Aerosol Sealing of Existing Homes from Attics and Crawlspaces

Final Report

ET22SWE0037

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Executive Summary

Overview

Residential homes in the US consume a significant amount of energy for heating and cooling. Of that energy, it is estimated that 29 percent is due to air infiltration from leaks in the building's envelope (DOE 2014). Weatherization programs across the country have been implemented with the goal of reducing energy consumption and improving indoor air quality. However, achieving tight envelopes using existing technologies can be expensive, ineffective, or both, especially in older buildings. Aerosol envelope sealing is a technique where a blower door first pressurizes a home. A sealant is then aerosolized and injected into the space where the particles follow air paths to automatically seal any leaks. The current process is rarely applied to existing homes, due to the challenges in protecting contents from sealant particle deposition. In new homes this is not an issue, but existing homes with finished surfaces must be protected, which is very labor intensive and sometimes not feasible.

Methodology

This project takes the existing process and moves to an "outside-in" method where the aerosol is dispersed into ventilated attics, crawlspaces, or basements while the home is depressurized. This process results in a sealing of the attic-ceiling and/or floor-crawlspace interface. Since the aerosol injection occurs in unfinished spaces, the need for protecting surfaces from the excess sealant is greatly reduced, allowing the process to be applied to occupied houses. The goals of this project were to demonstrate the process in California homes, measure the effectiveness of the sealing process, and develop a standard procedure as a guide for further implementation across a wider market.

Approach

The aerosol sealing process was demonstrated on 13 occupied homes in California from the attic and/or crawlspace. The test sites consisted of five single-family homes and eight multifamily homes. In all cases, there was no insulation in the zone from which the sealing was applied (attic or crawlspace) with the insulation removed as part of a weatherization effort or was never installed in the first place. The homes ranged in vintage from a 100-year old single-family home to a 20-year old multifamily building, showing that the process is versatile enough to be applied to a range of construction types. The application process was documented for each test site and the primary data that was collected focused on the air leakage impacts, including both the amount and fraction of leakage sealed. The eight apartments sealed also allowed the aerosol approach to be compared to typical manual sealing methods. In this case, four apartments were sealed with aerosol from the attic, while another four apartments were sealed manually with canned foam. For the four apartments that received manual sealing, the aerosol approach was applied after manual sealing to determine if a tighter building envelope could be achieved.

Key Findings

Aerosol sealing applied from the attic or crawlspace successfully sealed up to 50 percent of the total home leakage, compared to a maximum of 19 percent for the traditional canned-foam method. Overall, the aerosol approach sealed an average of 37 percent of the existing total leakage of the homes versus 14 percent using manual methods. It was also shown that a combination of canned foam followed by the aerosol technique did reduce the overall time required for the aerosol approach but did not impact the final tightness achieved in the homes. No surface protection was required inside the homes, and no contents were damaged during the demonstration, showing its potential for use on a commercial scale.

Table 1: Average percent leakage reduction for homes in this study.

Sealing Method	Average % Sealed
Aerosol Sealing	37%
Manual Sealing	14%

Stakeholder Feedback

The stakeholders in this project evaluation include the manufacturer, insulation contractors, and program implementers. All stakeholders were supportive of the work and provided feedback that would help the path towards commercialization. The manufacturer was receptive to feedback and modifications on the prototype equipment and is supporting further improvements. Contractors were especially helpful in determining the opportunities related to existing attic insulation removal and air sealing. They were receptive and interested in the technology, although education and training would be needed for wider implementation. Finally, program implementers provided positive feedback, and the team is awaiting responses from the Energy Savings Assistance program working group.

Recommendations

This project introduced an aerosol-based method for sealing homes from the attic and/or crawlspace which was tested on 13 homes in California. The results showed that the aerosol sealing method significantly improved retrofit air sealing measures, achieving air leakage reductions more than 2.5-times more effective than manual sealing with canned foam. Combining aerosol sealing with manual canned foam sealing showed no significant impact on the final air leakage achieved but did reduce the time required for aerosol sealing and minimized particle entry into occupied spaces. The project team recommends that some effort to seal larger leaks manually with foam should be part of the aerosol sealing application protocol, but detailed manual sealing is unnecessary. Contractors should monitor for excessive fogging and temporarily seal large gaps during the process.

The commercialization of the attic and crawlspace aerosol sealing method offers a promising tool for addressing air leakage in existing homes. The project results demonstrated improved performance compared to manual sealing, with impressive total leakage reductions. Further air sealing would require additional interventions, such as replacing windows and installing weatherstripping. The team recommends considering residential aerosol attic/crawlspace sealing for future energy efficiency measures and programs in California and suggests exploring its application to other building types, such as commercial buildings.

Abbreviations and Acronyms

Acronym	Meaning
ACH50	Air changes per hour at 50 Pascals
CFM50	Cubic feet per minute at 50 Pascals
CZ	Climate Zone
UC	University of California
WCEC	Western Cooling Efficiency Center

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Introduction

Residential homes consume about 21 percent of the total U.S. energy use (EIA 2022). Infiltration of outdoor air has been estimated to be responsible for 29 percent of residential heating and cooling loads (DOE 2014). California has adopted aggressive energy codes to reduce greenhouse gas emissions, but to meet California's stated climate goals it will be necessary to retrofit existing homes to improve efficiency and reduce their carbon footprint. Weatherization programs have provided opportunities and resources for addressing air leakage in existing homes. Air sealing efforts in the national Weatherization Assistance Program were reported in over 90% of the homes that participated in the program and contributed the highest fraction of natural gas savings of all measures achieving 28% of the program gas savings (Blasnik et al. 2015). Single-family homes in the weatherization program that received major air sealing (defined as leakage reduction ≥ 1,000 cfm at 50 Pa) resulted in an average natural gas savings of 7.2%. Furthermore, energy modeling results for single family homes in California showed a 50% reduction in leakage, from 15 air changes per hour at 50 Pa (ACH50) to 7 ACH50, resulted in 7-15% reduction in heating and cooling energy use (Bohac et al. 2024). The existing state-of-the-art sealing methods employed in current weatherization programs are all manual and rely on contractors to visually identify and seal leaks. A review of the impact of these programs has shown that air sealing work has resulted in average air leakage reduction of 27% in single family homes, 31% in mobile homes, and 18–20% in multifamily homes (Tonn et al. 2015). Another study reviewed the air sealing impacts from 85 homes in a program for the city of Lafayette, IN, showing an air leakage reduction of about 18% (Ye 2014). Achieving air leakage reductions beyond that using standard air sealing practices would require more intrusive and expensive air sealing methods. This project developed and investigated new technology for achieving air leakage reductions in existing, occupied homes using aerosol sealing methods from the attic and/or crawlspace.

