

Zone pressure diagnostics (ZPD) were also used to estimate the leakage between the house and attached zones. This method has been used by weatherization programs for more than 20 years to estimate leakage from the house to a variety of spaces including attics, attached garages, and crawlspaces. The protocol described in an Energy Center of Wisconsin report (2001) was used for this project. In summary, the pressure difference of the zone with respect to the house (or outside) is measured during the house envelope leakage test for a house with respect to outside induced pressure of -50 Pa. Then, an opening of known area is made either between the zone and the house or the zone and outdoors. A calculation tool provided by Residential Energy Dynamic was used to compute the estimated leakage through the zone and the uncertainty of that value. The method does not provide reliable results for well-vented attics or garages for which the leakage to the outside is much greater than the leakage to the house.[2] ZPD measurements were only conducted when conditions allowed and there was significant value in the more detailed information.

Guarded Zone Leakage Test

A compartmentalization air leakage test was performed for all multifamily units to measure the total (exterior and interior) air leakage of each unit. The total leakage change was the primary assessment of the air sealing's impact on the unit's envelope leakage. A guarded air leakage test[3] provides an estimate of the air leakage through different portions of the test unit. Depending on the test configuration, a guarded test can estimate the leakage from an individual unit to the exterior, to adjacent units, or to common areas. Guarded tests were included before and after the air sealing when there was sufficient access to the surrounding area and the additional measurements were likely to provide valuable information regarding the type of unit leakage sealed by the aerosol process.

A typical sequence of tests using two fans for a one-story apartment building with three units and a common area is shown in Figure 4. Test 1 (upper left) is a

[2] In general, the uncertainty of the ZPD estimate is greater than 25% for zone-with-respect-to-outside induced pressure differences less than 4 Pa.
[3] Sometimes referred to as the pressure-masking, pressure-balancing, or pressure-nulling method.

compartmentalization test that measures the total air leakage of Unit B. For Test 2, a second fan is installed in the hallway door of Unit A and the two fans adjusted so that the change in pressure (e.g., induced pressure difference) of Unit B to outside is 50 Pa and the induced pressure difference between the two units is zero. The difference in the leakage for the first two tests yields the air leakage between Units B and A. Test 3 repeats this process to measure the air leakage between Units B and C. This approach was used to measure the leakage to adjacent units for multifamily units in a Minnesota high-rise building. For Test 4, the hallway doors to Units A and C are opened and a fan is installed in the building exterior to induce a pressure difference of 50 Pa for the building interior. The airflow rate of the fan in Unit B is adjusted to induce a pressure difference of zero between Unit B and the rest of the building interior. With this configuration, the airflow of the Unit B fan is equal to the exterior envelope leakage of Unit B.

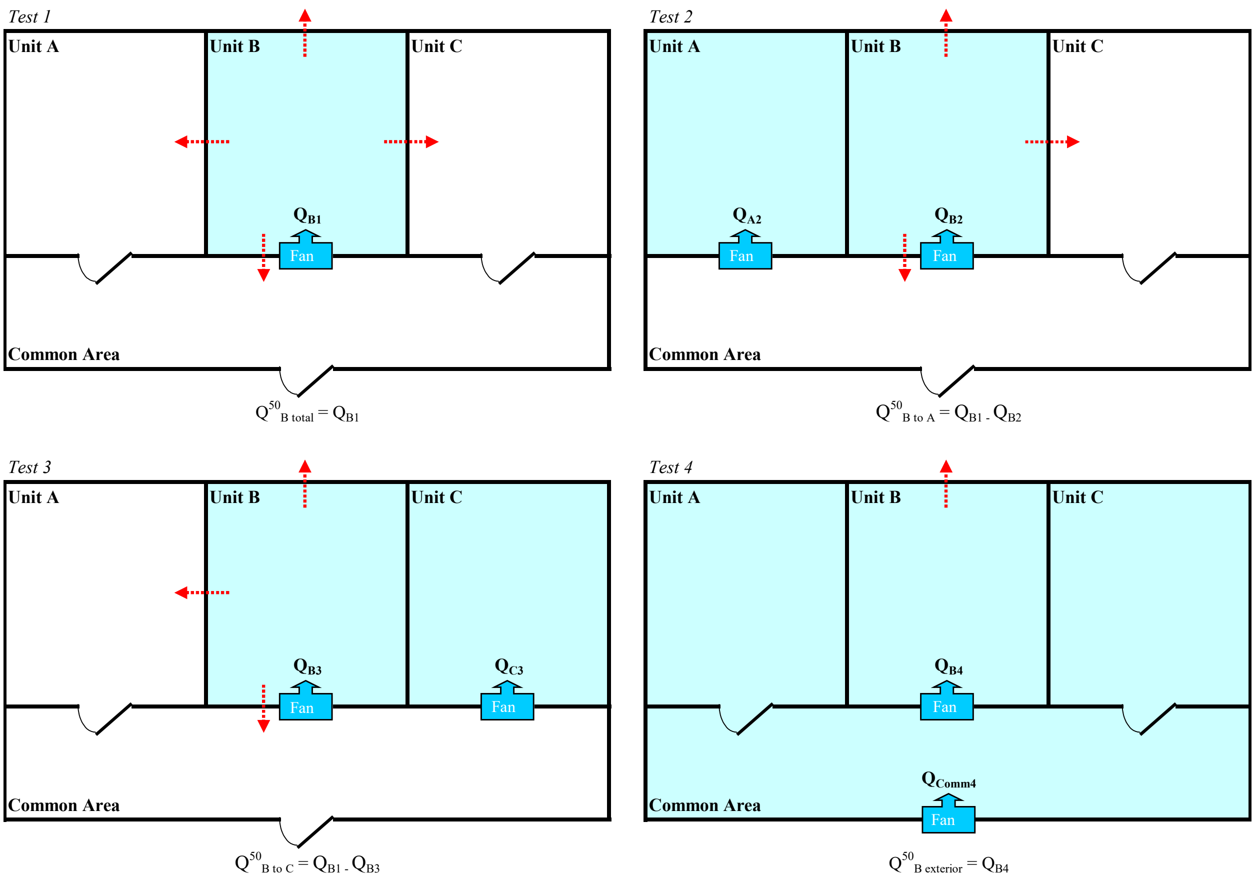


Figure 4. Guarded leakage test using one additional fan to guard individual areas adjacent to the test unit (B)

The four tests measure 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. For multi-story buildings, the second fan is installed in the units above and below to compute the leakage to those units. When it is not possible to install fans to depressurize the whole building, the individual unit tests (measurements 2 and 3) provide useful information about leakage to adjacent units.

The guarded zone test method shown for Test 4 in Figure 4 can be used to measure the exterior leakage of areas of a house that are separated from the main body of the house by walls or floors. A blower door fan is installed in an exterior door of the house's main body; all interior doors are opened, and the second test fan is installed in a door between the main body of the house and the area of interest. For example, the second test fan can be placed in the door between the first floor and basement or the first floor and second floor. It can also be placed in the hallway door to individual rooms or between the house and garage. As in Test 4, the first fan is used to produce an induced pressure difference of 50 Pa between the main body of the house and outside. The second fan is used to achieve zero induced pressure between the main body of the house and the area of interest. The airflow rate of the second fan is equal to the exterior leakage of that area. This approach was used for a sample of the Minnesota residences to measure the exterior leakage of basements, individual bedrooms, and upper floors. A modification to this approach was also used to measure the leakage between the house and attached garage.

There are no standards that provide a protocol for conducting guarded leakage tests or computing uncertainties. There must be a continuous air barrier between the main body of the house and the area of interest to make a reasonably accurate measurement. Uncertainty is increased for windy conditions. Hult, Dickerhoff, and Price (2012) describe many one- and two-fan test procedures to determine the interzonal and exterior leakage of adjacent zones. They noted that the two-fan method indicated by Test 4 produced the most accurate measurements. The guarded test procedures used for this project are similar to methods used for a DOE-funded project to conduct whole-building, compartmentalization, and guarded tests of 26 low-rise multifamily buildings (Bohac et al. 2020).

Individual Leakage Sites

The leakage of individual, isolated sites located on a flat surface can be measured by placing an air flow metering device over the area during a whole-house depressurization leakage test. The method is often used to evaluate the leakage of a variety of sites including duct penetrations, recessed light cans, and electric outlet boxes. Both WCEC and CEE teams performed this test on a sample of leak sites at a few residences. An enclosure with a fixed orifice is placed over the leakage site while the residence is depressurized to -50 Pa. The size of the opening is adjusted to minimize the pressure difference across the box while still providing a reasonably accurate measurement. The CEE team used an Exhaust Fan Flow Meter from The Energy Conservatory. A portion of the opening was taped over to produce an opening of 1 $in.^2$ (see Figure 5). The minimum measurable airflow rate was 0.5 cfm. WCEC used an orifice plate with multiple 0.5-$in.^2$-diameter holes (see Figure 6). The number of holes was adjusted as needed. The relationship between the pressure across the plate and the flow rate has been determined for one and multiple open holes. The uncertainty is approximately +/- 20% of the measurement. It helped identify leaks that are minor (<10 CFM_{50}), moderate (10 to 50 CFM_{50}), and significant (>50 CFM_{50}). It also helped estimate the impact of aerosol sealing on individual leaks.

Figure 5. Leakage measurement tool used by CEE staff

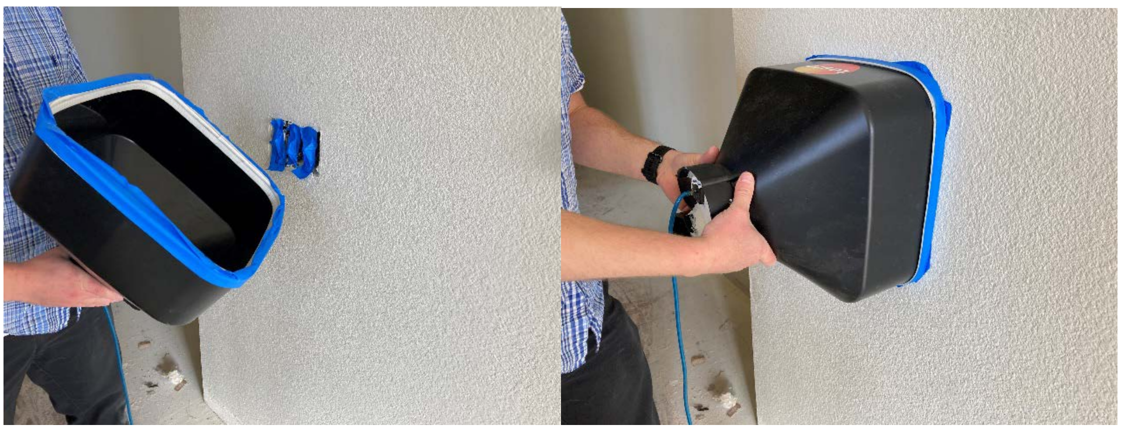


Figure 6. Leakage measurement tool used to measure leakage of light switch

3.1.3 Qualitative Envelope Leakage Assessment

Visual inspections were used to qualitatively evaluate significant envelope air leaks. Guidance provided by ASTM 1186-17 (2017) *Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Barrier Systems* was used to conduct the leakage assessments. The process categorized the type and severity of the leaks before and after the sealing to provide a better understanding of the type of leaks that were sealed using the aerosol method and those that required manual sealing. It was expected that typical locations would include electric outlets and switch plates, electric or gas service penetrations, baseboards, wall-mounted air-conditioning units, dryer vent penetrations, attic hatches, recessed lights, surface mounted lights, ceiling fans, ceiling exhaust fan housings, rim joist framing gaps, plumbing penetrations, appliance combustion vent penetrations, window trim, interior tongue and groove boards, built-in cabinets, cantilevered floors, cantilevered windows, attic knee walls, and dropped soffits. Infrared scans and the movement of smoke from a puffer were used to identify leakage paths and evaluate the severity of the leakage.

An infrared scan was used when there were acceptable weather conditions. The infrared scan covers large sections of the enclosure surface in a short amount of time to identify likely leakage locations. An infrared scan is typically performed from within the residence's interior as a two-step process. First, the scan of the interior surface of the envelope is performed with the residence in “as-found” conditions. This documents thermal anomalies from variations in insulation and significant air leakage from wind and stack effects. The scan is then repeated with the residence depressurized 15 to 25 Pa using a test fan. When the outside temperature is lower than the inside temperature, surfaces that are colder than observed during the initial scan indicate air leakage from the outside. When the outside air is warmer than inside, outside air leaks appear as new warm spots. Depending on the sensitivity of the infrared camera and other variables (e.g., wind speed, solar heating of exterior surfaces), a difference between outdoor and indoor air temperature of at least 10°F is needed for the scan to be useful. Although an infrared scan cannot quantify air leakage, it is sometimes useful to quickly identify leakage locations. In general, it will not help identify the interior leakage of multifamily units because there needs to be a temperature difference for an infrared scan to identify air leakage paths.

3.1.4 Labor and Material Requirements

Time and materials were tracked during each step of the sealing process. Because this was a research project, there were more staff on site than would normally be required during each installation. In determining the labor hours required, the project team only included the actual number of people required to perform a task. The materials used for manual sealing, home preparation, and any post-sealing cleanup were also tracked.

3.2 Alternative Sealant Testing

Durability testing was performed to assess the strength of new sealant formulations relative to the current sealant used for aerosol sealing installations. New formulations were sought to reduce the potential for microbial growth and improve the seals’ appearance. The reduced microbial growth would limit the potential for mold growth on sealant material after application, and only requires slight modification to the existing product. The other feature expected to improve the market for retrofit applications of aerosol envelope sealing is the seal's appearance. The sealant in current use dries white. Finding a material that dries translucent or clear would be preferred as minor overspray of the product would be less noticeable. Unfortunately, efforts to modify the formulation with the existing polymer were not successful, so new polymers were tested to achieve this goal.

The testing performed was conducted on three sealant formulations: (1) current sealant used in AeroBarrier applications (ABX1), (2) a modified version of the AeroBarrier sealant with the addition of an antimicrobial additive (ABX2), and (3) a new formulation using a different polymer that dries more translucent (ABF23). The testing focused on failure pressure of seals formed using the aerosol sealing process. Seals were formed at different application humidities to determine sensitivity to that process variable, which can fluctuate in field applications.

The process used for forming seals was meant to simulate as closely as possible the sealing process used in a building. This includes controlling differential pressure across the leak, application humidity, and nozzle conditions. Table 1 shows independent and dependent variables used for the experiments.

Table 1. Independent and Dependent Variables

Independent Variables	
Sealants	ABX1 (10% solid)
	ABX2 (10% solid)
	ABF23 (20% solid)
Application Humidity (RH)	40%
	60%
	80%
Leak Type (1/8" acrylic plate)	1/4"x4" slot
	1/8"x4" slot
Application Pressure	100 Pa across leak
Nozzle Pressure	80 PSI
Sealant Flow	20 CCM
Dependent Variables	
Burst Pressure	
Deposition Weight	
Time Required to Seal	

3.2.1 Testing Apparatus

A diagram of the sealing apparatus is shown in Figure 7. To control the independent variables, it was necessary to have precise control over humidity, flow rate, and pressure during the sealing process. Furthermore, to simulate the building envelope application as closely as possible, the distance between the injection nozzle and the leak panel was extended to 20 feet (see Figure 8). A bypass was used to maintain system airflow and pressure as the leaks sealed. While initial airflow rates and humidity conditions can be chosen to minimize bypass air, as the samples seal more air will be directed through the bypass to maintain the initial airflow rate and seal pressure condition. A combination of a fogging nozzle and electric resistance heaters was used to maintain relative humidity at the leak panel. Lastly, a filter box was used to scrub remaining particles in the exhaust air. Figure 9 shows the layout of the leakage slots.

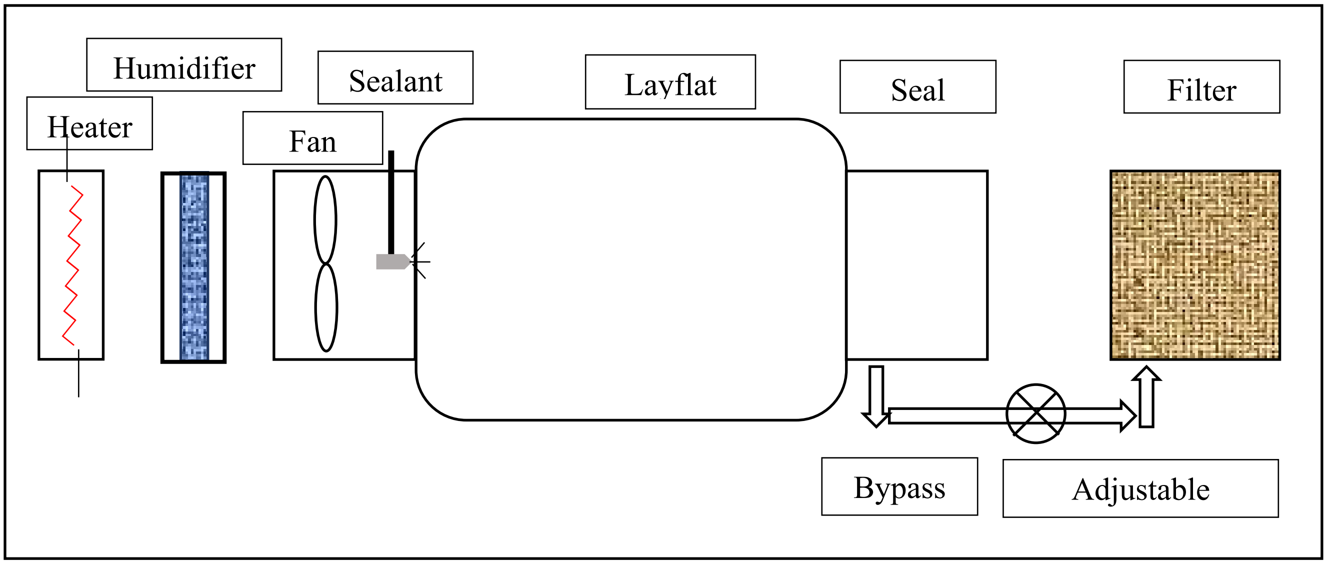


Figure 7. Sealing apparatus schematic

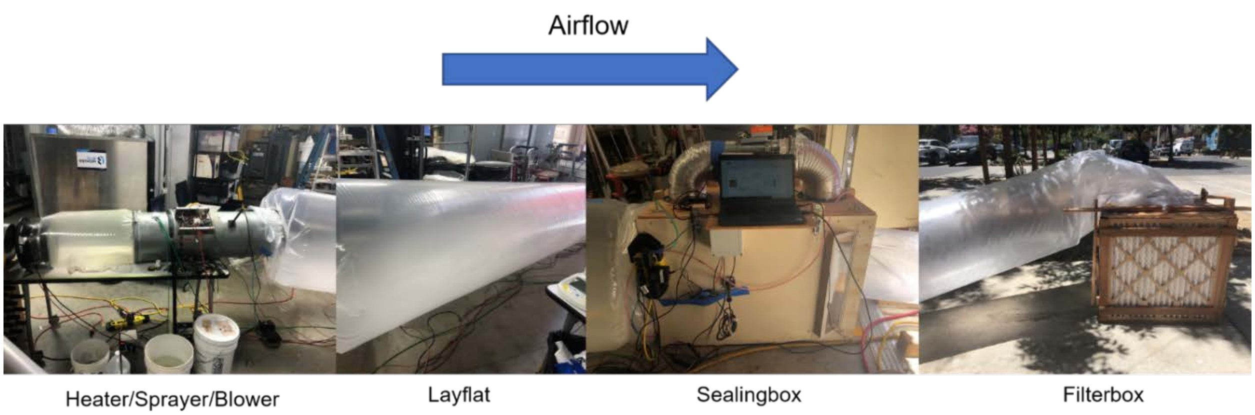


Figure 8. Composite image of sealing apparatus

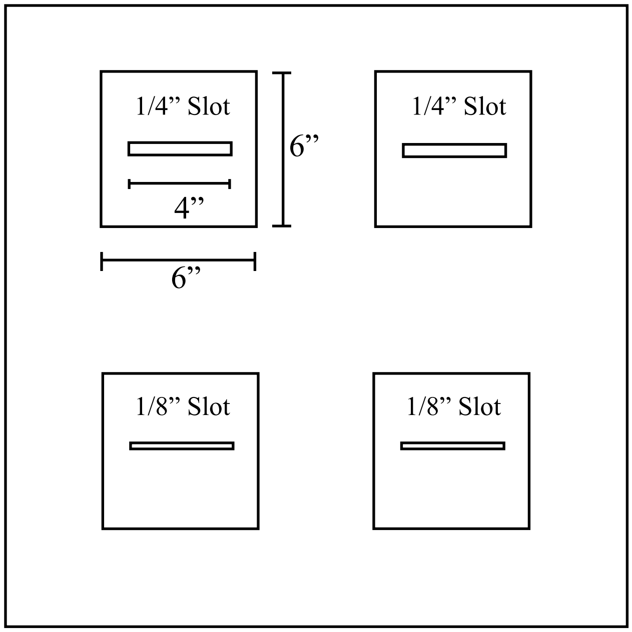


Figure 9. Seal plates

A diagram of the pressure testing setup is shown in Figure 10. Compressed air was filtered, dried, and regulated down to approximately 10 PSI. A pressure sensor was used with a digitally controlled valve to maintain a pressure setpoint within 0.01 PSI. When necessary, a relief valve was added upstream to prevent prematurely over-pressurizing the seal.

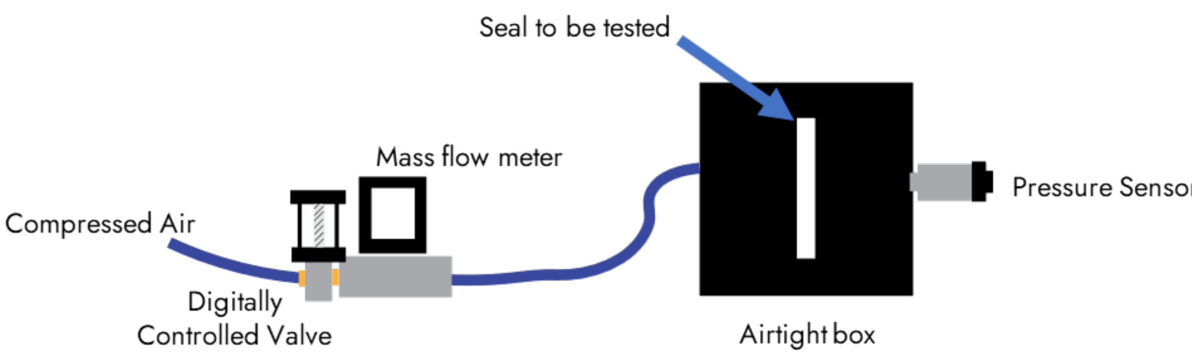


Figure 10. Diagram of pressure testing setup

3.3 Energy Modeling

Energy modeling was conducted to evaluate the impact of envelope sealing on home energy use. The simulations were conducted in each of the International Energy Conservation Code (IECC) climate zones to determine how climate conditions impact the results. Air sealing typically reduces the thermal loads on a building by reducing the amount of unconditioned air that enters buildings through leaks.

To model a building using common energy simulation software, several assumptions must be made about the construction of the building and the performance characteristics of many systems within the building. The value of the results obtained from such a simulation depends on the modeling software's specific capabilities and the extent to which the software allows 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 significantly influences the results.

BEopt was used to model energy savings when sealing homes to different leakage levels in several climate zones. The focus of this analysis is on single-family homes as they represent the largest opportunity for energy savings due to the amount of exterior surface area. BEopt is a parametric analysis tool that allows multiple building configurations to be compared using EnergyPlus as the simulation engine. The reference model used for the baseline was a modified version of the existing single-family home model in BEopt. The only modifications for the reference model were adding R-11 wall insulation to better represent the homes found in the field testing. The envelope leakage varied between 3 and 15 ACH_{50} to determine the impact of air sealing on building energy use. The existing home model had no continuous mechanical ventilation, so the hourly infiltration rate was only based on natural wind and stack forces. Window operation was assumed to occur three days of the week when outdoor temperatures were appropriate. Several IECC climate zones were modeled including 1A, 2A, 2B, 3A, 3B-CA, 3B-Other, 3C, 4A, 4B, 4C, 5A, 5B, 6A, 6B, 7, and 8.

The model selected was a two-story, slab-on-grade, four-bedroom, three bathroom, 2,400-ft^2 home with an attached garage (Figure 11). The ceilings were nine feet, and it was assumed that there were neighboring homes on each side to account for wind obstruction. All other inputs, other than the wall insulation and leakage level discussed earlier, were the same as the BEopt reference model. A gas furnace with a 78% Annual Fuel Utilization Efficiency was selected for heating, and a single package air conditioner with a seasonal energy efficiency ratio of 10 for cooling. The space heating and cooling used a central distribution system located entirely in an unfinished attic with a total leakage of 20% of the total air handler flow.

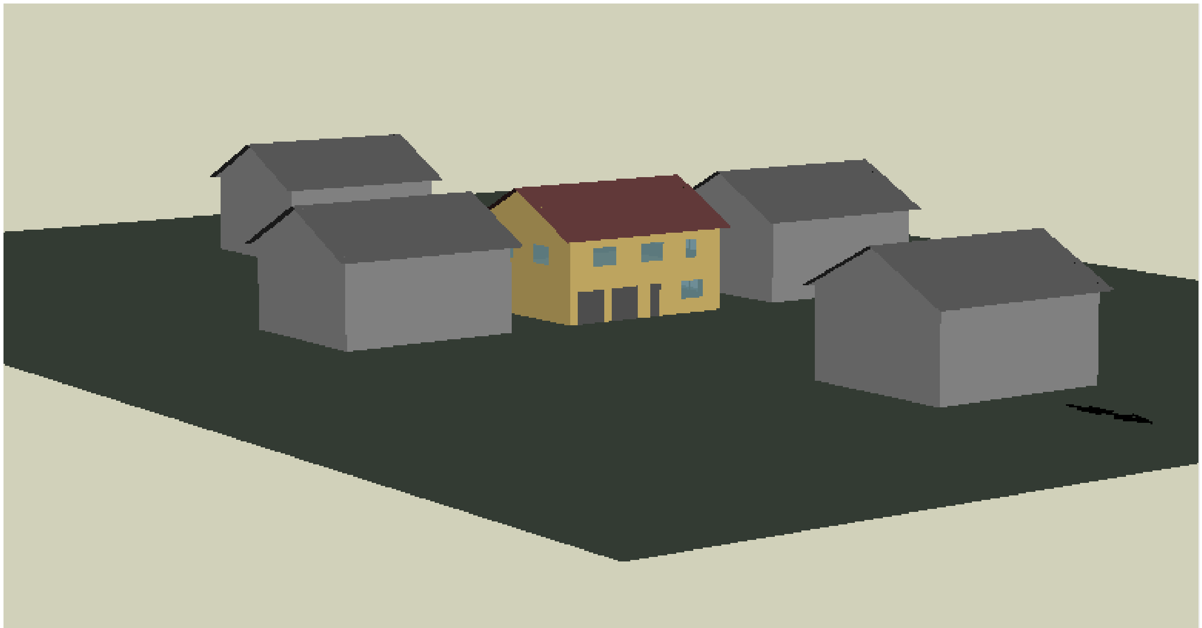


Figure 11. BEopt model showing obstructions from nearby homes

3.4 Selection Criteria

Initial outreach to recruit demonstration sites started with unoccupied homes. The project team worked with public housing providers and local utilities to identify apartments or houses that would be renovated or undergo a change in occupancy. An initial air leakage test was conducted on the demonstration sites to determine the air sealing opportunity. Eligibility criteria were broad and primarily focused on potential safety issues. Potential health and safety concerns related to combustion appliances or ventilation were identified and remediation requirements discussed with the owner.

The initial objective was for the sample to include about two-thirds multifamily units and one- third single-family houses. The split between multifamily units and houses was selected because houses are typically more costly to seal. However, the budget ultimately allowed for an even split between houses and multifamily units. It was expected that about 60% of the residences would be located in Minnesota and 40% in California. Residences were to be sealed at times of renovation, rental housing turnover, and owner purchase. At least a few residences were selected from each of the three groups to gain experience with conducting sealing when the residences were unoccupied for each of these reasons.

Sites were selected and procedures followed to assure that the residences would not have combustion safety or ventilation concerns after the sealing work was complete. Recruiting targeted residences that did not have induced draft or naturally vented gas space heating (i.e., furnaces and boilers) and water heaters within the conditioned space. This eliminated concerns that reducing envelope leakage would result in depressurization-induced combustion gas spillage. A second option was residences for which there were funds from a separate source (i.e., a weatherization or remodeling allowance) to address any combustion spillage issues that could occur after sealing. A third option was residences for which the improvement project includes replacement of induced draft and naturally vented gas appliances. For this option, the owner committed to complete any necessary upgrades.

Selected sites had characteristics that were most likely to impact the cost and effectiveness of aerosol sealing. The project team did not expect that the characteristics of the selected residences would occur with a similar frequency to that of the general U.S. housing stock. The goal was to provide the best learning opportunities for methods of aerosol envelope sealing of existing residences. The statistics from the sealed residences do not provide direct indications of expected impacts for all U.S. residences.

Selection criteria included many variables that impact the sealing process and its effectiveness including existing envelope tightness, construction type, ductwork location, garage type, window vintage, prevalence of carpeting, and foundation type. Each variable impacts either the potential percent reduction in envelope leakage, the sealant's ability to travel to leakage locations, or the cost of protection. Experience from previous projects was used to estimate the relative impacts and establish priorities for residence characteristics. Table 2 displays the list of initial site selection criteria. The criteria were reviewed on an ongoing basis to accommodate project sealing experience and partner feedback.

Table 2. Initial Selection Criteria for Project Residences

Characteristic	Type of Impact	Criteria
Existing envelope leakage	Higher starting leakage will produce greater absolute change in leakage for the same percent reduction. Leakier residences may have leaks with larger gaps that require more extensive manual pre-sealing.	Existing Leakage <10 ACH_{50}: at least 5 10–15 ACH_{50}: at least 5 >15 ACH_{50}: at least 5
Type of remodeling	Gut rehab is similar to new construction. Less extensive remodeling will be more similar to occupancy change without work.	None with gut rehab. Earlier projects may have some renovation work but need to include at least 4 sites by end of project that have no remodeling.
Ductwork location	When is it necessary to seal grilles? Houses/units with significant leakage to exterior could have some of the leakage sealed, creating greater savings.	At least 4 residences that have ductwork with significant leakage to the outside. Both leaks for metal ducts and building cavities used for distribution.
Garage type	Leakage to attached garages is sometimes significant.	At least 2 houses with attached garages.
Window vintage	Should not have to protect newer windows, but gaps of leakier windows may need protection.	At least 4 residences that have "leaky" windows (qualitative assessment).

