FINAL REPORT

Automated Aerosol-Sealing of Building Envelopes

ESTCP Project EW-201511

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ACRONYMS AND ABBREVIATIONS

ACH50	Air Changes per Hour at 50 pascal
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
Btu	British thermal unit
cfm	cubic feet per minute
cfm75/ft^2	cubic feet per minute at 75 Pascal per envelope area in square feet
DoD	Department of Defense
ESOH	Environmental, Safety, and Occupational Health
ESTCP	Environmental Security Technology Certification Program
ft^2	square foot
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, and Air Conditioning
IECC	International Energy Conservation Code
NIST	National Institute of Standards & Technology
OA	Outdoor air
Pa	Pascal
SCFM	Standard cubic feet per minute
TMI	Thermal Moisture Imaging
USACE	United States Army Core of Engineers
WCEC	UC Davis, Western Cooling Efficiency Center

ACKNOWLEDGEMENTS

We would like to express appreciation to Thermal Moisture Imaging for their efforts coordinating and executing demonstrations on this project. We would also like to thank Aeroseal for providing support with the sealing equipment used in the project. Finally, we would like to acknowledge the contributions provided by the following bases that participated in finding suitable demonstration sites for the project:

- Marine Corps Base Quantico
- Fort Bragg Army Base
- Navy Support Activity Mechanicsburg
- Marine Corps Recruit Deport, Parris Island

1.0 EXECUTIVE SUMMARY

The objective of this project was to validate an aerosol sealing application method for sealing building shells as a cost-effective means to meet the USACE tightness requirement for military facilities. The project involved a number of demonstrations on various building types and in multiple climates to show the ability for the technology to be applied on a large scale.

The results presented in this report are expected to facilitate the adoption of the aerosol sealing method for other DoD installations by providing a number of demonstrations on multiple building types and in multiple climate zones. Prior work in residential homes has demonstrated excellent results showing the ability to seal 80% of the building leakage in less than two hours with prototype equipment. Very few retrofit demonstrations have been performed which was the focus of this project. These demonstrations validated the performance of the sealing technology as an effective solution for retrofit installations.

The aerosol envelope sealing process involves pressurizing a building to normal testing pressures while applying an aerosol "fog" to the interior. As the air escapes through leaks in the shell of the building, the aerosolized sealant is transported to the leaks, and seals them as the particles try to escape from the building. This technology uses commercially available blower doors to positively pressurize the building during installation, as well as to provide real-time feedback on sealing progress, allowing the air-tightness to be tracked during the sealing. The entire process is controlled from outside the building and is capable of simultaneously measuring, locating, and sealing leaks in a building envelope, while also providing verification of building tightness.

This project demonstrated that the aerosol envelope sealing technology is very effective at sealing building leakage on DoD facilities. Ultimately, over 75,000 CFM at 75 Pa was sealed over the sixteen demonstrations cutting the air leakage of the buildings in half. presents the overall percent air leakage reduction for each demonstration. The most successful demonstration sealed 80% of the building leakage and three of the demonstrations brought the buildings to within the USACE specification for envelope leakage. This was impressive considering two of these buildings were in poor condition and scheduled for demolition.

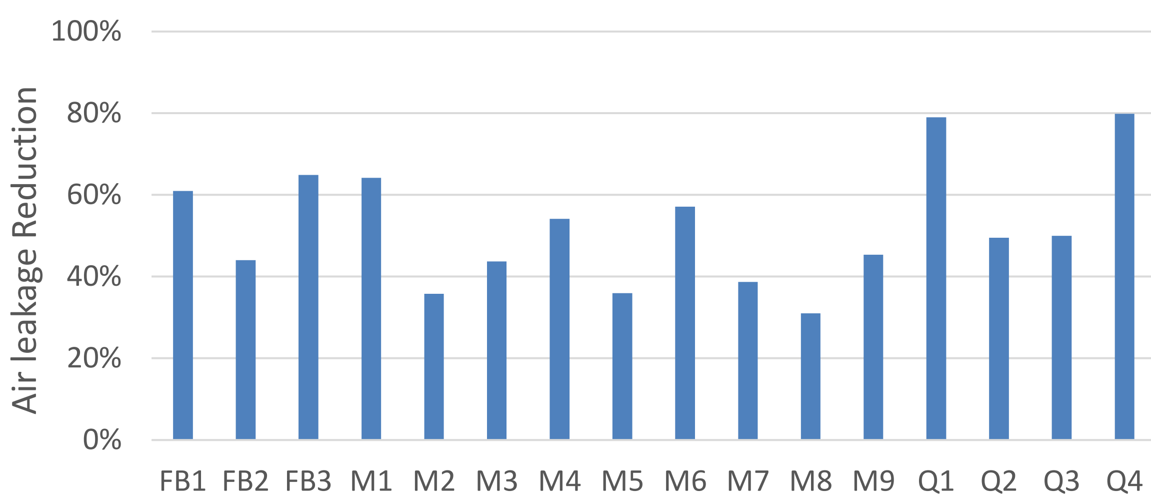


Figure 1: Percent air leakage reduction for all demonstrations

Durability testing was performed to assess the strength and longevity of the seals created using the aerosol sealing process. Seals were created under different humidity conditions to determine the sensitivity of seal strength to this parameter. Multiple tests were conducted on seals formed on test plates in the laboratory, including pressure cycling at medium and low pressures, temperature cycling at medium pressure, and holding high pressure for one hour.

In summary, there were no seal failures during the lab testing of seal durability in which the seals were subjected to pressures up to 5,000 Pa (equivalaent to a wind speed of more than 200 miles per hour). There was a gradual increase in leakage rates when subjected to prolonged pressures above 800 Pa. Cyclic tests at more reasonable pressures of 100 Pa showed that after 1,900 pressure cycles the overall change in leakage flow between the first and last 100 cycles was 0.067 scfm for the six sealed leaks tested. This translates to an increase in leakage area of approximately 0.004 in^2. For six sealed leaks each measuring about 1.2 in^2, this represents an overall increase of less than 0.1% in the sealed leakage area, indicating very little change over the course of the testing.

Modeling of facility energy saving and associated payback as a result of applying aerosol sealing to reduce infiltration showed long payback periods exceeding 20 years in some climate zones. Only in very cold climates was the payback calculated to be five years or less. However, when accounting for reduced outdoor airflow to meet a pressurization target in a building simple payback periods were much shorter with most scenarios modeled paying back in less than five years. Clearly the impact of reducing infiltration is much more significant in pressurized buildings. Lastly, this analysis does not account for improved indoor air quality and improved safety in the buildings.

The most significant challenge that was met during the demonstrations was the presence of significant leakage that was too large for the aerosol to address. This leakage was discovered at the roof-to-wall connection which is a common location for building air leakage since it attaches to continuous air barrier sections. The aerosol sealing process is still advantageous in this situation even though it does require supplemental manual sealing. Future aerosol sealing installations in commercial buildings should assess the roof-to-wall connection to determine if manual sealing work is required.

Another issue that came up during the demonstrations arose from the fact that most people are not familiar with the aerosol sealing process which led to questions about the safety of its application. ESOH staff at one base was questioning whether the material being applied could potentially have an environmental impact. After providing the safety data sheet and explaining that the amount of material applied to the building is really very small the ESOH staff were satisfied and allowed the demonstration to move forward. It is critical to work with ESOH staff to familiarize them with the process prior to performing the work in order to answer questions about the safety of its application.

2.0 INTRODUCTION

Department of Defense (DoD) facilities consumed 0.2 Quadrillion British thermal units of energy in Fiscal Year 2014 with an annual expenditure of $4.0 billion to cool, heat and power its facilities [1]. End-use surveys in the U.S. have shown that 37% of building energy use is for space heating and cooling [2]. To meet DoD's aggressive goal of reducing energy intensity by 3% annually, it is critical to reduce the energy consumed for heating and cooling buildings.

One method for reducing heating and cooling loads in buildings is to improve their air-tightness by reducing air leakage between conditioned spaces and unconditioned spaces or the outdoors. A study performed by the National Institute of Standards and Technology (NIST) has shown that reducing infiltration to levels similar to those required by the U.S. Army Corps of Engineers (USACE) [3] can result in 30% heating and cooling energy savings in office and apartment buildings [4]. This result is based on the average energy savings for different types of buildings, weighted by their respective energy consumptions, as predicted by models of these building types in five major U.S. cities.

2.1 BACKGROUND

Current methods for tightening building shells have relied primarily on manual sealing methods that are labor intensive and often insufficient, particularly in retrofit applications. Significant efforts have been made to reduce leakage in building shells within current construction practices; however the problem remains one of high labor costs, constant vigilance and quality control. Automating the sealing process removes contractor inconsistency, and in the case of the proposed technology, provides automatic verification that the desired sealing level has been reached.

The proposed work demonstrated a technology and process recently developed at the UC Davis Western Cooling Efficiency Center (WCEC) for automating the envelope sealing process, a technology that can be applied to a wide range of building types both during retrofit and at various stages of the new-construction process. The technology and process not only perform the sealing but also track the sealing process throughout the installation, providing immediate feedback to the installer, and a permanent record of the work performed, thereby allowing specific levels of air tightness to be achieved and verified. This project applied the aerosol envelope sealing technology to air-seal existing DoD facilities (focused on office buildings and barracks) to levels that meet or exceed the requirement outlined by the USACE. The aerosol envelope sealing technology can reduce the cost required to seal new and existing buildings to the required levels outlined by the USACE.

2.2 OBJECTIVE OF THE DEMONSTRATION

The objective of the demonstrations was to validate the aerosol sealing application method as a cost-effective means to meet the USACE tightness requirement for military facilities. The project involved a number of demonstrations on various building types and in multiple climates to show the ability for the technology to be applied on a large scale.

The results of the demonstrations are expected to facilitate the adoption of the aerosol sealing method for other DoD installations by providing a number of demonstrations on multiple building types and in multiple climate zones. Prior work has demonstrated excellent results showing the ability to seal 80% of the building leakage in less than two hours. These results were based on new contruction applications in both single-family and multi-family buildings using prototype equipment. Very few retrofit demonstrations have been performed on non-residential buildings which was the focus of this project. The demonstrations in this project validated the performance of the sealing technology as an effective solution for retrofit installations.

2.3 REGULATORY DRIVERS

Building envelope tightness guidelines have been outlined in standards as voluntary measures for more than 20 years. Recently, codes (see below) have begun to require specific levels of building sealing as a mandatory measure. The specific requirements for the level of tightness vary between organizations, a few of which are summarized here.