Background

California energy codes have required air sealing of the building envelope since 1982, and there are multiple pathways to compliance. One way is to use prescriptive designs and construction methods, and then perform a visual inspection. However, if a builder is trying to meet Title 24 requirements using the performance approach, the building must be tested to confirm the leakage rate. Discussions with builders in California have suggested that the prescriptive approach is taken more often, due to the added cost of detailed sealing work and testing, compared with the relatively low incentive for a tighter building envelope. The current prescriptive approach in California is assumed to achieve a building envelope leakage rate of 5 ACH50, but with no test requirements, this cannot be verified.

Aerosol sealing has been successfully deployed in new residential construction to achieve much tighter envelope assemblies than other methods. The basic process involves pressurizing the home, while injecting an aerosol fog of sealing material to the inside. As air escapes through leaks in the envelope, the sealant is transported with the air to the leak where it sticks and ultimately forms a seal. This process therefore finds and seals leaks in the building shell. The sealant particles require a significant impact to adhere and generally do not deposit on walls or the underside of horizontal surfaces. The sealant does deposit on the tops of horizontal surfaces due to gravitational settling. In new construction, the deposition on floors is not an issue due to the building being in an early stage of construction. For the retrofit applications, this creates a significant challenge to avoid sealant deposition on finished surfaces.

A previous project for the Department of Energy Building America program applied the traditional aerosol sealing process to existing homes and found a significant amount of time was needed to prepare the home for sealing, which reduced its cost effectiveness (Bohac et al. 2024). It was also found that protection used to prevent unwanted deposition could block leakage pathways, resulting in reduced air sealing performance. At the end of that project, a new installation method was attempted on a limited scale. The new method distributed the sealant material in the attic space while the home was depressurized causing the sealant to be drawn in through leaks in the ceiling of the homes. This limited study showed very promising results with about 55 percent of the total air leakage of the homes being sealed from the attic. This process also did not require any preparation of contents within the home (Harrington, et al. 2022).

Objectives

The objective of this project was to develop and evaluate the performance of a new aerosol envelope sealing method for sealing occupied residences. The site selection goal was to include both single and multi-family homes with a variety of constructions to identify the effectiveness or limitations of the new method. For the multi-family homes, an additional objective was to coordinate with insulation contractors to make a direct comparison between the aerosol and traditional canned foam methods. Finally, the project developed application protocols to aid stakeholders with future programs and commercialization.

Methodology & Approach

The new aerosol envelope sealing approach for occupied residences follows the same basic principle as the more traditional aerosol sealing process. The key change for sealing occupied homes is that the home is depressurized relative to outside using a blower door, and sealant is released in a ventilated attic or crawlspace zone. The sealant is drawn through leaks in the ceiling or floor where particles impact and seal the leaks. Most of the sealant material is contained within the unfinished attic or crawlspace zones, so there is no need to protect contents within the home. The leaks on the unfinished surfaces must be open to the air, so this process can only be applied in uninsulated spaces or during an insulation removal and upgrade retrofit.

Sealing Equipment

Prototype equipment was provided by the manufacturer with input from the research team. The sealing kit includes one control unit and four remote units each with two sealant pumps (Figure 1). Compressed air is routed through the control unit, which monitors pressure, and out to the remote units in the attic or crawlspace. Sealant is held in portable two-gallon containers near the remote units, which pump the liquid to the nozzle while monitoring relative humidity. The pumps will automatically shut off if the humidity exceeds 90 percent, and will restart once the humidity conditions drop. The manufacturer provides a 10-year warranty for the product and it is assume that this warranty would also apply to the new application for existing residences.

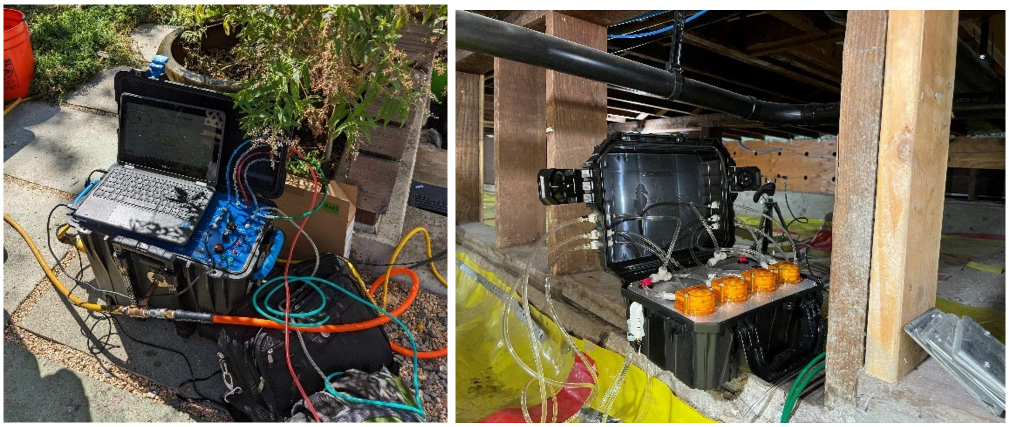

Figure 1. Aerosol sealing control unit (left) and remote injector unit (right).

Health and Safety Protocols

The sealant is a diluted version of a synthetic acrylic polymer material used as a spray or roll-on exterior air barrier. While the particles generally do not deposit on building contents using this new method, they can pose a health risk if breathed for an extended period. High levels of particulate matter inside the home have been measured during sealing, requiring the operators and anyone present in the home at that time to wear an N95 mask or fitted respirator to avoid breathing a potentially high concentration of particles.

If there is an issue that requires operators to enter the attic or crawlspace, the blower door fan and pumps should be stopped to keep sealant from entering the house. Fitted respirators and eye protection should be worn when entering this space. In the current commercialized process, contractors usually use full face respirators if they must enter the same space as the nozzles.

Occupants are asked to leave during the spraying process but may remain if proper personal protective equipment is worn at all times. Once the sealant pumps are stopped and flushed with water, the attic, crawlspace, and windows can be opened, and the blower door used to clear any remaining particles. This typically takes 15 minutes with the fan at the maximum setting. Once the particles are removed from the space, it is safe for occupants to return. The material is UL-certified Greenguard Gold, which is a standard for low volatile organic compound materials that can be safely applied around humans and pets.

Test Sites

Test sites were recruited in two California climate zones (CZ3 and CZ12). The project team worked with insulation contractors, non-profit weatherization entities, and others to find suitable sites. It is common for older homes in CZ3 (Bay Area) to be built without insulation, given the mild climate, making them good candidates for retrofit aerosol sealing. The sites in CZ12 (Sacramento Valley) all had insulation at one point, due to its more extreme climate, but were going through a weatherization process that included removal and reinstallation of insulation. The specific climate zone in which the demonstration was conducted does not have a direct correlation to the performance of the process, but localized weather events during a sealing effort can impact performance. For example, high humidity and cold temperatures tend to reduce sealing rates lowering the performance of the technology. This can be mitigated using heaters to increase air temperature and reduce relative humidity. This section provides an overview of the thirteen sites sealed as part of the demonstration work.