Characteristic	Type of Impact	Criteria
Floor area of residence with carpeting	Protecting carpeting from deposition will be a challenge and failures can require replacement. How to handle leaks under baseboard? Aerosol will need to travel to that leak but still needs to protect carpet that is against baseboard.	At least 4 residences with some carpeting.
Prevalence of interior items requiring more extensive protection	Certain items need to be protected. Need to document method and time required to protect.	Create list of items that need to be protected during sealing. Each item should be included in at least 2 residences.
Number of stories, foundation type	Homes with raised foundations or second stories may have additional considerations for prep to prevent damage to flooring from leaks in the flooring.	At least 2 two-story houses.
Fraction of residence sealed	There may be opportunities to seal a portion of the residence.	Project will focus on sites where the entire residence is sealed. At least 2 residences with only a portion of area sealed.
Multifamily unit sealing approach	Shared walls with occupied spaces adjacent to sealed residence need to be monitored for fogging. High capacity air filtration units or scrubber fans may be needed if sealant intrusion occurs.	At least 2 units where focus is on sealing exterior so that adjoining units are initially guarded and later the guarded pressure is reduced.
Heating system type	Need to protect furnace heat exchanger from deposition.	There appears to be enough experience from new construction; no criteria required.

4 Results

A total of 36 residences were sealed. Half the residences were single-family houses and half were multifamily units. All houses were detached dwellings. The multifamily units were a combination of six townhouses and twelve units in apartment or condominium buildings. Five houses and nine multifamily units were in California, and thirteen houses and nine multifamily units were in Minnesota. Thirty-two residences were sealed from the interior and four were sealed from the attic. The results for the interior and attic sealing are provided separately. The interior sealed residences had undergone different levels of renovation. Seventeen were sealed during major renovation work, four during minor renovations, and eleven during a change in occupancy (renter or new owner). Three townhouse units in California and one house in Minnesota were sealed from the attic while the residences were occupied.

4.1 Interior Sealed Single-Family Houses

Five California houses and twelve Minnesota houses were sealed from the interior space. There were significant differences between the California and Minnesota houses. For example, all the California houses had raised foundations and the Minnesota houses had basements or a combination of basement and crawl space. In addition, the median floor area of the California houses was 38% smaller than that of the Minnesota houses, and the California houses had a 59% higher median air leakage when normalized by volume. More than half the Minnesota houses had a larger floor area than four of the five California houses and almost half the Minnesota houses had a lower air leakage than all the California houses (Figure 12). Due to these differences, the results for the California and Minnesota houses are presented separately.

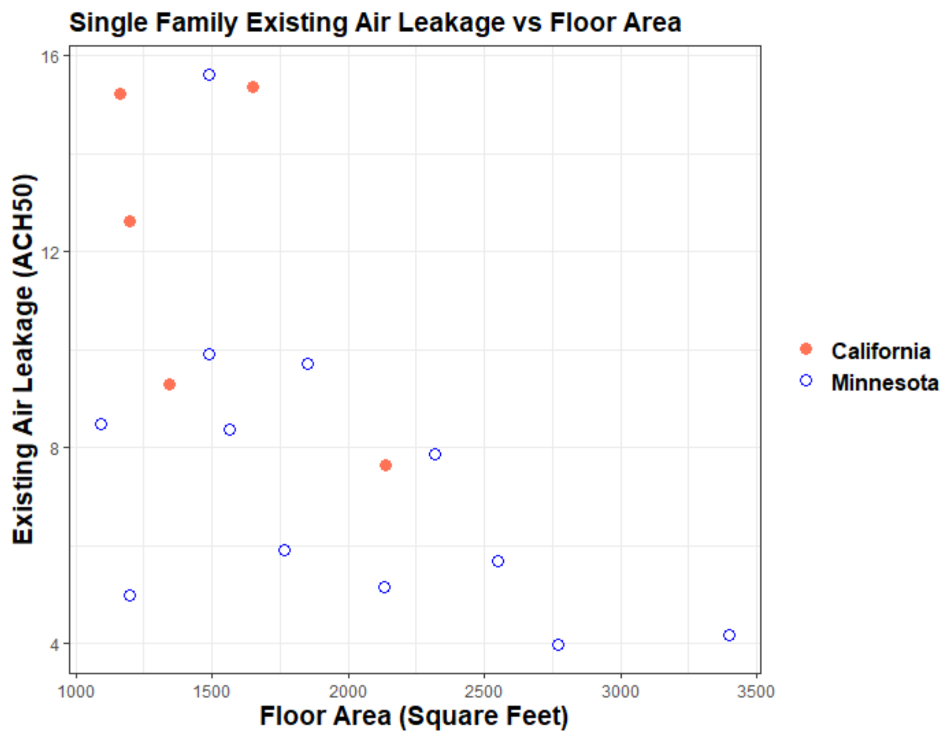


Figure 12. House air leakage and floor area for the California and Minnesota houses

4.1.1 California Houses

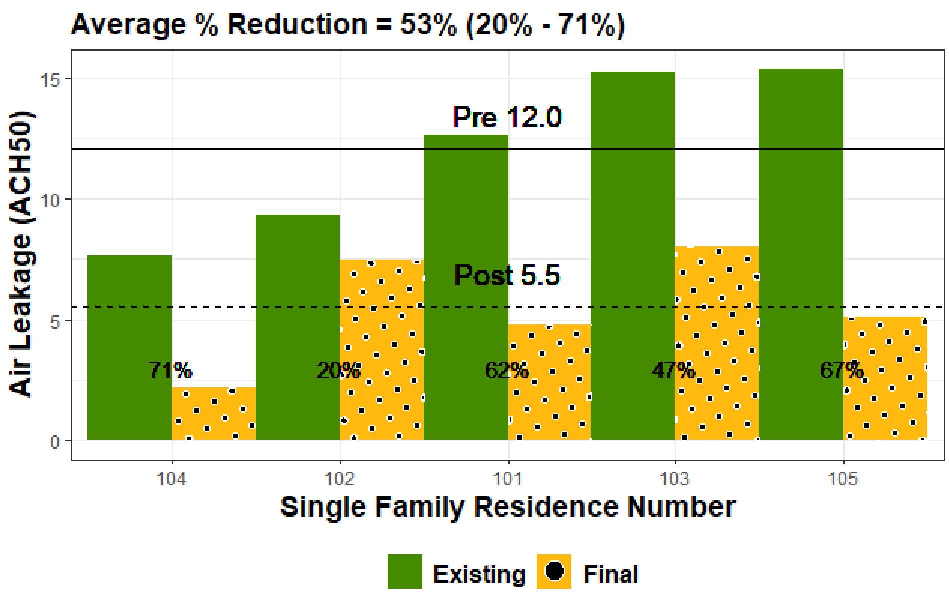
Four of the five single-family homes sealed in California were sealed at the time of an occupancy change and one was undergoing minor renovation (Table 3). Three were built before 1950 and two were built in the 1980s. The floor areas ranged from 1,162 to 2,137 ft.^{2} and averaged 1,498 ft.^{2} They all had peaked, vented attics. They were all constructed on raised foundations requiring the protective materials on the floor to be taped completely around the perimeter to prevent aerosol from migrating under the plastic to a leak in the middle of the floor. The floor covering process accounted for most of the time needed for building preparation. Section 4.6 provides information on time requirements for the sealing process. Table 4 and Figure 13 show the pre- and post-seal leakage results for the homes. Before the houses were sealed and before the surface preparations were in place, the house leakage ranged from 7.7 to 15.4 ACH_{50} and averaged 12.0 ACH_{50}. After sealing and removal of the surface preparations, the leakage ranged from 2.2 to 8.1 ACH_{50} and averaged 5.5 ACH_{50}. The leakage reduction ranged from 20% to 71% and averaged 53%. In Table 4, the pre-sealing values are displayed in the column labeled Existing and the post-sealing values are in the Final column. The leakage reductions are displayed in the column labeled Existing – Final.

Table 3. Key Characteristics: California Houses

Res. #	Floor Area (sf)	# Stories	Foundation	Garage	House Status	Year of Construction
101	1,198	1	Raised	Detached	Occupancy Change	1910
102	1,346	2	Raised	Attached	Occupancy Change	1986
103	1,162	1	Raised	Detached	Occupancy Change	1947
104	2,137	1	Raised	Attached	Minor Renovation	1985
105	1,648	1	Raised	Detached	Occupancy Change	1925

Table 4. Air Leakage Results: California Houses (ACH_{50})

Res. #	Existing	Post-prep	Post-aero	Final	Post-prep – Post-aero		Existing – Final	
					(ACH_{50})	(%)	(ACH_{50})	(%)
101	12.62	8.52	0.92	4.83	7.60	89%	7.79	62%
102	9.30	8.63	3.05	7.44	5.58	65%	1.86	20%
103	15.24	11.54	1.14	8.05	10.40	90%	7.19	47%
104	7.65	6.61	1.02	2.21	5.60	85%	5.43	71%
105	15.38	8.41	0.73	5.09	7.69	91%	10.29	67%
Min.	7.65	6.61	0.73	2.21	5.58	65%	1.86	20%
Max.	15.38	11.54	3.05	8.05	10.40	91%	10.29	71%
Med.	12.62	8.52	1.02	5.09	7.60	89%	7.19	62%
Avg.	12.04	8.74	1.37	5.52	7.37	84%	6.51	53%



Percent reductions are based on multipoint depressurization tests conducted before and after the sealing with no surface preparation or temporary seals in place.

Figure 13. Air sealing results for single-family homes sealed in California

The other values in Table 4 were generated from the AeroBarrier equipment single-point pressurization tests conducted immediately before and after the aerosol sealing with the surface preparation in place. The percentage reductions measured immediately before and after the sealing are displayed in the Post-prep – Post-aero column. The percentage reduction from the aerosol sealing process is consistently higher than the reduction measured without the surface preparation. The aerosol sealing resulted in an average reduction of 84% and the reduction without surface preparation was 53%. This demonstrates that the aerosol process seals a high percentage of the leaks that are not covered. The surface preparation does not allow all the leaks to be sealed and there are some intentional leaks (e.g., exhaust fans) that are not sealed. Figure 14 compares the percentage reductions without (green bars) and with (blue bars) surface preparation in place. The two leakage reductions differ not only by whether the surface preparation is in place, but also by the type of leakage test conducted (e.g., pressurization versus depressurization). Section 4.4 discusses the impact of leakage test methods, surface preparation, and intentional leaks in more detail.

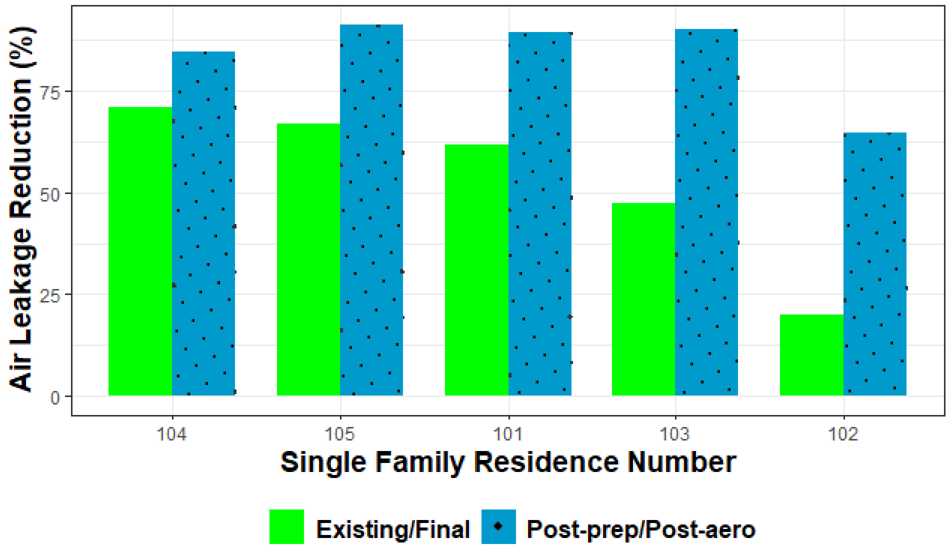
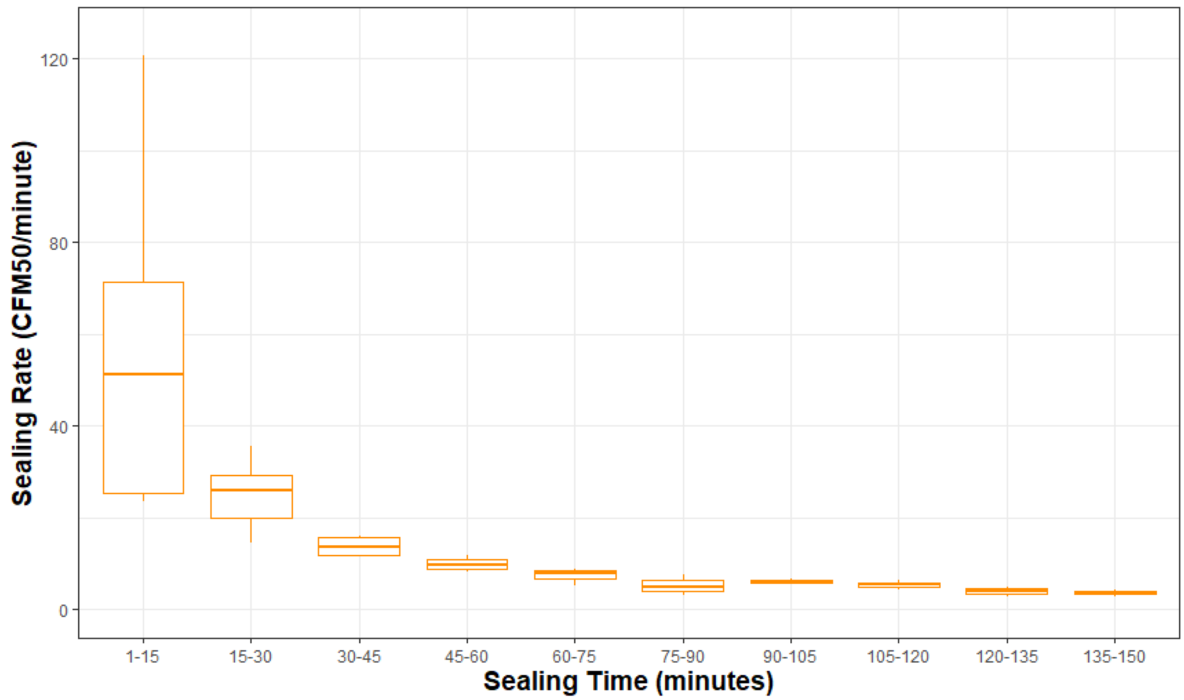


Figure 14. Comparison of percentage air leakage reductions of California single-family homes

Figure 15 displays a box and whisker chart of the 15-minute average sealing rate for the five California houses. The rate of sealing was greatest at the start of the sealing and gradually decreased over time. The unique feature of aerosol sealing is that all leaks are sealed simultaneously if the sealant is dispersed uniformly though the house. Narrower leaks are quickly sealed, and wider leaks take longer to seal. The greater rate of sealing at the start of the process suggests that the houses had a large length of narrow gap leaks. The median sealing rate for the first 15 minutes was 51 CFM_{50}/min (20 ACH_{50}/h), and that dropped by 73% to 14 CFM_{50} (3.4 ACH_{50}/h) for the 30-to-45-minute time period. The median sealing rate dropped below 10 CFM_{50}/min after 45 minutes and leveled out to 4 to 6 CFM_{50}/min after 75 minutes.



The bottom and top of the box are the first and third quartiles. The horizontal line in the box is the median. The top of the upper whisker is either the maximum value or the third quartile plus 1.5 times the difference between the third and first quartiles. A similar method is used for the bottom whisker. Values outside the whiskers are indicated by an asterisk.

Figure 15. Aerosol sealing rate for five California single-family homes

Figure 16 shows the sealing profile and Figure 17 shows air leakage test results for residence 101. In this case, the sealing time was short, requiring only 41 minutes of injection compared to the average of 1.6 hours for all five California houses. The sealing rate started around 95 CFM_{50}/min and went down to 5 CFM_{50}/min at the end of the process. The air leakage test results show the amount of leakage covered by surface protection (4.10 ACH_{50}) and the amount uncovered at the end of sealing (3.91 ACH_{50}), suggesting the tightest the building could be sealed through the aerosol process was around 4 ACH_{50}. Most of the air leakage covered by surface protection appeared to be from the floor, which was built on a raised foundation. The aerosol sealing process reduced the leakage by 89%, from 8.5 ACH_{50} down to 0.9 ACH_{50} before removing the surface preparation, and after removing the protection the final building leakage ended up at 4.8 ACH_{50}. For this house, the covered and uncovered air leakage were in general agreement. As a result, the leakage reduction measured by the AeroBarrier equipment immediately before and after the aerosol sealing (7.60 ACH_{50}) was nearly equal to the reduction measured before and after sealing with no surface preparation in place (7.79 ACH_{50}). In some cases, the amount of leakage covered differed from the amount measured when uncovering, which is discussed in more detail in a later section.

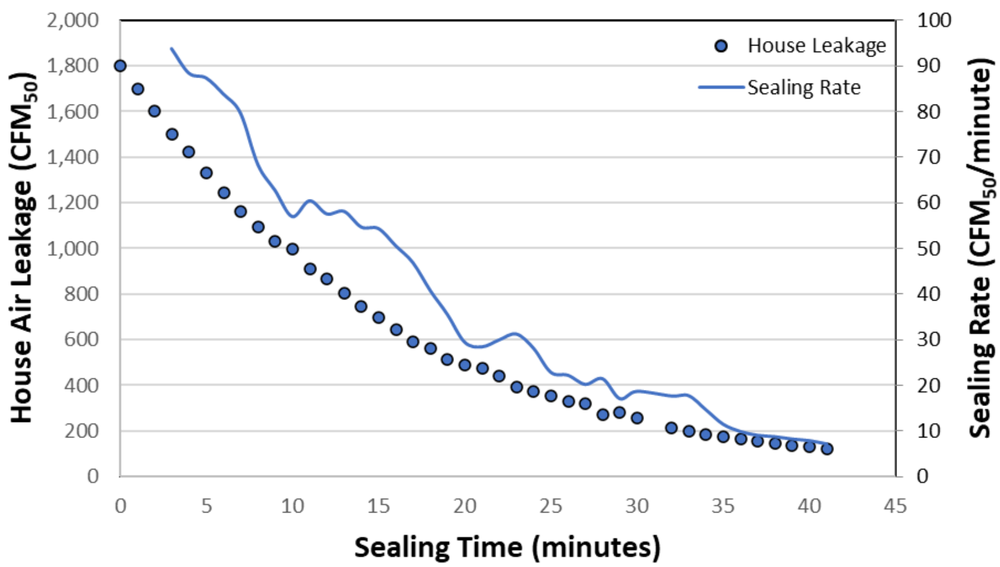


Figure 16. Sealing profile for California residence 101

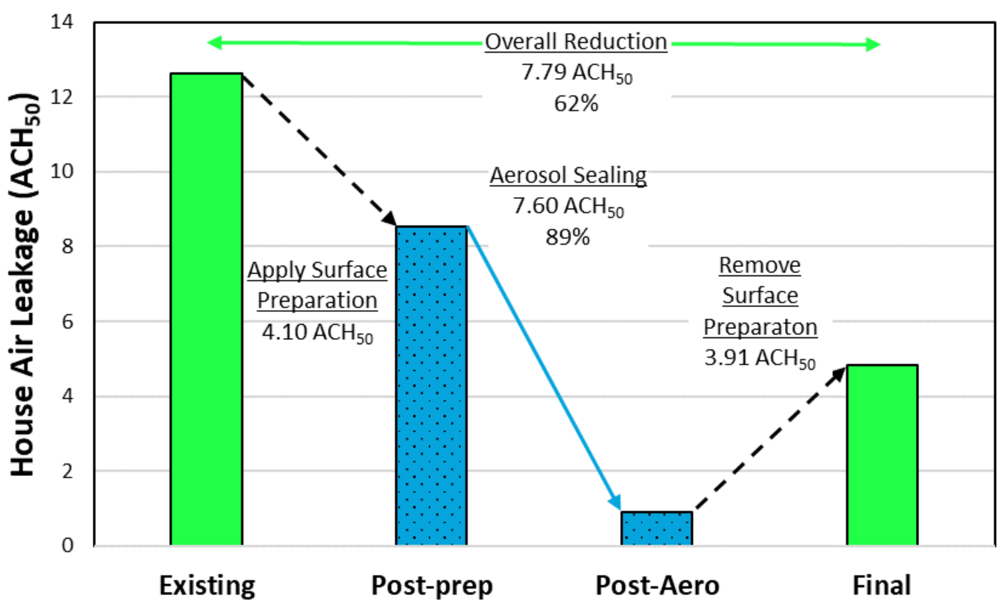


Figure 17. Leakage results summary for California residence 101

The retrofit air sealing for California residence 102 did not perform well, with only a 20% leakage reduction. Figure 18 shows the leakage results summary for the home, revealing a 65% reduction in leakage during the aerosol sealing process. However, the leakage covered during prep compared to the leakage reintroduced during prep removal were significantly different, which suggests that many seals were disturbed during cleanup. One potential reason for this result is that the existing test condition was measured several days before the sealing occurred. The homeowner was installing laminate flooring and could have increased the leakage of the house between the time of the baseline test for existing leakage and the time of aerosol sealing. If that occurred, the amount of leakage covered by the surface preparation would have been greater than indicated by comparing the post-prep leakage to the earlier measurement of existing house leakage. In addition, the overall leakage reduction measured would have increased.

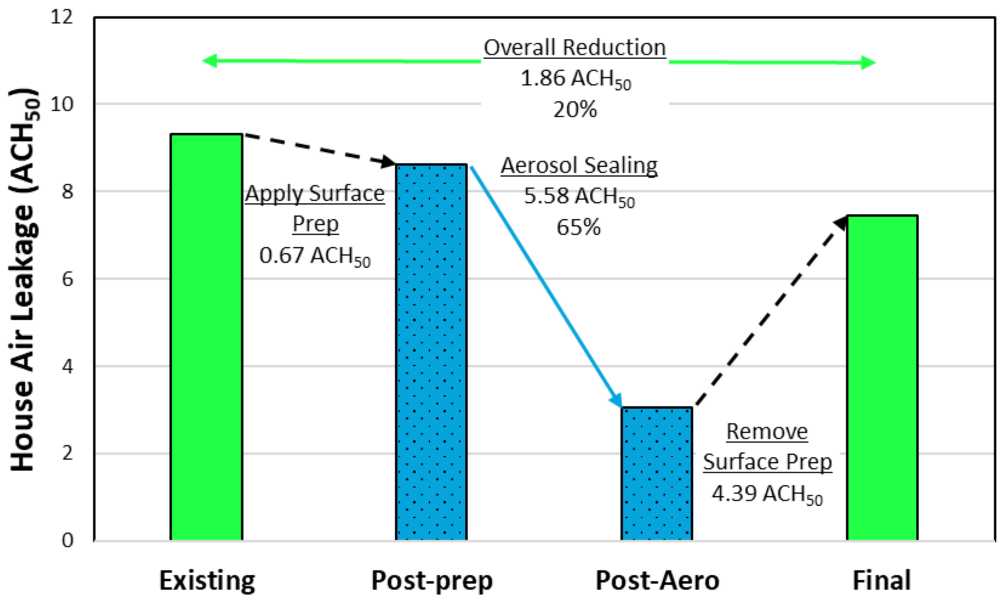


Figure 18. Leakage results summary for California residence 102

One significant source of leakage was the duct system that used interior building cavities as part of the distribution system and had significant leakage to outside. The return plenum was left open to evaluate whether the aerosol envelope sealing would reduce air distribution leakage to outside while sealing the rest of the home. In this case, the air handler was blocked to prevent sealant from reaching the blower and heat exchanger coils. Figure 19 shows aerosol deposition in and around the return plenum opening and supply ducts, suggesting significant leakage and sealant flow. The amount of deposition on the edges of the wall leading to the return plenum would only have occurred if extremely high air velocities were present. Typically, velocities would be low around a large opening that leads to smaller leaks in the plenum, so this deposition indicates a substantial amount of airflow entering the return cavity and escaping outside.

Figure 19. Return plenum opening inside wall cavity (left) and return entrance showing significant deposition (right)

Another large leak was observed where the bathroom tile had been partially removed, exposing the inside of an exterior wall (Figure 20). The large amount of sealant collected indicates substantial airflows into this wall cavity. In addition, sealant deposition was observed in the toilet as a result of the p-trap drying up and introducing a leak path out of the building.

Figure 20. Construction in bathroom exposing the wall cavity where significant sealant collected due to high amounts of leakage

The poor performance of the sealing process at California residence 102 was likely attributed to large leak paths that were not sealed adequately by the aerosol product. In general, the protocol is to manually address leaks that are larger than about 3/8 in. along their smallest dimension to improve the efficiency of the aerosol process. After reflecting on the experience sealing this site, it is apparent that leaving large openings without identifying the size of leaks within those cavities can lead to poor results. When large leaks are present, the aerosol process takes longer to seal, and more sealant is injected resulting in higher material costs and potential for unwanted deposition. Moreover, the larger leaks tend to draw sealant away from smaller leaks, making it challenging to produce uniform sealant distribution. It is recommended to temporarily cover larger openings unless the leak paths can be identified as appropriate for aerosol sealing. In the case of California residence 102, covering the HVAC and open wall cavity would likely have improved the aerosol sealing performance. Those locations would then need to be addressed with alternative sealing strategies. The average sealing result not including this site would have been over 60% for the remaining single-family homes.

4.1.2 Minnesota Houses

Of the 12 single-family homes sealed in Minnesota, four were undergoing major renovations, three were undergoing minor renovations, and five were changing occupancy (Table 5). Ten homes were built before 1961, with four built before 1916. The floor areas ranged from 1,092 to 3,398 ft^2 and averaged 1,969 ft^2. Three had finished upper levels and the rest had peaked, vented attics. Three were single-story. All had basements, and two homes had a combination of basements and crawlspaces. Because these homes were built with basements, the floor covering process did not require continuous sealing around the perimeter, saving some time on preparation.

Table 5. Key Characteristics: Minnesota Houses

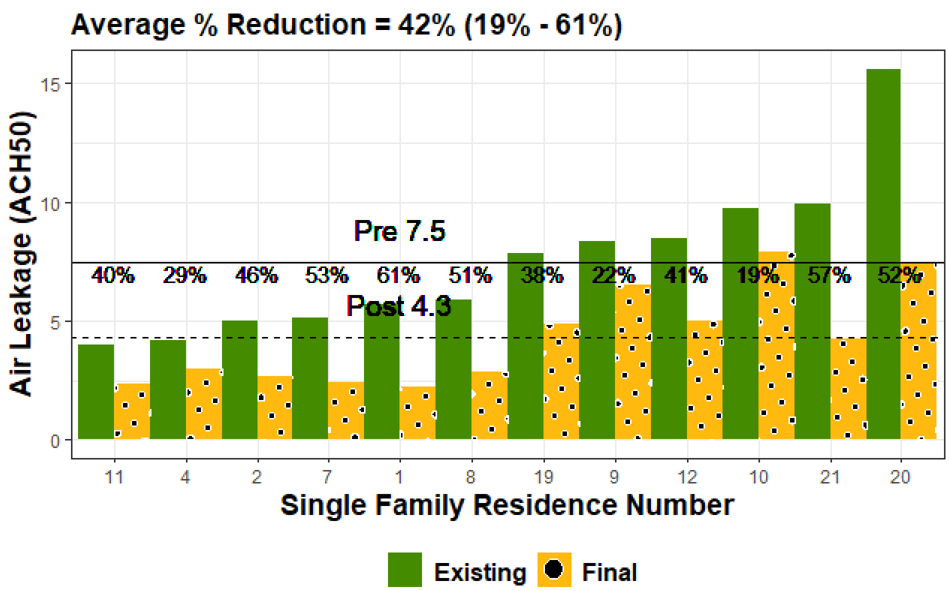
Res. #	Floor Area (ft^2)	# Stories	Foundation	Garage	House Status	Year of Construction
1	2,551	2	Basement	Detached	Major Renovation	1915
2	1,198	1	Base & CS*	Attached	Major Renovation	1960
4	3,398	split	Basement	Attached	Occupancy Change	1987
7	2,132	1	Basement	Detached	Occupancy Change	1957
8	1,768	3	Basement	Detached	Major Renovation	1904
9	1,565	2	Basement	Detached	Occupancy Change	1909
10	1,852	2	Basement	Detached	Occupancy Change	1909
11	2,773	2	Basement	Attached	Major Renovation	1948
12	1,092	1	Basement	Basement	Occupancy Change	1975
19	2,320	1.5	Basement	Attached	Minor Renovation	1950
20	1,487	1.5	Basement	Detached	Minor Renovation	1951
21	1,488	2	Base & CS*	Attached	Minor Renovation	1967

*Base & CS – combination of a basement and crawlspace

Table 6 and Figure 21 show the pre- and post-seal leakage results for the homes. Before the houses were sealed, the house leakage ranged from 4.0 ACH_{50} to 15.6 ACH_{50} and averaged 7.5 ACH_{50}. The leakage reduction ranged from 19% to 61% and averaged 42%. The average Minnesota reduction was 11 percentage points below the California average. After sealing, the leakage ranged from 2.2 ACH_{50} to 7.9 ACH_{50} and averaged 4.3 ACH_{50}. Compared to the California houses, the initial leakage was 38% lower and the final leakage was 22% lower. Consistent with the results for the California houses, the percent leakage reduction immediately before and after sealing was always greater than or equal to the leakage before or after leakage reduction when the surface preparation was not in place. Section 4.4 discusses the impact of leakage test methods, surface preparation, and intentional leaks in more detail.

Table 6. Air Leakage Results: Minnesota Houses (ACH_{50})

Res. #	Existing	Post-prep	Post-aero	Final	Post-prep – Post-aero		Existing – Final	
					(ACH_{50})	(%)	(ACH_{50})	(%)
1	5.68	4.56	1.39	2.20	3.17	69%	3.49	61%
2	4.97	5.35	1.99	2.68	3.36	63%	2.30	46%
4	4.17	4.66	2.36	2.97	2.30	49%	1.20	29%
7	5.14	4.60	1.29	2.42	3.31	72%	2.72	53%
8	5.91	5.06	2.45	2.87	2.60	51%	3.04	51%
9	8.36	8.24	3.25	6.53	4.99	61%	1.83	22%
10	9.72	9.50	5.96	7.89	3.54	37%	1.83	19%
11	3.97	3.54	0.97	2.38	2.57	73%	1.60	40%
12	8.47	9.91	3.35	4.98	6.56	66%	3.50	41%
19	7.86	6.73	3.58	4.90	3.15	47%	2.96	38%
20	15.62	12.94	3.42	7.49	9.51	74%	8.14	52%
21	9.92	9.69	2.03	4.27	7.66	79%	5.66	57%
Min.	3.97	3.54	0.97	2.20	2.30	37%	1.20	19%
Max.	15.62	12.94	5.96	7.89	9.51	79%	8.14	61%
Med.	6.89	6.04	2.40	3.62	3.34	64%	2.84	44%
Avg.	7.48	7.07	2.67	4.30	4.39	62%	3.19	42%



The percent reductions are based on multipoint depressurization tests conducted before and after the sealing with no surface preparation or temporary seals in place.