2.3.1 DoD Directive

In 2009, the USACE issued a directive requiring all new buildings and existing buildings undergoing renovation to meet an air leakage specification [5]. The leakage level required is ≤0.25 CFM75/sq. ft. using the entire envelope area including the floor. The directive states that any building undergoing renovation with costs that exceed 25% of the cost to replace the building must meet the USACE air tightness spec.

2.3.2 ASHRAE

ASHRAE produces standards for building energy efficiency including targets for adequate building envelope tightness. The ASHRAE ventilation standard for low-rise residential buildings, ASHRAE 62.2, has a compartmentalization requirement for low-rise multifamily buildings that require each apartment be sealed to 0.25 CFM50/sq. ft. of envelope area. Many states have adopted or are guided by the ASHRAE standard 62.2 for their low-rise ventilation code.

2.3.3 IECC

The DOE International Energy Conservation Code (IECC) provides an air leakage guide for homes. In 2009, the IECC required that building air leakage was no higher than 7 ACH50 in all U.S. climate zones, and verification of sealing was done either against a detailed checklist or a whole-house air leakage test using fan pressurization. In 2012, the building leakage requirement was made significantly more stringent requiring that building have an air leakage no higher than 5 ACH50 for climate zones 1 and 2 and no higher than 3 ACH50 in climate zones 3-8. The 2012 code also required mandatory building pressurization tests to verify that the appropriate building envelope tightness was achieved.

3.0 TECHNOLOGY DESCRIPTION

3.1 TECHNOLOGY OVERVIEW

The aerosol envelope sealing process involves pressurizing a building to normal testing pressures while applying an aerosol “fog” to the building interior. As the air escapes through leaks in the exterior shell of the building, the aerosolized sealant is transported to the leaks, and seals them as the particles try to escape from the building. This technology uses commercially available blower doors to positively pressurize the building during installation, as well as to provide real-time feedback on sealing progress, allowing the air-tightness to be tracked during the sealing. Multiple air-atomization nozzles that generate the aerosol are distributed around the inside of the building. The current system is capable of up to eight injection points that are distributed around the building, but it can be easily expanded with additional equipment. Expanding the system can be done at relatively low cost since the system can be used modularly allowing multiple to operate in parallel. The entire process is controlled from outside the building and is capable of simultaneously measuring, locating, and sealing leaks in a building envelope, while also providing verification of building tightness.

All leaks that are not intended to be sealed are blocked with tape or plastic (e.g. exhaust ducts, door seams). Depending on the condition of the building during application, the floor may need to be covered with plastic to protect it from sealant that settles during the process. While some sealant deposits on the top of horizontal surfaces (which are therefore also covered), there is no noticeable deposition on vertical surfaces or the bottom of horizontal surfaces. The ideal time to perform a retrofit aerosol sealing is during occupant changeover or during a major renovation where the contents of a building will be removed and carpets replaced. Without the removal of flooring it could be difficult to seal leaks at the baseboards, however one possible outcome of this research would be to determine how effective the sealing can be with carpets in-place and how time consuming the preparation of the carpets is. While it is conceivable that desks and computers can be covered with a tarp during the process, we feel that for the initial retrofit installations this should be avoided.

UC Davis has partnered with two manufacturers to provide the appropriate sealant and nozzles for this technology. The current sealant is GREENGUARD Gold Certified, which means that it meets the stricter certification criteria required for use in California schools and healthcare facilities. The toxicity of the sealant used for the aerosol sealing process is well below many other materials used in buildings such as interior paints; however because the sealant is atomized the contractor must wear appropriate personal protective equipment when possible exposure to atomized sealant is apparent and avoid entering the building if possible. If entering the building during the installation is necessary the contractor should have a fitted respirator to prevent breathing the aerosol. When the installation is complete the aerosol is flushed out by continuing to pressurize the space for several minutes after stopping the sealant injection.

3.2 TECHNOLOGY DEVELOPMENT

The aerosol sealing technology was developed over several years by UC Davis primarily through research grants with the Department of Energy and California Energy Commission. Shortly before this project the technology was licensed by Aeroseal LLC. Aeroseal developed an injection system that was ultimately rented for application in this project for ESTCP. The equipment was based off of the system developed by UC Davis but included software and controls for automating the process. This project was the first application of the technology in large commercial buildings requiring in some cases that the building be sealed in phases over multiple days. This project was also first to utilize commercized equipment for sealing, and was the first instance of a subcontractor being trained to perform the sealing.

3.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Current state-of-the-art methods for retrofit air-sealing are all manual, relying on contractor personnel to visually identify and manually seal leaks one-by-one. The resulting level of air-tightness achieved is highly variable, and is based on the time allotted and the vigilance and experience of the individual contractor that performs the work. In addition, it is common for air-tightness verification to be performed by a different contractor after the sealing is completed, making it difficult for the sealing contractor to assure that a specific level of sealing has been accomplished.

One demonstration of the aerosol sealing process on the Honda Smart Home in Davis, CA, highlighted the advantage of aerosol sealing over manual methods. This demonstration achieved a reduction in building air leakage from 5.5 ACH50 to 1.0 ACH50. Photographs from this installation, including examples of seals formed, are shown below in Figure 2 and Figure 3. This building was initially sealed using standard methods and the photos show areas where the aerosol sealant found and sealed leaks that were not properly sealed with foam and caulk. The ultimate goal was to meet the very aggressive Passive House standard of 0.6 ACH50, which also requires that the air barrier be applied to the external building envelope.

Figure 2: Photos of aerosol sealing installation on single-family home including examples of seals formed.

Figure 3: Photos of Honda Smart Home before aerosol envelope sealing application.

Figure 4 summarizes the results of the demonstration, highlighting the three discrete phases in the sealing process. The first aerosol sealing application used an airless nozzle injection system with five injection points and without any temperature/humidity control. This injection reduced the building leakage from 5.5 ACH50 to 3.3 ACH50. After the first application, three contractors spent 24 person-hours attempting to further seal the building manually with expanding foam and caulk, resulting in an almost negligible impact on the overall tightness of the building shell. Finally, the aerosol envelope sealing process was applied again, this time using air-atomization nozzles and temperature/humidity control. That process reduced the building leakage from 3.2 ACH50 to 1.0 ACH50 in about four hours. This is the process that is used currently including for this project.

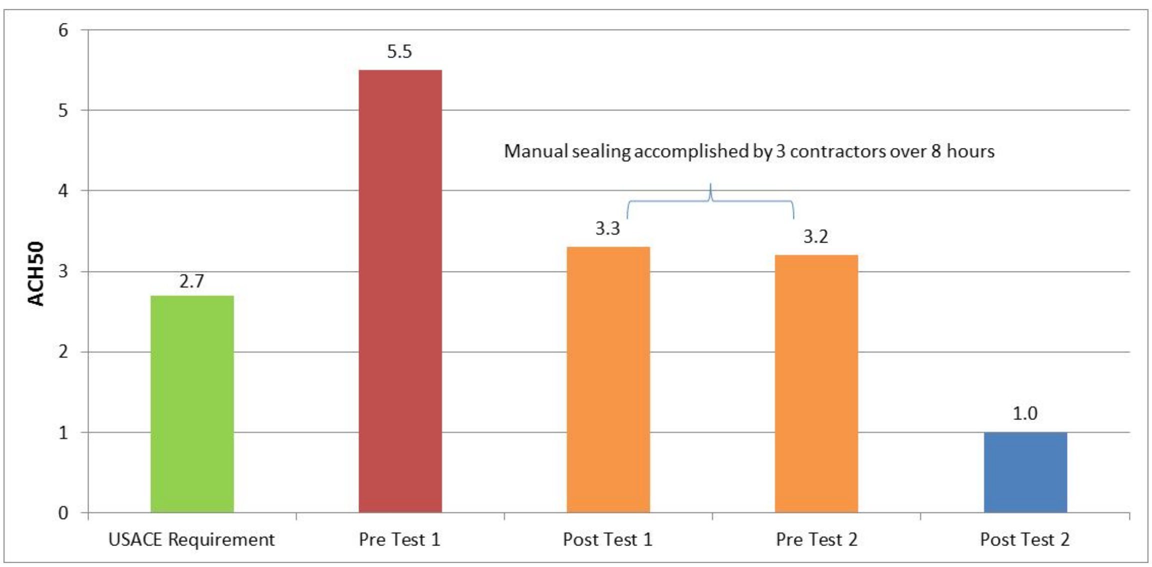


Figure 4: Summary of results from aerosol envelope sealing demonstration in Honda Smart Home.

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

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

The appeal of the proposed technology is that it is well suited for sealing buildings tighter and more reliably at a lower cost than manual methods (reducing sealing costs to between $0.50-$1.50 per square foot of building floor area) and that it automatically provides verification of the entire sealing process, certifying the performance of the envelope.

The highest potential risk of this technology is that if a building is not prepped appropriately it could lead to unwanted deposition of sealant. For example, if the HVAC registers are not taped off this could lead to deposition of sealant on an air conditioner or furnace coil. There are also potential limitations of the application when buildings are occupied. Occupied buildings tend to have a lot of contents that would need to be protected making the preparation process more time consuming, and thus, more expensive. Sensitive electronics need to be powered off and protected when applying the aerosol which could also disrupt the productivity of a business.

4.0 PERFORMANCE OBJECTIVES

The key performance objectives for this project were the level of air tightness achieved in the buildings and cost to perform the sealing. Other performance parameters that were investigated include the durability of the seal created, and the energy savings that result from sealing the building envelope.

The aerosol sealing technology provides real-time feedback of building leakage and automatic verification of the sealing accomplished. This was used along with the staff time required and cost of disposables to develop and accurate cost estimate. EnergyPlus models were used to estimate the impact that sealing had on the energy use of military buildings including greenhouse gas reduction as a result of lower heating and cooling requirements.

4.1 "TABLE 1" SUMMARY OF PERFORMANCE OBJECTIVES

Data was collected to measure the performance objectives outlined in Table 1.