Site 1

The first site recruited was a single-family 1,420 ft^2 home in California climate zone 3. It was originally built in the early 1900s but underwent a gut rehabilitation project within the last 10 years. The home was a single story with a conditioned attic, which prevented the sealing technique from being used in that space. The attic was sealed and insulated below the roof deck, essentially making it part of the conditioned envelope. There was an unfinished basement under part of the house and a crawlspace in the remaining portion. Minor preparatory work was required, including covering a whole house battery and other items stored in the basement (Figure 2). Four nozzles were placed centrally in the crawlspace, pointed outward to provide maximum coverage of the area. This site was chosen because of the easy basement access and the eagerness of the homeowner to participate.

Figure 2. Basement/crawlspace area of Site 1.

Site 2

Site 2 was a 1,614 ft^2 single-family home in California climate zone 3. This home was more than 100 years old, with an unknown history of additions and renovations. This house had both a basement and attic. The attic was accessible through multiple doors on the second floor, which required temporary sealing to prevent excessive aerosols from entering the house (Figure 3). Similar to Site 1, drop cloths were used to protect items stored in the basement (Figure 4). This site was chosen because it had no attic insulation. A visual inspection also found significant leakage pathways which provided the opportunity to test the aerosol sealing process in a home with high leakage levels.

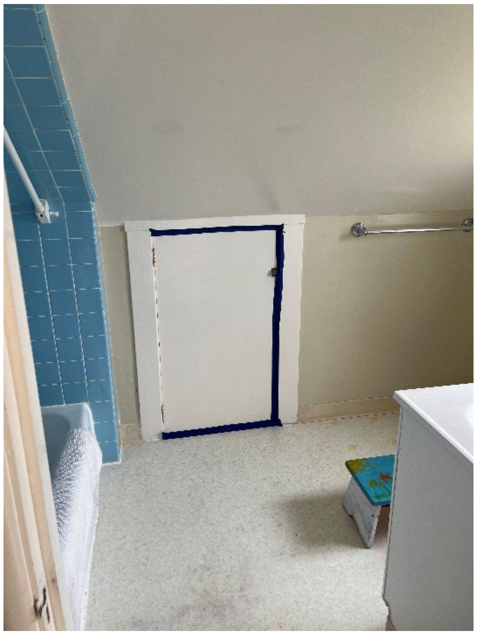

Figure 3. One of four attic access doors that were temporarily sealed for the aerosol sealing installation.

Figure 4. Example of plastic used to protect a storage area.

Site 3

Site 3 was a 1,191 ft^2 single-family home in California climate zone 12 with a vented attic and crawlspace. The owner was in the process of replacing the HVAC system and windows, so there were some rough openings that had to be temporarily blocked for the sealing work. Preparatory work was minor, with some holes in the wall from renovation work that needed to be taped over. An attic access hole installed by the homeowner had to be temporarily covered during sealing and the crawlspace access was taped at the seams to avoid sealing the door shut. The only manual sealing was a small amount of canned foam around a bath fan housing (Figure 5). This house was chosen because of the homeowner's desire for enhanced air sealing while renovating other parts of the house.

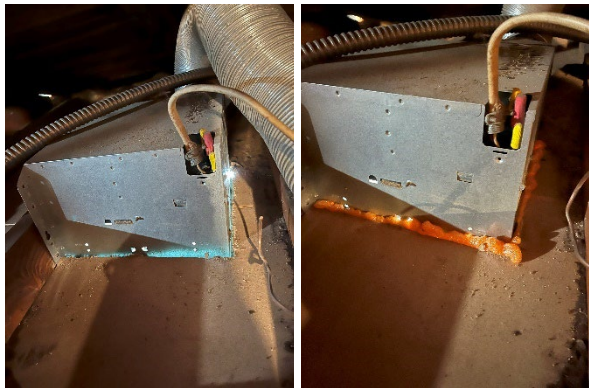

Figure 5. Photo showing before and after photos of foam applied around bath fan housing

Site 4

Site 4 was a 2,491 ft^2 two-story home in California climate zone 3, with denim insulation in the attic and a small ~600 sq. ft. crawlspace below part of the home (Figure 6). The rest of the home's footprint was slab-on-grade with a garage and covered outdoor space. The insulation would have been labor intensive to remove, so the team elected to attempt crawlspace sealing only. Despite the limited available opportunity for sealing with the aerosols, this home was chosen to see if the technology could be effective on this limited scale.

Figure 6. Photo of crawlspace sealed at Site 4.

Site 5

Site 5 was a single story 2,136 ft^2 house built in 1972 with slab-on-grade construction in climate zone 12. A ventilated attic covered approximately 1,500 sq. ft. of the building footprint, with the rest being vaulted ceilings. The home was preparing for a full electrification upgrade, including replacing a natural gas furnace and hot water heater. These systems were both located in the home, but the new systems were getting installed outside of the conditioned space. Large openings for combustion makeup air were present between the location of the gas appliances and the attic space (Figure 7). These openings were temporarily blocked for the aerosol sealing but scheduled to be permanently sealed as part of the retrofit work, so the results do not include the flow through those openings. This house was chosen because of the homeowner's desire for enhanced air sealing while renovating other parts of the house.

Figure 7. Makeup air grilles between the attic and water heater location in the home.

Figure 8. Attic access hole (left) and view from inside the attic (right).

Multifamily Sites 6-13

Sites 6 through 13 were located at an affordable housing community in Davis, CA. This site was chosen because the whole apartment complex was receiving attic insulation upgrades and attic air sealing. Two buildings with four apartments each were selected to be sealed using the aerosol approach. The first four apartments were sealed from the attic only, using the aerosol method and with minimal preparation. The other set of four apartments were first sealed manually by the insulation contractor with canned foam, and then sealed with the aerosol method. The goal was to determine the effectiveness of the approach with a combination of detailed canned foam sealing, followed by aerosol sealing. Aerosol sealing is most effective for sealing small, distributed leak sites. Larger leaks, which are easier to identify and seal manually, take much longer for the aerosol process to completely seal, so manually sealing with foam was expected to speed up the process.

Sites 6, 9, 10, and 13 were three-bedroom, 2.5 bath, 1,225 ft^2 two-story slab-on-grade townhome-style apartments built in 2004. There were a few unique aspects that required special attention. Two apartments had attics with inaccessible spaces that were closed off with plywood. Under direction from the property manager, the contractor cut holes in these spaces to replace insulation and allow access for sealing. Another issue was a built-in linen closet with unfinished backing. These storage spaces had decorative rear panels that had become detached, opening up a large leak directly with the attic. Measurements allowed the project team to estimate that this single leak site contributed approximately 300 CFM50 or 1.8 ACH50 to the overall leakage. Checking for major leaks like this during a pre-test screening is necessary to prevent damage to the occupant's belongings. Due to the size of the leak, researchers chose to tape off the rear of the closet, in order to avoid excessive sealant entering the space, and the property management was informed of the defect. Ideally these leaks would be sealed manually but access makes it difficult to resolve.