Figure 21. Air sealing results for single-family homes sealed in Minnesota

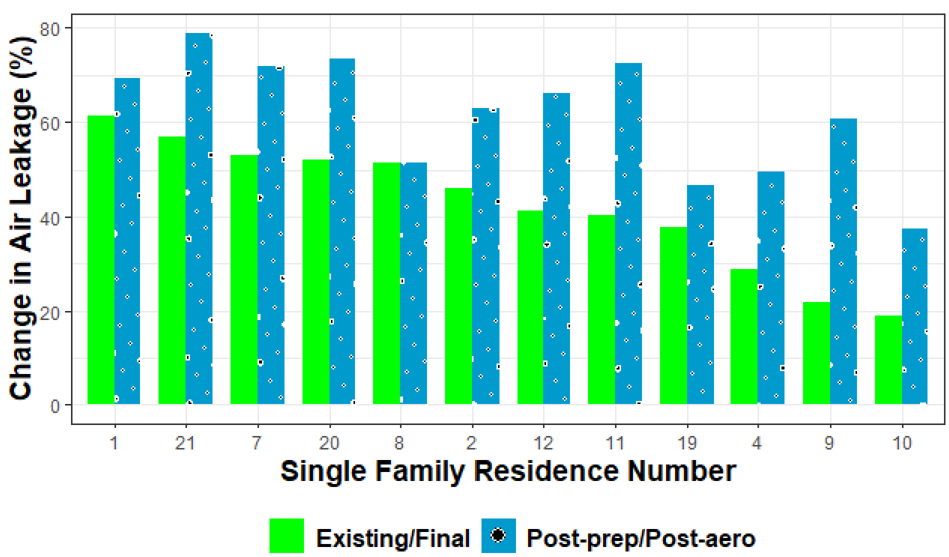


Figure 22. Comparison of percentage air leakage reductions of Minnesota single-family homes

Figure 23 displays a box and whisker chart of the 15-minute average sealing rate for the 12 Minnesota houses. The sealing profile is somewhat similar to that of the California houses, but there are many differences. Like the California houses, the rate of sealing was greatest at the start of the sealing and gradually decreased over time. Overall, the median sealing rate for the first 15 minutes was 12.1 CFM_{50}/min (2.5 ACH_{50}/h) and that dropped by 6% to 11.4 CFM_{50}/min (2.1 ACH_{50}/h) for the 30-to-45-minute time period. The initial sealing rate for the Minnesota houses was about four times less than that of the California houses, but after the first 30 minutes the rates were about the same. One reason for the low initial sealing rate for the Minnesota houses is that there was more variation in the sealing profile over the first 45 minutes. Five of the houses had a more than 50% decrease in sealing rate from the first 15 minutes to the 30-to-45-minute time period; three houses had a greater than 20% increase, and four had less than a 20% change in the sealing rate. In contrast, the decrease in the sealing rate was greater than 40% for all five California houses. Due to the higher initial sealing rate, the total sealing time was 90 minutes or less for three of the five California houses. All the Minnesota houses had sealing times greater than 90 minutes and the sealing was longer than 120 minutes for eight of the twelve houses.

There were many reasons for the lower initial sealing rate for the Minnesota houses. The crews were using a new version of the equipment which required some troubleshooting for the earlier houses. Some houses were sealed in colder weather, which required modifications to the equipment setup. In addition, the protection had to be reinstalled for a few of the houses. Also, it is possible that a larger portion of the leakage for the Minnesota houses had wider gaps that required longer sealing or could not be sealed. This suggests that additional pre-aerosol sealing leakage investigation and manual sealing may be required for Minnesota houses.

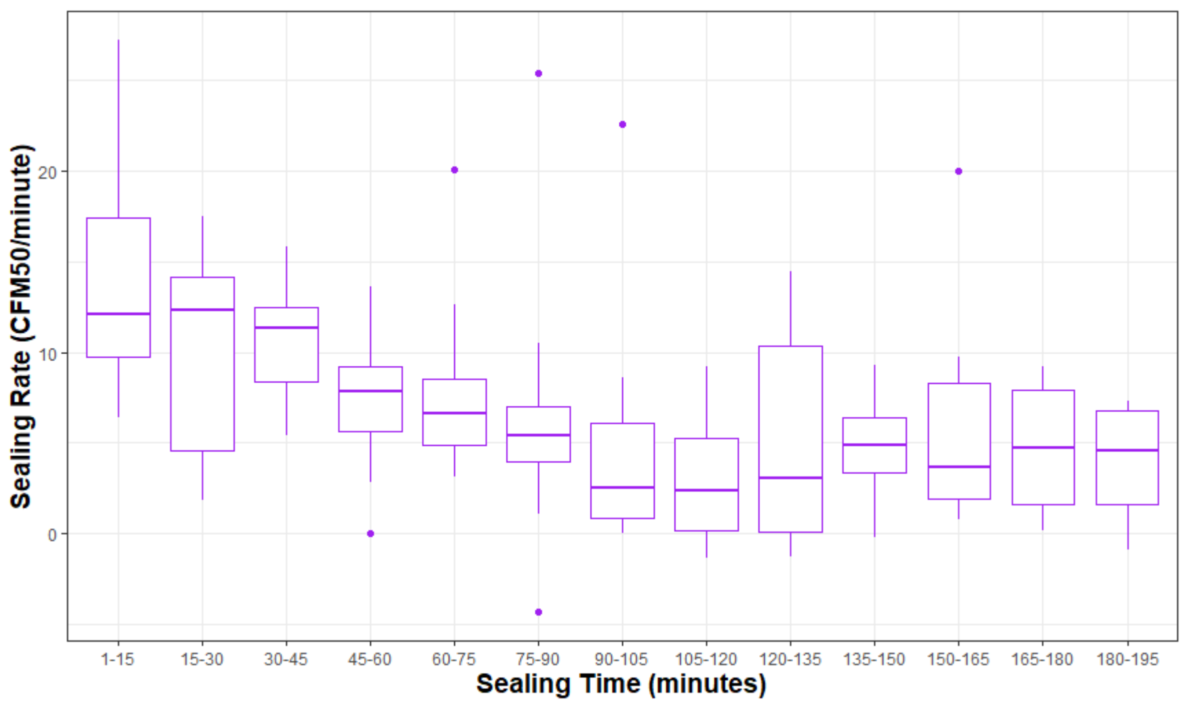


Figure 23. Aerosol sealing rate for 12 Minnesota single-family homes

The sealing process for Minnesota residence 7 was fairly typical of the Minnesota houses. It is a three-bedroom, one-story house built in 1957 with a finished basement, detached garage, and floor area of 2,132 ft^2. Figure 24 shows the sealing profile and Figure 25 shows air leakage test results. The sealing rate started between 10 and 15 CFM_{50}/min and decreased gradually. After 95 minutes, the sealing was still above 5 CFM_{50}/min, so the system was paused for 15 minutes to refill some sealant containers.

The initial leakage was 5.1 ACH_{50} and was reduced by 2.7 ACH_{50} (53%) to 2.4 ACH_{50}. There was a 72% reduction in leakage from the start to the end of the aerosol sealing, which was above the average of 62% for Minnesota houses. The measurements showed a reduction of only 0.54 ACH_{50} (10%) from the initial depressurization test to the AeroBarrier pressurization test prior to aerosol sealing. That is less than the reduction observed in all of the California houses with raised foundations where the floors had to be fully protected. The leakage increased by 1.12 ACH_{50} (22%) when the surface protection was removed. The difference between the leakage reduction when the preparations were put in place (0.54 ACH_{50}) and the leakage increase when the preparations were removed (1.12 ACH_{50}) suggests that some aerosol seals were disturbed when the preparations were removed. Minimizing that difference would improve sealing effectiveness. This issue is examined in greater detail in section 4.4.

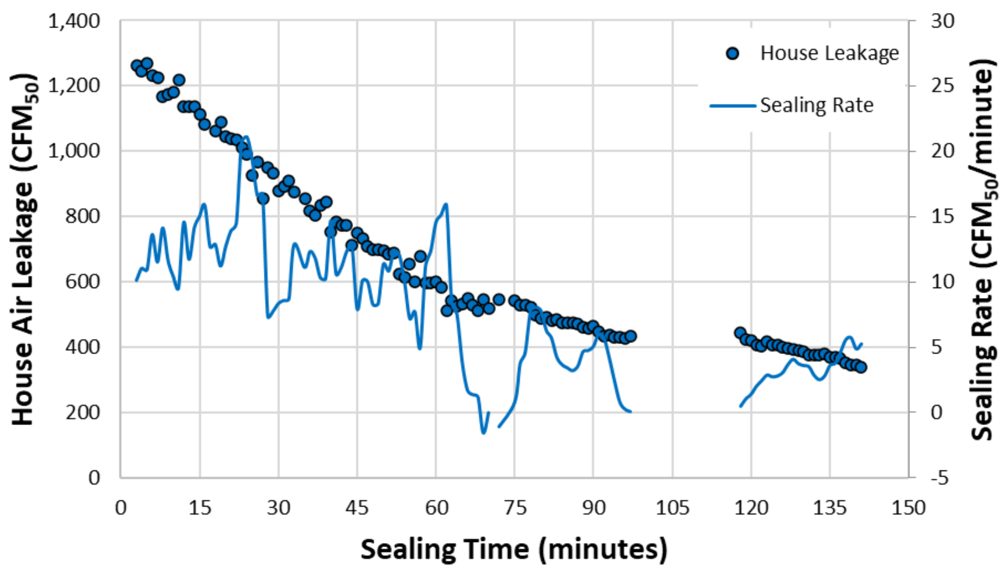


Figure 24. Sealing profile for Minnesota residence 7

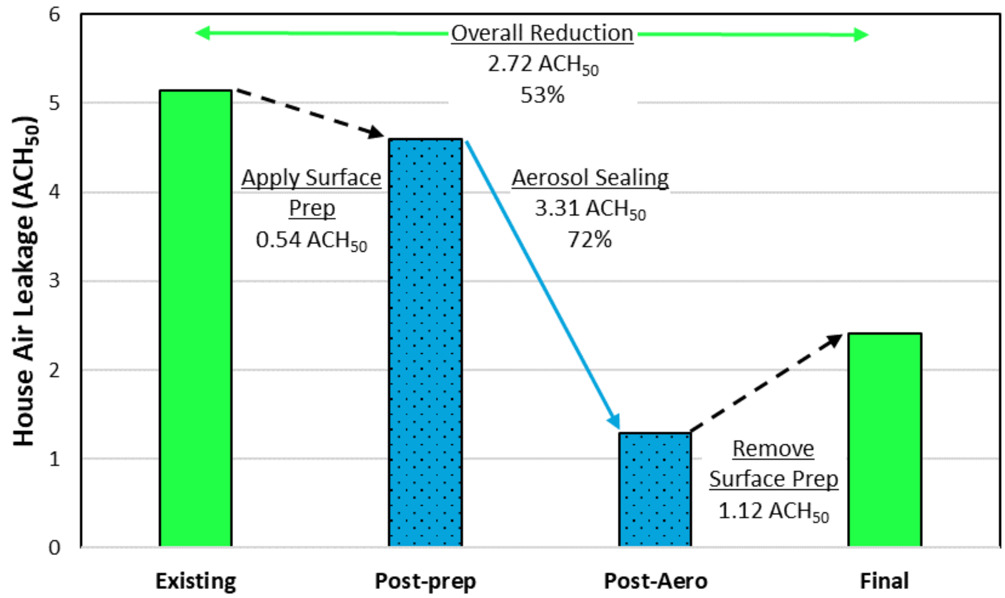


Figure 25. Leakage results summary for Minnesota residence 7

Attic leakage zone pressure diagnostics and exterior duct measurements were conducted before and after aerosol sealing to help evaluate the distribution of house leakage and the reduction of the leakage paths from aerosol sealing. The measurements suggest that the leakage reductions were similar for the attic, exterior duct, and other locations (Figure 26). The initial attic leakage is estimated to be responsible for 60% of the total. The reduction to 54% was not statistically significant. The uncertainty of the pre-sealing attic leakage was 340 CFM_{50} (39%) and it was over 100% for the post-sealing measurement.[4] The heating system ductwork was almost entirely within the envelope. Before sealing the exterior duct, leakage was only 29 CFM_{50} and that was reduced by 52% to 14 CFM_{50}.

[4] With the attic hatch closed, the pre-sealing attic-to-outside induced pressure change was -4.8 Pa for a house pressure of -50 Pa. That was reduced to -1.1 Pa after sealing. The low induced attic pressure change results in high uncertainty.

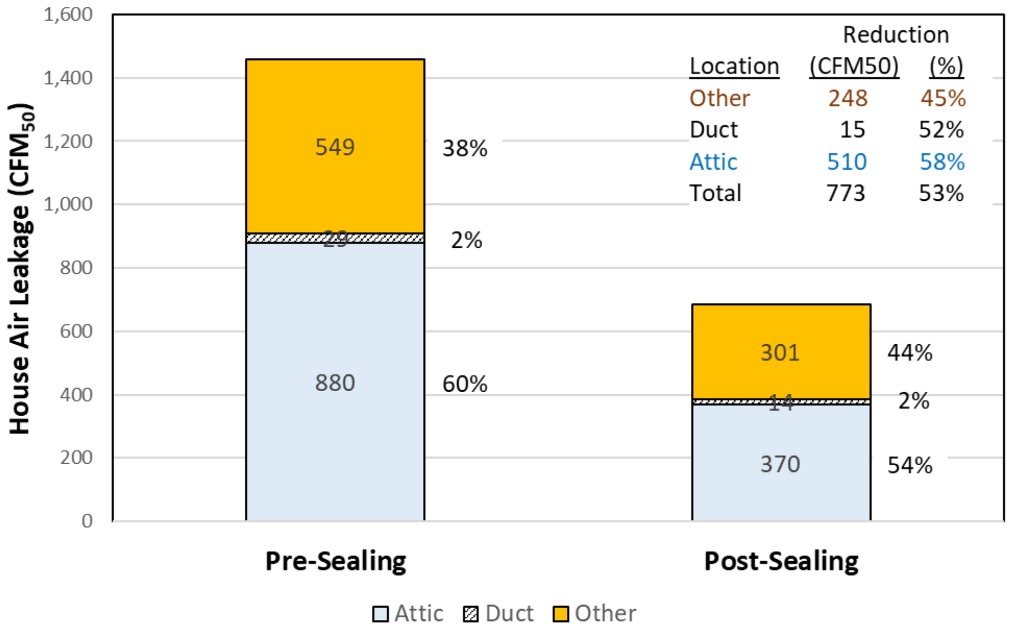


Figure 26. ZPD attic and exterior duct leakage results for Minnesota residence 7

Figure 27 through Figure 32 display infrared and visual images from before and after the sealing. The images were recorded when the outside temperature was lower than the inside temperature and the blower door depressurized the house. Cooler surface temperatures[5] indicate air leakage. The first three infrared images from before and after sealing show a reduction in leakage at an interior wall top, exterior wall light switch, and exterior door/wall top. Figure 30 and Figure 31 show that the interior plumbing wall was not sealed, either because the sealant deposited on other surfaces before it reached the leakage at the attic penetration or because the gap in the leak was too large. These leaks need to be identified prior to sealing and sealed manually. Figure 32 indicates that the basement rim joist was not sufficiently sealed. It was sometimes difficult to clear a sufficiently large path for the sealant to reach basement rim joists. It is even more challenging for sealant to reach upper floor band joist leakage. When a pre-aerosol sealing inspection indicates that there is significant air leakage in areas where the aerosol sealant particles will likely impact materials rather than be transported to the leakage location, it would be necessary to create openings to the leakage areas.

[5] White/yellow = warmer and purple/blue = cooler.

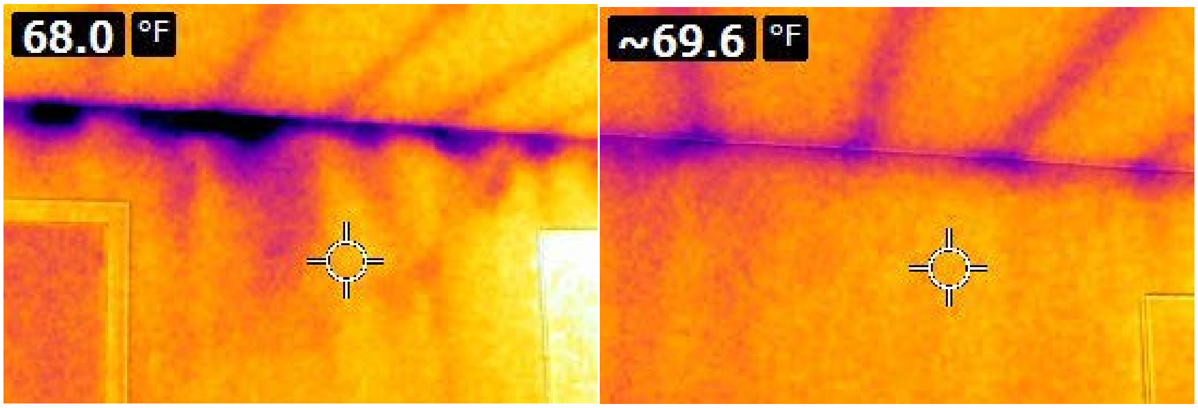


Figure 27. Dining room interior wall top plate leakage reduced from before (left) to after sealing (right)

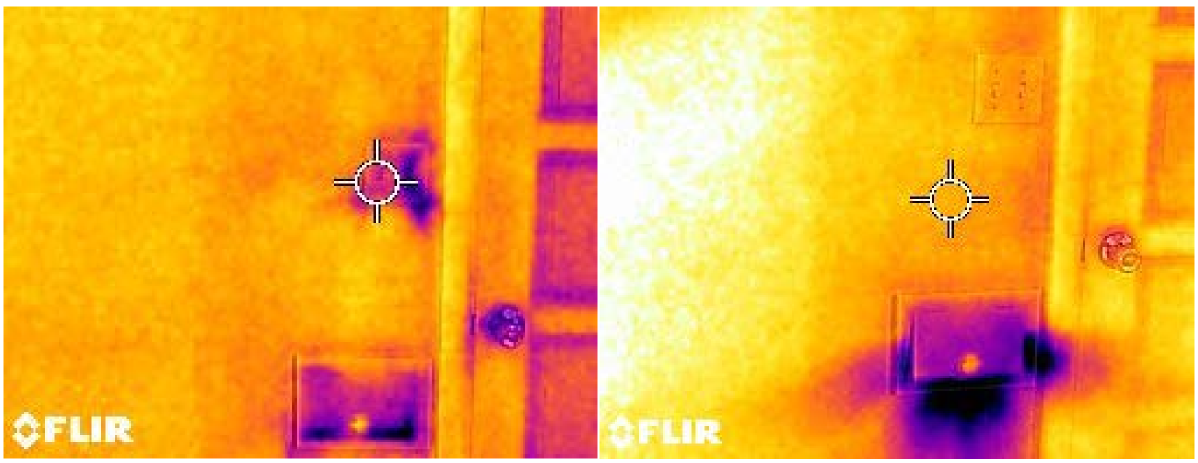


Figure 28. Exterior wall light switch leakage reduced from before (left) to after sealing (right). Mailbox in lower portion of image was purposely not sealed

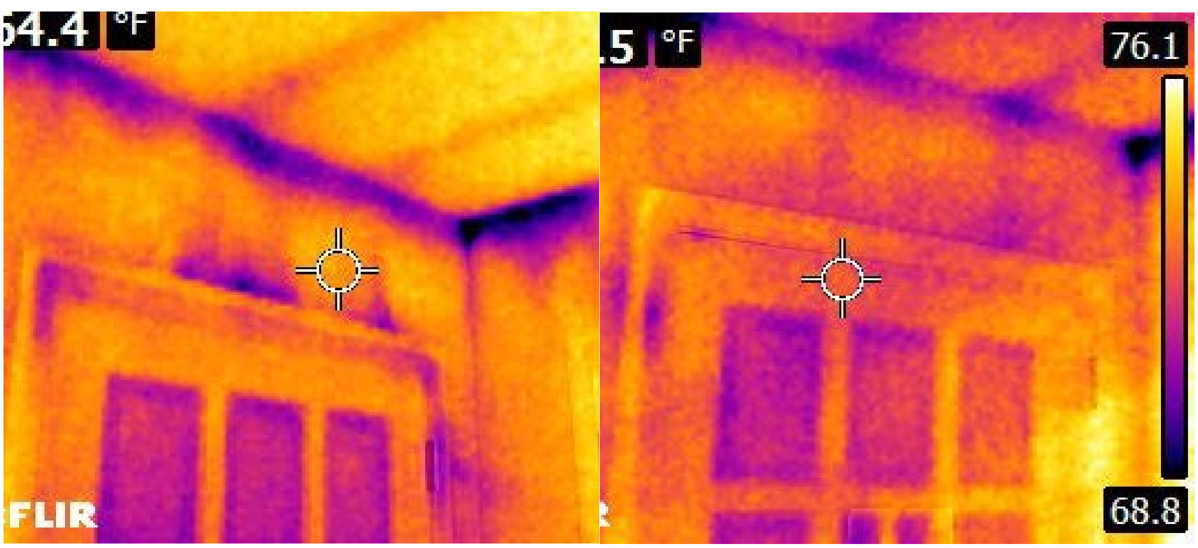


Figure 29. Front door trim and top plate leakage reduced from before (left) to after sealing (right)

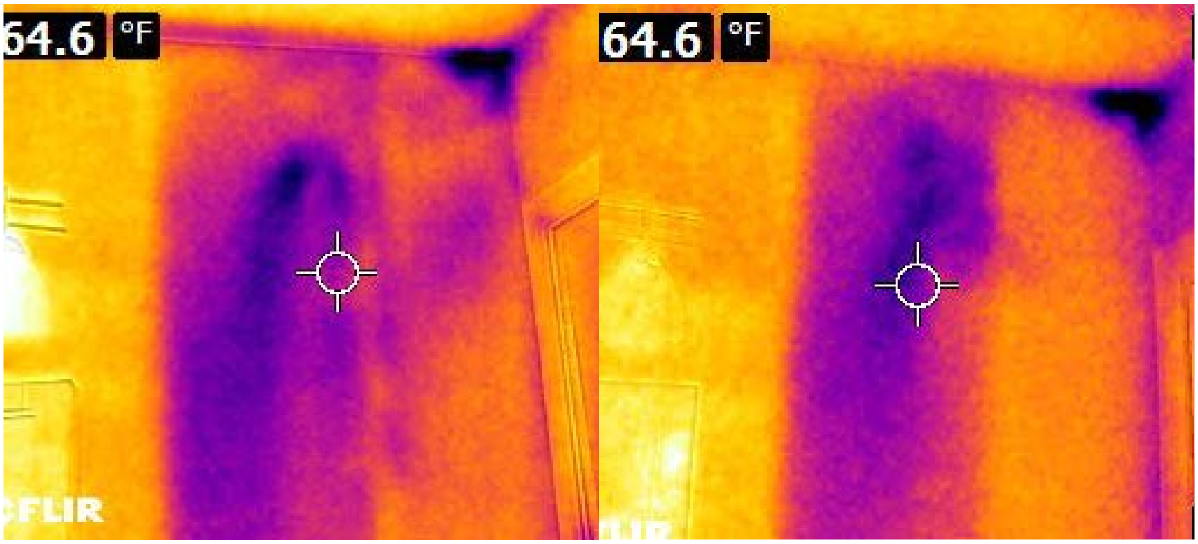


Figure 30. No change in bathroom plumbing wall leakage from before (left) to after (right)

Figure 31. View of plumbing wall from basement where sealant deposition indicates air leakage up the wall

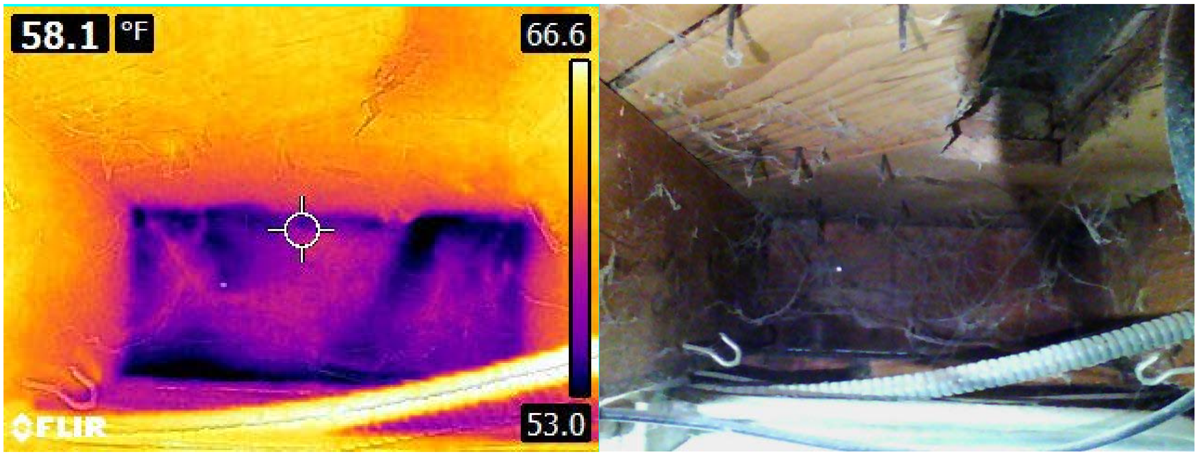


Figure 32. Post-sealing infrared and visual image of basement rim joist showing air leakage and limited sealant deposition

The aerosol sealing was not as successful for Minnesota residence 9 (Figure 33). It is a three-bedroom, two-story house built in 1909 with an unfinished basement, detached garage, and floor area of 1,565 ft^2. Figure 34 shows the sealing profile and Figure 35 shows air leakage test results. The sealing rate started between 20 and 35 CFM_{50}/min and decreased gradually. After 90 minutes, the rate decreased to about 5 CFM_{50}/min and the leakage measured by the AeroBarrier system had dropped by about 60%, so the sealing was stopped.

The initial leakage was 8.36 ACH_{50} and was reduced by 1.8 ACH_{50} (22%) to 6.5 ACH_{50}. There was a 61% reduction in leakage from the start to the end of the aerosol sealing, which was near the average of 62% for Minnesota houses. The measurements showed a reduction of only 0.12 ACH_{50} (1%) from the initial depressurization test to the AeroBarrier pressurization test prior to aerosol sealing. The leakage increased by 3.28 ACH_{50} (39%) when the surface protection was removed. The difference between the leakage reduction when the preparations were put in place (0.12 ACH_{50}) and the leakage increase when the preparations were removed (3.28 ACH_{50}) suggests that more than half of the aerosol seals were disturbed when the preparations were removed. This issue is examined in greater detail in section 4.4.

Figure 33. Front view of Minnesota residence 9

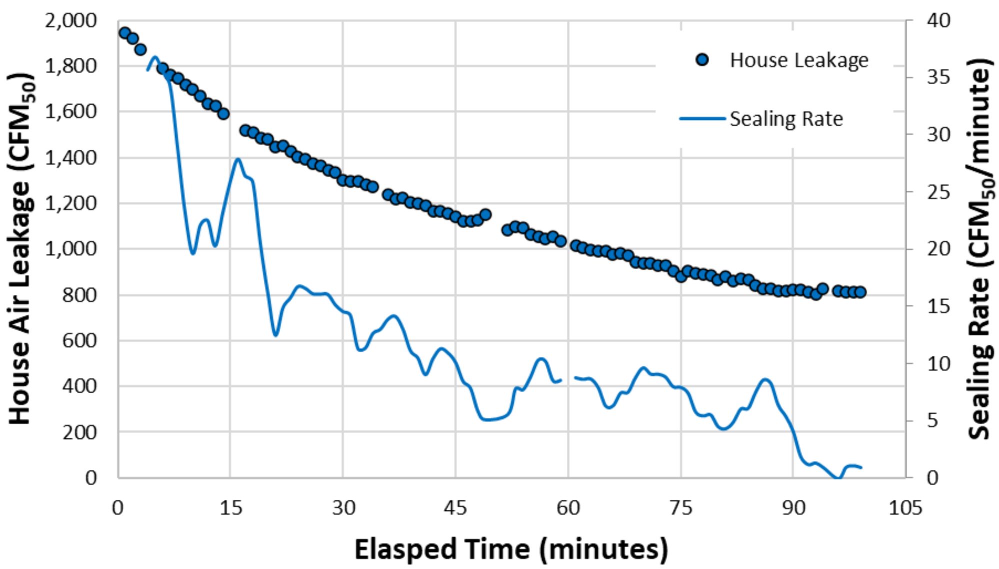


Figure 34. Sealing profile for Minnesota residence 9

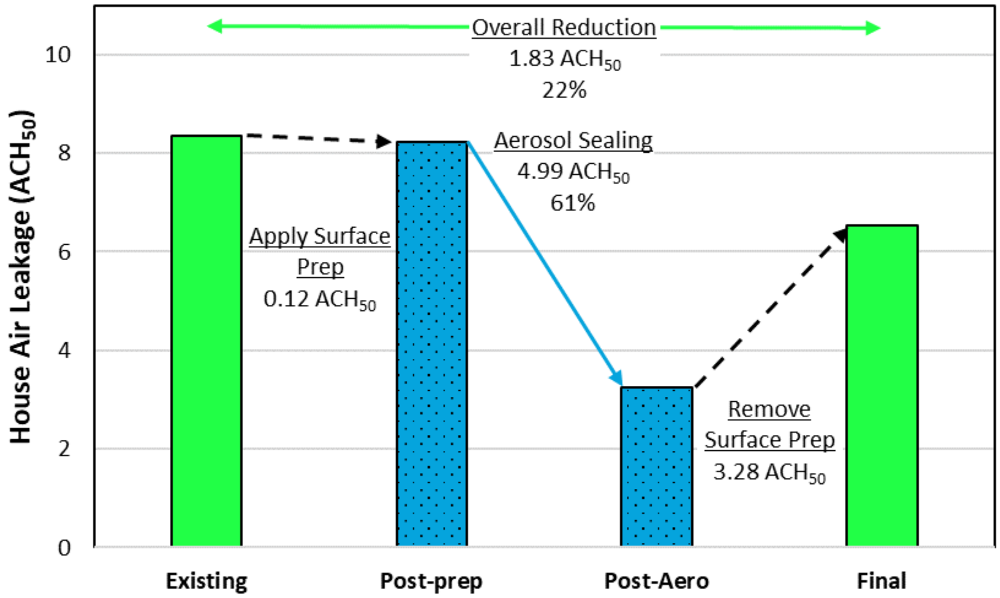


Figure 35. Leakage results summary for Minnesota residence 9

Attic leakage ZPD measurements were conducted before and after aerosol sealing to help evaluate the distribution of house leakage and the reduction of the leakage paths from aerosol sealing. The measurements suggest that the leakage reduction was similar for the attic and other areas of leakage (Figure 36). The initial attic leakage is estimated to be responsible for 32% of the total. The attic leakage was about half that measured for residence 7. However, for residence 9, the second-floor ceiling area constitutes a much lower portion of the exterior envelope area. Residence 9 has two stories and only a peak attic over the second floor. In addition, the uncertainties of the computed attic leakage are 73% of the reported value for the pre-sealing condition and 108% for post-sealing.