Table 1. Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Facility Building Leakage	cfm/ft^2 at 75 Pa	Building leakage test performed before and after technology installation	≤0.25 cfm/ft^2 at 75 Pa	Partially met: Successful in three demonstrations
Seal Failure Pressure	Pascal	Pressure measurement across leak during failure test (Laboratory)	≥1,500 Pa	Met: No seal failure after loading to 5,000 Pa
Cyclic Pressure Loading	# of cycles to failure	Pressure measurement across leak, cycle counter (Laboratory)	≥1,000 cycles	Met: No seal failure after cyclic loading
Cyclic Temperature Loading	# of cycles to failure	Temperature measurement at leak, cycle counter (Laboratory)	≥1,000 cycles	Met: No seal failure after temperature cycling
System Economics	Person-hours to seal 1,000 sq. ft., $ for disposable materials	Tracking of labor requirements and materials used	≤ 16 person-hours to seal 1,000 sq. ft.	Met: Only buildings 1,500 ft^2 or smaller require >16 person-hours
Qualitative Performance Objectives				
Installer feedback on safety protocols for installation	Survey results	Feedback on experience during installations (i.e. are masks uncomfortable, are masks worn all the time, etc.)	Concerns regarding safety measures are determined and appropriately addressed	Feedback from ESOH personnel indicated no concerns with application of technology
Impact of aerosol sealing on flooring (only if encountered)	Description of impact of aerosol on flooring materials	Photos of baseboard leaks before and after sealing using smoke to demonstrate leakage. Photos of prepped areas versus those not prepped.	Determination of how to best prep flooring for aerosol sealing	Demonstrations showed that with proper preparation floors can be successfully protected from aerosol deposition

4.2 PERFORMANCE OBJECTIVES DESCRIPTIONS

PO -1

Name and Definition: **Facility Building Leakage** is the measured building leakage that describes the amount of uncontrolled air transfer between conditioned and unconditioned space.

Purpose: The purpose for collecting data on facility building leakage before and after sealing was to quantify the impact of the aerosol sealing. This was the primary metric used to assess the performance of the sealing technology.

Metric: The metric that was used to quantify facility building leakage is cfm at 75 Pascal per ft^2 of total envelope area (cfm75/ft^2). This was the measurement of the flow through leaks in the building shell when the building was subjected to a 75 Pascal pressure difference with respect to outside, and normalized to the total surface area of the building including the floor.

Data: The data required to calculate the above metric was the flow measured by a blower door at 75 Pascal of pressure and the building geometry including perimeter and building height.

Analytical Methodology: The only analytics required to obtain this metric was applied to the airflow measurement. When performing the airflow measurement a baseline building pressure must be obtained first under natural conditions in order to account for natural forces that impact the building pressure (i.e. wind). The baseline measurement was used to correct the value obtained by fan pressurization. Each measurement point was the average of 100 samples taken over several seconds under steady state conditions.

Success Criteria: Success was assessed based on the ability to seal each building to the USACE required 0.25 $cfm75/ft^2$.

Results: Three of the demonstrations completed for this project met this performance objective reducing envelope leakage to below the USACE requirement of 0.25 ($cfm75/ft^2$); however, many of the demonstrations did not meet this criteria. Considering many of the building were in very poor shape, it is understandable that some buildings did not ultimately achieve this objective.

PO - 2

Name and Definition: **Seal Failure Pressure** is the failure pressure of seals created using the aerosol sealing technique under controlled conditions and measured in the laboratory. Failure was determined by tracking the rate that pressure in the test apparatus dissipates due to leakage.

Purpose: the purpose for collecting data on seal failure pressure was to determine the durability of seals formed using the aerosol sealing process.

Metric: The metric that was used to quantify seal failure pressure is the pressure required to burst the seal. Our apparatus was capable of measuring seal failure pressure up to 5,000 Pa which is well above the pressure experienced by a seal on the shell of a building. If the seal did not fail after applying a pressure of 5,000 Pa to it there was no failure pressure reported.

Data: The data required to determine the above metric is the pressure of the test apparatus at time of failure.

Analytical Methodology: Failure was determined based on the rate that pressure dissipates from the test apparatus. A higher than normal pressure dissipation indicates a seal failure.

Success Criteria: Success was assessed based on the ability for the seal to maintain pressures above 1,200 Pa which corresponds to the wind pressure induced by 100 mile per hour winds.

Results: Six slot leaks were tested up to 5,000 Pa with no observed failures. The testing apparatus used could not test above 5,000 Pa so ultimate failure pressure was not determined.

PO -3

Name and Definition: **Cyclic Pressure Loading** is the process of repeatedly subjecting the seal to a pressure then releasing the pressure. The cycles were meant to simulate repeated loading applied to a seal over the life of the seal in an accelerated fashion.

Purpose: the purpose for collecting data on cyclical pressure loading was to determine the long term durability of seals formed using the aerosol sealing process.

Metric: One metric used to quantify the long term durability of seals formed using the aerosol sealing process was the number of pressure cycles a seal can withstand before failure.

Data: The data required to determine the above metric was the number of pressure cycles experienced by the seal before failure.

Analytical Methodology: Failure was determined based on the rate that pressure dissipates from the test apparatus. A higher than normal pressure dissipation indicates a seal failure.

Success Criteria: Success was assessed based on the ability for the seal to withstand 1,000 pressure cycles at pressures up to 800 Pa.

Results: The cyclic loading showed a gradual increase in seal leakage after 1,000 cycles of pressure cycling at 800 Pa but no seal failure was observed. Testing at more reasonable building pressures of 100 Pa observed very little chance in seal leakage after 1,900 cycles.

PO - 4

Name and Definition: **Cyclic Temperature Loading** is the process of repeatedly subjecting the seal to a wide temperature range. The cycles were meant to simulate repeated heating and cooling of a seal over the life of the seal in an accelerated fashion.

Purpose: the purpose for collecting data on cyclical temperature loading was to determine the long term durability of seals formed using the aerosol sealing process.

Metric: One metric used to quantify the long term durability of seals formed using the aerosol sealing process was the number of temperature cycles a seal can withstand before failure.

Data: The data required to determine the above metric was the number of temperature cycles experienced by the seal before failure.

Analytical Methodology: Failure was determined based on the rate that pressure dissipates from the test apparatus. A higher than normal pressure dissipation indicates a seal failure.

Success Criteria: Success was assessed based on the ability for the seal to withstand 1,000 pressure cycles at temperatures from 40°F to 120°F.

Results: The temperature cycling test did not lead to a seal failure or cause a rapid decline in seal strength due to extreme temperature cycling. Temperature did have an effect on the seal leakage, causing the seals to expand or contract. The seal leakage was slightly higher when subjected to colder temperatures.

PO - 5

Name and Definition: **System Economics** describes the cost and performance of the aerosol sealing in order to develop accurate payback periods, as well as allow for an accurate comparison to be made with other air sealing methods.

Purpose: the purpose for collecting data on system economics was to develop accurate predictions for the total cost to install aerosol envelope sealing in various building types and sizes. This includes all costs related to the sealing such as set-up and clean-up. This provides the information required to include aerosol sealing in renovation projects around the country.

Metric: The metrics that were used to describe the system economics include the person-hours required and cost of disposables per 1,000 square feet of building floor area sealed.

Data: The data required to determine the above metric was the number of hours and staff requirements to complete each sealing along with the physical dimensions of the building and performance of the sealing process. This includes setup, injection, and cleanup.

Analytical Methodology: The cost to install aerosol envelope sealing per 1,000 square feet of floor area was expected to vary significantly based on the state of the building, size of the building, and whether multiple jobs were completed on the same building. The estimate for cost included the range of results found during the demonstrations.

Success Criteria: Success was assessed based on the ability for a four-person crew to be able to seal a small (<3,000 ft^2) building to the USACE spec or better in a single day.

Results: The cost model developed and described in more detail below suggests that only buildings at under 1,500 ft^2 time of tenant changeover would require more than 16 person-hours per 1,000 ft^2. All buildings sealed during major renovation would meet this criteria.

PO - 6

Name and Definition: **Installer feedback on safety protocols for installation** describes results from surveys and conversations with Environmental, Safety, and Occupational Health (ESOH) personnel regarding safety concerns around the application of aerosol envelope sealing.

Purpose: the purpose of this qualitative performance objective was to collect and address concerns around the application of aerosol envelope sealing.

Metric: Surveys were sent out to ESOH staff at each base that demonstrations occurred. The project team also worked with ESOH staff prior to address any specific concerns prior to the demonstrations.

Data: The data collected include responses to the survey questions and general feedback from ESOH staff and installers.

Success Criteria: The success of this objective is based on the ability for the project team to address any concerns around the safety of aerosol envelope sealing.

Results: This objective was met considering all demonstrations ultimately moved forward. NSA Mechanicsburg ESOH staff required the project team to provide material data sheets and description of the process prior to allowing the demonstrations. Quantico provided their feedback in a survey indicating that they have no concerns with the process. Lastly, Fort Bragg carried out an environmental study on one of the buildings used for the demonstration and found now issues related to the technology.

PO - 7

Name and Definition: **Impact of aerosol sealing on flooring (only if encountered)** describes the ability for floors to be protected during the aerosol envelope sealing process.

Purpose: the purpose of this qualitative performance objective was to demonstrate that floors could be protected from aerosol deposition by covering horizontal surfaces with plastic and tape.

Metric: Description of impact of aerosol on flooring materials.

Data: Photos of prepped areas versus un-prepped areas as well as qualitative assessment of condition of floors after demonstration.

Success Criteria: The success of this objective was based on the ability to maintain the condition of the floors after the installation of aerosol envelope sealing.

Results: This objective was met in the demonstrations for this project. It was shown that in cases where the demonstration site was going to be repurposed, the flooring was successfully protected from aerosol deposition. Building operators were pleased after final walk-throughs after the demonstrations were performed.

5.0 FACILITY/SITE DESCRIPTION

This project had commitments from several military bases to provide buildings for testing the aerosol sealing process. Potential sites were reviewed to determine whether the buildings were appropriate as a test site. There were several criteria used when selecting appropriate demonstration sites including building type, size, type and state of flooring, and whether the building was occupied. This project demonstrated the sealing technology on buildings up to 22,000 square feet. The demonstrations included both residential and commercial buildings, and all buildings were temporarily unoccupied at the time of sealing.

5.1 FACILITY/SITE LOCATION, OPERATIONS, AND CONDITIONS

This project tested the aerosol sealing process in nine buildings on three military bases. Overall, 15 smaller spaces and three larger spaces were sealed over 16 different demonstrations. The bases that were involved included: Marine Corps Base Quantico in Virginia, Fort Bragg Army Base in North Carolina, and Navy Support Activity Mechanicsburg in Pennsylvania.

5.1.1 MCB Quantico

The demonstrations at Quantico included a wing of the Ashurst Elementary school and an office building (Figure 5). The 5,000 ft^2 elementary school wing included four classrooms and an adjoining hallway that were sealed over three different demonstrations. The school was closed in 2015 and is being repurposed as a training ground and eventually additional office space. This building was also used for the initial training of TMI staff who was involved in each of the demonstrations for the project.

Figure 5: South classroom at Ashurst Elementary school sealed at Quantico MCB

The office building at Quantico was the final demonstration completed for this project. This building was unoccupied at the time of the demonstration but was expecting to be used in the near future as office space (Figure 6). Given the status of this building, it was the only demonstration that required detailed preparation to protect surfaces from sealant deposition.