Sites 7, 8, 11, and 12 were two-bedroom, 1.5 bath, 1,039 ft^2 two-story slab-on-grade townhome-style apartments. The two apartment types in the study had similar attic designs, including a whole house fan that make the results comparable between the two apartment types. Unlike the three-bedroom units, the linen closet did not have any obvious construction defect causing excessive leakage with the attic, and none were found to have inaccessible attic spaces.

Test Plan

The test plan was developed to capture the potential for the new aerosol method to seal leaks in existing homes. Data was collected on the starting leakage of the each of the homes before sealing and again after sealing was completed. Other leakage measurements were conducted during the sealing process to monitor sealing rates and to determine when sealing was complete. Application protocols were refined over the project period as the team gained more experience and used to develop a standard procedure for future installations.

Prior to enrolling a participant into the study, the residence was screened to determine if the aerosol process would be safe and effective. An initial site visit first determined safe access to the attic and/or crawlspace. Also, it is important to educate the owners on the sealing process to ensure they informed. The condition of the insulation was also noted, and if necessary, a plan was developed to remove insulation prior to sealing.

Once a demonstration site was selected, the sealing process started with an initial walk-through to identify leakage pathways, identify large leaks that should be sealed manually, and identify any preparation needs in the space prior to sealing. The aerosol sealing process is most effective for leaks smaller than about 3/8 inch to avoid extended sealing times and slow sealing rates. By far the easiest way to identify larger leaks is to depressurize the house with a blower door and briefly check every room for excessive drafts. Experienced operators can do this by feeling for air movement, but smoke generators or “puffers” that indicate airflow direction are less subjective. The most common large leaks were identified above range hoods, make-up air for gas burning appliances, bathroom exhaust fans, unfinished walls, ducts, and wall plates. Exhaust fans without backdraft dampers can be a significant source of infiltration but may not be a concern for aerosols if the duct is terminated outdoors. Ducts terminated in the attic (or broken ducts) may allow excessive sealant into the occupied space. If the HVAC system has ducts in the attic or crawlspace being sealed, there should be care taken to avoid sealant from depositing on the heat exchanger coils. Some homes in this project had an air handler in an indoor closet with supply ducts in the attic. It was decided to tape off the return duct to prevent the sealant from makings its way through leaks in the ductwork through the air handler, and out of the return in the conditioned space. These leak sources are a good starting point, but by no means exhaustive. Visually monitoring the amount of aerosol fogging in the occupied space was adequate to address large leakage sites that were not apparent in the initial walk-through. Addressing these issues quickly was sufficient to avoid excess fogging and the potential for deposition on interior surfaces or contents.

Next, the sealant equipment is set up in a similar procedure to the existing aerosol process for new homes. Aerosols are sprayed using compressed air and liquid sealant pumped into a nozzle that atomizes the material. Nozzles are mounted to tripods and directed to maximize coverage and avoid obstructions. This can be challenging in attics or crawlspaces that have structural beams, ducts, and plumbing. The number of nozzles is chosen based on the overall leakage, specific layout of the attic or crawlspace, and the ambient dewpoint. Nozzles can be remotely turned off if humidity is too high, and heaters can be used if ambient conditions are unfavorable. Researchers used small propane heaters at sites 4 and 5 to increase the sealant injection rate for those installations.

After setup, the spray pattern is visually checked using water. This helps avoid obstructions and ensure nozzles are operating correctly. Then the attic and/or crawlspace is closed off and the house is depressurized to a range of 100 to 150 Pa. The sealant pumps are started remotely, the start time is noted, and the operators don respirators if they are remaining inside. Operators who remain inside check for excessive fogging to prevent unwanted sealant deposition. Windows can be cracked to provide fresh air to help flush out particles, especially when leakage levels in the home are lower. However, depressurization should be maintained at a minimum of around 100 Pa.

At this stage in the process operators should monitor fogging inside the occupied space. If excessive fogging is noticed, then the installer can track the source of particles, using a number of methods, such as shining a bright light through the particulates to determine where the flow is coming from. The real-time leakage rate should also be monitored to calculate the sealing rate and monitor the sealing performance. The sealing rate is defined as the amount of CFM50 sealed per minute. Sealing rates decrease exponentially over time, and the sealant pumps can be stopped when the profile flatlines or is below a predetermined target. After some hands-on experience, the research team chose would target a sealing rate less than 2 CFM50 per minute as an indicator that sealing has slowed sufficiently to end the process.

Once the sealant pumps are stopped, the house is kept depressurized for 10 to 15 minutes to clear the remaining aerosol particles. During this period the injection lines are flushed by remotely switching to the water pump for several minutes. Once this is completed, the attic/crawlspace can be opened, and all remaining aerosols cleared. The equipment is removed and cleaned for another use. The blower door is left running throughout this process to further expel any remaining sealant particles. All temporary seals are removed, and an air leakage test is conducted in the same condition as the baseline test to determine the final total leakage rate. The amount of time occupants must leave, or wear fitted respirators is typically 1.5 hours, but this period may be longer for leakier envelopes. Pets should also be removed from the home during the injection process.

Findings

Overview

The results are presented in terms of the reduction in total envelope leakage. Leakage is measured as CFM50, or when normalizing the leakage rate to the volume of the building as ACH50. The results are presented first for the single-family homes (sites 1-5) and then for the multifamily units (sites 6-13). Since a primary objective of this project is to evaluate the feasibility of the method and to develop a standard operating procedure, these results are presented in discussion form. Important points that will be addressed include implementation costs, risk to occupant’s belongings, and the details of the operating procedure.

Results

Single-Family Homes

Table 2 re-iterates the main characteristics of sites 1 to 5 that were described in the test sites section. Three sites were in California climate zone 3, and two in climate zone 12. The climate zone does not necessarily affect the sealing results, but ambient conditions do. Houses in climate zone 3 are more likely to have cool humid air, which would slow down the sealing process. This was especially true for Site 4, which is described in more detail later.