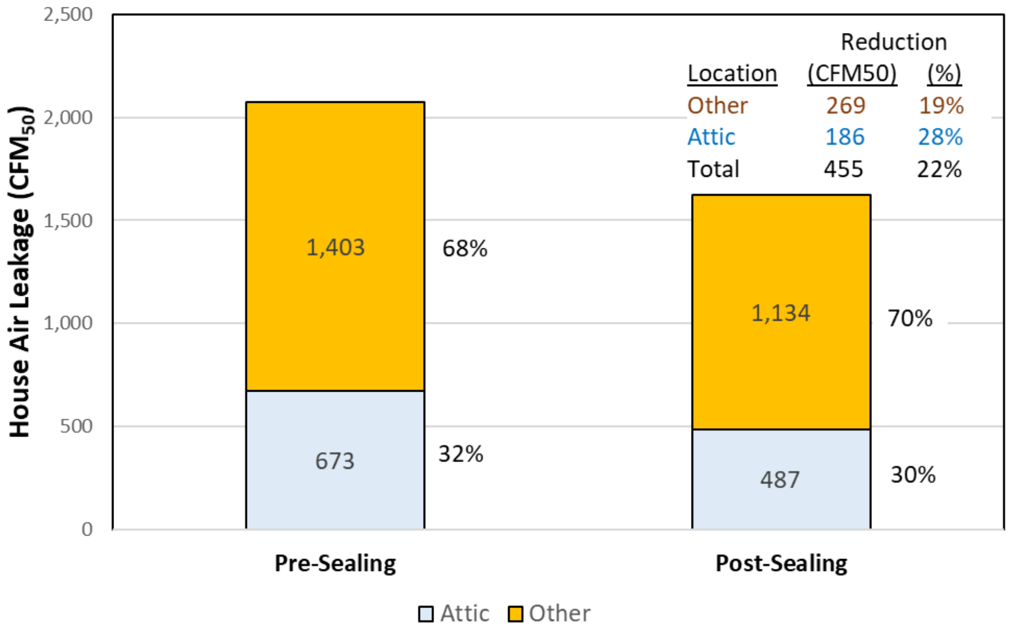


Figure 36. ZPD attic leakage results for Minnesota residence 9

Figure 37 displays infrared and visual images from before and after the sealing for a section of the basement rim joist. The images were recorded when the outside air temperature was above that of the inside. Air leakage is indicated by warmer surface temperature. The lower outside-to-inside air temperature difference makes it more challenging to interpret the images. However, a scan of multiple areas indicated reduced air leakage through the rim joist area after aerosol sealing. The joist area was somewhat more accessible for this house than for residence 7, which likely allowed for greater aerosol sealing. This suggests that aerosol sealing of rim joists can be effective when there is appropriate access. The infrared scans indicated that there were other leakage paths that were not sealed. These included multiple leakage paths into an attached porch and leakage through an eyebrow roof over a bay window. If the aerosol does not seal the interior location of the leakage path (which appears to be the case for those leaks), another method other than aerosol sealing is necessary to seal the leaks. Some houses will have more leakage paths that cannot be addressed with aerosol sealing.

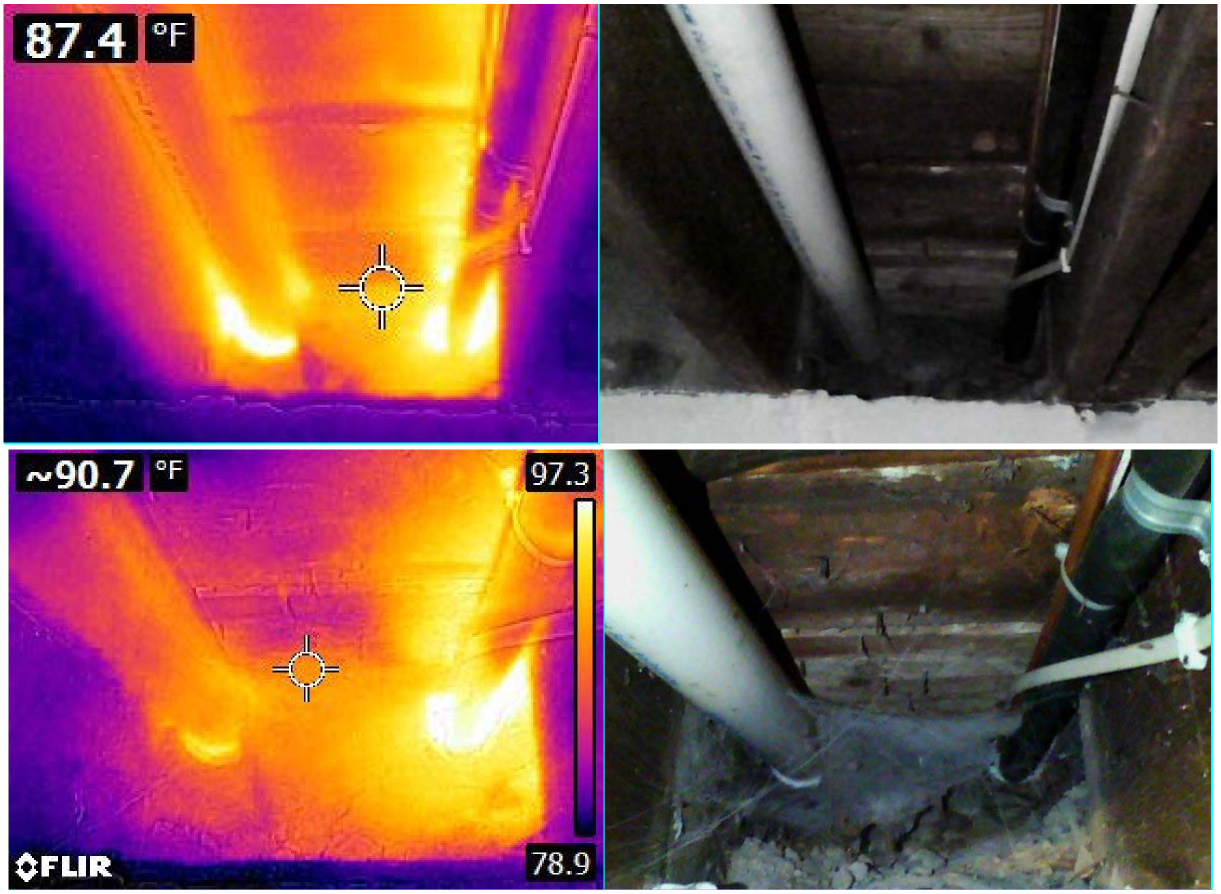


Figure 37. Pre- (top) and post- (bottom) sealing infrared and visual images of basement rim joist showing reduced air leakage through penetrations and joints

4.2 Interior Sealed Multifamily Units

There were six California multifamily units and nine Minnesota houses sealed from the interior space. All six units in California were located in the same apartment building. The nine Minnesota units consisted of three townhouses, as well as six units in one high-rise apartment building. The average floor area of the Minnesota apartment units was 52% less than the California average. The average floor area of the Minnesota townhouses was 6.8 times the average of the Minnesota apartment units. The average leakage of the California apartment units was 8.9 ACH_{50}; the average for the Minnesota apartment units was 10.9 ACH_{50}, and the average for the three townhouses was 7.4 ACH_{50} (Figure 38). Because the California units came from a single building and the Minnesota apartment units were from a single building in addition to three townhouses, the results for the California and Minnesota units are presented separately.

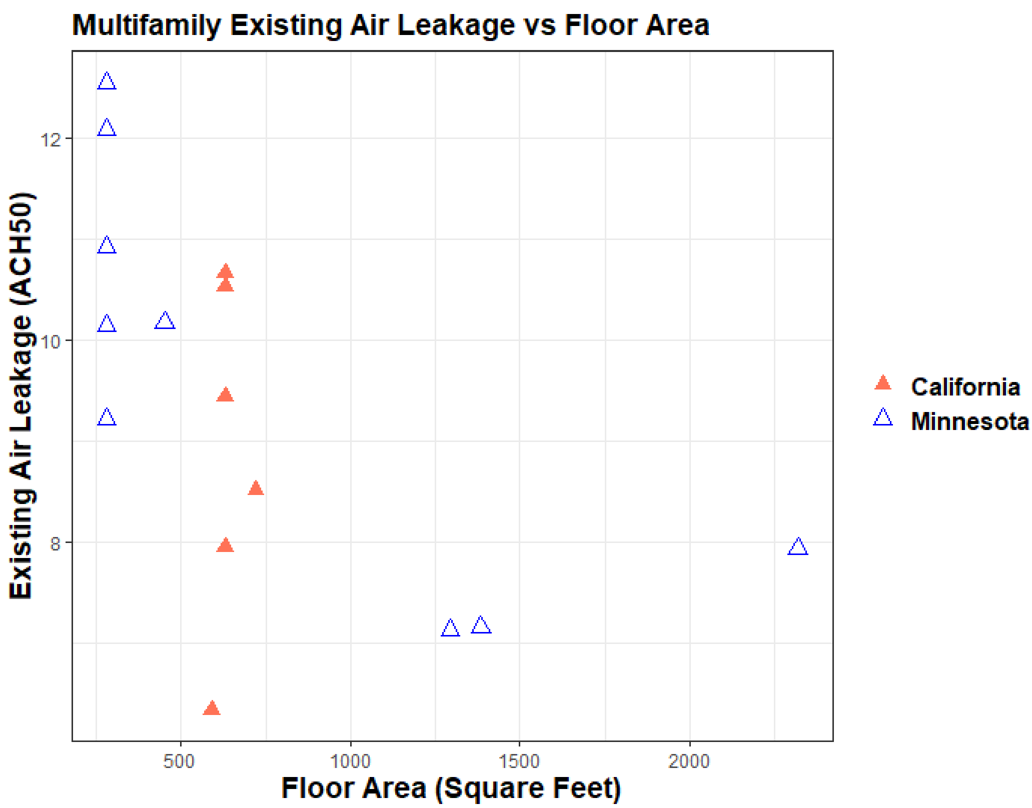


Figure 38. Multifamily unit air leakage and floor area for the California and Minnesota houses

4.2.1 California Multifamily Units

The apartments that were sealed were part of a mixed-use building built in 2001, with apartment units above a commercial space on the ground floor (Figure 39). The building was undergoing a major renovation that included replacement of flooring, appliances, counters and cabinets, HVAC, and interior paint. The sealing in three of the units occurred after much of the demo and paint, requiring significantly less surface preparation. The floor area for the apartments ranged from 590 to 720 ft^2 and averaged 638 ft^2 (Table 7). The duct systems for heating and cooling were disconnected in some apartments, and therefore temporarily sealed for the pre- and post-air leakage measurements.

Figure 39. West apartment building

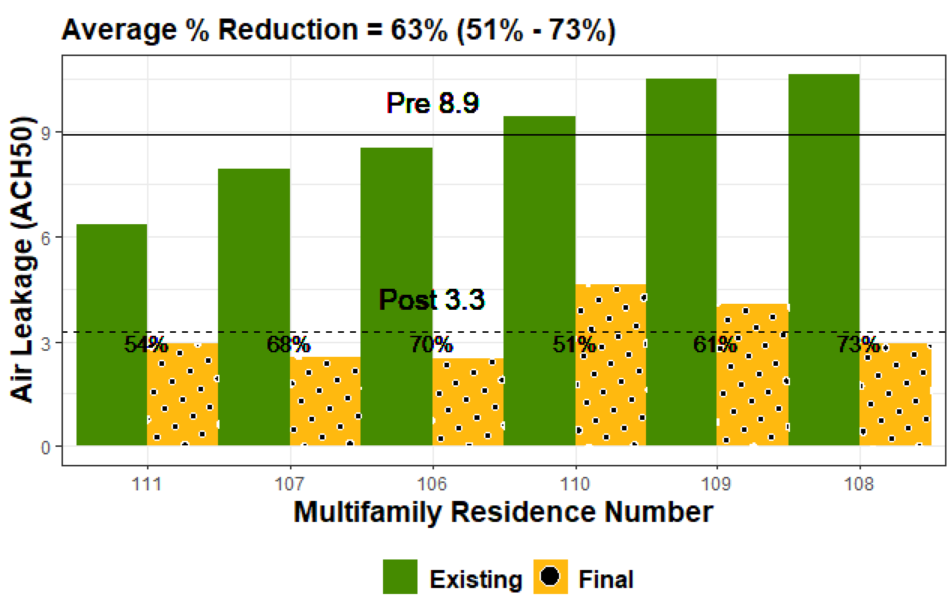
Table 7. Key Characteristics: California Multifamily Units

Res. #	Floor Area (ft^2)	Type	# Bedrooms	Unit Status	Year of Construction
106	720	Apartment	2	Major Renovation	2001
107	630	Apartment	1	Major Renovation	2001
108	630	Apartment	1	Major Renovation	2001
109	630	Apartment	2	Major Renovation	2001
110	630	Apartment	1	Major Renovation	2001
111	590	Apartment	1	Major Renovation	2001

Due to the minimal surface protection, the overall envelope leakage reductions were greater than those of the single-family homes. The average leakage reduction was 64%, from an average initial leakage of 9.2 ACH_{50} to a final average leakage of 3.3 ACH_{50} (Table 8 and Figure 40). Consistent with the results for the single-family houses, the percent leakage reduction immediately before and after sealing was always greater than or equal to the overall leakage reduction when the surface preparation was not in place (see Table 8). The average percent reduction immediately before and after aerosol sealing was 80%, or 16 percentage points greater than the reduction based on the existing and final leakage measurements without surface protection. Section 4.4 discusses the impact of leakage test methods, surface preparation, and intentional leaks in more detail.

Table 8. Air Leakage Results: California Multifamily Units (ACH_{50})

Res. #	Existing	Post-prep	Post-aero	Final	Post-prep – Post-aero		Existing – Final	
					(ACH_{50})	(%)	(ACH_{50})	(%)
106	9.13	7.31	1.31	2.53	6.00	82%	6.60	72%
107	8.85	6.97	1.57	2.56	5.40	77%	6.29	71%
108	11.03	9.15	1.40	2.92	7.74	85%	8.10	73%
109	10.53	7.66	1.83	4.06	5.83	76%	6.48	61%
110	9.44	6.76	1.21	4.60	5.55	82%	4.84	51%
111	6.35	6.26	1.54	2.93	4.72	75%	3.42	54%
Min.	6.35	6.26	1.21	2.53	4.72	75%	3.42	51%
Max.	11.03	9.15	1.83	4.60	7.74	85%	8.10	73%
Med.	9.28	7.14	1.47	2.92	5.69	80%	6.38	66%
Avg.	9.22	7.35	1.48	3.27	5.87	80%	5.95	64%



The percent reductions are based on multipoint depressurization tests conducted before and after the sealing with no surface preparation or temporary seals in place.

Figure 40. Air sealing results for multifamily units sealed in California

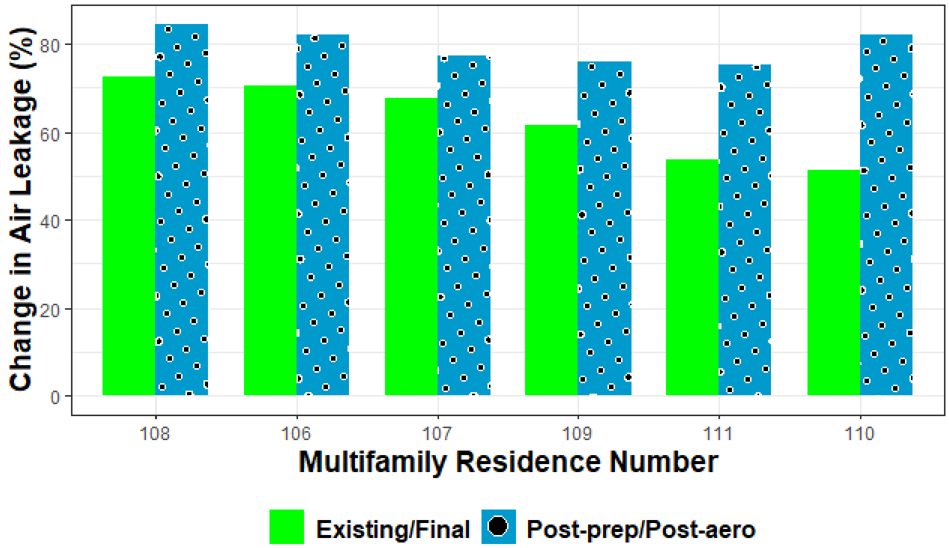


Figure 41. Comparison of percent air leakage reductions of California multifamily units

Figure 42 displays a box and whisker chart of the 15-minute average sealing rate for the five California multifamily units. The sealing profile is similar to that of the California houses except that the rates are lower. The median sealing rate of 16 CFM_{50}/min (10 ACH_{50}/h) for the first 15 minutes was about three times lower than that of the houses. This was partly due to the smaller size of the multifamily units. The rate for the first 15 minutes dropped by 62% for the 30-to-45-minute period which was slightly lower than the 73% drop for the houses. The median sealing rate dropped below 8 CFM_{50}/min after 45 minutes and all units were sealed by the end of 90 minutes.

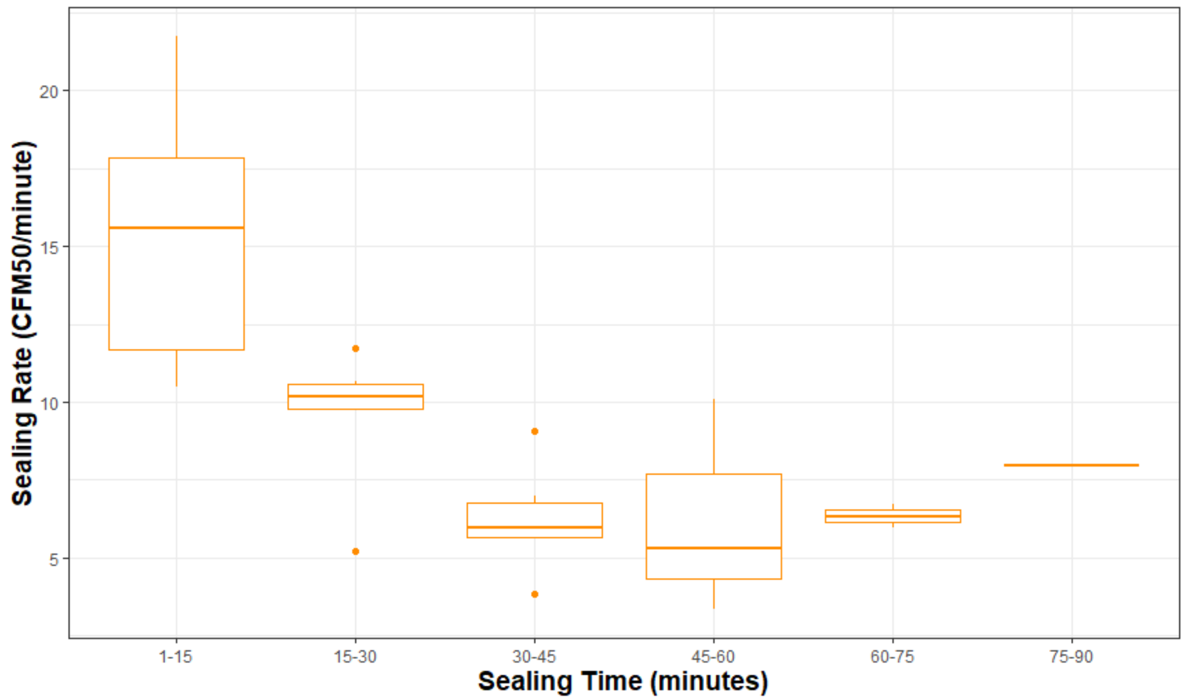


Figure 42. Aerosol sealing rate for five California multifamily units

The preparation for aerosol sealing in the multifamily installations in California was similar to new construction due to the types of renovation activities being performed. The floors were not covered, kitchen appliances were removed, and only a few finished surfaces needed to be protected. The biggest challenge was working with the building owner and other trades to coordinate the sealing effort within the overall retrofit. For example, the aerosol application occurred with the existing carpet in place. It would have been preferable to seal the home after the carpet was removed to avoid potentially disturbing seals at the baseboard during removal. In some cases, new cabinets installed prior to sealing required additional prep work. The ideal scenario would be removing the flooring as part of the demolition phase and reinstalling after cabinet work.

The preparation, sealing, and cleanup for all six units was completed in just two days. When sealing multiple apartments in the same building, installation staff could work on preparing (or cleaning) one unit while another was sealing, increasing the efficiency of the sealing work. When arriving on-site, the AeroBarrier contractor used a three-man crew to set up the trailer and unload equipment for the first hour to prepare for the sealing. The preparation for the first apartment was complete in a little over an hour. The nozzles were placed and sealant equipment set up, including installation of the blower door and power for the fan and heaters. The equipment was set up in under an hour. It took about three hours from arriving on site to beginning the sealing process.

While sealing the first apartment, one team member started preparing the second unit and was ready to seal by the time the first apartment finished sealing. The AeroBarrier control station was positioned such that all apartments could be sealed from that central point. After the first unit sealed, it took about 30 minutes to move the nozzles, run a pretest, and begin sealing the second apartment. At that point, the first apartment was cleaned up and the same process was repeated for the remaining apartments.

4.2.2 Minnesota Multifamily Units

Six of the multifamily homes sealed for this project were in the same building, built in 1975, which was undergoing a major renovation (Minnesota residences 13–18; Figure 43). The flooring and cabinets were being replaced and sections of drywall cut out as needed for electrical upgrades. These were mostly small studio apartments of only 280 ft^2 and one single bedroom apartment that was 452 ft^2. The sealed units were in one vertical stack on floors two through four, six, eight, and nine. The other three multifamily homes (Minnesota residences 3, 5, and 6) were townhouse apartments with floor areas ranging from 1,294 to 2,319 ft^2 and averaging 1,666 ft^2. Two of the townhouses were sealed during a change of occupancy and the third (residence 6) was undergoing major renovation to sections of the unit.

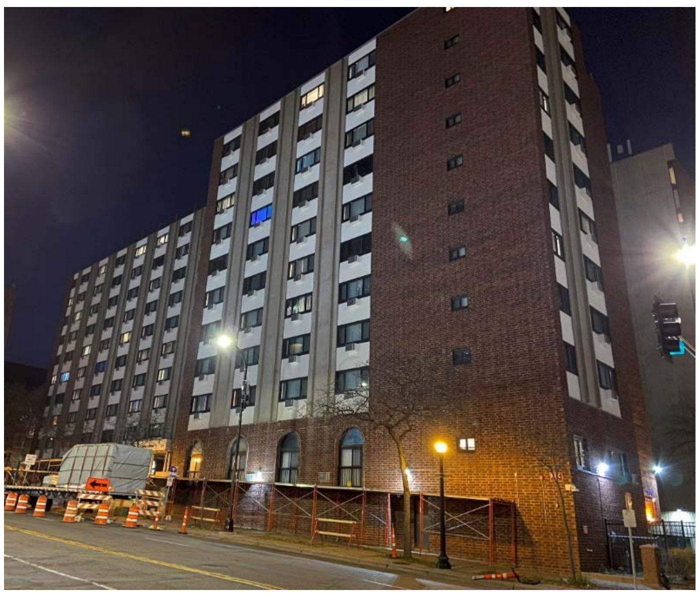


Figure 43. Minnesota multifamily apartment building

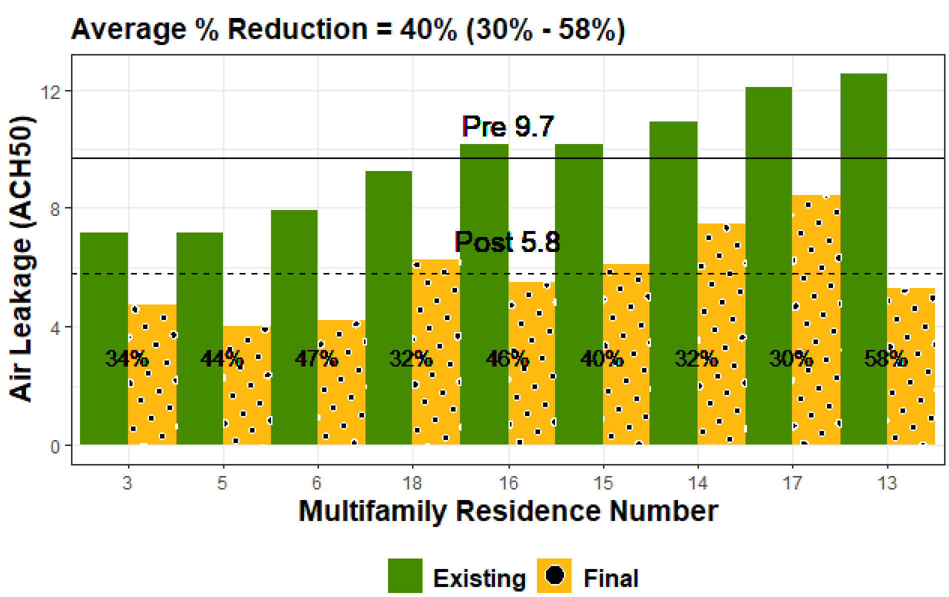
Table 9. Key Characteristics: Minnesota Multifamily Units

Res. #	Floor Area (ft^2)	Type	# Bedrooms	Garage	Unit Status	Year of Construction
3	1,294	Townhouse	3	Attached	Occupancy Change	1995
5	1,384	Townhouse	3	Attached	Occupancy Change	1999
6	2,319	Townhouse	2	Attached	Major Renovation	1979
13	280	Apartment	Studio	NA	Major Renovation	1975
14	280	Apartment	Studio	NA	Major Renovation	1975
15	452	Apartment	1	NA	Major Renovation	1975
16	280	Apartment	Studio	NA	Major Renovation	1975
17	280	Apartment	Studio	NA	Major Renovation	1975
18	280	Apartment	Studio	NA	Major Renovation	1975

Table 10 and Figure 44 show the pre- and post-seal leakage results for the nine Minnesota multifamily units. This section will first describe the results for the six apartment units, then the three townhouses. The average starting leakage of the six apartment units was 10.9 ACH_{50}. Aerosol sealing reduced the leakage by an average of 4.4 ACH_{50} (40%) to 6.5 ACH_{50}. The average reduction was similar to the average of 42% for the Minnesota houses. Consistent with the results for all other project residences, the percent leakage reduction immediately before and after sealing was always greater than or equal to the leakage before and after leakage reduction when the surface preparation was not in place (see Figure 45). The average percentage reduction immediately before and after was 80%, which was twice the average of the reduction based on the existing and final leakage measurements without surface protection. The difference for these apartments was much greater than that of any other group of residences. This is possibly because the units had multiple sections of drywall removed to run electrical cable (Figure 46). The walls were open for the existing and final tests and sealed for the post-prep and post-aero tests. Section 4.4 discusses the impact of leakage test methods, surface preparation, and intentional leaks in more detail.

Table 10. Air Leakage Results: Minnesota Multifamily Units (ACH_{50})

Res. #	Existing	Post-prep	Post-aero	Final	Post-prep – Post-aero		Existing – Final	
					(ACH_{50})	(%)	(ACH_{50})	(%)
3	7.14	7.17	3.67	4.71	3.50	49%	2.43	34%
5	7.17	7.17	2.05	4.04	5.12	71%	3.13	44%
6	7.94	7.64	3.37	4.23	4.26	56%	3.70	47%
13	12.56	9.71	2.65	5.31	7.06	73%	7.25	58%
14	10.93	8.65	1.50	7.44	7.14	83%	3.49	32%
15	10.17	9.10	2.56	6.09	6.54	72%	4.09	40%
16	10.15	9.00	1.26	5.47	7.74	86%	4.68	46%
17	12.09	10.73	2.41	8.43	8.32	78%	3.67	30%
18	9.22	8.95	1.01	6.24	7.93	89%	2.98	32%
Min.	7.14	7.17	1.01	4.04	3.50	49%	2.43	30%
Max.	12.56	10.73	3.67	8.43	8.32	89%	7.25	58%
Med.	10.15	8.95	2.41	5.47	7.06	73%	3.67	40%
Avg.	9.71	8.68	2.28	5.77	6.40	73%	3.94	40%



The percent reductions are based on multipoint depressurization tests conducted before and after the sealing with no surface preparation or temporary seals in place.

Figure 44. Air sealing results for multifamily units sealed in Minnesota

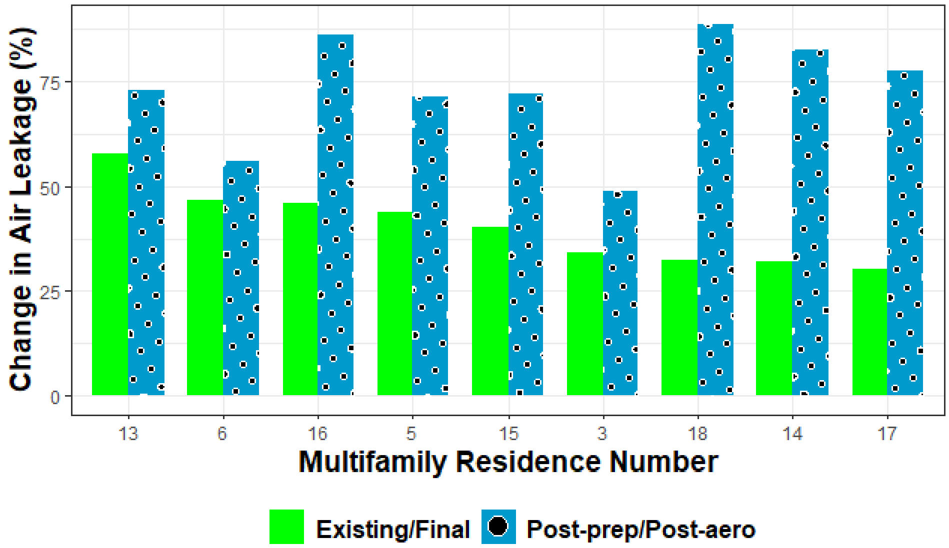


Figure 45. Comparison of percentage air leakage reductions of Minnesota multifamily units

Figure 46. Drywall cut open for renovation (left) and temporary sealing (right)

Figure 47 displays a box and whisker chart of the 15-minute average sealing rate for the six Minnesota apartment units. The sealing profile is similar to that of the California apartment units, except the rates are lower. The median sealing rate of 9.6 CFM_{50}/min for the first 15 minutes was 39% lower than that of the California units. This was primarily due to the smaller size of the Minnesota multifamily units. The volume-normalized initial air leakage rate of 13.9 ACH_{50}/h for the Minnesota units was 42%

greater than the rate of 9.8 ACH_{50}/h for the California units. The rate for the first 15 minutes dropped by 59% for the 30-to-45-minute period, which was nearly equal to the 62% drop for the California houses. The median sealing rate dropped below 4 CFM_{50}/min after 30 minutes. The total sealing time was much shorter than for the Minnesota houses. The sealing time was 30 minutes for one of the units; three of the units were sealed by 60 minutes; and all units were sealed after 75 minutes.