Figure 6: Office building sealed at Quantico MCB

5.1.2 Fort Bragg Army Base

Three buildings were identified at Fort Bragg for demonstrating the aerosol envelope sealing process. All of these buildings were scheduled for demolition and were in various states of disrepair.

Building A5436 is a one story WWII era frame structure on a crawl space open to the outdoors, and in poor condition (Figure 7). Bathroom ceilings were collapsed and required temporary blocking during the sealing process due to the size of the hole.


Figure 7: Building A5436 at Fort Bragg Army Base

Building A6372 is a one story relocate-able metal structure on a crawl space vented to the outdoors. The building was in fair to pool condition and part of the floor was partially collapsed.

Figure 8: Building A6372 at Fort Bragg Army Base

Building M2338 is a one-story wood frame slab-on-grade structure with sloped gable roof and ridge vent (Figure 9). No soffit venting was observed at the building. The buildings was in poor condition and about 2/3 of the ceilings were collapsed and open to the attic.

Figure 9: Building M2338 at Fort Bragg Army Base

5.1.3 NSA Mechanicsburg

The majority of sealing demonstrations occurred at the Navy facilities in Mechanicsburg. The demonstrations included a large training facility, five apartments, a large Officer's Club, and a section of a warehouse.

Building M-608A is an industrial facility used for training electricians. The building was about 8,400 ft^2 and was a conventional concrete-masonry-unit (CMU) commercial frame structure on a concrete slab. The garage doors were deteriorating and the building was scheduled for demolition.

Figure 10: Building M-608A at Mechanicsburg Navy Base

The apartments sealed at Mechanicsburg Navy Base were located at 5450 Carlisle Pike, Mechanicsburg, PA (Figure 11). The building is a conventional wood-frame structure on a poured concrete basement. The building was in poor condition and scheduled for demolition. Five apartments were sealed each measuring about 2,000 ft^2.

Figure 11: Apartment complex where several apartments were sealed at Mechanicsburg Navy Base

Building 15 Officer's Club at Mechanicsburg Navy Base was the largest facility sealed with the aerosol envelope sealing process. The building is about 22,000 ft^2 and includes a large ballroom, commercial kitchen facility, and several other gathering rooms (Figure 12). The OC is a one-story building on a crawl space foundation, in poor condition and slated for demolition. The original building is circa 1940/1950, with two later building additions. The original section is CMU wall with low slope roof over wood rafters. The first addition is frame with steep slope roof over wood trusses enclosing a non-vented attic. The newest addition is conventional steel frame with steel stud walls, low slope roof over metal bar-joist type trusses, and steep slope roof over light weight metal trusses on the 3 elevations visible from the streets.

The steep slope roof portion of the newest addition has a "ventilated conditioned attic". The insulation is on top of the steep slope roof panels. A suspended ceiling separates the underside of the roof from the conditioned finished floor space below (therefore the space above the suspended ceiling forms an attic within the thermal envelope). The soffits were ventilated to the outdoors and open the space above the suspended ceiling. The OC building was substantially larger than any others planed or sealed in the ESTCP demonstrations, and more equipment was required than available. For this reason, TMI™ attempted to seal the building in sections, starting with the steep-slope roof sections.

Figure 12: Building 15 Officer's Club at Mechanicsburg Navy Base

Building 408 is a 128,000 square foot single story wood frame warehouse structure (Figure 13). Construction is heavy wood timber frame with low slope wood frame roof deck and slab on grade floors. Raised clearstory lighting wells constructed of wood framing with painted transite asbestos cladding and painted steel tilting windows extend above the main roof line. Curtain walls are a combination of CMU, tilting steel windows with painted glazing, and wood stud framing with painted transite asbestos panel exterior cladding. The overall structure is divided into four sections by masonry firewalls. The three sections toward the North are occupied by offices and warehouse space and appear to be in good condition.

The southernmost section of Building 408 is designated 408S and is approximately 32,000 square feet. 408S was vacant at the time of the aerosol sealing demonstration. The curtain walls and cladding and most of the heavy timber framing appear to be in good condition, but the roof and clearstory are in poor condition. Roof leaks were apparent in numerous locations. Repairs had been made to a few of the heavy timber columns that were compromised by roof leaks. Bays 28, 29, & 30 of had been partitioned off from slab to roof deck, resulting in a 3,600 square foot section of warehouse space suitable for the demonstration.

Figure 13: Building 408 at Mechanicsburg Navy Base

6.0 TEST DESIGN

This project consisted of sixteen demonstrations of the aerosol envelope sealing technology on multiple military bases. The fundamental problem this project was attempting to solve was whether the aerosol technology can be used as a method for cost-effectively sealing air leakage in the shell of existing buildings. The overall objective is to determine whether the process can be applied consistently and efficiently in multiple locations around the U.S.

6.1 CONCEPTUAL TEST DESIGN

The aerosol sealing process was tested to determine the feasibility of applying the process on a large scale to meet the USACE tightness requirement for existing military facilities. There was a general test design that remained consistent between demonstrations; however, each demonstration required a specific application protocol to be developed. Each test site required an in initial walk-through to identify how the building should be prepped before injection and how much equipment would be needed. The walk-through noted what features of the building would need to be protected during the process.

The independent variable that was tested was the total building/space envelope air leakage which can be expressed as the flow rate through the shell of the building under a given pressure differential, or as a physical size leak in the shell of the building (i.e. equivalent hole size). The tightness goal is to meet or exceed the USACE requirement of 0.25 cfm at 75 Pascal per square foot of envelope area.

The dependent variables that was tested included the leakage reduction achieved by the aerosol process for each demonstration, and the time required to perform the sealing. The cost is expected to vary based on building floor area, building type, and condition of the building (e.g. being renovated, occupied).

The controlled variable was the application process which includes precise percent relative humidity control in the space during sealing. Humidity levels during the sealing process can impact sealing rates and seal durability, and therefore, were controlled throughout the process.

Each test measured the performance of the aerosol sealing technology by measuring the total leakage reduction of the building and cost of the sealing. Reasonable estimates were made to estimate the actual cost of the sealing after commercialization. The personnel time required was monitored as well as the cost for materials to develop the cost estimate. Section 6.5 presents the tasks that were tracked for time and cost estimates.

Each test included the following phases: pretest site visit and installation plan, initial leakage measurement, building preparation, aerosol sealing, building clean-up, and final leakage measurement. While the pretest site visit was the best way to develop the installation plan, in some cases a reasonable installation plan was developed using accurate building plan and photos of the building followed by an initial walk-through before sealing. The initial leakage test was performed on the building prior to any prep and was used as the baseline to measure performance. Building preparation involves all of the work needed to prevent sealant waste, protect building contents from damage, and limit the cleanup required after sealing. Once prepped sealing began by pressurizing the building and injecting the aerosol. After sealing the building was cleaned and the final leakage test was performed.

6.2 BASELINE CHARACTERIZATION

The primary baseline data that was collected on each demonstration is the total building leakage before and after sealing. The baseline data was used to inform accurate inputs to an energy model that was used to develop energy savings estimates for the DoD. A standard blower door was be used to collect the leakage data for each building.

6.3 DESIGN AND LAYOUT OF SYSTEM TECHNOLOGY COMPONENTS

The aerosol sealing technology is capable of remotely sealing leaks in a building shell by briefly pressurizing the building while applying an aerosol “fog” to the interior. The system consists of two major components (Figure 14): 1) the building pressurization system, and 2) the injection system.

The building pressurization system includes a large fan capable of controlling and measuring the airflow supplied to the building. The fan was controlled to maintain a constant building pressure throughout the process by allowing the air flow to drop as the building seals. An electric heater for heating the air entering the building was used to improve sealing rates by increasing the water-carrying capacity of the air, and thus allow more sealant to be injected in to the space.

The injection system consists of an air compressor, sealant injection pump, and nozzles. The injection system is controlled to maintain the humidity target during the process in order to promote seal durability while also limiting sealant deposition on the floor. Each injector nozzle is placed strategically around the building to allow for adequate aerosol distribution. Depending on the building geometry, a single nozzle can seal up to 400 square feet of floor area.

Figure 14: Photo of aerosol sealing equipment setup

6.3.1 Installation Protocol

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

Setup

1. Setup the blower door and run combo-cords through the doorway
2. Run a multipoint leakage test or single point test at 50 Pa or 75 Pa
3. Identify and block any leaks that are larger than the sealing capabilities of the aerosol process (leaks > 3/8")
4. Temporarily seal any known intentional leaks with duct mask, tape, or other means
5. Cover anything that should not have sealant deposition on it with plastic or tape
6. Place the aerosol injection nozzles in the unit using these guidelines:
    a. Nozzles should be distributed throughout the building
    b. Nozzles should be oriented such that the spray is
        i. NOT directed into the pressurization air flow stream
        ii. NOT directed onto walls or other vertical surfaces.

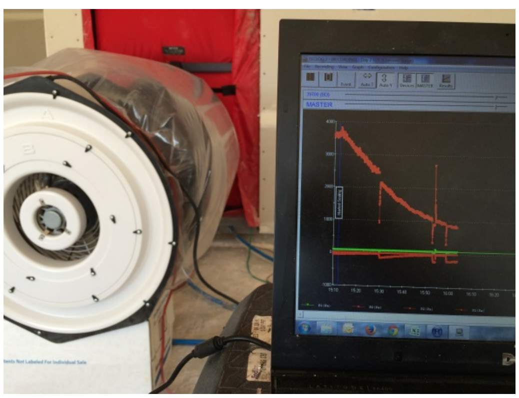
c. Aerosol fog is distributed throughout the building

7. Spray water from the nozzles to determine final orientation


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

Sealing

1. Monitor the sealing profile.



2. Monitor the calculated indoor relative humidity and adjust the sealant injection rate accordingly (it should be ~90%)
3. Seal until the leakage rate has been reduced by 85%, the sealing rate drops below 1 cfm50/minute, or another established metric has been met
4. Purge liquid sealant lines with water either by
    a. Switching the liquid source to water when the sealing is near completion and finishing sealing with sealant in the lines until water has purged through the system, or
    b. Placing the liquid sealant lines in a bucket and purging water through the lines after the sealing is complete

Cleanup

1. Purge the unit of aerosol by opening doors/windows and running a fan
2. Remove the nozzles, take them apart, and rinse with water to begin cleaning
3. Coil up the liquid sealant and compressed air lines
4. Remove any of the plastic or tape that was used to block the known leaks and protect surface
5. Perform a final multipoint leakage test or single point test at 50 Pa or 75 Pa
6. Perform Remove the blower door

6.4 OPERATIONAL TESTING

The technology tested for this project did not require any operational testing since it is only applied briefly to seal the building envelope. EnergyPlus was used to estimate the impact that sealing building envelopes has on the heating and cooling energy use of buildings. Data from the installations, as well as existing data, was used to determine appropriate model inputs for building envelope tightness. The models were run in several U.S. climate zones to determine relative impact in different parts of the country.