Table 2. Summary of the Main Attributes of Sites 1-5

Site	Floor Area [Sq. Ft.]	Stories	Attic Sealed?	Crawlspace Sealed?	CA Climate Zone	Vintage
1	1420	1	No	Yes	3	~1900
2	1614	2	Yes	Yes	3	~1900
3	1191	1	Yes	Yes	12	1957
4	2491	2	No	Yes	3	1961
5	2136	1	Yes	None	12	1972

SITE 1 DETAILED RESULTS

Site 1 had a small basement connected to the crawlspace area and included an exterior door that allowed the research team to perform guarded testing. With the basement depressurized to -50 Pa, the house reached -10 Pa relative to outside, which provided a qualitative assessment of the extent to which the house and basement were connected through air leakage. A guarded test showed that there was a total of 283 CFM50 of envelope leakage through the floor between the house to the basement. A post-seal test showed that the aerosols successfully sealed 87 percent of this floor leakage, and another guarded test showed no measurable pressurization of the occupied space when pressurizing the basement, demonstrating that very little leakage connection remained between the zones. Total sealing time was about one hour, with about 1.5 hours of setup, including covering of contents in the basement and cleanup. The overall envelope leakage sealed was 247 CFM50 (1.14 ACH50) for a final result of 400 CFM50 (1.9 ACH50).

Aerosol fog inside the occupied space was noticeable, but very minor, especially compared with the traditional “inside-out” method. No deposition on the owner’s belongings was observed, but one window was opened a small amount during the sealing to help flush particulates out of the building. Opening the window did not affect the sealing process since overall leakage flow was low, and therefore pressure was able to be maintained. Figure 9 shows photos of some of the aerosol seals formed on the underside of the floorboards.

Figure 9. Seals formed at penetrations in the floorboard at Site 1

The main conclusion from site 1 was the success of the crawlspace method, and that opening windows can help to flush out sealant while maintaining building static pressure. Prior to this site, sealing from the crawlspace had been done only twice as part of an unrelated project. While the theory is the same, the application is different because gravity is working against the direction of sealing. Also, crawlspaces tend to be cooler and more humid, which can slow the sealing process. The result from this site shows that the floor/crawlspace can be sealed very effectively using the aerosol sealing method.

SITE 2 DETAILED RESULTS

The baseline leakage for Site 2 was 3,738 CFM50, or about 18.6 ACH50 and included an attic and crawlspace. The sealing preparations included a temporary blocking of leaks, including large door undercuts leading to the attic and wiring penetrations near the entertainment center. This preparation resulted in a reduction of 665 CFM50, showing a significant potential for further sealing, with permanent sealing of those particular leakage sources. The sealing process took about 3.25 hours, including setup and teardown. Partway through sealing, a large hole under a sink was identified and manually sealed, which represented 250 CFM50 of total leakage. There was also a decision to move two crawlspace nozzles to the attic during the sealing process to improve sealing of the top envelope. In the future, more injection units would be desired to avoid the additional time required to move equipment. Overall, the process was quite successful, considering the initial state of the envelope. The leakage sealed, including the manual sealing under the sink, was 1,639 CFM50 (8.1 ACH50), or 44 percent of the total, for an end result of 10.4 ACH50. Figure 10 shows examples of aerosol seals formed between floorboards at Site 2.

Figure 10. Example seals formed between floorboards at Site 2.

SITE 3 DETAILED RESULTS

Site 3 presented some challenges due to the limited access in the crawlspace. That issue, along with equipment limitations, prevented proper development of a high-humidity aerosol fog in both the attic and crawlspace, resulting in humidity levels that were lower than optimal. Even with these challenges, the aerosol sealing process was very effective. The initial house leakage was 1,628 CFM50 or 10.2 ACH50, and sealing was able to reduce that by 596 CFM50 (3.7 ACH50) or 37% for an end result of 5.7 ACH50. The lack of adequate fogging due to limitations with the prototype equipment caused sealing rates to be slow. Ultimately, the research team ran out of time before fully completing the sealing. This impacted the total amount of sealing accomplished, and it is expected that additional nozzles would have resulted in more leakage sealed and faster sealing rates. After sealing, some deposition was noted on the ball-joint in a ceiling fan (Figure 11). This deposition was easily cleaned but was noted as an area potentially requiring surface protection in future installations.

Figure 11. Buildup of sealant on ceiling fan.

SITE 4 DETAILED RESULTS

Site 4 had an initial house leakage of 4,190 CFM50, and by running the fan at full speed, the team was only able to depressurize the space to 70 Pa. It was later discovered that the chimney damper was open, causing additional airflow during the leakage tests. The open damper was not an issue for measuring sealing performance but did reduce the application pressure the team was able to achieve.

The weather on the day of sealing was considered the worst-case scenario for aerosol sealing with high levels of humidity and significant moisture on the ground. The aerosol sealing process is sensitive to humidity levels and relies on some evaporation of moisture around the particles to achieve the appropriate tackiness. It rained most of the day and local observations recorded 100 percent humidity with a high temperature of 60°F. To address the high humidity levels, the team used a 30 kBTU/hr propane space heater to raise the temperature of the air entering the crawlspace. The heater was placed at the outdoor entrance of the crawlspace, allowing preheating of the makeup air entering the cavity. Two sets of nozzles were used for the sealing, each with independent pump controls to manage humidity levels. The heater allowed stable operation of one set of nozzles, while the other set was cycled off intermittently due to high humidity.

Sealing was conducted for 2.5 hours with very little impact on home leakage. The total leakage reduction was only 129 CFM50 or three percent of the total home leakage (with fireplace damper open). It was unclear the amount of leakage that was available to be sealed from the relatively small section of floor that was the target of the sealing (floor area above crawlspace), but particles were noticeable in the zone above the floor, suggesting that leaks within the crawlspace were present. Researchers identified some leaks, including a large hole behind the washer, baseboard leaks, and around a chimney, but manual sealing efforts at those locations showed no measurable impact on total home leakage flow. It is possible that there were other holes too large for the aerosol to effectively seal but this could not be verified.

For this test site the team placed two particulate matter (PM) sensors in the house (Sensirion SPS30). One was placed near the blower door and the other upstairs. The purpose of the PM sensors was to give some indication of the particle size and concentration in the living space, and potentially provide additional information to the installer about the status of the sealing. The PM sensor downstairs by the blower door initially read a low baseline concentration of only 10 particles/cm^3. After sealing started, PM counts increased significantly, as expected, to a maximum of 13,000 particles/cm^3.

One useful PM measurement was to determine the impact of opening the windows during the sealing process. In this case, a sliding door was opened a small amount, and the PM was measured with the door closed and open. Particle concentrations near the blower door when the slider door was open dropped to about 750-1,000 for PM2.5. These measurements confirmed high particle concentrations in the home during the sealing process, reinforcing the need to wear respirators when inside during the sealing. This result also shows the value of using operable windows and doors to increase the air change rate in a zone of the house to reduce particle levels.