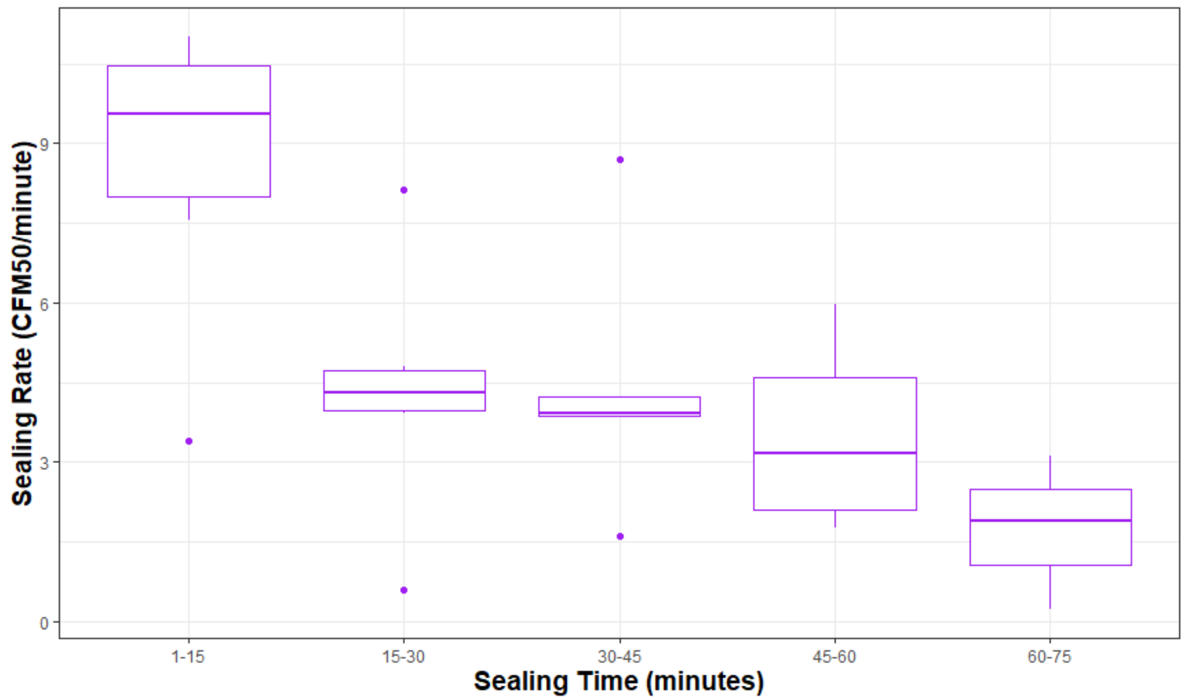


Figure 47. Aerosol sealing rate for six Minnesota multifamily units

In addition to the unit leakage measurements conducted shortly before and after aerosol sealing, a multipoint depressurization test was repeated after all renovation work was complete. This is referred to as the end of construction test. Compared to the final leakage after aerosol sealing, the leakage could increase due to seals being disturbed or the creation of additional leakage. It could decrease from additional weatherization measures or other work. The existing, final, and end of construction leakages are displayed in Table 11. The leakage decreased from the final to the end of construction for four of the six units, and those four units had an average reduction of 26%. The leakage increased by an average of 6% for the other two units. The average leakage reduction from the existing to the end of construction measurements was 50%, which was 10 percentage points greater than the reduction computed from the final measurement. This is not surprising, as replacing the cut-out sections of drywall would have decreased the unit envelope leakage.

Table 11. End of Construction Air Leakage Results: Minnesota Multifamily Units (ACH_{50})

Res. #	Leakage (ACH_{50})			Difference (%)		
	Existing	Final	End Const.	Exist – Final	Final – EC*	Exist – EC*
13	12.56	5.31	6.84	58%	-8%	46%
14	10.93	7.44	6.18	32%	36%	44%
15	10.17	6.09	5.43	40%	22%	47%
16	10.15	5.47	4.46	46%	-4%	56%
17	12.09	8.43	5.06	30%	17%	58%
18	9.22	6.24	4.87	32%	30%	47%
Min.	7.14	4.04	4.46	30%	-8%	44%
Max.	12.56	8.43	6.84	58%	36%	58%
Med.	10.15	5.47	5.24	36%	19%	47%
Avg.	9.71	5.77	5.47	40%	16%	50%

**EC – end of construction*

Guarded leakage tests of the horizontally adjacent units were conducted for the existing and final conditions when adjacent units were accessible. Figure 48 shows a dual blower door setup for one of the tests. The sealed units were in one vertical stack on floors two through four, six, eight, and nine. Table 12 displays the leakage results for the units on the upper four floors. Before sealing, the average leakage to the units to the right of the sealed units was 37% of the average total leakage. Also, the average leakage to the units on the right (3.9 ACH_{50}) was 8.5 times higher than the average leakage to those on the left (0.5 ACH_{50}). The average percentage air leakage reduction of the units to the right was 41%, which was about the same as the percentage reduction for the total unit leakage. Consequently, after sealing, the leakage to the right was still about a third of the total. The sealed unit bathrooms adjoined the bathrooms for the units to the right and there were multiple penetrations through the wall between the units. The demising wall between the sealed units and the units to the left had no significant penetrations.

Figure 48. Two-fan guarded zone test of side-by-side units

Table 12. Guarded Air Leakage Results: Minnesota Multifamily Units (ACH_{50})

Res. #	Right Adjacent Unit		Existing - Final Diff.		Left Adjacent Unit		Existing - Final Diff.	
	Existing	Final	(ACH_{50})	(%)	Existing	Final	(ACH_{50})	(%)
15					0.91	0.24	0.67	73%
16	3.34	1.45	1.89	56%	0.41	0.11	0.31	74%
17	4.96	3.52	1.44	29%	0.32	0.08	0.24	75%
18	3.36	2.14	1.22	36%	0.21	0.11	0.11	50%
Avg.	3.89	2.37	1.51	41%	0.46	0.13	0.33	68%

The average initial leakage of the three townhouse units (Minnesota residences 3, 5, and 6) was 7.4 ACH_{50}. Aerosol sealing reduced the leakage by an average of 3.1 ACH_{50} (41%) to 4.3 ACH_{50}. The average reduction was similar to the average of 42% for the Minnesota houses. The percentage leakage reduction immediately before and after sealing was always greater than or equal to the leakage before and after leakage reduction when the surface preparation was not in place (see Figure 45). The average percent reduction immediately before and after was 59%, which was similar to the percentage reduction of 62% for the Minnesota houses.

Figure 49 displays a box and whisker chart of the 15-minute average sealing rate for the three townhouses. The sealing profile is more like that of the Minnesota houses than the apartment units. That is not surprising as the type of construction and floor area of the townhouses is closer to the houses than the apartment units. The initial sealing for the three residences went smoothly. As a result, the median sealing rate of 16.8 CFM_{50}/min for the first 15 minutes was 39% greater than that of the Minnesota houses. The volume-normalized rate of 5.4 ACH_{50}/h was more than twice that of the houses. The rate for the first 15 minutes dropped by 32% for the 30-to-45-minute period. The median sealing rate dropped below 10 CFM_{50}/min after 45 minutes. The total sealing time was slightly less than that of the Minnesota houses. The sealing times were 80, 150, and 160 minutes for the three units.

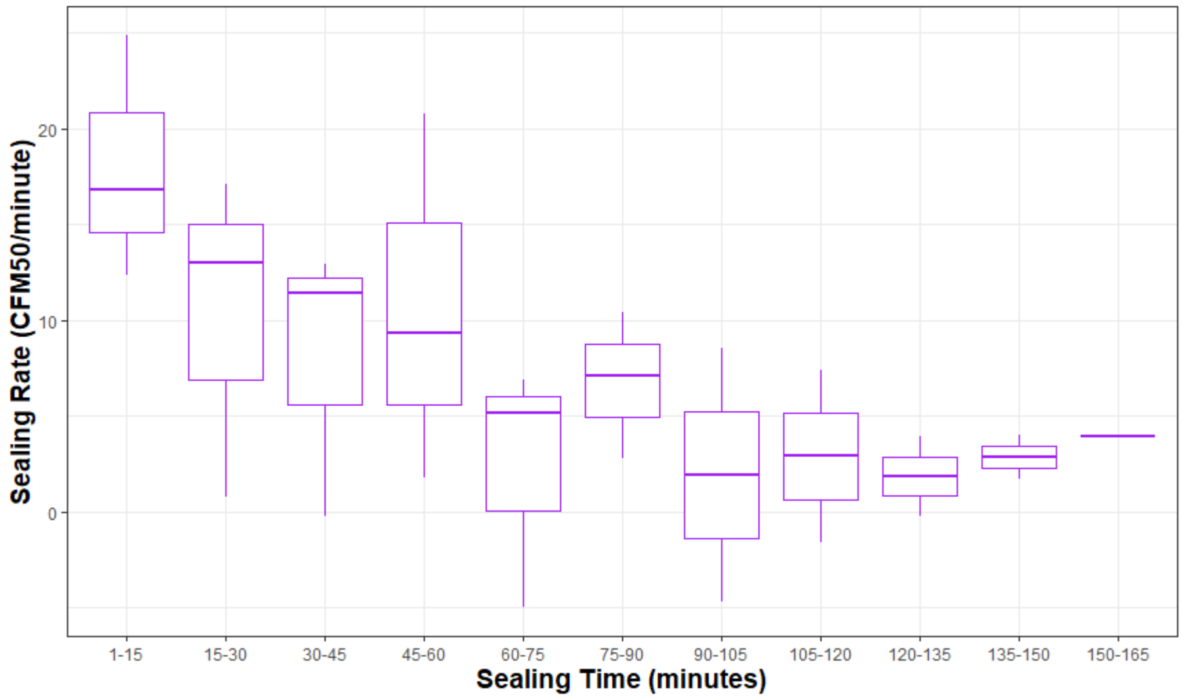


Figure 49. Aerosol sealing rate for three Minnesota townhouses

4.3 Additional Leakage Measurements

4.3.1 Zone Pressure Diagnostics

ZPD measurements were used to estimate the leakage between the house and adjoining partially heated or unheated zones: attics, attached garages, and crawlspaces. A calculation tool provided by Residential Energy Dynamic[6] was used to compute the estimated leakage through the zone and the uncertainty of that value. The leakage through attics, garages, and other zones was computed as a percentage of the total leakage for seven single-family houses and three townhouses in Minnesota (Table 13). Table 13 also includes the percentage leakage reduction from aerosol sealing for each zone. The average leakage through attics was 41% of the total, and the leakage was 16% for attached garages. In addition, there was an average attic leakage reduction of 32% from aerosol sealing. This suggests that attic aerosol sealing has the potential to seal a significant percentage of leakage and could be more effective than interior aerosol sealing.

[6] https://www.redcalc.com/

Table 13. Exterior Leakage From ZPD Measurements

House #	Attic dP (Pa)[1]	Leakage Relative Uncertainty (%)[2]	% of Existing Leakage			Leakage Reduction (%)			
			Attic	Garage+	Other	House	Attic	Garage+	Other
2	-2.1	118%	7%	33%	60%	46%	-	-	-
3*	-1.2	164%	29%	7%	64%	34%	-	-	-
4	-1.9	82%	58%	21%	21%	29%	28%	47%	13%
5*	-0.6	192%	36%	5%	59%	44%	-	-	-
6*	-5.2	36%	44%	6%	50%	47%	49%	6%	49%
7	-4.8	39%	60%	-	40%	53%	58%	-	45%
9	-2.1	73%	32%	-	68%	22%	28%	-	19%
10	-1.0	118%	7%	-	93%	19%	-4%	-	21%
11	-1.1	206%	98%	-	2%	40%	-	-	-
12	-1.0	132%	33%	27%	41%		-	-	-
Avg.	-2.1	116%	41%	16%	50%	37%	32%	26%	29%

[1] *Change in attic to outside pressure when house depressurized by 50 Pa*
[2] *Relative uncertainty of the existing attic leakage (uncertainty/computed value)*
* *Townhouse; all other residences are single-family houses*
+ *Measurements were conducted for attached garages, except for residence 11 where the overhead door was not present*

The validity of most of the ZPD attic leakage measurements is poor. The attic leakage uncertainty was greater than the computed value for over half the residences (third column from left in Table 13). For the six residences that had an attic leakage relative uncertainty greater than 100%, the attic leakage was an average of 35% of the total leakage. The average attic leakage was 49% for residences with uncertainty less than 100%. Higher attic leakage for more accurate measurements is expected because higher leakage generates higher attic-to-outside pressure differences, which also generates more accurate measurements. Other measurement methods are needed for more accurate estimates of leakage through different portions of the exterior envelope. However, these results suggest that attic leakage is often 30% to 60% of the total leakage of residences with vented attics and the attic leakage reduction from aerosol sealing is likely to be less than 50%.

4.3.2 Guarded Zone Tests

Guarded leakage tests were used to break out the amount of leakage through different portions of the envelope. Tests of units horizontally adjacent to the Minnesota apartments were conducted for the existing and final conditions when adjacent units were accessible. Table 12 displays the leakage results for the units on the upper four floors, and a description of the results is included at the end of section 4.2.2. The key finding was that the leakage to adjacent apartments where there was plumbing and other penetrations was more than twice as high as that of the apartments on the other side where there were no significant penetrations.

Due to the large uncertainty of the ZPD attic leakage measurement for most residences, guarded leakage tests were used toward the end of the project to measure the exterior leakage of two- and one-and-a-half-story houses. The guarded zone test method can be used to measure the exterior leakage of areas of a house that are separated from the main body by walls or floors. The reliability of the measurements depends on the degree of separation between the zone and the main body of the house. The tested houses had central, forced air distribution systems. The system grilles were temporarily sealed to increase the level of separation.

When evaluating the results, it is important to note that the ZPD and guarded methods measure the exterior leakage through different surfaces. ZPD tests measure the leakage across the surface between the residence and the attached zone. Guarded tests measure the exterior leakage of the exterior surface area of the zone being guarded. For the upper level of a house, the ZPD method can measure the leakage through the attic, while the guarded test of an upper floor will measure the exterior leakage to the attic and exterior walls.

Guarded tests were used to measure the exterior leakage of second floors, basements, and the remainder of the house for Minnesota single-family houses 19, 20, and 21 (Table 14). Table 14 also includes the percentage leakage reduction from aerosol sealing for each area. The total leakage of the houses averaged 11.1 ACH_{50} before sealing and the exterior leakage of the second floor ranged from 22% to 54% and averaged 39%. On average, the leakage of the second floor was 27% higher than the basement leakage. Also, the leakage reduction from aerosol sealing was more than twice as high for the second floor (55%) as for the basement (25%). This suggests that it is challenging to seal basement leakage with the aerosol process. While the percentage leakage reduction is greater for the second floor, attic aerosol sealing may be a more effective method if it can reduce leakage to the attic by more than 50%.

Table 14. Exterior Leakage by Level From Guarded Measurements

House #	# Stories	Type of Foundation	% of Existing Leakage			Leakage Reduction (%)			
			2nd Floor	Base-ment	Other	House	2nd Floor	Base-ment	Other
19	1.5	Base.	22%	26%	52%	36%	32%	-11%	62%
20	1.5	Base.	54%	18%	28%	52%	67%	23%	42%
21	2	B & CS*	41%	27%	32%	59%	66%	63%	45%
Avg.			39%	24%	37%	49%	55%	25%	50%

** Basement and crawlspace*

4.3.3 Individual Leakage Sites

Individual leakage site measurements were conducted at two California apartments and one Minnesota home. At the California apartments, the leakage measurements were taken at individual leakage sites including light switches, cable boxes, electrical outlets, smoke detectors, and ceiling lights. The total leakage measured from the 15 leak sites in two apartments was 210 CFM_{50}, which was reduced to 52 CFM_{50} after sealing, representing a 75% reduction in flow from these leakage sites. The individual leakage ranged from 6 CFM_{50} to 24 CFM_{50}. One outlet showed very minimal sealing, with a reduction of only 12% after sealing, while nine leak sites showed no measurable leakage after sealing.

Measurements were conducted for light switches, electrical outlets, a cable box, and ceiling lights at Minnesota house 3 after aerosol sealing was completed. Only four of the thirteen leak sites, including switches, outlets, and the cable box, had measurable leakage. Three had a minimum detectable leakage of 0.5 CFM_{50} and one had a leakage of 1 CFM_{50}. Two of the three ceiling light fixtures had a minimum detectable leakage of 0.5 CFM_{50} and one had a leakage of 1.3 CFM_{50}. The total leakage was approximately 5 CFM_{50}. At Minnesota residence 2, consecutive single-point house air leakage tests were conducted to measure the change in house leakage when 16 electric outlets were covered. The leakage reduction was 10 CFM_{50}, which is about equal in precision to repeated single-point measurements on a calm day. These results are somewhat lower than the post-sealing 52 CFM_{50} leakage measured for the 15 leakage locations at the California house. The results suggest that the aerosol sealing process can seal leaks through light switches, electrical outlets, cable boxes, and ceiling lights to an average of 0.5 to 3 CFM_{50} per device.

4.4 Impact of Temporary Surface Protection and Seals

Temporary protection of finished surfaces and sealing of intentional openings can significantly impact the amount of leakage that is eliminated with aerosol sealing.[7] This project focused on documenting the differences between the protected and unprotected leakage. Measurements indicated that preparations prior to aerosol sealing reduced leakage for all California residences and 81% of Minnesota residences. The average reduction was 22% for California residences and 6% for Minnesota residences, with an overall average reduction of 11%. When the preparations were removed after aerosol sealing, the average leakage increase was 26% for California residences and 27% for Minnesota residences with an overall average increase of 27%. Aerosol sealing leakage reductions can be improved by quantifying and better understanding the causes of the leakage increases.

There are two types of temporary protection: seals on intentional openings and protection of finished surfaces. Intentional openings include ventilation system ducts, clothes dryer ducts, combustion air openings, and vented combustion appliance flues. Intentional openings constitute leakage that remains after aerosol sealing in the same

[7] These results are only relevant to residences sealed from the interior. There was no preparation needed for attic sealed residences.

way that large-gap leaks remain. The leakage from most of these leaks cannot be reduced while others, like ventilation ducts, may be reduced with lower leakage dampers. There is more opportunity for improved surface protection methods to provide aerosol sealants with better access to reach leakage paths and reduce the disturbance to seals when the protection is removed. However, there is often a tradeoff between:

- Keeping the sealant flow path open so the particles stay in suspension until they reach the leak
- Separating the protection from seals so that the seals are not disturbed when the protection is removed
- Adequately protecting finished surfaces to minimize cleanup
- Required labor and cost.

In addition, there are two types of aerosol seals that can be disturbed when the surface protection is removed.

1. Seals at an envelope leak that adjoins surface protection. Ideally, these seals remain in place. However, removing the surface protection can also damage the seal across the envelope leak. Examples of this include (a) painter’s tape to poly at window trim, (b) tape used to adhere poly sheet to the floor near the wall-floor interface, and (c) painter’s tape used to protect electrical devices.

2. Surface protection or temporary seals intended to restrict inside-to-outside air movement that do not form a perfect air seal, where the aerosol sealant improves the seal. This can include temporary seals on exhaust fan inlets, combustion air ducts, heating/cooling ductwork grilles, and sprinkler heads. Any seal on those items is eliminated when the temporary seal is removed. The drawback to this type of seal is that it gives a false impression of permanent sealing. The added leakage when the seal is removed could end up exceeding the target leakage goal.

It is important to note that the leakage that reappears when temporary protection is removed needs to be considered when establishing leakage targets for the end of the aerosol sealing process.

Finally, the testing process affects the perceived leakage change. Depressurization measurements often provide significantly different leakage values than pressurization tests. Single- and multipoint depressurization tests with intentional openings left unsealed are most commonly used to measure residential building leakage. The AeroBarrier equipment is configured to perform pre- and post-pressurization tests with protection in place. To be consistent with leakage measurements typically conducted for residential building programs, the project performed multipoint depressurization tests before protection was applied and after the sealing was complete with the protection removed. The AeroBarrier equipment pressurization measurements were used for pressurization leakage measurements immediately before and after sealing with protection in place, just as occurs for market sealing work.

4.4.1 Depressurization and Pressurization Test Comparison

In addition to whether or not protection is in place, the type of leakage test changes from depressurization for the existing test to pressurization for the post-prep test. To evaluate the impact on the different test methods, both depressurization and pressurization leakage tests were conducted on a subset of residences at the existing (pre-sealing) and final (post-sealing) conditions. The measurements were conducted for three Minnesota houses and the six Minnesota apartment units.

The pressurization leakage was higher than the depressurization measurement for 16 of the 18 pairs of tests (Table 15). The ratios of pressurization to depressurization measurements for existing conditions averaged 1.14 for the houses and 1.08 for the multifamily units. For post-sealing conditions, the average ratio was 1.09 for houses and 1.04 for multifamily units. There are many reasons why the measured leakage would be higher under pressurization than depressurization. First, exhaust fan and clothes dryer dampers are designed to close tighter under depressurization and can blow open during pressurization. Second, inswing exterior doors will close tighter against weatherstripping under depressurization. Third, it is possible for some leakage paths to be tighter under depressurization. For example, weather-resistant barriers may pull tight against sheathing when depressurized and loosen slightly under pressurization. There is a slight trend for lower ratios after sealing than before sealing. For seven of the nine residences, the ratio is higher for pre-sealing conditions than post-sealing. The average pre-sealing ratio of 1.10 is higher than the average of 1.05 for post-sealing. It is possible that the aerosol sealing changes the nature of the leakage paths or the type of remaining leakage.

Table 15. Comparison of Pressurization and Depressurization Leakage

	Existing Leakage					Post Sealing Leakage				
Res. #	Leakage (ACH_{50})		Pres./ Depr. Ratio	Difference		Leakage (ACH_{50})		Pres./ Depr. Ratio	Difference	
	Pres.	Depr.		(CFM_{50})	(ACH_{50})	Pres.	Depr.		(CFM_{50})	(ACH_{50})
Single-Family Houses										
12	1,834	1,643	1.12	191	0.98	1,092	965	1.13	127	0.65
19	2,716	2,353	1.15	363	1.21	1,588	1,468	1.08	120	0.40
21	2,627	2,267	1.16	360	1.58	975	936	1.04	39	0.17
Avg.	2,392	2,088	1.14	305	1.26	1,218	1,123	1.09	95	0.41
Multifamily Units										
13	512	459	1.12	53	1.45	244	250	0.98	-6	-0.16
14	328	324	1.01	4	0.11	222	226	0.98	-4	-0.11
15	636	600	1.06	36	0.61	338	320	1.06	18	0.31
16	396	371	1.07	25	0.68	179	163	1.10	16	0.44
17	497	442	1.12	55	1.50	202	185	1.09	17	0.47
18	363	337	1.08	26	0.71	182	178	1.02	4	0.11
Avg.	455	422	1.08	33	0.84	228	220	1.04	8	0.17

These results impact the interpretation of the change in leakage between existing and post-prep conditions. If no protection is installed, the leakage should typically increase by about 10% between testing first with a depressurization test and then testing with the AeroBarrier equipment. Instead, the leakage decreased by an average of 11%. This suggests that the average reduction in leakage due to protection as measured by a pressurization test was actually about 21%. Similarly, the average increase in leakage from removing the protection was higher, by about 30%.[8]

4.4.2 Temporary Protection Leakage Change

Three values were computed to evaluate the impacts of temporary surface protection on envelope leakage.

1. Preparation applied. The change in leakage when protection is applied prior to aerosol sealing. It is the difference between the existing depressurization and post-prep pressurization measurements. A positive value indicates a reduction in

[8] 27% + 3% = 30%. There was an average difference of 5% between the pressurization and depressurization tests for the post-sealing conditions and the 5% adjustment is applied to a lower leakage.

leakage. The measured leakage reduction can be negative (i.e., the leakage increases). This is due to two factors. First, leakage is often higher for a pressurization test than a depressurization test. Consequently, the apparent leakage can increase from the depressurization test of existing leakage to the pressurization test after the protection is applied. Second, electric outlet covers and ceiling fan covers are removed as part of the surface preparation process. Removing the covers can result in increased leakage.

2. Preparation removed. The change in leakage when the protection is removed after aerosol sealing. It is the difference between the final depressurization and post-aero pressurization measurements.

3. Seal removed. The difference between the preparation removed and preparation applied values. It is approximately equal to the amount of aerosol seals created during the sealing process that are removed when the protection is removed after aerosol sealing.

The bar charts shown in Figure 17, Figure 18, Figure 25, and Figure 35 show the values for preparation applied (difference between the two bars to the left) and the preparation removed (difference between the two bars to the right).

Table 16 displays the averages of the three values in units of ACH_{50} and percentage of existing leakage for each of the four groups of residences and across all residences. Tables and figures of the three values for individual residences are included in Appendix C. The application of protection reduced leakage by an average of 1.2 ACH_{50} or 11% of the existing leakage. Because switching from a depressurization measurement for the existing leakage to a pressurization measurement after the protection was applied is expected to increase the measured leakage by about 10%, this indicates that about 22% of the leakage was covered by sealing preparations and could not be sealed. When the preparations were removed, the leakage increased by an average of 2.6 ACH_{50} or 27% of the existing leakage. Comparing the leakage reduction during the application of preparations to the leakage increase when preparations are removed suggests that an average of about 1.4 ACH_{50} (16% of existing leakage) of seals created by aerosol sealing were disturbed when the preparations were removed. The combination of leakage covered (20%) and seals lost (16%+) totals to more than a third of the existing leakage. Further work is required to identify changes in the sealing process that would allow some of that leakage to be cost-effectively sealed.

Table 16. Impact of Protection on Leakage: Summary

Group	Existing Leakage (ACH_{50})	Leakage Reduction (%)	Preparation Applied		Preparation Removed		Seals Removed	
			(ACH_{50})	(%)	(ACH_{50})	(%)	(ACH_{50})	(%)
CA SF*	12.04	53%	3.29	25%	4.15	34%	0.86	9%
MN SF	7.48	42%	0.42	5%	1.62	21%	1.21	16%
CA MF*	8.91	63%	1.88	19%	1.79	20%	0.45	7%
MN MF	9.71	40%	0.87	8%	3.50	35%	2.32	24%
Avg.	9.09	47%	1.22	11%	2.58	27%	1.38	16%

**SF: Single family; MF: Multifamily*

Note: For each residence, the difference between preparation removed and preparation applied is equal to seals removed. The preparation applied and seals removed values were not available for one California multifamily residence and three Minnesota multifamily residences. As a result, the difference of the average preparation and preparation applied values is not equal to the seals removed.

There are some significant trends in the summary results. As noted, the California houses had raised foundations that required the finished floor surfaces to be sealed with a sheet of poly taped at the edges. This resulted in the highest level of preparation leakage reduction (3.3 ACH_{50} and 25%) of the four groups of residences. The houses also had low levels of seals removed (9%) and high aerosol sealing reduction (84%), which led to an above-average overall leakage reduction of 53%. A higher percentage of the leakage could be sealed if it were possible to seal the lower level from below the floor. For example, the procedure used for aerosol sealing from the attic could be applied in crawlspaces. A second trend indicated that the Minnesota multifamily units had the highest level of seals removed (24%). For five of the units, single-point pressurization leakage measurements were conducted while the protection was removed. The largest leakage increase occurred when the poly sheet protection was removed from open wall sections.[9] There were concerns that if the wall sections were left open, sealant could move through the wall cavities and cause sealant deposition in the adjacent units. In hindsight, the wall sections could have remained open if equipment was placed to filter or dilute any significant sealant that entered adjacent units. That arrangement requires advance notice and the cooperation of other tenants.

The type and area of finished surfaces is expected to impact the percentage of leakage covered and seals disturbed. Four of the Minnesota houses were undergoing major renovation, three undergoing minor renovation, and five were sealed at the time of occupancy change. The houses undergoing major and minor renovations had an average leakage reduction of 49% compared to 33% for the houses sealed at the time of occupancy change. The average leakage covered by protection was 13 percentage points lower for houses undergoing renovation and the percentage of seals removed

[9] Sections of wall were opened for electrical wiring upgrades.

was 17% lower. This confirms the greater challenges for aerosol envelope sealing of houses with all finished surfaces in place.

Separate regressions of the overall percentage leakage reduction[10] as a function of preparation applied, preparation removed, and seals lost were conducted to evaluate the impact of the variables on the overall leakage reduction. The regression plots are shown in Figure 50 and the slope and p-value of the slope are displayed in Table 17. There is an expected negative relationship between the overall percentage leakage reduction and both the percentage leakage increase from removing protection and the percentage of seals removed. The p-values are lower for seals removed, and a multivariable regression that includes both variables indicates a stronger relationship with percentage seals removed. The regression with all sites included indicates that the overall leakage reduction decreases by 0.6% for each percentage seal removed.

Table 17. Regression Slopes for Protection Impacts on Leakage Reduction

Group	# of Sites*	Preparation Applied		Preparation Removed		Seal Loss	
		Slope	p-value	Slope	p-value	Slope	p-value
CA SF	5	0.80	0.30	-1.38	0.06	-0.86	0.03
MN SF	12	0.50	0.15	-0.51	0.27	-0.53	0.05
CA MF	6/3	0.08	0.85	-0.89	0.02	-0.29	0.48
MN MF	9/8	0.67	0.14	-0.31	0.09	-0.38	0.04
All SF	17	0.59	0.02	-0.42	0.23	-0.71	<0.01
All MF	15/11	0.57	0.05	-0.65	<0.01	-0.46	<0.01
All	32/28	0.58	<0.01	-0.53	<0.01	-0.60	<0.01

** Measured existing leakage is not available for one California multifamily unit and one Minnesota multifamily unit. Those sites were not included for the analysis of preparation applied and seal loss.*

[10] Computed from Existing – Final.