6.5 SAMPLING PROTOCOL

The data for these demonstrations was collected by both the WCEC and TMI, and includes pre and post building envelope leakage measured using a standard blower door. Multipoint leakage data was measured up to 75 Pascal using ASTM E779 as a basis. The data was recorded on a laptop and copied to an external storage device before removing test equipment.

To estimate the cost of sealing, the time and materials for each demonstration was recorded. The time required to complete the following tasks were monitored:

- Setup
    - Walk-through
    - Setup blower door
    - Take pre-sealing leakage measurement
    - Prepare building
        - Protect floors
        - Block HVAC registers
        - Tape doors
        - Check/tape operable windows
    - Setup nozzles
    - Connect all injection equipment
- Sealing
    - Seal
    - Purge aerosol and injection lines
- Cleanup
    - Remove nozzles
    - Remove plastic and other protective materials
    - Take post-sealing leakage measurement

The equipment used to test building air tightness met the USACE air leakage test protocol standard with a resolution of 0.1 Pascal and accuracy of 1% of the reading. The instruments were calibrated at least every two years to assure this accuracy, and the WCEC was responsible for getting the instruments calibrated. The data collected to determine the air leakage of a particular building was based on the average of at least 10 measurements to reduce the impact of wind and stack or other environmental factors.

6.6 SAMPLING RESULTS

This project demonstrated that the aerosol envelope sealing technology is very effective at sealing building leakage. Ultimately, over 75,000 CFM at 75 Pa was sealed over the sixteen demonstrations cutting the air leakage of the buildings in half. Figure 15 presents the pre and post air leakage measured in each of the demonstrations and Figure 16 presents the overall percent air leakage reduction for each demonstration. The most successful demonstration sealed 80% of the building leakage and three of the demonstrations brought the buildings to within the USACE specification for envelope leakage. This was impressive considering both of these buildings were in poor condition and scheduled for demolition.

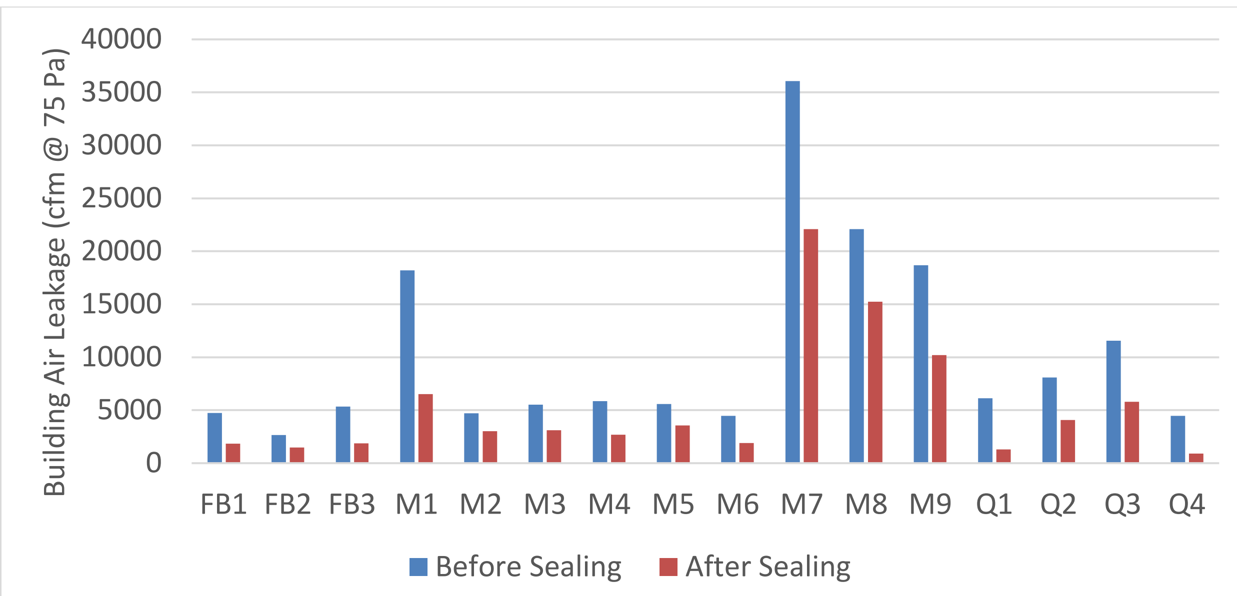


Figure 15: Pre and post air leakage test results for all demonstrations

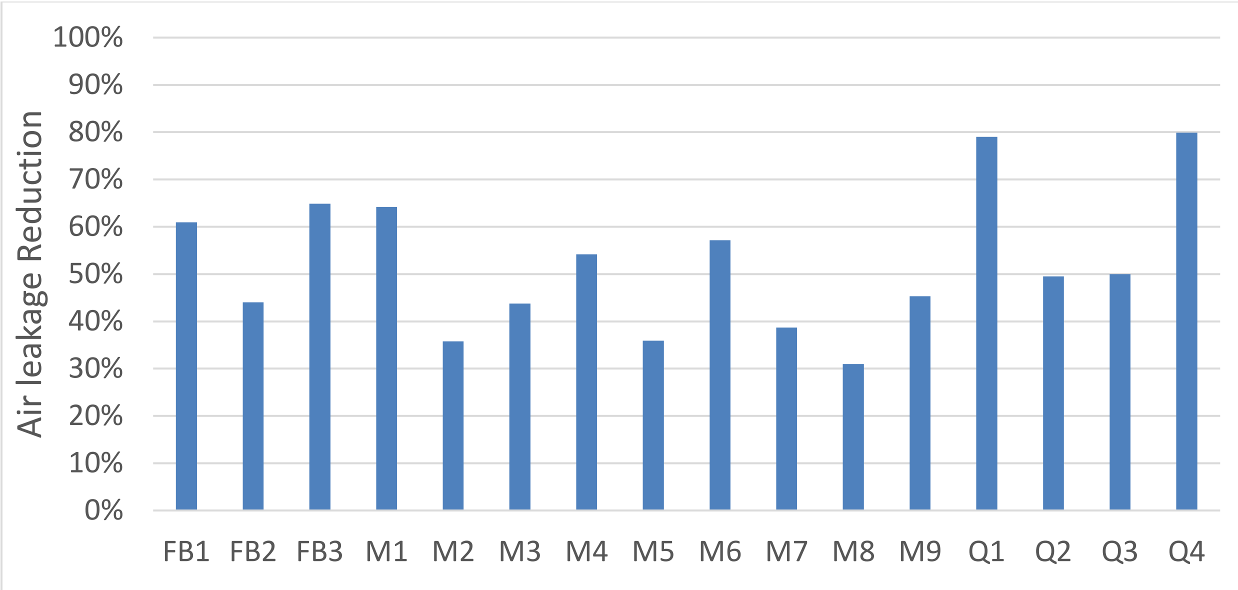


Figure 16: Percent air leakage reduction for all demonstrations

6.6.1 MCB Quantico

Two buildings were sealed at MCB Quantico including a wing of Ashurst Elementary school and a small office building. Ashurst was used as both an initial training site, and for three multiple aerosol sealing demonstrations. The training was conducted by UC Davis and AeroBarrier staff to provide the subcontractor, TMI, with the necessary information on how to apply the aerosol sealing technology, and how to operate and troubleshoot the sealing equipment.

The sealing at Ashurst was the first demonstration for this project and presented some interesting challenges. An initial attempt was made to seal one of the classrooms during the training with very little impact on building leakage. After further investigation it was discovered that there was a very large gap at the roof-to-wall connection that was too large for the aerosol process to address. Manual sealing efforts were used to reduce the size of the gap at the roof-to-wall connection in order to allow the aerosol to seal the remaining leakage. In addition, the nozzles were placed above the roof tiles to help distribute the material to the leaks at the corrugated metal roof. After these changes to the installation protocol, the first classroom was successfully sealed by 79% bringing the leakage after manual sealing efforts from 6,130 CFM at 75 Pa to 1,286 CFM at 75 Pa.

The second demonstration sealed the adjoining classroom and only required manual sealing of one roof-to-wall connection between the room and the hallway. After only a short injection period this demonstration effort stopped due to a relay failure in the equipment. The relay was repaired and sealing continued reducing the leakage by 50% from 8,109 CFM75 to 4,023 CFM75.

The final demonstration sealed the remaining rooms in the building wing which included two classrooms and the adjoining hallway. Manual sealing was required for the roof-to-wall connection around much of the perimeter of the building. The aerosol sealing reduced the leakage from 11,566 CFM75 to 5,792 CFM75 representing a 50% reduction in building leakage.

Table 2 provides a summary of the results for the Quantico Ashurst Elementary sealing work and Figure 17 shows a diagram of the building sealing including where manual sealing was applied at the roof-to-wall connection. The building zone numbers in Table 2 and Figure 17 describe what part of the building was sealed in each effort. Overall, 57% of the building leakage was sealed which includes leakage between classrooms and the hallway. There was not a total building leakage test performed to measure the total reduction in building air leakage to outside.

Table 2: Summary of Ashurst sealing results

			Leakage [cfm@75 Pa]		
Date	Building Zone		Start	Finish	Sealed
7/19		Manual sealing and mobilization			
7/20	1	Perimeter previously sealed manually	6130	1286	4844
7/21	2a	Inside perimeter sealed manually (injection stopped - compressor failure)	8093	7321	772
8/29		Manual sealing and mobilization			
8/30	2b	Inside perimeter previously sealed manually (injection stopped - hour of the day)	8109	4086	4023
8/31		machine and building prep for next day			
9/1	3	Sealing with **two machines and 4 fans** (Aeroseal software on both)	11566	5783	5783
				TOTAL	15422

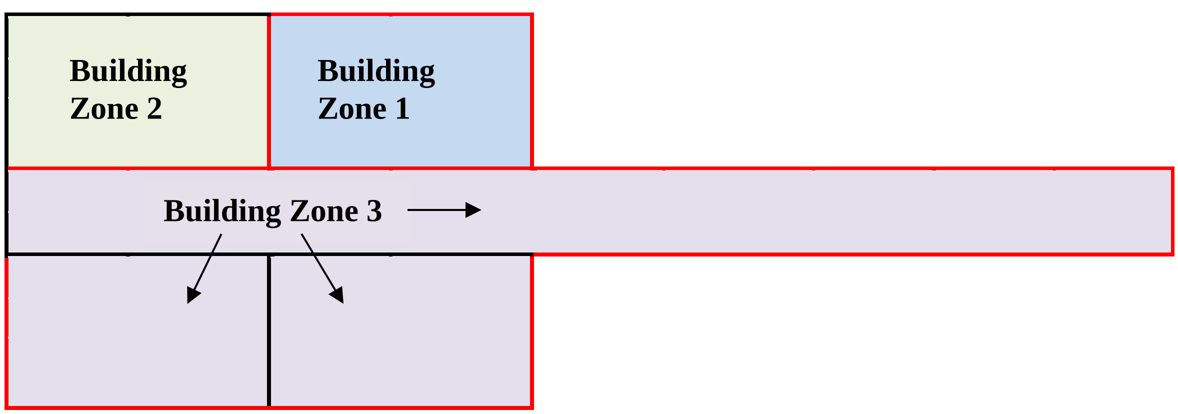


Figure 17: Diagram of Ashurst Elementary wing sealed with red border indicating where manual sealing was performed at the roof-to-wall interface and building zone numbers corresponding to results shown in Table 2.