SITE 5 DETAILED RESULTS

Blower door tests were conducted at Site 5 before the manual sealing of large openings was performed, showing a relatively high leakage of 12.7 ACH50. The leaks identified for manual sealing included a large gap around a light fixture and around an exhaust fan housing. The home was preparing for a full electrification upgrade, including replacing a natural gas furnace and hot water heater. These systems were both located in the home, but the new systems were getting installed outside of the conditioned space. Large openings for combustion makeup air were present between the location of the gas appliances and the attic space. These openings were temporarily blocked for the aerosol sealing but scheduled to be permanently sealed as part of the retrofit work, so the results do not include the flow through those openings. Another blower door test was performed after the temporary seals were placed and was considered the baseline condition for the aerosol sealing effort, which showed 8.6 ACH50.

Weather conditions were relatively cool and damp during this installation, with intermittent rain showers, but attic conditions were much drier than experienced at Site 4. Two propane heaters were stationed in the attic during the sealing that provided adequate heating to avoid reaching humidity limits for the aerosol injection system. Even with these challenges, the air sealing was successful, sealing 1,250 CFM50 (4.3 ACH50) or 50 percent of the total home leakage for an end result of 4.3 ACH50.

Another advantage of the attic and crawlspace sealing approach is that any ductwork in those locations in the building could potentially be sealed in the process. Site 5 had sheet metal ductwork present in the attic, and a duct leakage test before and after sealing was performed to determine the impact on duct leaks. The metal ducts were wrapped in fiberglass insulation which was not removed as part of the attic insulation removal process. The insulation on the ductwork impacted the duct sealing effectiveness, but the exposed parts near register boot connections were available to be sealed (Figure 12). Overall, the process sealed 133 CFM25 or 34% of the total duct leakage. There were signs of leakage beneath the insulation as evident by sealant buildup on the insulation and it is expected that removing the insulation prior to sealing would have resulted in better performance.

Figure 12. Sealant deposition on ductwork at register boot connection.

SINGLE-FAMILY HOME SUMMARY

Table 3 presents the air leakage results for each of the single-family homes sealed in terms of CFM50 and ACH50 before and after the aerosol sealing process. Four of the five single-family homes experienced a reduction of 37 to 49 percent of total envelope leakage. This is significantly better than the manual sealing methods, as reported in the analysis of weatherization programs in the U.S., especially considering that the sealing was applied to a limited part of the overall air barrier. Site 4 presented a number of challenges and only achieved a three percent reduction in overall leakage. Weather conditions at Site 4 were an issue, as well as other factors that limited the effectiveness of aerosol sealing.

Table 3. Envelope Leakage Reduction For Sites 1-5

Site	CFM50 Before	ACH50 Before	CFM50 After	ACH50 After	Percent Reduction
1	643	3.0	400	1.9	38%
2	3738	18.6	2099	10.4	44%
3	1620	9.1	1018	5.7	37%
4	3321	10.0	3222	9.7	3%
5	2364	8.3	1196	4.2	49%

Multifamily Homes

The discussion of results for the multifamily homes (Site 6-13) are combined since the application of aerosol sealing was similar for each. One unit, Site 10, was unoccupied, allowing an opportunity to perform guarded testing of the attic leakage. This test was more invasive than a standard leakage test, which makes it challenging to accomplish in other occupied units. The guarded test works by measuring total envelope leakage with and without pressurizing the attic to the same level. The difference in the two measurements provides information on the amount of leakage flow through only the attic-ceiling surface. It was found that approximately 46 percent of the total leakage was from the attic, which is in-line with previous tests and published research.

The eight units were sealed over seven consecutive business days in coordination with the insulation contractor. The insulation and sealing work were coordinated to avoid excessive time between vacuuming and re-insulation. Sites 6 to 9 were sealed with the aerosol method only while Sites 10 to 13 were sealed with canned foam prior to the aerosol sealing demonstration. This approach enabled a side-by-side comparison of aerosols sealing method with the “business-as-usual” canned foam method. This also allowed testing of the aerosol approach with two different starting leakage conditions.

The weather for these demonstrations was warm and dry, so more nozzles were needed to reach the desired relative humidity in the attic. These conditions also allow higher sealant injection rates, which tends to improve sealing rates. The manufacturer repaired and provided additional injector units to ensure that the process went smoothly. Each of the three-bedroom units were sealed using six nozzles distributed in the attic space, while the two-bedroom units required four nozzles. There were no major issues with the equipment, but compressed air does become a limiting factor when injecting with six or more nozzles. In those cases, the team used two compressors in parallel to ensure adequate pressure.

Table 4 presents the air leakage results for sites 6 to 13 before and after the different sealing approaches, which is also illustrated in the plot in Figure 13. The as-found leakage rate for each apartment was generally consistent, except for units that had linen closets with unfinished walls, and excessively leaky range hoods. Manual sealing using canned foam resulted in a leakage reduction of 8- to 19 percent, which is significantly less than aerosols alone which sealed 32 to 50 percent. However, the canned foam did fill larger leaks which would have been more time consuming with the aerosol method. The combination of aerosols and canned foam did not result in a significantly better final result, but it did reduce the time for aerosol spraying. For sites 6 to 9 the average aerosol sealing time was 88 minutes, while sites 10 to 13 took an average of 52 minutes.

Table 4. Envelope Leakage Reduction for Sites 6-13

Site	CFM50 Before	ACH50 Before	CFM50 After Foam	ACH50 After Foam	CFM50 After Aerosol	ACH50 After Aerosol	Percent Reduction
6	1500	8.6	-	-	522	3.0	35%
7	1401	9.5	-	-	448	3.0	32%
8	1488	10.1	-	-	601	4.1	40%
9	2006	11.6	-	-	1005	5.8	50%
10	1774	10.2	1630	9.4	700	4.0	39%
11	1511	10.3	1232	8.4	563	3.8	37%
12	1582	10.7	1278	8.7	585	4.0	37%
13	1526	8.8	1395	8.0	616	3.5	40%

Figure 13. ACH50 for multifamily sites before sealing, after manual sealing for sites 10-13, and after aerosol sealing.

Discussion

Aerosol sealing of new and existing homes has proven to be an effective way to reach envelope tightness goals (Bohac, Harrington and Meyers 2024). The results of this study show that the method can be extended to occupied homes, thereby expanding the market while being less intrusive than inside-out aerosol sealing. The aerosol sealing method was able to seal 32 to 50 percent of the total envelope leakage in 12 of the 13 installations. This is impressive considering the aerosol process was limited to addressing leakage in the air barrier surface only between the attic and/or crawlspace and the home. The one exception was Site 4, where very wet conditions and an unusual house construction prevented the aerosol method from being effective.

The total time spent on sealing varied depending on the initial leakiness of the home and ambient conditions. At Site 2, for example, sealant was injected for 3.25 hours since the starting leakage was so high. While Site 1 injection time was one hour and reduced overall leakage by 38%. Setup and teardown times averaged about 1.5 hours in all cases, but researchers did spend extra time documenting the demonstrations and did not try and rush the process. Further discussion on the time spent at multifamily units is summarized later in this section.