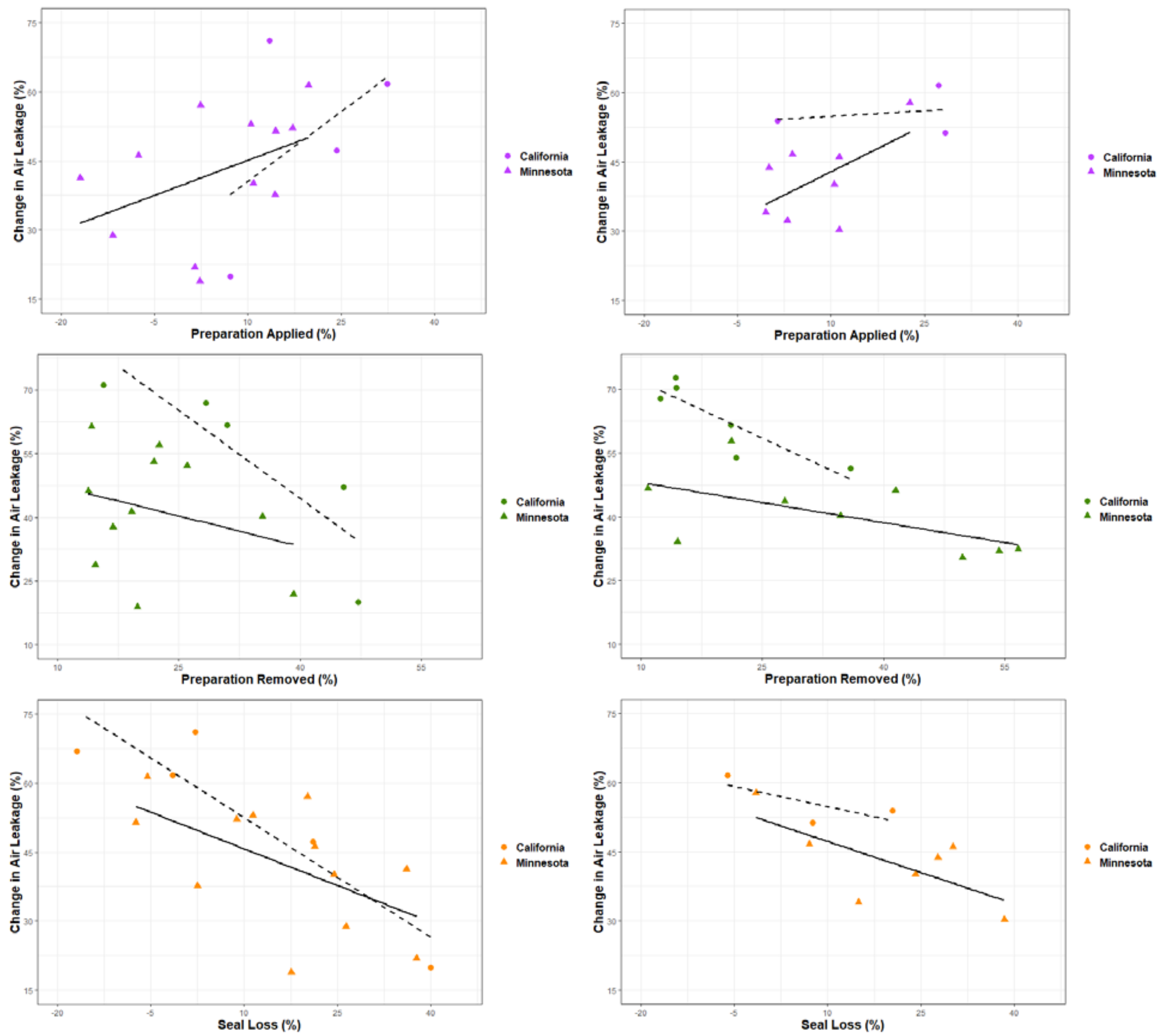
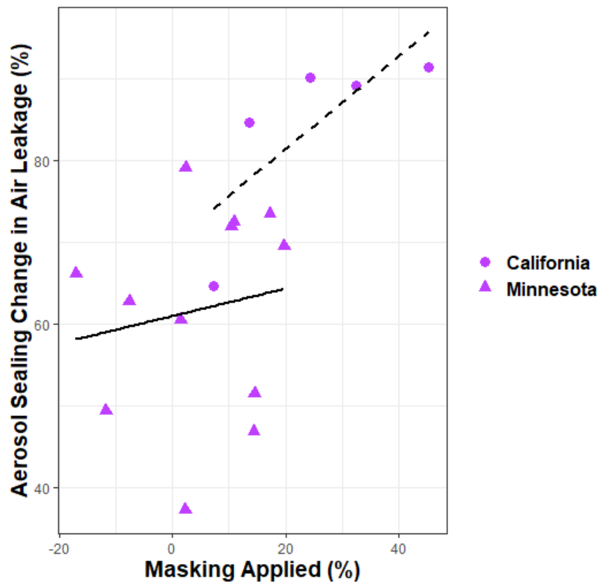


Figure 50. Relationship between leakage reduction and percentage change for preparations applied, preparations removed, and seal loss for houses (left) and multifamily units (right). Regression lines for California (dashed) and Minnesota (solid)

There is a weak positive relationship between the overall leakage reduction and the percentage leakage reduction from applying preparations with slope p-values ranging from 0.08 to 0.85. This is counterintuitive as covering leaks should reduce leaks that can be sealed with aerosol sealing. However, there is also a positive relationship between the percentage of leaks sealed as measured immediately before and after aerosol sealing and the percentage reduction from applying preparations (Figure 51). It is possible that residences that require greater levels of protection (primarily where protection is applied to eliminate air movement through flooring) have characteristics that enable a high percentage of the remaining leaks to be sealed. In addition, the relationship with the percentage leakage reduction from applying preparations is not statistically significant when a multivariable regression of leakage reduction is conducted with all three variables.



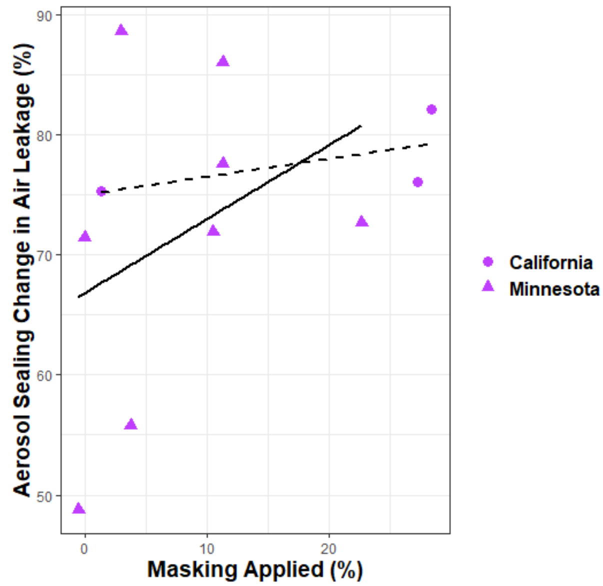


Figure 51. Relationship between leakage reduction for pre/post aerosol sealing and percentage change when preparations are applied for houses (left) and multifamily units (right)

4.4.3 Leakage Through Intentional Openings

Intentional openings include ventilation system ducts, clothes dryer ducts, combustion air openings, and vented combustion appliance flues. Intentional openings constitute leakage that remains after aerosol sealing in the same way that large-gap leaks remain. Single-point pressurization leakage measurements were conducted before and after an intentional opening was sealed or after the seal was removed. The sealing was almost always applied at the interior of the residence. The difference between the measurements was used to estimate the leakage through the opening. The tests were conducted for two to five openings at each of five residences. The measurements were repeated two or three times at two of the residences (Minnesota residences 20 and 21). All the measurements were made with pressurization tests. There were a variety of configurations for the diameter, length, and termination. Significant variation in the results was expected. The measurements were conducted to provide the range of and typical leakage for common intentional openings.

Table 18 displays the leakage measurements for bathroom exhaust fans, kitchen exhaust fans, clothes dryers, water heater and/or furnace combustion vents, and combustion air ducts. The averages range from 26 CFM_{50} for clothes dryer vents to 88 CFM_{50} for kitchen exhaust fans. The average leakage measurement of the five openings was 51 CFM_{50} and the sum of all five was about 250 CFM_{50}. This suggests that for Minnesota houses, about half of the change in leakage from pre-sealing protection could be due to temporary sealing of intentional openings.[11]

[11] The average existing leakage for Minnesota houses was 2,186 CFM_{50}. Pressurization leakage was typically 14% higher than depressurization leakage and on average the pressurization measured leakage after protection was in place was 141 CFM_{50} lower than the depressurization leakage. This indicates an average pressurization leakage reduction due to protection of about 450 CFM_{50}.

Table 18. Leakage of Intentional Openings Using Pressurization Test (CFM_{50})

Residence #	Bathroom Fan	Kitchen Fan	Clothes Dryer	WH/ Furnace Vent	Combus-tion Air*
10	34		80		
12			30	57	
19	55		3	55	69
20	61	114	3		72
21	6	62	12	22	34
Average	39	88	26	44	58

* Commonly a 6-in.-diameter, 25-ft-long flex duct with multiple bends and not elongated.

There is a high level of uncertainty for the individual measurements of leakage from intentional openings. A change in leakage of 25 CFM_{50} from sealing an opening would account for 0.5% to 3% of the house leakage. Depending on wind conditions, a 25 CFM_{50} change in leakage is within the expected repeatability of the leakage measurement. The uncertainty of the lower leakage openings (e.g., clothes dryers and bathroom fans) is expected to be as high as 100%. Accuracy is greater for the leakage values from residences 20 and 21, where two or three repeat measurements were conducted for each opening.

4.5 Attic Air Sealing

One new strategy investigated to address occupied homes was to install aerosol envelope sealing from the attic space. The focus was on the ceiling-attic surface, which contributes 51% of the total air leakage of the homes as demonstrated in a study of new California homes (Proctor, Chitwood, and Wilcox 2011). The aerosol sealing process was modified for this application by depressurizing the house to 100 Pa while applying the aerosol fog of sealant material in the ventilated attic space (see Figure 52). The sealant particles deposited on leaks as the particles were drawn into the home (green arrows in diagram). The attic insulation was removed prior to the installation to give the sealant a path to the leaks on the attic floor. The attics tested were well ventilated, and attic pressures monitored during the process showed very little attic depressurization relative to the outside. This led to some loss of sealant material through attic vent openings (see Figure 53), but did not have a noticeable impact on sealant material use relative to other applications. Sealant loss could be reduced by temporarily blocking some attic ventilation openings or using a secondary fan system to reduce attic pressures.

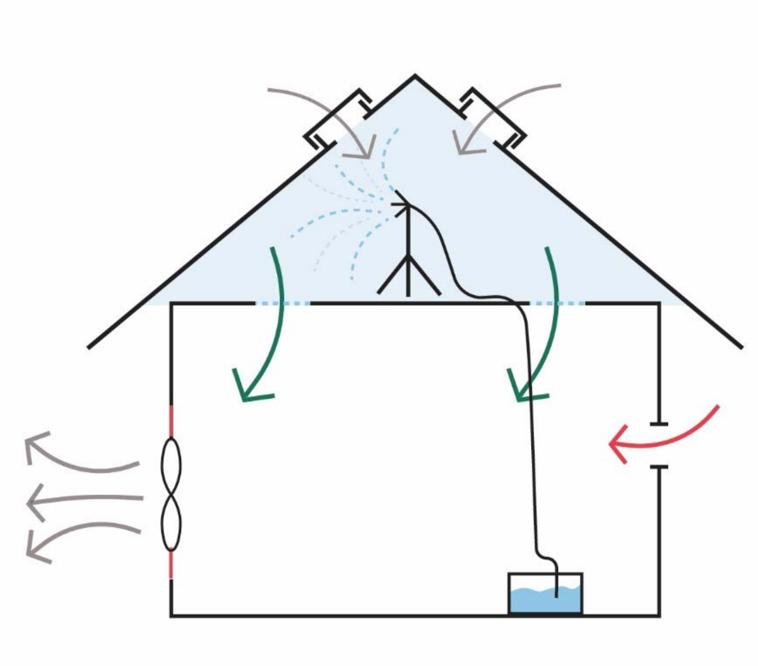


Figure 52. Diagram of attic air sealing process

Image from CEE

Figure 53. Sealant fog moving out of attic from a gable vent

This method for aerosol sealing required no preparation of interior surfaces in the home, which greatly reduced the setup time. Some sealant particles blew through larger leaks and entered the home but were quickly removed by the blower door fan. Sealant particles entering the living space can be further mitigated by running a high-capacity room air filter or making small, intentional openings in windows to allow the blower door to run at a higher airflow rate and create more room air changes at the same operating pressure.

4.5.1 California Townhouses

The test site included 938-ft^2 and 764-ft^2 single-story apartments built on a slab with a ventilated attic. The aerosol sealing process was applied to three apartments, while the remaining 37 apartments received conventional foam sealing of the attic by the insulation service contractor. The foam sealing focused on electrical penetrations, HVAC connection boots, and construction seams. Two conventionally sealed apartments were tested and compared to the three that were sealed with aerosols. All baseline and post-sealing leakage tests were performed with the attic insulation removed. Figure 54 shows the sealing results for each attic sealed with the aerosol process and those sealed with manual foam application. The aerosol sealing reduced the homes' total envelope leakage by an average of 4.4 ACH_{50} or 55%, from an average initial leakage of 8.0 ACH_{50} to a final leakage of 3.6 ACH_{50}. The average reduction was 0.59 CFM_{50} per ft^2 of ceiling area. By contrast, the conventionally sealed attics reduced the homes' leakage by an average of only 14%, from an initial leakage of 7.2 ACH_{50} to a final leakage of 6.2 ACH_{50}.

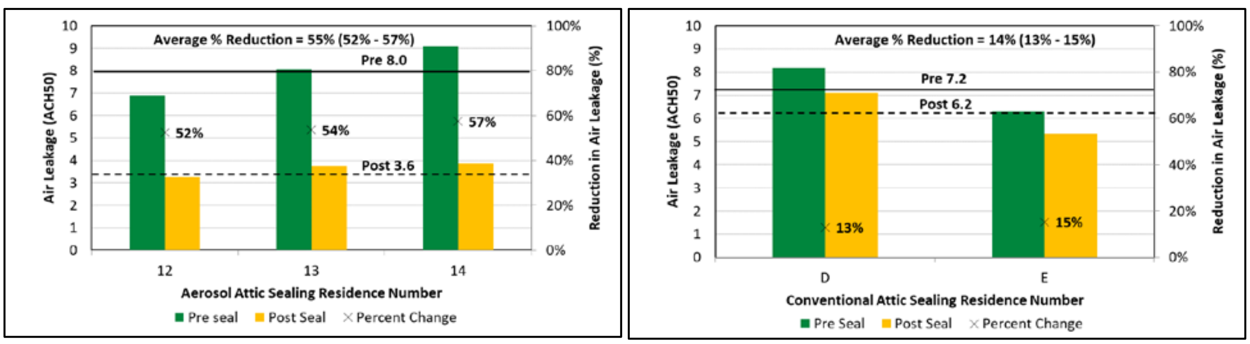


Figure 54. Attic sealing results for aerosol application (left) and conventional foam application (right)

The aerosol sealing process effectively reduced overall air leakage, particularly when considering the limitations of only applying sealant from the attic. Figure 55 displays aerosol seals at typical attic leakage locations. With slab-on-grade construction, it is understandable that a significant portion of a home's leakage would flow through a ventilated attic where wire penetrations in the top plates and ceiling-mounted fixtures provide paths for air to leak. This project also highlights the challenges of manual sealing. Leaks can be challenging to reach near the exterior walls, and it is not always obvious where leakage occurs, so contractors tend to apply sealant products along entire seams that may not be a source of leaks (Figure 56). Contractor experience is a key factor when evaluating the performance of manual sealing methods, which is one reason why an automated approach could provide more consistent results. This project presents results for one contractor. Further evaluation is needed to understand the approach's broader benefits relative to current conventional methods.

Figure 55. Attic seals made at duct (upper left), fan housing (upper right), ceiling light box (lower left), and wire penetrations (lower right)

Figure 56. Photos of aerosol seals targeting specific leaks (left) vs. manual foam sealing applied liberally along seams (right)

4.5.2 Minnesota House

A three-story, 4,370-ft^2 house built in 1989 was sealed using aerosol sprayed in the attic (see Figure 57). The contractor had planned on removing the attic insulation, using can foam to manually seal large house-to-attic air leakage, spraying two-inch-thick two-part foam over the attic floor, and blowing insulation over the foam. A number of contractors provide this service to enable more extensive sealing of attic bypasses and remove animal feces and other accumulated contaminants from the attic. In this case, the contractor performed all the planned work and the project team conducted aerosol attic sealing after the manual sealing and before the skim coat of two-part foam. Figure 58 shows images of the attic after the insulation was removed and manual sealing completed.

Figure 57. Back view of Minnesota residence 22 sealed from attic

Figure 58. Manual sealing performed before aerosol sealing

House leakage tests were conducted four times during the process: prior to any work, after the insulation was removed, after manual can foam sealing, and after aerosol attic sealing. The house started with an air leakage of 1,756 CFM_{50} (Table 19). Removing the attic insulation increased the leakage by 293 CFM_{50} (17%), and the manual sealing reduced it by 231 CFM_{50} (11%). This indicates that the reduction in leakage from manual sealing was less than the amount of sealing that had been provided by the loose insulation. It is not known what amount of leakage reduction would have occurred by reapplying loose insulation. However, the process of removing insulation, air sealing, and reinsulating requires effective air sealing to result in a significant leakage reduction.

The aerosol attic sealing reduced the house leakage by 387 CFM_{50} (21%) to achieve an overall reduction of 325 CFM_{50} (19%) from the existing condition. The lower percent reduction is partially due to the greater exterior wall surface area of the house, which results in the top-level ceiling area being a lower fraction of the total surface area. If it were possible to accurately measure the leakage between the house and attic,[12] it likely would have constituted less than half of the total leakage. In addition, the leakage per square foot of the upper-level ceiling area was lower for the house than for the California townhouses. The reduction of 387 CFM_{50} after the manual sealing is equal to a ceiling surface-area-normalized leakage of 0.27 CFM_{50}/ft^2. This is 55% lower than the average normalized leakage that was obtained for the three California apartments. Because most of the gaps sealed by the can foam were narrow, it is expected that a large fraction of the manual can foam sealing could have been achieved with the aerosol sealing. A combination of the manual and aerosol sealing is equal to a normalized leakage reduction of 0.42 CFM_{50}/ft^2, which is only 28% lower than the average for the California apartments. It is likely that both the manual can foam sealing and skim coat of spray foam could have been replaced by limited manual sealing of only large gaps and the aerosol sealing. As noted, further evaluation is needed to understand the attic aerosol's broader benefits relative to current methods.

Table 19. Minnesota Residence 22 Attic Sealing Leakage Measurements

Status	Leakage (CFM_{50})	Difference From Prev. Meas.		Difference From Existing	
		(CFM_{50})	(%)	(CFM_{50})	(%)
Existing	1,756	-	-	-	-
Insulation Removed	2,049	293	17%	293	17%
After Manual Sealing and Before Aerosol Sealing	1,818	-231	-11%	62	4%
After Aerosol Sealing	1,431	-387	-21%	-325	-19%

[12] It was possible to use ZPD diagnostics to measure the leakage between the house and attic. However, house-to-attic ZPD leakage measurements of newer houses with code-required attic venting typically results in uncertainties that are similar to the computed leakage.

4.6 Sealing Process Time Requirements

The surface protection activities were successful with only one instance of property damage due to inadequate covering of a water heater. The issue with the water heater was caused by not sealing off the combustion air intake on the bottom of the unit, allowing the aerosol to find its way into the burner section. This was an oversight and compensation for the water heater was provided to the owner due to this error. All noticeable unwanted deposition was cleanable from surfaces including minor overspray on carpets and sealant buildup around large leaks on other surfaces.

Table 20 shows the average time to complete major steps in the sealing process for the California residences. This includes information from the five houses, the first three multifamily units, and the three attic-sealed townhouses. The sealing preparation for existing homes took a team of three approximately 8 hours to protect a 1,500–2,500-ft^2 home. Most of the time and materials were for covering floors, and while a significant amount of disposable plastic is used, according to the Inventory of Carbon and Energy database (Hammond and Jones 2011), the embodied carbon in 3.5 mil plastic sheeting used to cover 1,000 ft^2 is less than 16 kg CO2e. This carbon could be offset by saving 41 kWh of electricity or less than 3 therms of natural gas based on emissions factors from the EPA. The time will vary widely depending on the type of flooring, number of windows and mounted fixtures, and building geometry. Additionally, as teams develop preparation strategies and experience, this time could be reduced. The time required to seal the multifamily apartments undergoing major renovation was significantly lower, as many surfaces, including the flooring, were scheduled to be replaced and therefore did not require protection. For the attic sealing applications, no surface protection was required, but insulation needed to be removed and replaced as part of the retrofit.

Table 20. Summary of Labor to Complete Each Task in the Sealing Process for the California Residences

Construction Type	Average Labor Time (Person-Hours)			
	Preparation	**Equipment setup**	**Sealing**	**Cleanup**
Single Family	23	2	1.6	7
Multifamily Renovation	6	1	1.25	1
Multifamily From Attic	TBD*	1	1	0.5

* Attic preparation was not evaluated during this study.

Manual pre-sealing of larger leaks should also be performed prior to aerosol sealing. This allows the manual process to be performed faster and with less precision as the aerosol can fill in any small errors. The preparation time reflected in Table 20 includes any pre-sealing that was performed. Manual sealing of larger leakage can also be performed during the aerosol sealing process if an installer notices the sealing is not progressing as expected. This sealing can involve can foam, caulk, or other dense foam products that can be lodged in holes to block the bulk airflow path. Temporarily covering large holes is also acceptable but does not address the leakage caused by the hole. If the size of leaks behind a large hole cannot be determined, it is best to cover it and determine how it can best be sealed later. For example, data cable access points may not have any housing within the wall cavity; in this case, leaving this opening to the wall cavity can create significant sealant deposition around the opening of the hole without impacting the air leakage due to the size of the opening. This would also lead to the use of more sealant product.

4.7 Alternative Sealant Testing

4.7.1 Qualitative Results

Qualitative results are useful because aerosol sealants in existing homes may produce undesirable visual or tactile results. For example, a sealant that dries with residual tack will make unwanted deposition more noticeable and possibly harder to clean. The standard formulation (ABX1) has many desirable characteristics, including little or no tack after drying and good sealing performance. The new formulations, ABX2 with fungicide and ABF23, have not been used in commercial applications, so the qualitative observations can help determine if formulation changes are needed.

ABX1 is the currently available commercial product that dries white and is non-tacky. In liquid form, it is milky and viscous like a very thin paint, and after sealing it resembles flexible calking (Figure 59). The ABX2 formulation is a modification of ABX1 with 0.1% wt/wt of fungicide and was observed to be visually identical to ABX1, both before and after application. This implies that the addition of fungicide did not have any noticeable effects on the appearance of seals.

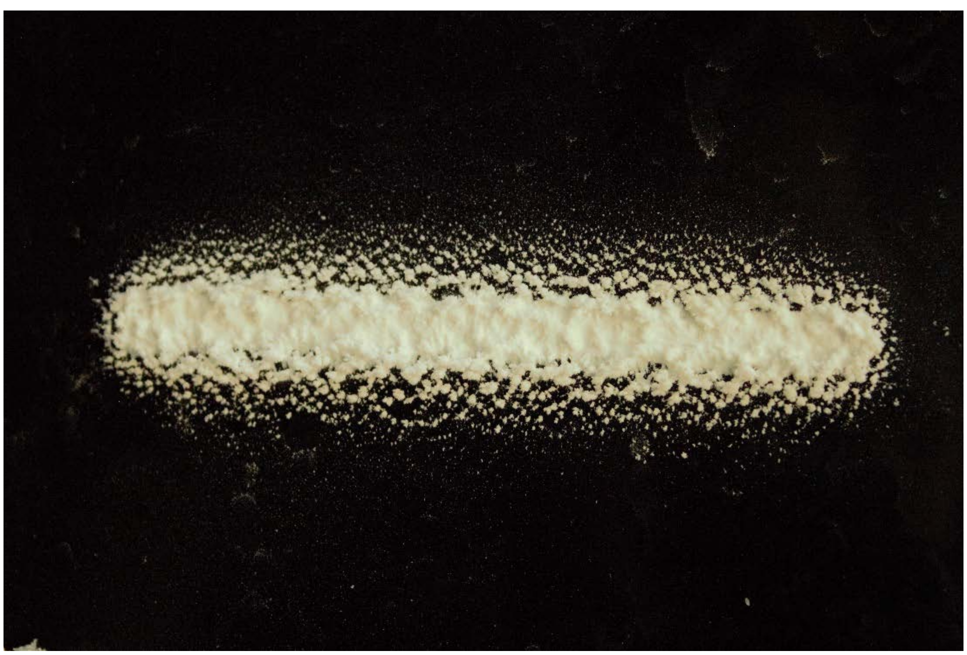


Figure 59. AX1 seal formed on 1/4-in. slot leak

The ABF23 uses a different polymer than ABX1 and ABX2, which resulted in a more translucent seal (Figure 60 and Figure 61). The transparency of the sealant is the result of the application process. The seal is formed by the adhesion of many smaller sealant particles which tend to diffract light, resulting in lower transparency. While transparency of the seal is one of the primary goals in exploring alternative sealants, other characteristics of seals formed with ABF23 were not ideal. The ABF23 seals remained tacky after drying even after several days. In addition, some tests were unable to fully seal the 1/4-in. slot leak within a reasonable sealant injection period. Improved sealant appearance is expected to increase acceptance of minor overspray on building materials, but increased tackiness and poorer sealing performance are major steps backward from the ABX1 and ABX2 products.

Figure 60. ABF23 seal formed on 1/4-in. slot leak

Figure 61. Incomplete ABF23 seal formed on 1/4-in. slot leak showing improved transparency after several days

4.7.2 Sealing Process

Prior to beginning sealant injection, a warm-up period allowed for sealing conditions to be reached. A LabView control system maintained sealing conditions throughout the process with humidity ranges within ±8% relative humidity of the target. Seal pressure was mostly controlled but had brief periods of fluctuation of high or low pressure due to the bypass damper receiving significant sealant depositions. Overall, the average pressure was within 10 Pa of the target. The sealant injection typically required 1–1.5 hours of total injection time to completely seal the leak plates. It was difficult to objectively determine when seals were fully formed because airflow and seal pressure were held constant. A combination of damper position and views from a sight glass were used to determine when the seals were complete. Furthermore, the time required to seal a leak is dependent on the smallest dimension of the leak, so the 1/4-in. slot leaks determined the overall seal time.

4.7.3 Pressure Testing

Failure was defined as the point when the flow measured at the lower baseline pressure of 0.1 PSI doubled from the initial measurement. Ideally, the leakage area of a seal would not change until failure; however, minor changes in baseline flow rates were observed. The failure point was chosen to be when the flow at baseline pressure doubled in order to have an objective target to compare the performance of each seal. Each leak was tested individually and the labels indicate the independent variables tested including sealant type, leak type, and application humidity used. The "down" and "up" labels indicate the direction the pressure was applied to the seal; down indicates the pressure was applied to the upstream side of the leak (nozzle side), and up indicates the pressure was applied from the downstream side (exhaust side).

Figure 62 shows example data collected during the failure testing. Leaks were subjected to incremental increases in test pressure; each test pressure was held for 30 seconds. After the test pressure was applied, the leakage flow at the low-pressure benchmark was recorded. It can be seen in Figure 63 that the benchmark leakage flow measured is relatively consistent at lower test pressures. The leakage flow measured at the low pressure benchmark increased sharply once failure occurred for ABF23, whereas the leakage increase for ABX1 was much more gradual. Figure 62 also shows that the leakage flow through the ABX1 seal doubled after about 1.2 PSI test pressure, while the leakage flow through the ABF23 leak doubled after about 0.4 PSI test pressure.

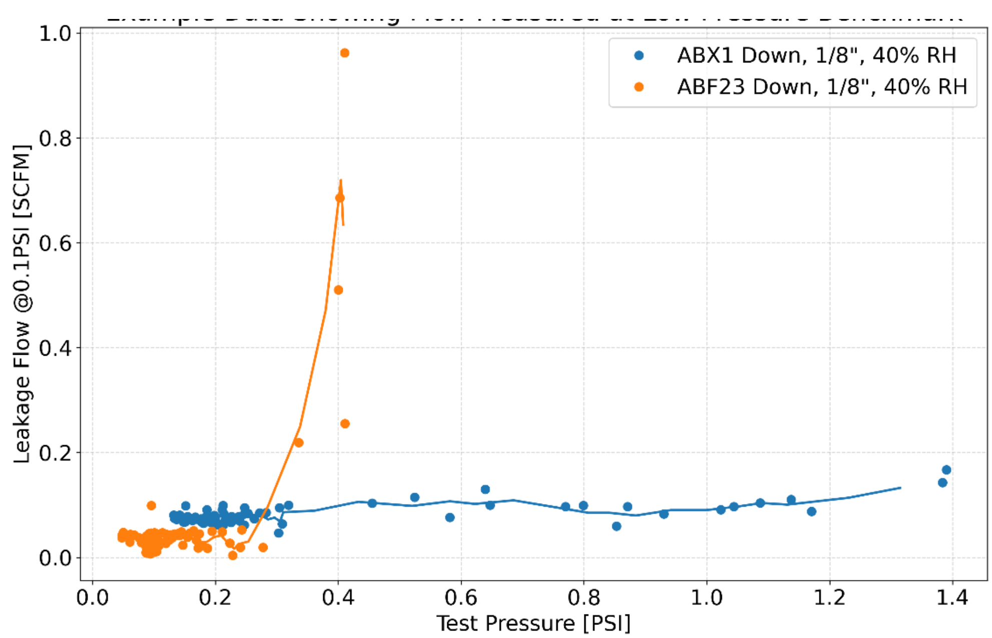


Figure 62. Example flow data at the low-pressure benchmark for two leaks plotted against the test pressure applied to the leak

The ABF23 exhibited very tight seals with minimal air leakage relative to the ABX1 and ABX2 sealants, which generally had some measurable air leakage through the seals themselves. Figure 62 shows about half of the leakage through the ABX23 during the first low pressure tests as compared to ABX1. Failure of the ABF23 seal, however, happened more suddenly and at lower pressure with a fast rise in benchmark leakage after pressurizing to about 0.35 PSI. The ABX1 seal gradually increased over a much larger range of pressure, doubling after about 1.15 PSI. This suggests that the ABX1 is a more flexible seal with the ability to stretch under higher pressures and return to its original form.

Figure 63 presents the results for all pressure testing performed under each sealant type, application humidity, and leak type. Each data point is the average of two tests under the same conditions. The results show a large variation in the maximum pressure across the seals before failure. The following are some general takeaways from the trends shown in Figure 63: (1) higher application humidity resulted in stronger seals; (2) seals formed on smaller leaks resulted in stronger seals; (3) seals were stronger when pressurized from the upstream side of aerosol injection toward the nozzle (labeled as “down”); and (4) all seals can withstand typical pressures experienced by a building. These observations are not true in every test case due to the challenge of repeatability in the formation of seals in the lab, but are based on the overall assessment of results.