Another demonstration that took place at Quantico was the last demonstration for this project on a small office building. This building was vacant at the time of the aerosol sealing installation but was planned to be re-occupied at a later date requiring that the horizontal surfaces inside the building be protected (Figure 18). The prep work required about 16 person-hours or about one day for a two person crew.

Figure 18: Building 2177 at Quantico prepped for aerosol envelope sealing

The sealing results for building 2177 at Quantico were very impressive sealing 80% of the available leakage area in three hours of injection. Figure 19 shows the sealing profile for the demonstration. The pre and post air sealing results with the “as found” condition showed a total air leakage reduction of 68% going from 4,503 CFM at 75 Pa to 1,440 CFM at 75 Pa which brought this building to within the USACE specification for air leakage in new buildings. This demonstrations highlights the overall capability of the aerosol sealing approach by showing a 1950s era building getting sealed in only a couple days of work to the standard outlined for all new military installations.

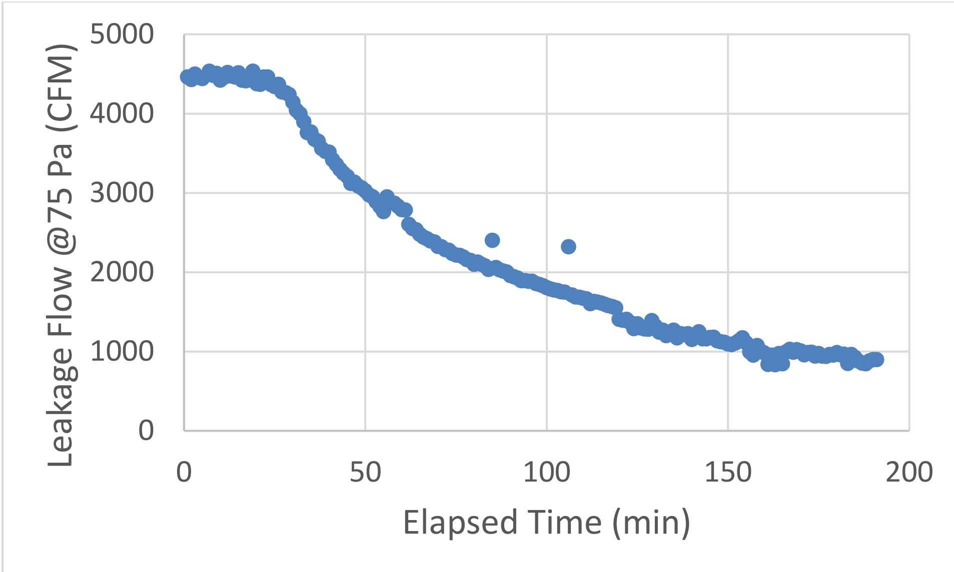


Figure 19: Sealing profile for building 2177 at Quantico MCB

6.6.2 Fort Bragg Army Base

The three building sealed at Fort Bragg Army Base were completed between June 27-29, 2016. The weather during the demonstrations was considerably warm and humid, and in the case of the first demonstration, building A5436, there was periods of heavy rain (Figure 20). A total of eight nozzles were used during sealing of A5436 and Figure 21 shows the nozzle arrangement.

Figure 20: Setting up sealing equipment in A5436 during heavy rain

Figure 21: Nozzle arrangement during sealing in A5436 (left) and photo of nozzle setup (right)

Due to the building being in very poor condition, initial prep work was required to block a portion of the bathroom ceiling that was collapsed. The building leakage was sealed from 4,730 CFM75 to 1,847 CFM75 representing a 61% leakage reduction. The total time of injection was about 2.5 hours. Figure 22 shows the leakage profile during sealing.

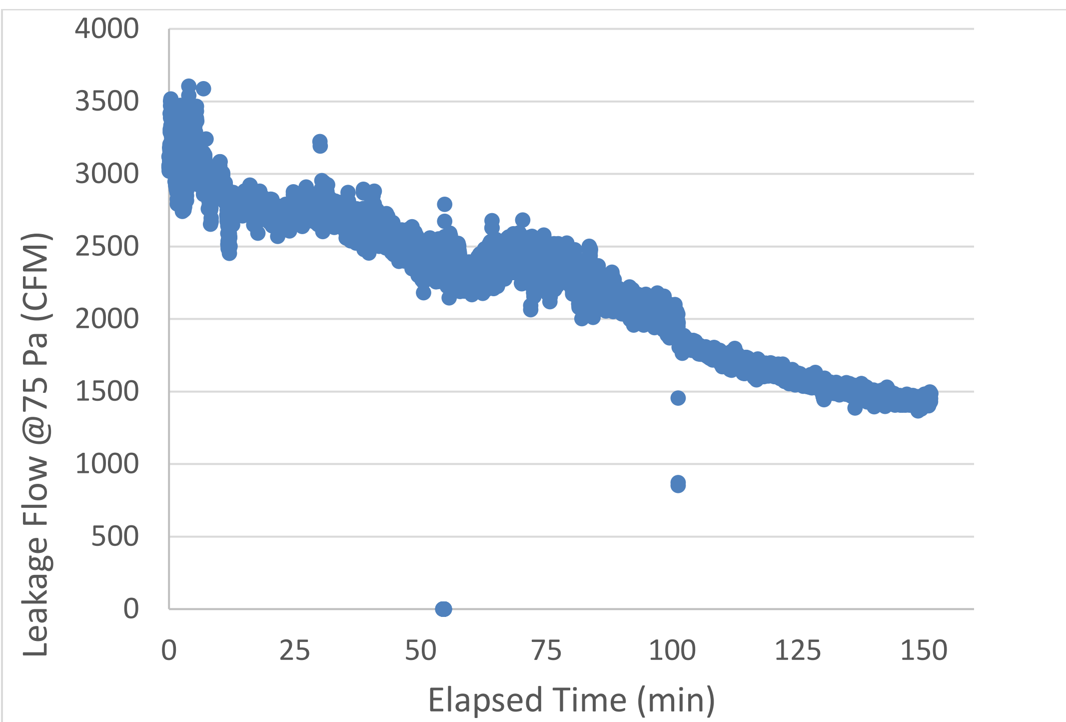


Figure 22: Sealing profile for building A5436 at Fort Bragg Army Base

Building A6372 was sealed June 28, 2016. The building was in poor condition with the floor partially collapsed. There also appeared to be retrofits performed to the building to introduce network wiring through large conduits. The holes drilled for these conduits introduced significant leakage that was too large for the aerosol sealing to address (Figure 23). The overall impact of the aerosol sealing demonstration reduced overall building leakage by 44% from 2,643 CFM at 75 Pa to 1,479 CFM at 75 Pa. Figure 24 shows a seal formed at the baseboard of the building.

Figure 23: Conduits installed in building A6372 for network wiring

Figure 24: Photo of a seal formed at baseboard of building A6372 at Fort Bragg Army Base

The final demonstration at Fort Bragg was performed on June 29, 2016. This was the first installation performed by only TMI staff. Building M2338 was in very poor condition with most of the ceiling collapsed and open to the attic. The sealing demonstration sealed 82% of the overall building leakage reducing the building leakage from 5,332 CFM at 75 Pa to 1,873 CFM at 75 Pa. Figure 25 presents the sealing profile for the final demonstration at Fort Bragg Army Base.