The aerosol sealing procedure developed as part of this study is detailed in the Test Plan section and outlines the basic steps of the process. The procedure evolved over the course of the project, and it is important to note how the team's experience informed improvements. For example, it was known from previous studies that manually sealing holes larger than 3/8" improved sealing rates, but addressing larger holes before aerosol sealing in retrofit applications has the added benefit or reducing aerosol particles from entering the living space. This proved essential at the multifamily sites, where a few apartments had unfinished linen closets that were connected directly to the attic through a large leak path. In one case, sealant deposition was noticeable on interior surfaces in the linen closet that required cleaning. Having one person inside the house during sealing, particularly in the first 30 minutes, greatly reduces the risk of unwanted deposition inside the home.

The outside-in method can make it difficult to check the operation of the nozzles directly if the access to attic or crawlspace is within the envelope of the home. The prototype equipment helped monitor the nozzles indirectly through temperature and humidity sensors at each pump station. There were occasions in this project that the process was interrupted to refill sealant containers, but this is easily avoidable by supplying ample sealant to the stations. The commercial equipment has a sealant use tracker that allows the operator to monitor sealant levels. Overall, the team was able to streamline the process through hands-on experience and the manufacturer is expected to include these tracking features in the commercialized attic sealing equipment.

One area of particular interest was the direct comparison of manual foam sealing with the aerosol sealing process in the multifamily buildings. Manual sealing with foam was the insulation contractor's standard method for addressing attic leakage. The results clearly show the improved performance of the aerosol sealing approach, but it comes with increased labor and costs. To compare the methods for cost-effectiveness, the team met with the contractor on site and interviewed the technician that performed the sealing. The technician reported using about two cans of foam and spent about 30 minutes in the attic of each apartment. The aerosol method requires more preparation and cleanup time in addition to the time for the sealing to occur. The material cost of the aerosol sealant was also higher, although material costs for both methods were relatively low.

Table 5 shows the labor time and materials cost for sites 6 to 13 using both sealing methods, as well as the total CFM50 sealed. Sites 10 to 13 include the measured results for foam only and the result for foam plus aerosol sealing. The labor estimates assume two people are required for the aerosol method, while one person is required for manual sealing. It is important to note that these times are reported in person-hours to better compare labor between the two sealing processes. The actual time required to complete the process is dependent on the number of contractors. It is possible that only one contractor would be required to monitor and operate the aerosol sealing, which would reduce the labor hours reported in Table 5.

Table 5. Labor and Materials for the Aerosol and Manual (Canned Foam) Sealing Methods. All Times Are In Person-Hours.

Site	Sealing Method	Total Person Hours	Sealant Costs	CFM50 Sealed
6	Aerosol	4.7	$91	522
7	Aerosol	3.9	$46	448
8	Aerosol	4.7	$61	601

Site	Sealing Method	Total Person Hours	Sealant Costs	CFM50 Sealed
9	Aerosol	4.4	$83	1005
10	Foam	0.5	$20	144
11	Foam	0.5	$20	279
12	Foam	0.5	$20	304
13	Foam	0.5	$20	131
10	Foam + Aerosol	3.6	$66	700
11	Foam + Aerosol	4.1	$59	563
12	Foam + Aerosol	3.7	$52	585
13	Foam + Aerosol	3.6	$65	616

The manual foam sealing was very low cost in terms of material and labor but was not able to achieve the envelope leakage reductions that the aerosol process was. This suggests the manual foam process is more cost-effective than the aerosol process for leak sites that can be identified visually, but there is a limit to the level or air tightness that can be achieved. Combining foam with the aerosol process resulted in a similar final air tightness but reduced the time required to perform the aerosol sealing, showing the value of performing some manual sealing as part of the aerosol installation protocol.

When combined with aerosol sealing, it is expected that an even more streamlined manual foaming effort that only addresses larger leaks would provide similar results, while also reducing the costs of foam sealing. This is evident in Figure 14, which shows aerosol seals formed near manual foam seals. Even the most experienced contractors will miss smaller leaks and apply sealant to locations that are not leaking. Simplifying the manual foam sealing process to focus on larger and more obvious leak sites with the intention of supplementing with the aerosol sealing would take much of the guess work out of the task.

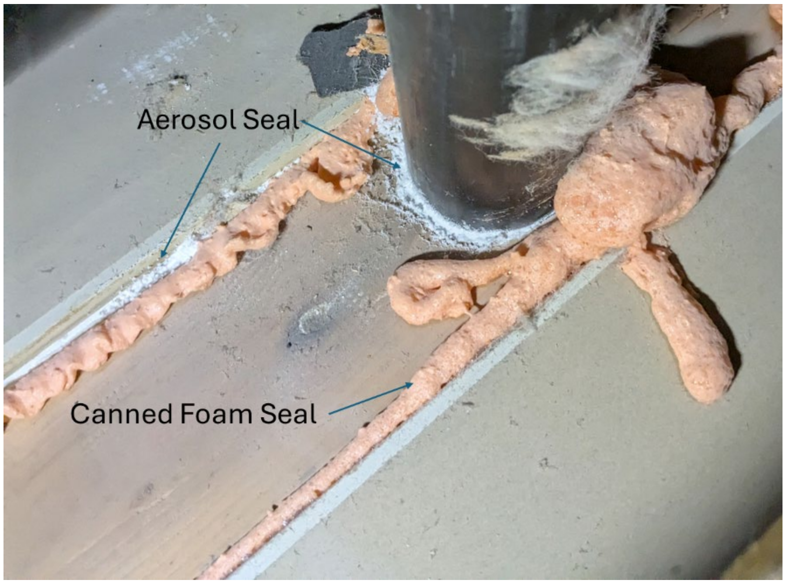

Figure 14. Photo of top plate of a wall in attic with a drainpipe. Canned foam sealing filled larger gaps and then aerosols filled in missed spots.

Another lesson learned in this field study is when not to proceed with the aerosol sealing process. Of course, safety is the first priority, so asbestos, structural issues, and inaccessibility would disqualify a residence until such issues are addressed. Weather conditions are also a concern. Trying to seal during active precipitation is slow and somewhat ineffective, since it prevents the development of a good aerosol fog at the correct humidity. The inside-out method allows heat to be applied to the air before entering the building, but the outside-in approach relies on makeup air from attic or crawlspace ventilation. This presents challenges for adding heat to assist with the sealing process when conditions are very wet. On the other end of the spectrum, sealing in a very hot attic can result in an aerosol fog that is too dry. This issue is easier to overcome by providing more injection nozzles, assuming there is ample compressed air available, or by sealing early in the day.