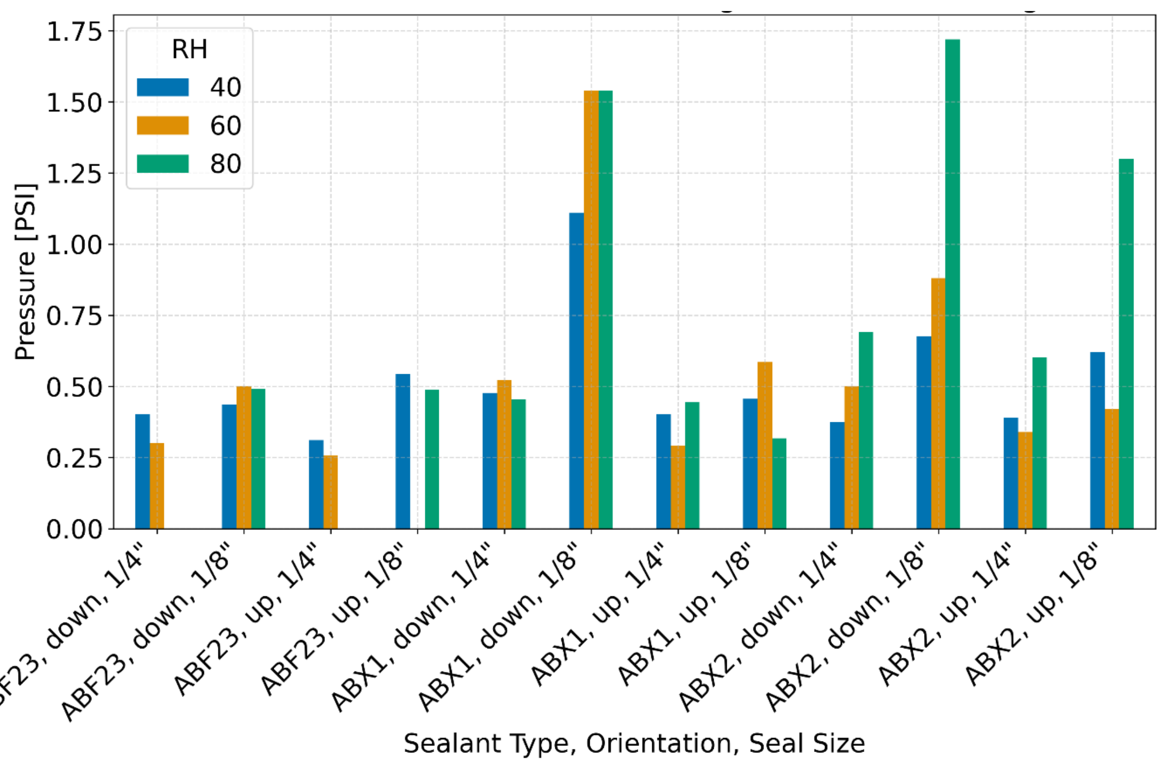


Figure 63. Failure pressure measured for each sealant type, leak type, and application humidity tested. The down and up labels represent the direction of applied pressure on the seal. Missing data indicates seals were unable to be formed completely under those conditions

Overall, the sealant failure pressure testing demonstrated that the aerosol sealing process can create durable seals that can withstand high pressure loads. The lowest failure pressure measured was 0.25 PSI (1,700 Pa), which is well above the pressure experienced by building envelopes even in extreme weather conditions. Most seal failures occurred in the middle of the seal, which suggests the cohesion bonds between sealant particles were first to fail. Figure 64 shows an example of a seal failed in the middle versus on the edge of the leak. The leak material is expected to have an impact on this observation, but testing for this study was only conducted with acrylic plastic.

Figure 64. Failed seals occurring in the middle (left) and edge (right) of leak

4.8 Energy Modeling

Evaluating the benefit of producing tighter building envelopes requires an understanding of the energy savings associated with sealing homes. There is a lack of data showing measured energy savings from retrofit air sealing. In many cases, the impact is too small to measure with appropriate accuracy. Thus, building energy simulations are used to evaluate the relative impact of air sealing for different U.S. climate zones.

A BEopt analysis was performed to evaluate the impact of envelope air leakage on house energy use. Figure 65 shows a chart of the source energy savings for various levels of sealing for 16 U.S. locations across 16 climate zones. The results showed that reducing the leakage of a 2,400-ft^2 single-family home from the 15 ACH_{50} to 10 ACH_{50} would save between 3% and 15% of the source energy use for a home depending on the climate zone. Sealing a home from 15 ACH_{50} to 7 ACH_{50} would achieve 5% to 23% savings, and sealing a home from 15 ACH_{50} to 3 ACH_{50} would achieve 8% to 35% source energy savings. Colder climates benefited the most from air sealing, with climate zones 5A, 6A, 7, and 8 showing the largest savings.

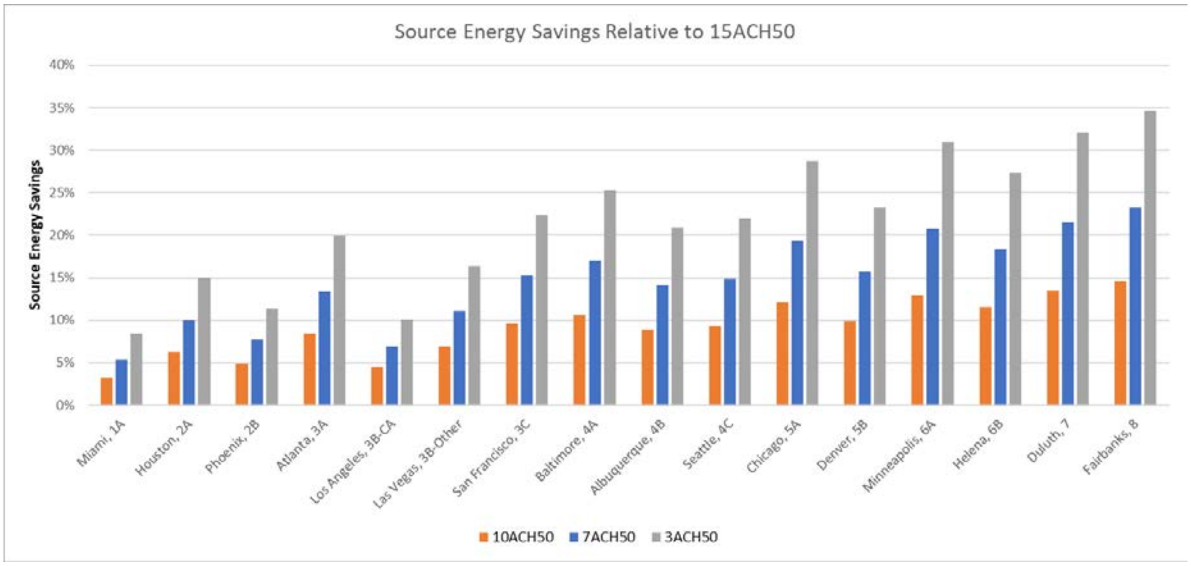


Figure 65. Source energy savings from reducing air leakage from 15 ACH50 in each U.S. climate zone

Figure 66 and Figure 67 present the site energy savings from reducing envelope leakage of homes in each of the 16 climate zones. Most of the energy savings from air sealing in the model were due to reduced natural gas energy use. All but one climate zone (Miami) showed gas savings of over 10% when reducing leakage to 10 ACH_{50} and around 30% or more when sealing all the way down to 3 ACH_{50}. One climate zone (Los Angeles) showed an increase in electricity energy use as a result of sealing due to the benefits of increased infiltration during periods when the air outside is cooler than inside, providing free cooling to the homes. This occurred even with some window operation considered in the simulation, allowing windows to be opened when temperatures were cooler outside than inside. Overall, source energy savings were still achieved in Los Angeles due to the reduction in gas use.

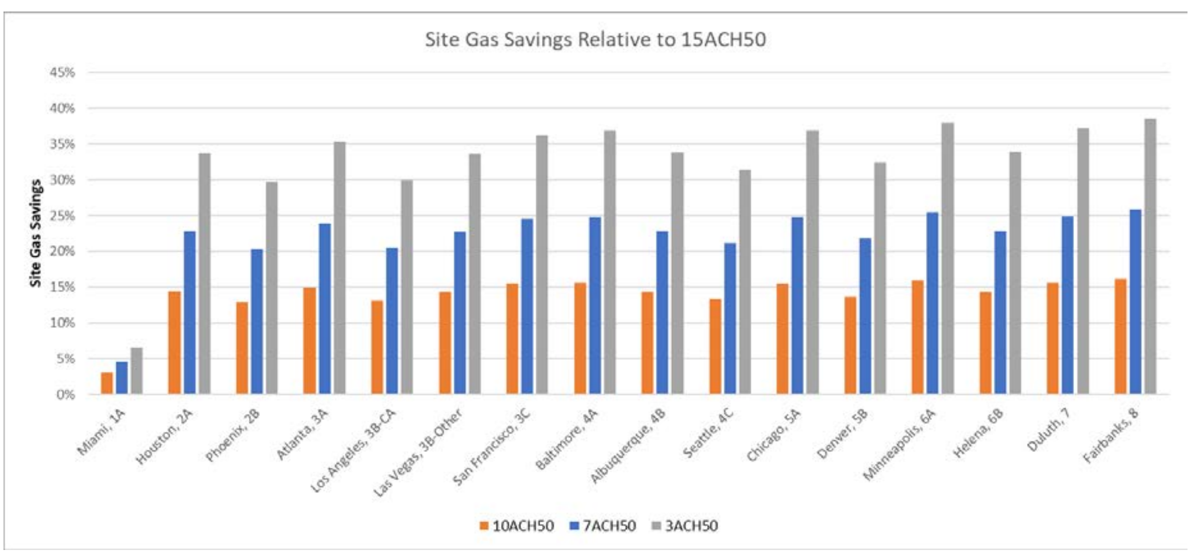


Figure 66. Heating energy savings from reducing air leakage in the model home in each U.S. climate zone

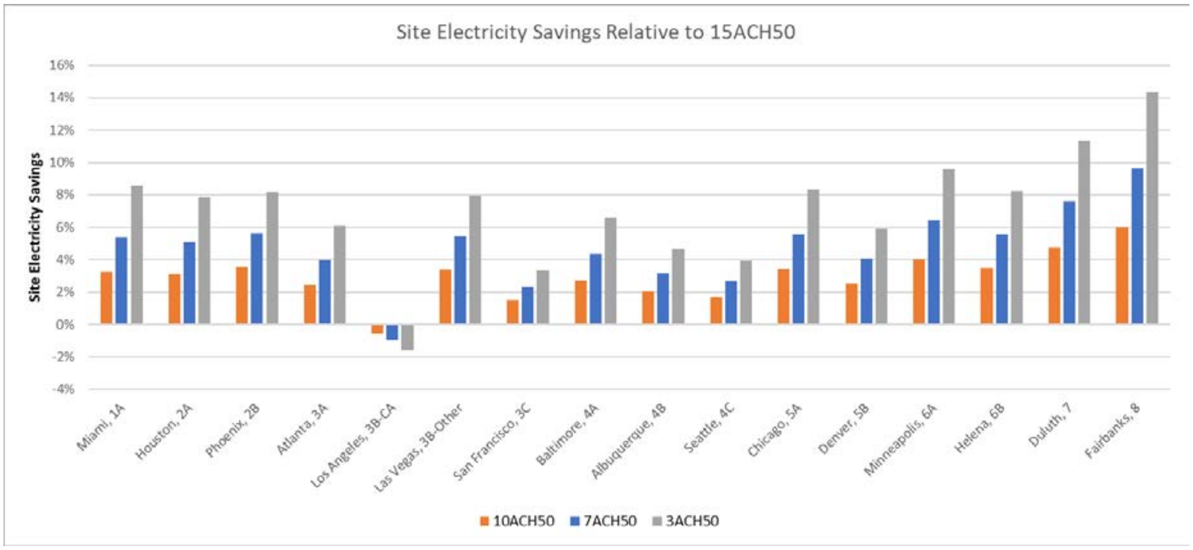


Figure 67. Cooling energy savings from reducing air leakage in the model home in each U.S. climate zone

The energy savings results show an increase in energy savings that is proportional with the reduction in envelope leakage. Because the air sealing results found no correlation between the percentage of leakage sealed in a particular home and its initial envelope leakage, it is reasonable to assume that the payback for this technology would be a function of the initial starting leakage and climate zone. Homes with higher starting leakage would achieve faster payback periods than homes with lower starting leakage given the same percentage of leakage sealed. Additionally, homes in colder climate zones would achieve shorter payback periods.

5 Discussion

5.1 Interior Aerosol Sealing

For all 34 residences, the average leakage reduction was 47%, with somewhat higher reductions for the California residences (Figure 68 – blue boxes). The California homes were 19% leakier than Minnesota residences, which could be due to construction differences between the regions or differences in preparation of the home by the contractors. It was thought that higher leakage reductions could be the result of higher initial leakage; however, as shown by Figure 69, there is almost no correlation between the existing air leakage and the percent leakage reduction with an R^2 of 0.05 for both the multifamily and single-family residences.

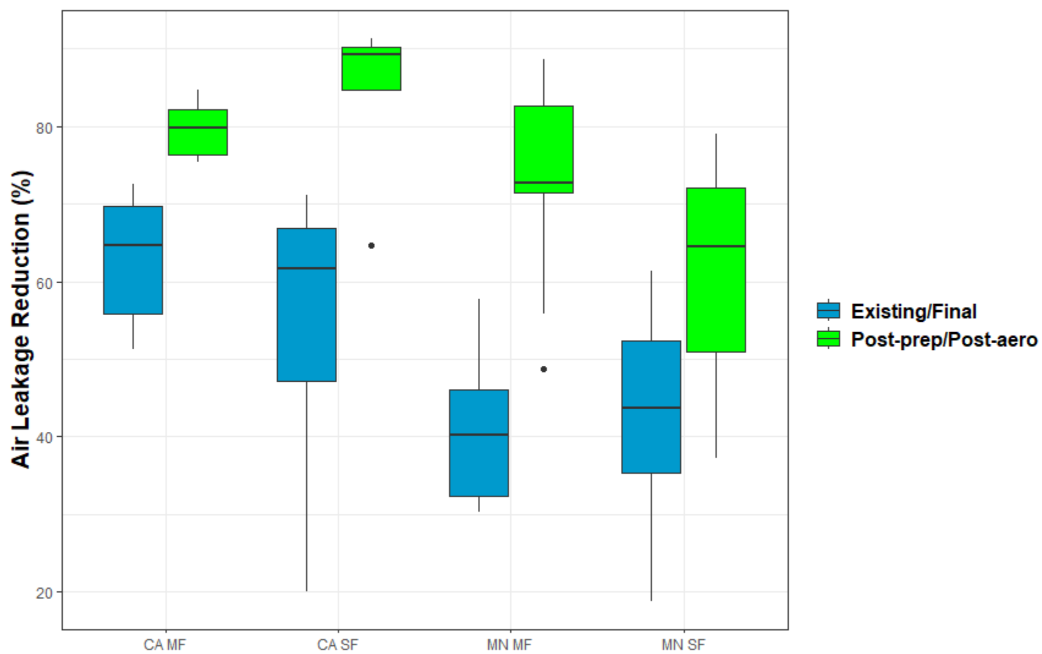


Figure 68. Air leakage results summary for all residences

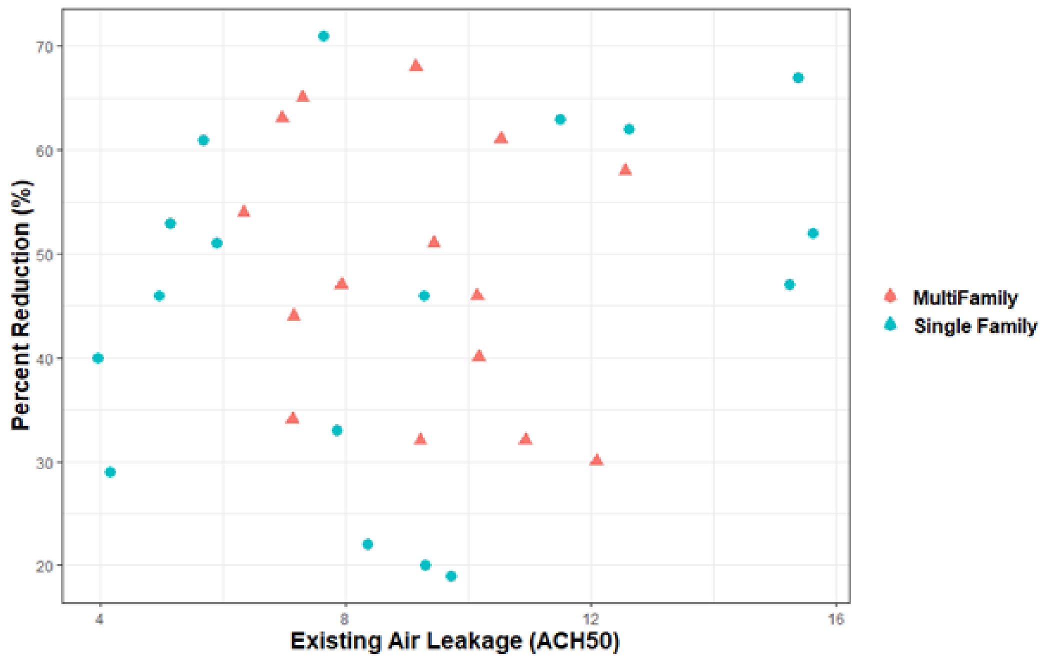
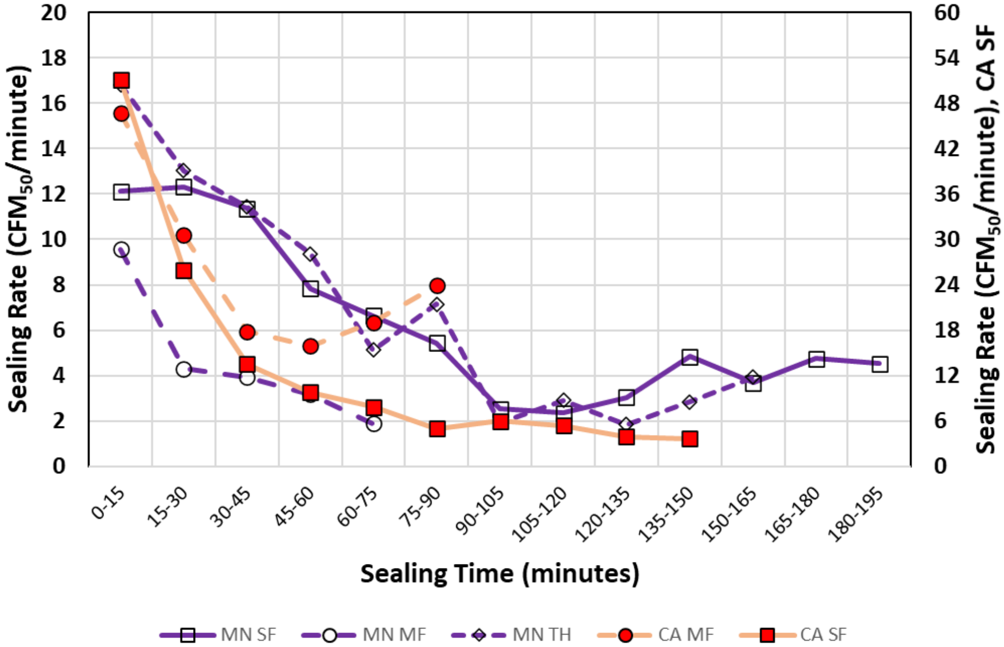


Figure 69. Air leakage reductions vs. existing air leakage showing no correlation to existing leakage levels

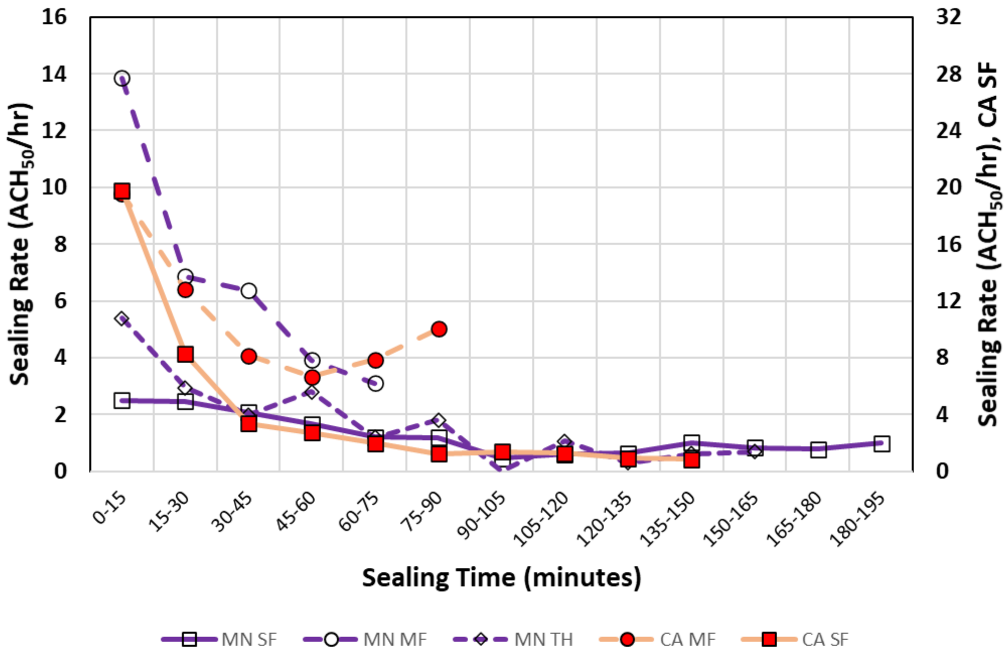
Figure 70 displays the median 15-minute average sealing rate for the five groups of residences. The median sealing rate for the first 15 minutes of aerosol sealing ranged from 9.6 CFM_{50}/min for Minnesota multifamily units to 51 CFM_{50}/min for California houses. For most residences, the rate of sealing was greatest at the start of the sealing and gradually decreased over time. The greater rate of sealing at the start of the process suggests that the houses had a large length of narrow gap leaks that seal faster than wider leaks. The trend was not as significant for Minnesota houses, but that was likely due to start-up issues stemming from the use of next-generation equipment and colder weather protocol adjustments. It is possible that the California houses had a higher fraction of narrow leaks that sealed quicker, and the Minnesota houses had more large gap leaks that took longer to seal or were not sealed effectively. Also, the initial sealing rates were generally greater for larger residences.



Results for California single-family houses plotted on right vertical axis; all others plotted on left axis.

Figure 70. Median air sealing rate for five groups of residences (CFM_{50}/minute)

The California and Minnesota apartment units had the lowest initial sealing rates of 15.6 and 9.6 CFM_{50}/min, respectively. However, the volume-normalized sealing rates of 9.8 and 13.9 ACH_{50}/h, respectively, were higher than for the other groups of residences except California houses (Figure 71). Additionally, the sealing times were shorter for the apartment units than for the houses and townhouses. The median sealing time for the apartment units was 56 minutes, while it was 95 and 171 for the California and Minnesota single-family houses, respectively. The sealing times are likely longer than would be typical for market-based sealing. Sealing was often extended by 15 to 30 minutes to evaluate the typical decrease in the sealing rate for longer sealing periods. Sealing periods of 45 to 60 minutes for apartments and 90 to 120 minutes for houses are more typical for AeroBarrier contractors. After the first hour of sealing, the sealing rates typically leveled out to between 3 and 6 CFM_{50}/min or 0.5 to 1.5 ACH_{50}/h.



Results for California single-family houses plotted on right vertical axis; all others plotted on left axis.

Figure 71. Median air sealing rate for five groups of residences (ACH_{50}/h)

Figure 68 shows the percent leakage reductions by comparing the pre-sealing leakage measured before preparations were applied to the post-sealing leakage after the preparations were removed (blue boxes). It also shows the percent reduction immediately before and after the aerosol sealing when the preparations were in place (green boxes). With preparations in place, the aerosol process reduced leakage by an average of 72%. This indicates that the aerosol process sealed almost three-quarters of the leaks that were not covered by preparations.

The 72% reduction is significantly greater than the average overall reduction of 47% from before the preparations were applied until after they were removed. The lower reduction when the preparations were not in place was due to the percentage of leaks that were covered during the preparation process and the aerosol seals that were disturbed when the preparations were removed. For the California single-family residences, an average of 25% of the house leakage was covered by the preparations, and the average was 19% for the multifamily units (Figure 72). For the Minnesota residences, the averages were 5% and 8% for the single-family and multifamily residences respectively. The average percentage of house leakage covered by preparations across all of the residences was 11%. The amount of aerosol seals that were disturbed for each residence was estimated from the amount of leakage covered by preparations subtracted from the increase in leakage when the preparations were removed. The average was 9% for the California single-family residences and 7% for the multifamily units. The average was 16% for the Minnesota single-family residences and 24% for the multifamily units. The average for all of the residences was 27%. It appears that improved methods for applying surface protection could increase leakage reduction by 10 or more percentage points.

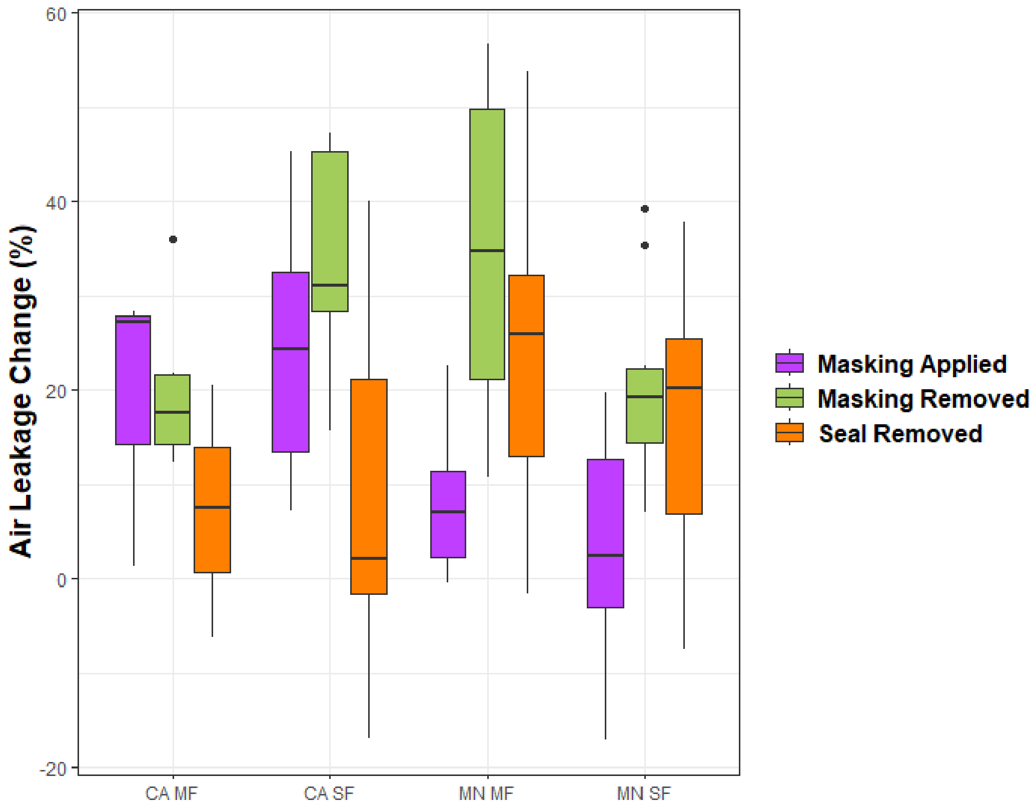


Figure 72. Air leakage covered when applying and removing preparations, and reintroduced leakage from seal disturbance when removing preparations

5.2 Attic Air Sealing

The attic air sealing performed better than expected. For the three California townhouses, the effectiveness of the attic sealing approach was close to the average result for the conventional approach from the interior of the home; however, the potential impact is higher from the conventional approach because it addresses all air barrier surfaces. The performance observed, the fact that attic sealing can be performed with building contents in place, and the significantly reduced preparation time suggest the attic sealing pathway could offer the greatest potential impact in the market. Future work should focus on validating performance in more building types and the potential for application in other zones such as crawlspaces. The results from this limited study were very encouraging, but were only applied to a narrow selection of buildings. Conventional sealing applications on buildings with crawlspaces showed a significant impact from floor coverings blocking leakage pathways through the floor. Aerosol sealing applications from the crawlspace could provide a better solution for sealing the floor of buildings with crawlspaces.

5.3 Alternative Sealant Testing

This testing was conducted to evaluate the impact of sealant modifications on aerosol sealing performance. The modifications were intended to improve the quality of the sealant product by adding a fungicide to inhibit mold growth in the resulting seal and to change the appearance of the sealant material to be more transparent. The addition of 0.1% by weight of a fungicide to the existing sealant used in commercial applications showed no mold growth on samples tested by an independent agency. The sealant performance testing on that formulation (ABX2) showed similar results to the current commercial sealant (ABX1). Another sealant formulation (ABF23) was developed to address the overall appearance, which used a different polymer than the commercial sealant. The sealant performance testing of ABF23 showed lower sealing rates, and in some cases it was unable to seal the test leaks. The sealant also dried with residual tack, which lowers the product's acceptability for use in homes. ABF23 did appear more translucent than the ABX1 and ABX2 formulations.

Given the similarity in performance demonstrated in these tests by ABX1 and ABX2, it would be appropriate to move forward with testing the ABX2 in whole-building applications. The ABX2 sealant has many of the same qualities as ABX1 with respect to sealing rates, seal durability, and appearance with the added benefit of a mold growth inhibiter.

The ABF23 sealant is not recommended for further testing in its current formulation. This sealant did display some good qualities such as low leakage levels through the seal and improved transparency. However, the low sealing rates, difficulty forming complete seals on test leaks, and residual tack would limit the success of this sealant in building applications. It is possible that adjusting the sealant formulation could result in improved outcomes. For example, increasing the solid content to levels similar to ABX1 and ABX2 would increase particle size, which could improve sealing rates. There should also be efforts to reduce the residual tack to improve the overall acceptability of the sealant.

5.4 Energy Modeling

The energy modeling results show source energy savings in all U.S. climate zones considered when reducing leakage from a baseline of 15 ACH_{50}. The savings were highest in the colder climates and lowest in hot and humid climate zones. The range of source energy savings was 3% to 34% depending on climate zone and the ultimate envelope sealing achieved. Most site energy savings came from reduced gas use for heating the home, with most climate zones reducing site gas use by over 10% when reducing leakage from 15 ACH_{50} to 10 ACH_{50}. Site gas use savings was often over 30% when leakage was reduced all the way to 3 ACH_{50}. Site electricity use was lower—most sites achieved at least 2% savings when reducing leakage to 10 ACH_{50} and over 5% savings when reducing to 3 ACH_{50}. In Los Angeles, results show a small increase in electricity use at all leakage levels. This is because increased infiltration in that climate zone often provides a cooling effect to the building, especially during the night. It is assumed that increasing window operation in that climate zone would reduce this impact.