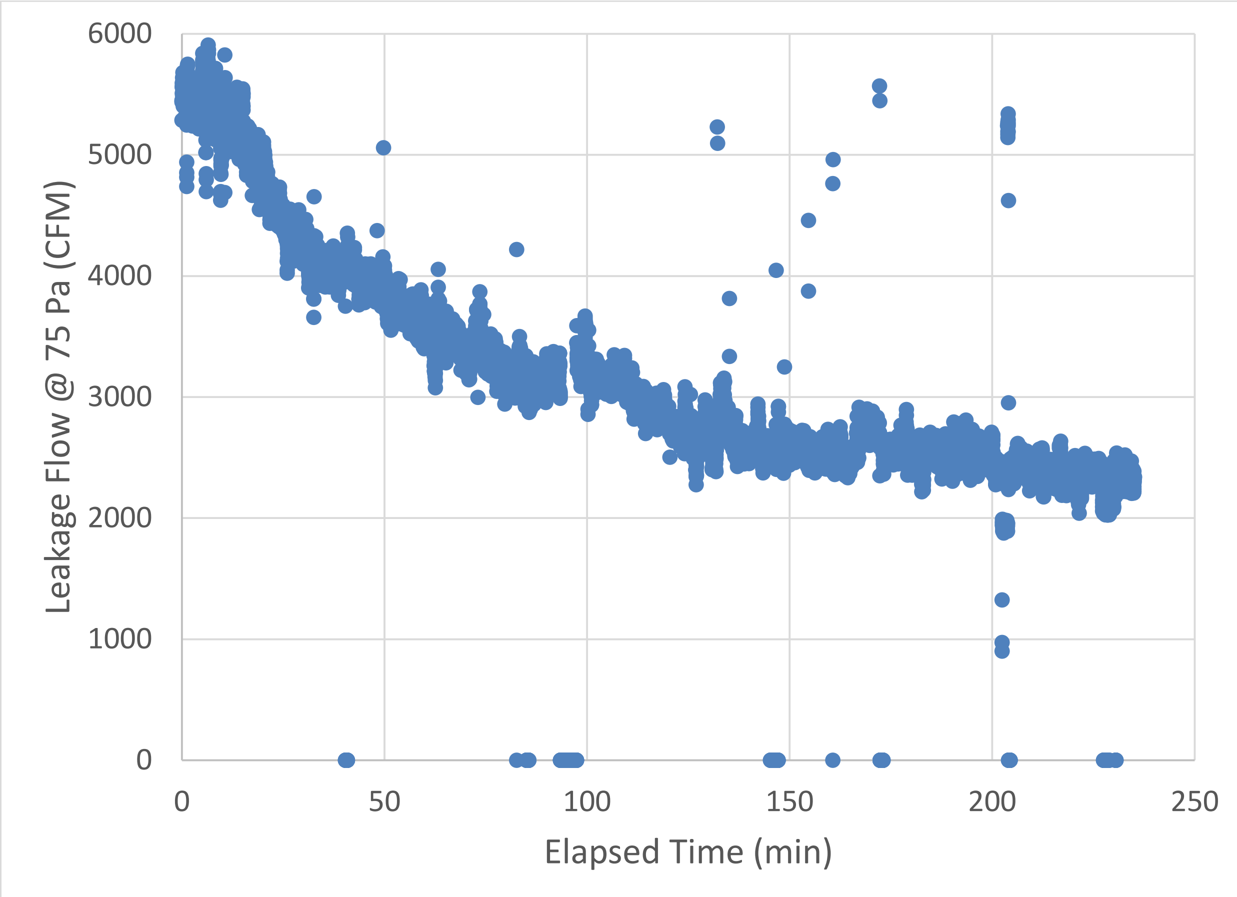


Figure 25: Sealing profile for building M2338 at Fort Bragg Army Base

6.6.3 NSA Mechanicsburg

The largest number of demonstrations occurred at NSA Mechanicsburg in Pennsylvania. Overall, three non-residential buildings and five apartments were sealed at this installation.

The first building sealed at Mechanicsburg was a large industrial facility, building M/608A, used for training and storage. This was also the first large building sealed for the project with a total floor area of about 8,400 ft^2. This building was scheduled for demolition so very minimal interior preparation was required.

At first inspection it was assumed that some manual sealing would be required to deal with large holes in the wallboard (Figure 26), but after a closer look it appeared that the soffit construction behind the wallboard was built with suitable gaps for the aerosol sealing method to address. It was therefore decided to begin sealing without supplemental manual sealing. The building had several large roll-up doors that were temporarily sealed prior to the aerosol injection to prevent sealing those doors.

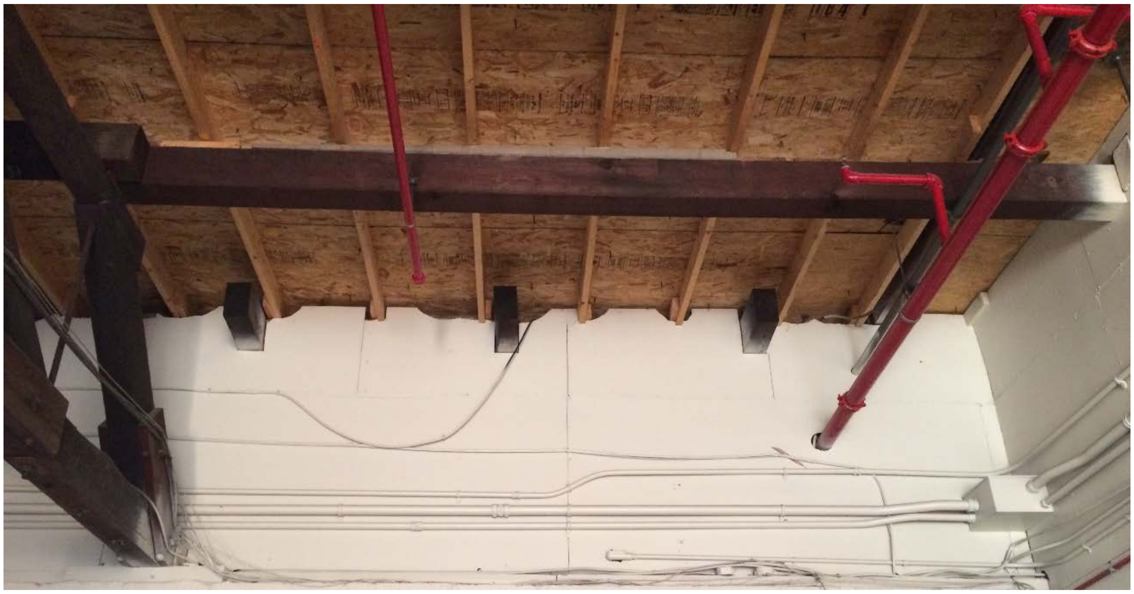


Figure 26: Photo showing large holes in wallboard at the roof rafters of building M/608A at NSA Mechanicsburg

Two distinct sealing events occurred sealing 82% of the available leakage. Figure 27 shows the sealing profile for both sealing events. Each sealing effort sealed about 60% of the available leakage in two hours of injection. Ultimately, 64% of the building leakage was sealed over only four hours of total injection time. The building leakage started at 18,210 CFM at 75 Pa and was reduced to 6,515 CFM at 75 Pa.

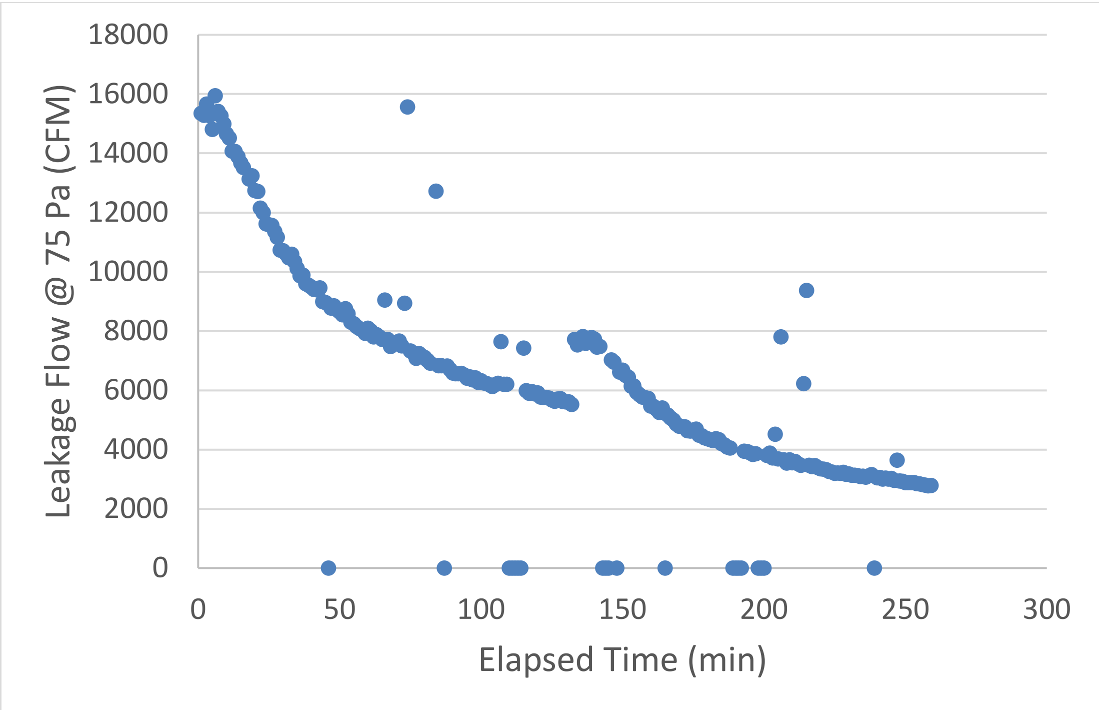


Figure 27: Sealing profile showing both sealing events for building M/608A at NSA Mechanicsburg

Five demonstrations occurred on individual apartments at a multifamily building at NSA Mechanicsburg. The apartment complex was scheduled for demolition and therefore did not require horizontal surfaces to be protected during sealing.

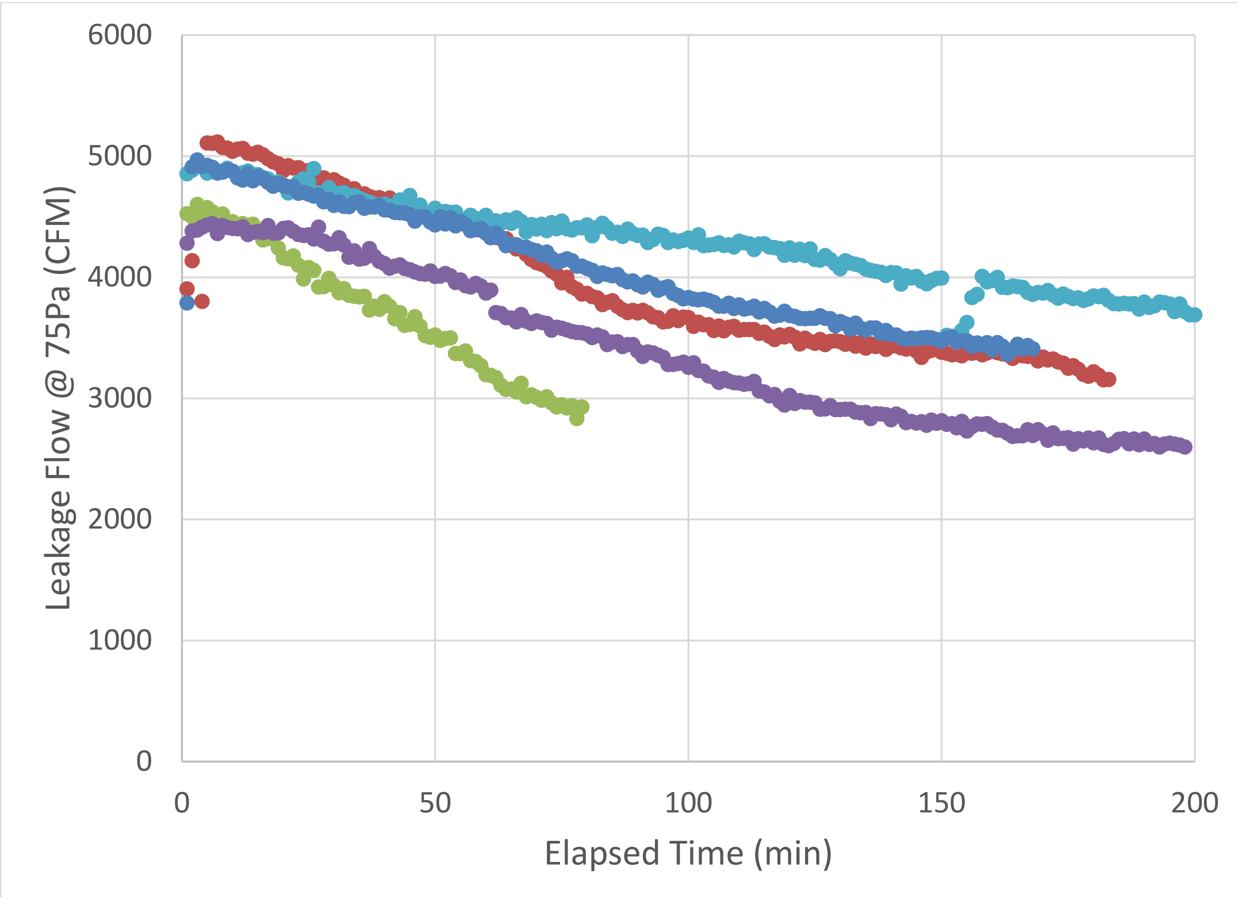


Figure 28: Sealing profiles for all five apartments sealed at NSA Mechanicsburg

Figure 28 shows the sealing profiles for the five apartments sealed. Most of the installations required a little over three hours of injection and the average leakage reduction for the apartments was 45%.