Stakeholder Feedback

The stakeholders in this project evaluation include the manufacturer, insulation contractors, and program implementers. Feedback from stakeholders was generally positive. The manufacturer is planning to launch a commercial product around this approach, and a follow up study funded by the Department of Energy will explore the process in more home types and climate zones. Insulation contractors have shown interest in the technology and have approached the manufacturer about the timeline for a commercial product. The project team discussed the results with CalTF and the Energy Savings Assistance working group to identify potential pathways to include the process in existing or new measures. The following is a summary of feedback received from each of these stakeholders throughout the project.

Technology Manufacturer

The manufacturer of the prototype equipment used in this project worked closely with the research team, and the study provided valuable experience for future commercialization. The main feedback to the manufacturer has been the standard operating procedure the research team developed through field experience. This procedure, detailed in the test plan section, limits the risk to a given occupant's belongings while maximizing the amount of leakage sealed by the aerosol process.

The prototype equipment worked well for the field study, and the research team met with the manufacturer several times to discuss how to improve the commercial product. The prototype injector units are smaller than the commercially available units used today, which helps when applying the process in cramped crawlspaces and attics. There were some issues with durability that would be resolved with a production unit. The manufacturer is also working on a new product to allow for more injector nozzles with less equipment. This development would allow for sealing larger spaces or multiple units simultaneously.

Insulation Contractors

Insulation contractors were interviewed to assess market potential. These interviews were informal and occurred during the field demonstrations, at the 2024 ASHRAE Winter Conference, and when requesting quotes for insulation removal. First, the research team asked how common insulation removal is (as opposed to simply adding insulation on top). While adding insulation is cheaper, removal is recommended when there is a pest infestation. This was described as a "frequent" request, but it is unknown what percentage of jobs involve removal. Also, contractors indicated they were open to adding the aerosol process to their air sealing offerings, provided it was cost effective. There would be some outreach and education needed since some contractors are not aware of existing aerosol methods and the reasons why this new approach opens a much wider market of occupied homes.

Some insulation contractors have expressed keen interest in the attic/crawlspace sealing approach, having requested a timeline for commercialization from the technology manufacturer. These contractors tend to be more interested in innovations and moving the industry forward with new technology.

Program Implementors

The research team also engaged with representatives from CalTF and the Energy Savings Assistance (ESA) program implementors, seeking feedback on the study and the steps required for the process to become part of a program. Initial feedback raised concerns about the potential cost of the technology, that insulation must be removed, and that tenants must temporarily leave during sealing. The results of the field demonstrations show that the aerosol sealing process can repeatably achieve tighter building envelopes than standard manual sealing. Tighter building envelopes have implications for energy savings and improvement in indoor air quality that could justify program development. Contractors have also indicated that there is already an existing market of homes where the insulation must be removed. With this information the team submitted a public comment to the ESA working group in May of 2024. The working group is tracking a response, but it has not been finalized at the time of writing.

Recommendations and Conclusions

This project demonstrated a new approach for sealing existing homes with an aerosol-based method from the attic and/or crawlspace. A test was performed on 13 homes in California including both single-family and multifamily residences. The results show that the aerosol sealing methods applied can significantly improve retrofit air sealing measures for homes. The air leakage reductions achieved with the aerosol approach were more than 2.5-times more effective than manual sealing with canned foam with three sites achieving reductions of over 1,000 CFM50. Figure 15 shows the summary of test results for all sites, including the testing conducted on manual sealing with canned foam. The average leakage reduction across all test sites was 687 CFM50 or 37 percent of the total leakage of the homes.

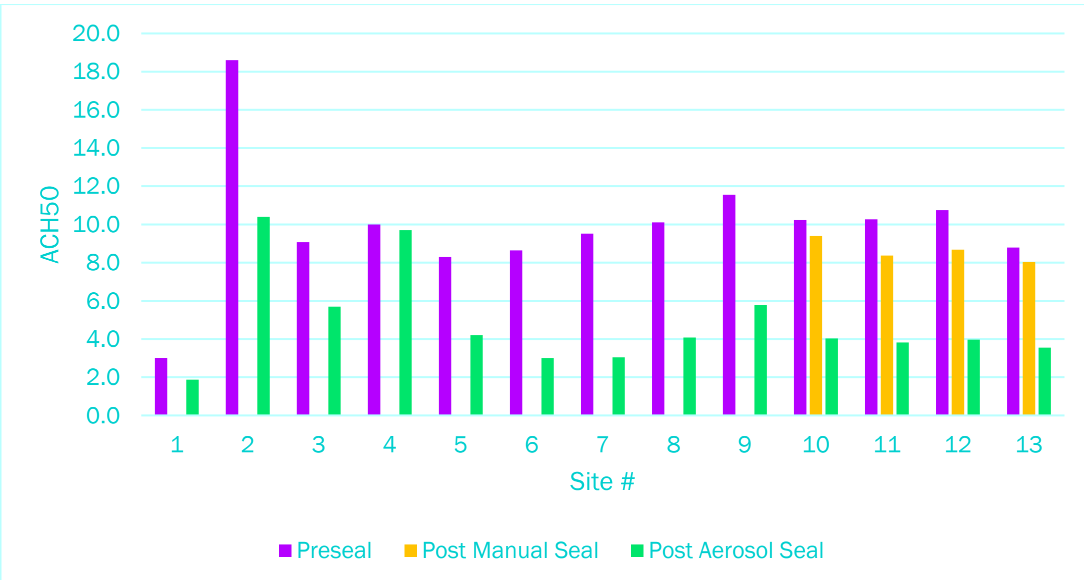

Figure 15. Summary of results from aerosol attic/crawlspace sealing.

Testing performed in combination with manual canned foam sealing showed no impact on the final air leakage achieved, but did reduce the amount of time required for aerosol sealing and appeared to reduce the number of particles that entered the occupied space. The project team recommends that some effort to seal larger leaks manually with foam should be part of the aerosol sealing application protocol, but that detailed manual sealing is not necessary.

It is important for the aerosol sealing contractor to monitor for excessive fogging of the occupied space. In some cases, the aerosol sealing process was paused to address a large connection between the injection zone (attic or crawlspace) and the conditioned space. For these large gaps it is appropriate to temporarily seal the opening during the aerosol process and address the leakage after completing the aerosol sealing. Deposition on interior surfaces was only apparent near one of these large leaks but was easily cleanable once identified.

Commercialization of the attic and crawlspace aerosol sealing method would provide a new tool for addressing air leakage in our existing building stock. The results from this project demonstrate the improved performance over manual sealing with 2.5-times more leakage sealed using the aerosol method. The total leakage reductions were impressive considering the process is limited to sealing air barrier surfaces between the attic/crawlspace and the home. Further air sealing would require additional interventions such as replacing windows, installing weatherstripping, and other weatherization practices. The team's recommendation is that residential aerosol attic/crawlspace sealing be considered for future energy efficiency measures and programs in California to improve the performance of existing building envelopes. It is also conceivable that this process could also be applied to other building types such as commercial buildings from above a drop ceiling which should be considered for future work.

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