6 Conclusion

The aerosol sealing performance in existing homes was effective with an average leakage reduction of 47% across all 34 sites. This is in comparison to leakage reductions of 25%–30% from a review of the national weatherization programs (Blasnik et al. 2015). The preparation of the homes undergoing occupancy change is extensive, requiring an average of 23 person-hours for a single-family home, but this work can be significantly reduced when aerosol sealing is incorporated into a renovation project. The materials used for protecting surfaces in the home during the sealing process prevented the sealant from reaching some leaks. For homes on raised foundations, the leakage covered by protecting floors was significant and reduced the achievable air tightness. The sealing of occupied slab-on-grade apartments from the ventilated attic space showed very encouraging results, with these homes achieving a 52%–57% leakage reduction while requiring no protection of the interior of the residence. In these cases, the attic insulation would need to be removed and the sealing could be included as part of an overall attic insulation and air sealing upgrade package. A similar approach could be evaluated for use with crawl spaces for homes on raised foundations to address floor leakage that would otherwise be covered by surface preparation when applying the aerosol from inside the home.

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Appendix A. Surface Preparation for Aerosol Sealing

The surface protection activities performed balance the time required for preparation and cleanup, while avoiding covering potential leak sites. The sections below provide brief descriptions and pictures of standard surface preparation methods for common items located inside residences.

Finished Flooring (Carpeted and Non-Carpeted): over slab or above finished space

Put plastic sheet over entire area. The sheet must be very carefully placed to the edge of the carpet while still allowing a small gap between the plastic and baseboard so that leaks below the baseboards can be sealed by the aerosol. Painter's tape is spaced every few feet to keep plastic from pulling back from baseboard, but does not provide a continuous seal of the plastic to baseboard. This is acceptable protection when there is no air flow through the flooring (i.e., no pressure difference across the floor during sealing).

Figure 73. Poly sheet protection for flooring over slab or above finished space

Carpeted Floor or Open Flooring: over crawlspace or non-conditioned basement

The plastic sheet must be very carefully taped to the edge of the wall while still allowing a small gap between the plastic and the baseboard so that leaks below the baseboards can be sealed by the aerosol. If there are gaps around the edge of the plastic, aerosol can migrate underneath the plastic to seal any leakage in the floor itself. First, a stronger duct tape was carefully laid down at the perimeter of the carpet near the baseboard. This tape provided a straight edge and a good base to attach the plastic covering with painter's tape.

Figure 74. Poly sheet protection for flooring over crawlspace or non-conditioned basement

Stairway

This process is similar to the approach used for flooring. Protect finished flooring that will remain in place. Place plastic sheet over the treads and risers. If the cavity under the stairs is adjacent to the exterior, the sealant fog will flow through any gaps in the stairway. Secure the edges of the plastic to the treads and risers. If the cavity is not adjacent to the exterior, the stairway finished surfaces need to be protected from sealant deposition. Use painter's tape spaced as necessary to keep the plastic in place.

Figure 75. Poly sheet protection for flooring over slab or above finished space

Windows

Cover gaps in operable components with painters tape. Place plastic over window. There are two slightly different approaches.

Figure 76. (1) Drape plastic over top half of the window and secure at top

Figure 77. (2) Cover entire pane with plastic. Tape at sides and top, but leave open at bottom. Permanent window fixtures (e.g., blinds, curtains) need to be protected by plastic and painter's tape

Bay Windows

Use painter's tape to secure plastic across opening.

Figure 78. Painter's tape used to secure plastic across bay window

Kitchen Cabinets and Appliances and Exhaust Fan

Cover with plastic that is taped to the wall at the top to prevent aerosol from settling on surfaces. The plastic can be left loose and open on the bottom as aerosol does not travel upward without assistance from an air current leading to a leak. All cabinets with potential leaks inside need to be left open to allow aerosol to reach those leaks and prevent sealing the cabinet door. Consider applying a cleaning solution to countertops to make it less likely that sealant will adhere and allow for easier cleanup. There are two options for the cabinet doors.

Figure 79. (Left) Cabinet doors open and (right) cabinet doors closed

Bathroom Shower and Tubs

Cover showerhead with bag or painter's tape over top surface. There are two options.

Figure 80. (Left) Cover walls with plastic. Drape over tub so that upper edge of tub is covered. Leave open at bottom. (Right) Tape plastic sheet to wall surrounding the tub about a foot above the tub and drape the plastic over the tub so that the upper edge is covered. Leave open at bottom

Toilets

Cover top surface of tank and bowl. Leave sheet open at bottom.

Figure 81. Drape poly over toilet tank and bowl

Sprinkler Heads

Place bag or duct mask over sprinkler head to protect sensor.

Figure 82. Protect sprinkler heads from sealant intrusion

Electrical Outlets and Switches

Remove electrical outlet and switch plates. Tape outlet plugs to prevent sealant from flowing into electrical box.

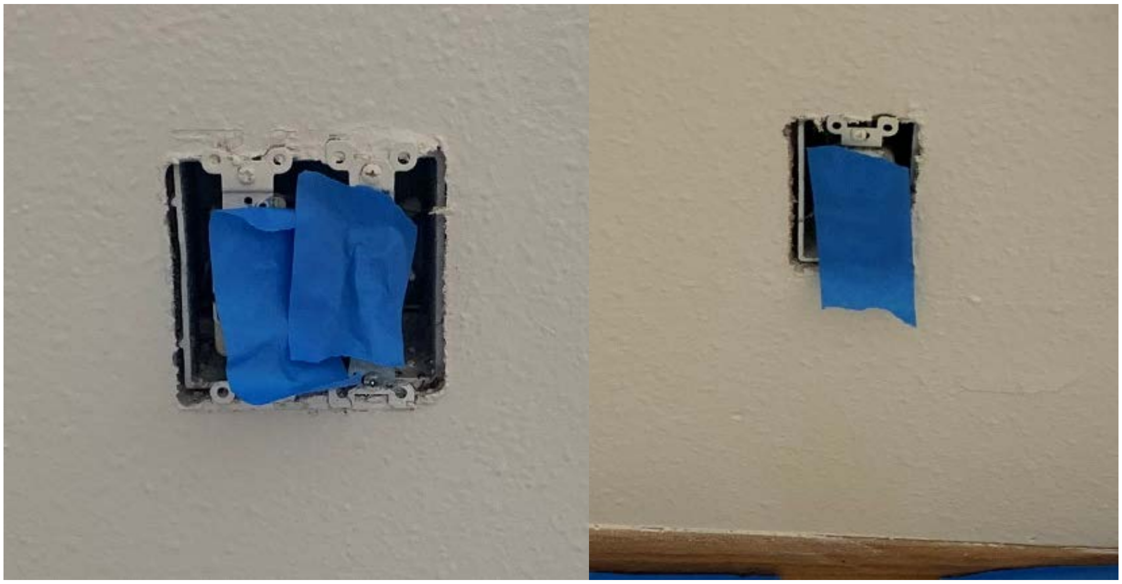

Figure 83. Painter’s tape over electrical devices

Smoke Detectors

Seal over sensor opening or over entire face of detector. If there is no electrical connection, the detector can be removed from the residence.

Figure 84. Painter's tape over smoke detector sensors

Ceiling Light Fixtures

There are two options.

Figure 85. (Left) Remove fixture from ceiling and place bag over fixture. (Right) Keep fixture in place. Seal plastic bag to upper edge of fixture

Recessed Light Fixtures

Remove trim and lamp. Leave open for sealing.

Figure 86. Painter's tape over recessed ceiling fixtures

Ceiling Paddle Fans

Place bag over fan motor and blades.

Figure 87. Plastic bags over ceiling fan

Interior Doors

Two options:

(1) Remove fixture from ceiling and place bag over fixture.

(2) Keep fixture in place. Seal plastic bag to upper edge of fixture.

Figure 88. Painter's tape over doorknob and hinges

Closets

Cover shelves or remove and place under plastic sheet that covers the floor. Apply painter's tape over top of clothes rods.

Figure 89. Poly sheet and painter's tape over closet hardware

Shelves and Bookshelves

Two options:

(1) Remove the shelves and place under plastic over the floor.

(2) Tape plastic sheet above the shelves or bookcase and leave open at bottom.

Figure 90. Poly sheet over built-in cabinet and closet shelves

Supply and Return Registers

There are three options:

1. Low exterior duct leakage: leave as-is unless there is a concern that sealant will travel through the furnace. If significant exterior duct leakage is likely, possibly remove registers near likely leakage locations.

2. Significant exterior duct leakage with an attempt to seal with aerosol sealant: remove supply and return registers. Note: do not leave some registers open and others sealed. This might cause air flow through the furnace/heat pump/air conditioner, which could cause damage.

3. Significant exterior duct leakage and no attempt to seal: seal registers with duct mask (see picture below) or remove registers and plug opening with foam.

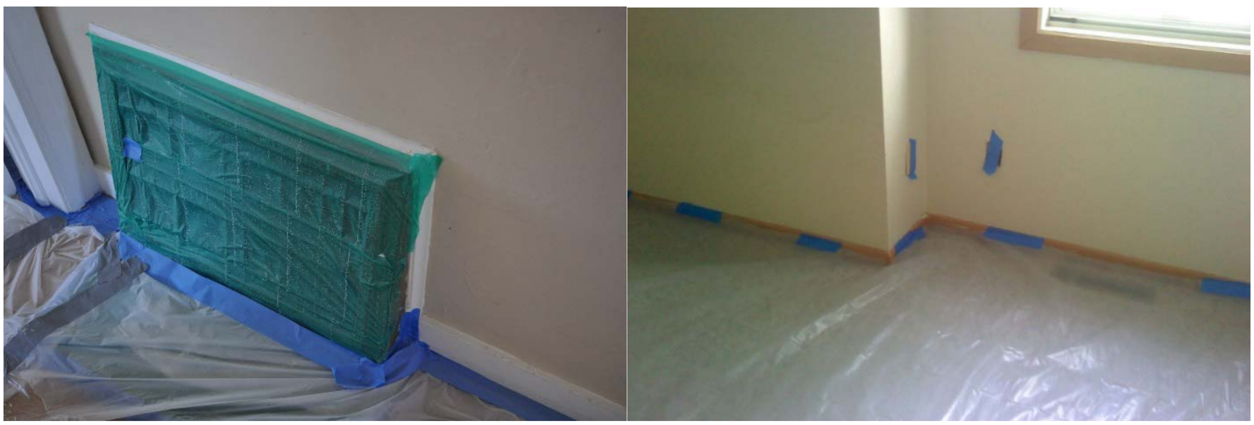

Figure 91. Poly sheet and duct mask over air distribution system grilles

Window Air-Conditioning Unit

Seal with plastic and tape or duct mask so that there is no air movement through the unit.

Skylights

Cover gaps in operable components with painter’s tape.

Furnace

If natural or induced draft, remove vent pipe from furnace and seal open pipe to both outside and inside. If power-vent, seal combustion air inlet. Drape plastic over furnace to protect horizontal surfaces.

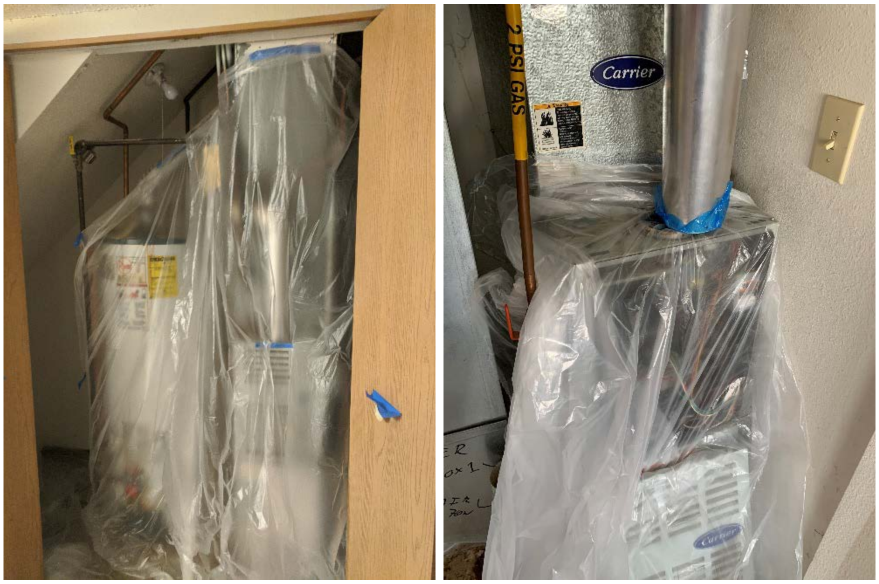

Figure 92. Poly sheet to protect water heater and furnaces

Boiler

If natural or induced draft, remove vent pipe from boiler and seal open pipe to both outside and inside. If power-vent, seal combustion air inlet. Drape plastic over boiler to protect horizontal surfaces.

Water Heater

If natural draft, remove vent pipe from water heater and seal open pipe to both outside and inside. Seal burner inlet. If power-vent, seal combustion air inlet. Drape plastic over water heater to protect horizontal surfaces.

Figure 93. Duct mask and poly sheet to protect water heater vent pipes

Heat Recovery Ventilator

Remove ducts to the exterior. Seal two openings to HRV and end of ducts inside the house with duct mask or plastic and tape.

Figure 94. Duct mask to protect HRV disconnected ducts

Combustion Air Duct

Seal end of open duct inside the house with duct mask or plastic and tape.

Figure 95. Duct mask to protect combustion air duct opening

Radiators/Baseboard

Use painter’s tape to secure plastic sheet over top of radiator or baseboard. Leave open at bottom and side. Pipe penetrations into walls and floors should be left open and accessible.

Ceiling Exhaust Fans

Remove grille and tape over the fan inlet so that sealant does not enter the exhaust duct. The gap between fan housing and wall should be left accessible so that it can be sealed.

Figure 96. Duct mask to protect ceiling exhaust fan grille

Clothes Dryer

Remove dryer exhaust duct from dryer and seal end of duct. Drape plastic over dryer to protect horizontal surfaces but leave open at bottom.

Figure 97. Poly sheet to cover clothes dryer and washer

Fireplace

Completely block the fireplace to prevent aerosol from depositing in and around the fireplace. To ensure that the plastic stays in place and the aerosol sealant does not find a path through the plastic covering, it is important to sufficiently block the leak prior to covering with plastic.

Figure 98. Plywood and poly sheet to protect fireplace opening

Appendix B. Pressure Testing

The primary method for evaluating the sealants was to test the failure pressure of seals formed in each test condition. Testing the seals under pressure is intended to characterize the overall strength of the formulation for comparison purposes. It is not intended to directly measure material properties such as modulus of elasticity. It was found that failure generally occurred gradually, which impacted the approach for evaluating seal performance.

Each sample was allowed to cure for at least 24 hours before pressure testing. To evaluate seal degradation, pressure was gradually increased across the leak and held for a short period of time. After each step increase in pressure, the leakage of the seal was measured at a baseline pressure to see if there were any measurable changes in the original leakage of the seal. This process allows elastic deformation of the seal to be distinguished from plastic deformation that affects the long-term leakage of the seal. The goal was to find the maximum pressure before measurable plastic deformation of the seal is observed. The following procedure describes each step in the testing:

1. Raise the pressure across the seal to the test pressure point and hold for 30 seconds.

2. Lower the pressure to 0.1 PSIG and hold for 10 seconds; this is referred to as the low pressure benchmark.

3. Lower the pressure to 0 PSIG (to allow the compressor to recharge its tank).

4. Increase the test pressure point by 0.01 PSI and repeat.

5. The test is stopped when an increase in airflow does not increase the pressure across the seal.

All data was recorded at 4 Hz, and the following metrics were analyzed:

- Maximum pressure
- Flow rate at 0.1 PSIG
- The test pressure that caused the flow rate at the low-pressure benchmark to double, referred to as the failure point, where plastic deformation was observed.

The flow rate at 0.1 PSIG was used as a metric to compare the quality of seals. This metric allows for the comparison of initial seal quality as well as seal degradation. It should be noted that 0.2 PSIG is much higher than standard building pressures; for example, a wind speed of 75 miles per hour would create a maximum pressure of 0.1 PSIG on a building surface. Because leakage was observed to change as pressure increased, the leakage flow was evaluated at a baseline (low pressure benchmark) to determine if durability of the seal was compromised. When holes first developed, abnormal changes in pressure or flow rate were difficult to separate from normal noise or variation. By returning to a low-pressure benchmark, it was possible to measure the slow increase of airflow related to the seal failing. The failure point was defined as the pressure that caused the benchmark leakage to double.

Appendix C. Impact of Protection on Leakage for Individual Residences

The following tables and figures display the leakage reduction from applying protection (Preparation Applied), removing protection (Preparation Removed), and disturbing seals (Seals Removed). The values are displayed in units of ACH_{50} and percentage in the tables, and ACH_{50} in the charts.

Table 21. Impact of Protection on Leakage: California Houses

Res. #	Existing Leakage (ACH_{50})	Leakage Reduction (%)	Preparation Applied		Preparation Removed		Seals Removed	
			(ACH_{50})	(%)	(ACH_{50})	(%)	(ACH_{50})	(%)
101	12.62	62%	4.10	32%	3.91	31%	-0.19	-2%
102	9.30	20%	0.67	7%	4.39	47%	3.72	40%
103	15.24	47%	3.70	24%	6.91	45%	3.21	21%
104	7.65	71%	1.03	14%	1.20	16%	0.16	2%
105	15.38	67%	6.96	45%	4.36	28%	-2.60	-17%
Min.	7.65	20%	0.67	7%	1.20	16%	-2.60	-17%
Max.	15.38	71%	6.96	45%	6.91	47%	3.72	40%
Med.	12.62	62%	3.70	24%	4.36	31%	0.16	2%
Avg.	12.04	53%	3.29	25%	4.15	34%	0.86	9%

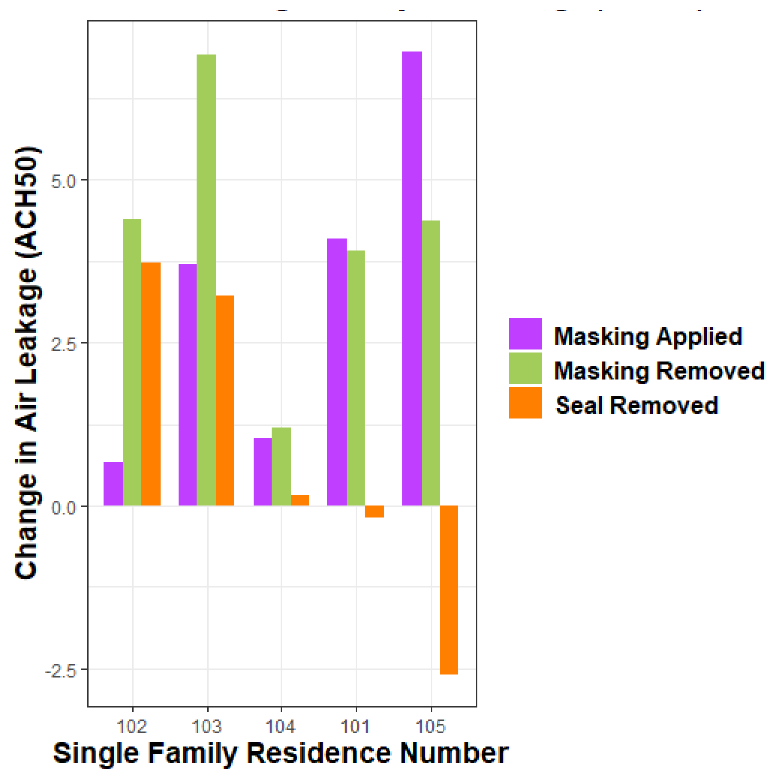

Figure 99. Impact of protection on leakage for California houses

Table 22. Impact of Protection on Leakage: Minnesota Houses

Res. #	Existing Leakage (ACH_{50})	Leakage Reduction (%)	Preparation Applied		Preparation Removed		Seals Removed	
			(ACH_{50})	(%)	(ACH_{50})	(%)	(ACH_{50})	(%)
1	5.68	61%	1.12	20%	0.81	14%	-0.32	-6%
2	4.97	46%	-0.38	-8%	0.69	14%	1.06	21%
4	4.17	29%	-0.49	-12%	0.61	15%	1.10	26%
7	5.14	53%	0.54	10%	1.12	22%	0.59	11%
8	5.91	51%	0.86	14%	0.42	7%	-0.44	-7%
9	8.36	22%	0.12	1%	3.28	39%	3.16	38%
10	9.72	19%	0.22	2%	1.93	20%	1.71	18%
11	3.97	40%	0.43	11%	1.40	35%	0.97	24%
12	8.47	41%	-1.44	-17%	1.62	19%	3.06	36%
19	7.86	38%	1.13	14%	1.32	17%	0.19	2%
20	15.62	52%	2.69	17%	4.06	26%	1.38	9%
21	9.92	57%	0.23	2%	2.24	23%	2.00	20%
Min.	3.97	19%	-1.44	-17%	0.42	7%	-0.44	-7%
Max.	15.62	61%	2.69	20%	4.06	39%	3.16	38%
Med.	6.89	44%	0.33	6%	1.36	20%	1.08	19%
Avg.	7.48	42%	0.42	5%	1.62	21%	1.21	16%

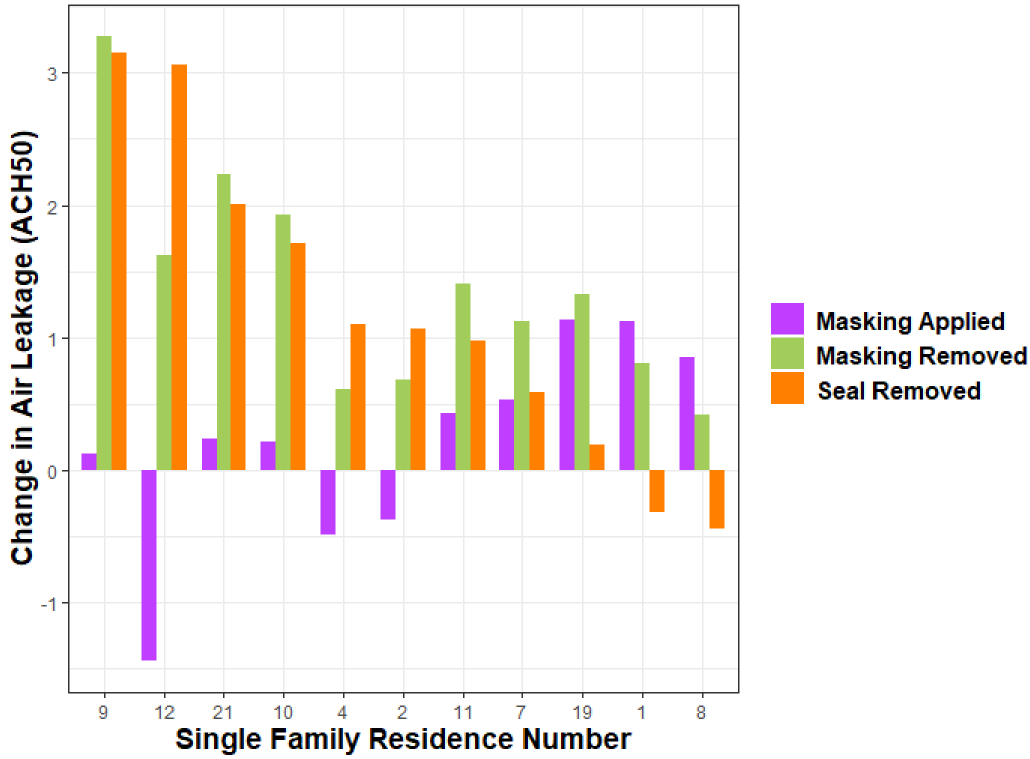

Figure 100. Impact of protection on leakage for Minnesota houses

Table 23. Impact of Protection on Leakage: California Multifamily Units

Res. #	Existing Leakage (ACH_{50})	Leakage Reduction (%)	Preparation Applied		Preparation Removed		Seals Removed	
			(ACH_{50})	(%)	(ACH_{50})	(%)	(ACH_{50})	(%)
106	8.53	70%	*		1.22	14%	*	
107	7.95	68%	*		0.99	12%	*	
108	10.67	73%	*		1.52	14%	*	
109	10.53	61%	2.87	27%	2.22	21%	-0.65	-6%
110	9.44	51%	2.68	28%	3.40	36%	0.71	8%
111	6.35	54%	0.09	1%	1.38	22%	1.30	20%
Min.	6.35	51%	0.09	1%	0.99	12%	-0.65	-6%
Max.	10.67	73%	2.87	28%	3.40	36%	1.30	20%
Med.	8.98	65%	2.68	27%	1.45	18%	0.71	8%
Avg.	8.91	63%	1.88	19%	1.79	20%	0.45	7%

** Measured existing leakage not available; estimate only*

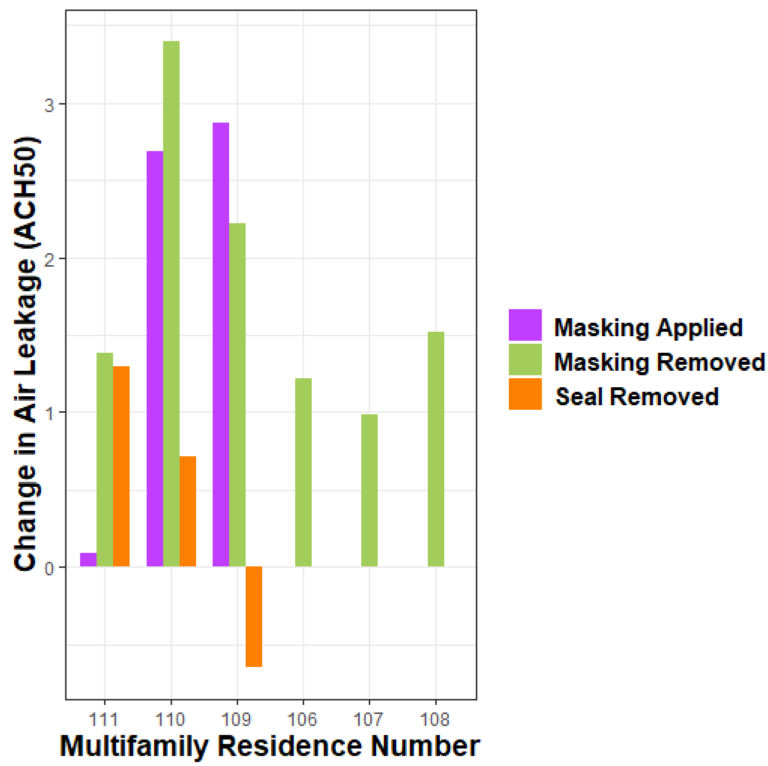

Figure 101. Impact of protection on leakage for California multifamily units

Table 24. Impact of Protection on Leakage: Minnesota Multifamily Units

Res. #	Existing Leakage (ACH_{50})	Leakage Reduction (%)	Preparation Applied		Preparation Removed		Seals Removed	
			(ACH_{50})	(%)	(ACH_{50})	(%)	(ACH_{50})	(%)
3	7.14	34%	-0.04	-1%	1.03	14%	1.07	15%
5	7.17	44%	0.00	0%	1.99	28%	1.99	28%
6	7.94	47%	0.30	4%	0.86	11%	0.56	7%
13	12.56	58%	2.85	23%	2.65	21%	-0.19	-2%
14	10.93	32%	*		5.94	54%	*	
15	10.17	40%	1.07	11%	3.53	35%	2.46	24%
16	10.15	46%	1.15	11%	4.21	42%	3.06	30%
17	12.09	30%	1.37	11%	6.02	50%	4.65	38%
18	9.22	32%	0.27	3%	5.23	57%	4.95	54%
Min.	7.14	30%	-0.04	-1%	0.86	11%	-0.19	-2%
Max.	12.56	58%	2.85	23%	6.02	57%	4.95	54%
Med.	10.15	40%	0.68	7%	3.53	35%	2.22	26%
Avg.	9.71	40%	0.87	8%	3.50	35%	2.32	24%

* *Measured existing leakage not available; estimate only*

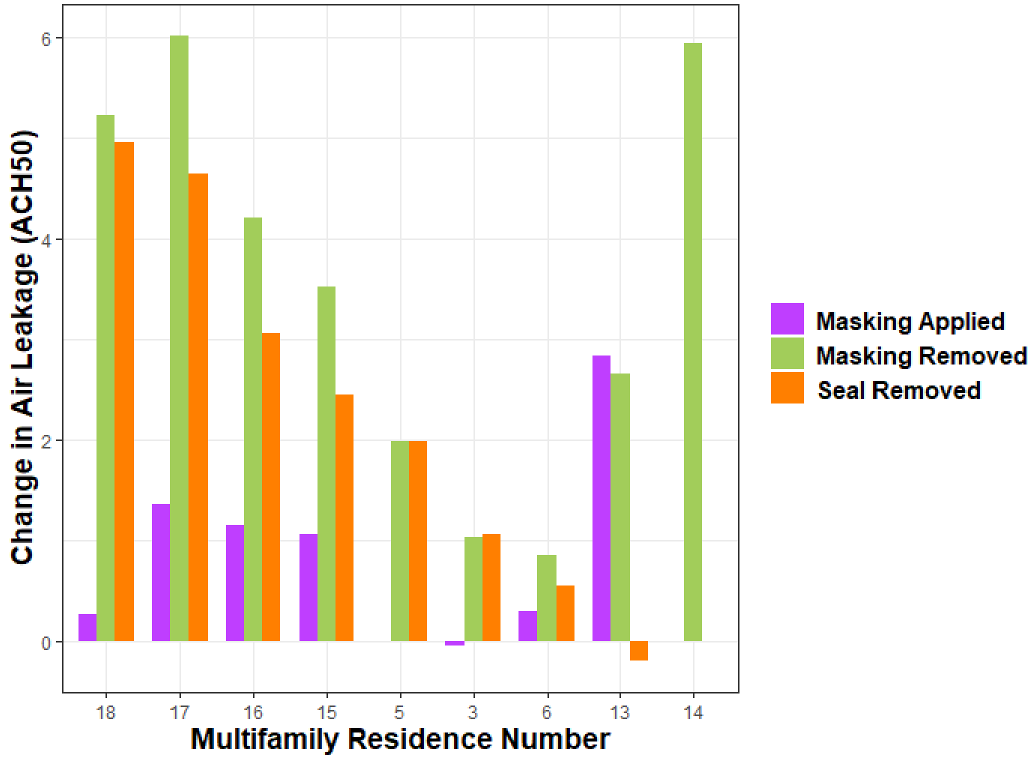

Figure 102. Impact of protection on leakage for Minnesota multifamily uni

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