The largest building sealed for the project was the Officer's Club at NSA Mechanicsburg which was a 22,000 ft^2 building with several meeting areas, a large ballroom, and commercial kitchen. This building was also scheduled for demolition and did not require extensive prepping before the demonstration. Due to the size of the building and the limitation of the equipment used for this project, only half the building could be sealed during a single effort.

During the first sealing attempt the building leakage was only slightly reduced from 35,000 CFM at 75 Pa to about 33,000 CFM at 75 Pa. The nozzles were then moved to a different location and sealing commenced the following day with much better results. The second day of sealing saw the building leakage reduced down to 25,000 CFM at 75 Pa. A total of 10,000 CFM at 75 Pa was sealed on the first deployment to the building over more than six hours of aerosol injection.

A second deployment to the Officer's Club was arranged to seal the building further since a plateau in the sealing rate was not observed. During the second effort another 10,000 CFM at 75 Pa was sealed in about the same amount of time. Figure 29 shows the sealing profile for the entire sealing effort. Between the first and second deployment there was some initial demolition work on the building that introduced some additional leakage in the basement of the building. That additional leakage was too large for the aerosol process to address and was therefore removed from the sealing profile below.

Ultimately, 58% of the building leakage was sealed over 13 hours of total injection. This demonstration tested the limit of the technology and highlighted the need for scaled-up equipment for buildings this large. The multiple additions to the building over the years also showed a general lack of consistency for where the air barrier was applied. While the aerosol method was successful at sealing significant air leakage, this building would have benefited from a larger renovation to resolve other issues which is perhaps why the building was scheduled to be demolished.

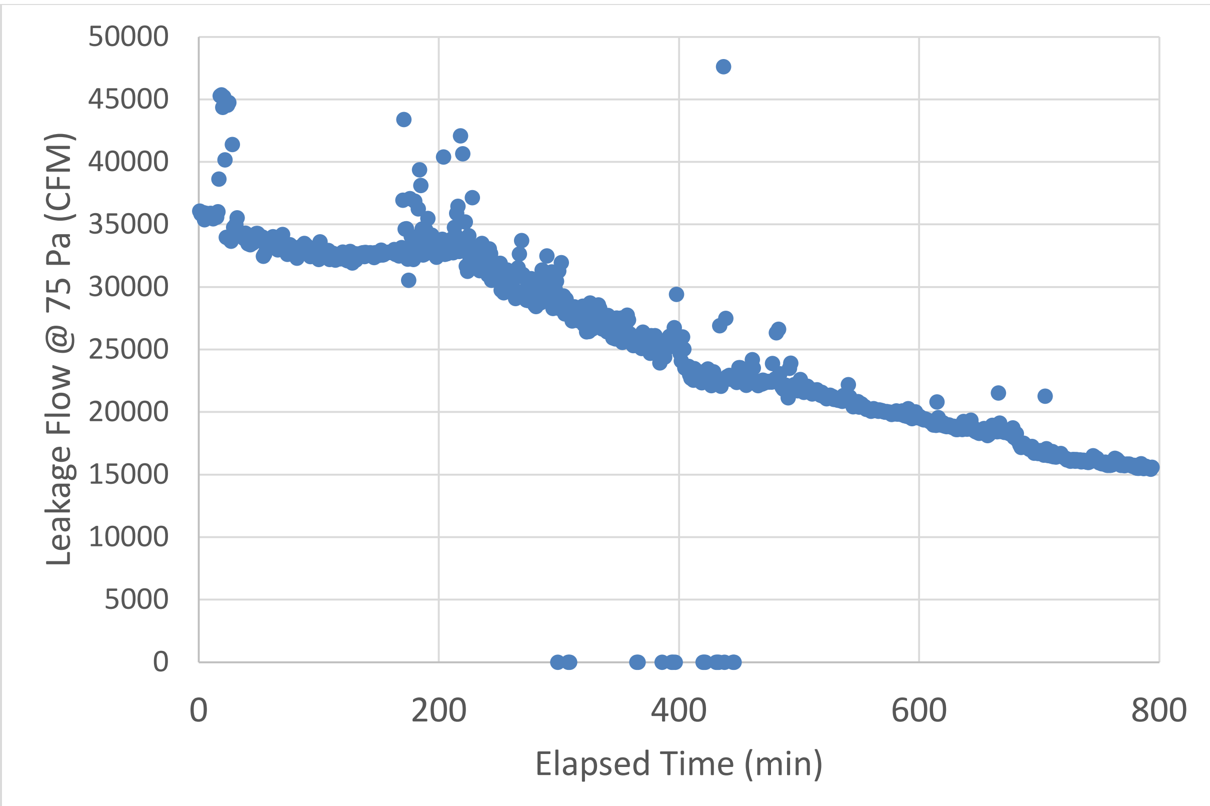


Figure 29: Sealing profile for Officer's Club demonstration at NSA Mechanicsburg

The last demonstration performed at NSA Mechanicsburg was on a relatively small bay of a larger building. Building 408 was a warehouse style construction with high ceilings and significant leakage issues at the roof (Figure 30). Much of this building was occupied including some adjoining spaces to the bay that was sealed.

Figure 30: Photo of clerestory on roof at building 408 at NSA Mechanicsburg

The building started out with 18,760 CFM at 75 Pa and after sealing it dropped down to 10,205 CFM at 75 Pa representing a 45% reduction in envelope leakage.

7.0 PERFORMANCE ASSESSMENT

This section describes the analysis performed for each of the performance objectives described in Section 3.0. Some of the performance objectives are based on the results of energy models and durability testing executed as part of this project. A description of the energy modeling performed for estimating the potential impact of air sealing building envelopes, and of the durability testing performed in the laboratory are also included below.

7.1 FACILITY BUILDING LEAKAGE

The data analysis that was used to evaluate the performance of the aerosol envelope sealing technology focused primarily on obtaining accurate measurements of building envelope leakage. The performance of the aerosol sealing technology was quantified by evaluating the difference between the preliminary leakage measurement and final leakage measurement of the demonstration site. When performing each airflow measurement, a baseline building pressure was obtained first under natural conditions in order to account for natural forces that impact the building pressure (i.e. wind). The baseline measurement was used to correct the value obtained by fan pressurization. Each measurement point was the average of 100 samples taken over several seconds under steady state conditions.

The sealing profiles that were generated during the sealing process were not used as the ultimate pre and post air sealing results. The sealing equipment has the capability to measure leakage in real-time but in many cases the fan was encumbered with other sealing equipment that affected the fan calibration. The sealing profiles do contain useful information about sealing process and provide reasonable estimates for sealing rates during installation.

Three of the demonstrations completed for this project met this performance objective reducing envelope leakage to below the USACE requirement of 0.25 ($cfm75/ft^2$); however, many of the demonstrations did not meet this criteria. Considering many of the building were in very poor shape, it is understandable that some buildings did not ultimately achieve this objective.

Table 3: Building leakage data collected pre and post-aerosol sealing demonstration

	Building Surface Area (ft^2)	Pre (CFM75)	Post (CFM75)	Leakage Sealed (CFM75)	Percent Sealed
Fort Bragg					
Building 1 A5436	5158	4730	1847	2883	61%
Building 2 A6372	7639	2643	1479	1164	44%
Building 3 M2338	3941	5332	1873	3459	65%
Mechanicsburg					
M/608A	27098	18210	6515	11695	64%
Apartment 710	5872	4709	3025	1684	36%
Apartment 711	6492	5509	3100	2409	44%
Apartment 712	7042	5841	2678	3163	54%
Apartment 714	5616	5571	3569	2002	36%
Apartment 715	5338	4456	1909	2547	57%
Officer's Club 1	53126	36049	22100	13949	39%
Officer's Club 2	53126	22100	15251	6849	31%
Warehouse	10800	18670	10205	8465	45%
Quantico					
Ashurst (Class 1)		6130	1286	4844	79%
Ashurst (Class 2)		8093	4086	4007	50%
Ashurst (Class 3, 4, and hall)		11567	5783	5784	50%
Office Building		4461	898	3563	80%

7.2 DURABILITY TESTING

Durability testing was performed to assess the strength and longevity of the seals created using the aerosol sealing process. Seals were created under different humidity conditions to determine the sensitivity of seal strength to this parameter. Multiple tests were conducted on seals formed on test plates in the laboratory, including pressure cycling at medium and low pressures, temperature cycling at medium pressure, and holding high pressure for one hour.

The following describes the approach for each test performed:

1. *Seal Failure Pressure*: The pressure was ramped up incrementally, 100 Pa at a time, up to 1,500 Pa. As per ASTM E2357, the pressure was held constant for 10 seconds at each

100 Pa increment up to 1,500 Pa. Once the pressure reached 1,500 Pa the pressure was maintained for an hour. A second test increased the seal pressure up to just over 5,000 Pa, which was the highest pressure the test apparatus was capable of measuring due to the limitations of the mass flow meter.

2. *Cyclic Medium Pressure Test*: The pressure across the seal was cycled from 0 Pa to 800±25 Pa where it was held for 10 seconds for each cycle. A total of 1,000 cycles were performed for each test.
3. *Cyclic Low Pressure Test*: The pressure across the seal was cycled from 0 Pa to 100±25 Pa where it was held for 5 minutes for each cycle. More than 1,500 cycles were performed for this test.
4. *Cyclic Temperature Test*: The temperature surrounding the pressure vessel was cycled between 80 °F and 120 °F while maintaining a pressure differential across the leak of 800±25 Pa. A total of 1,000 temperature cycles were performed.

7.2.1 Experimental Apparatus

A pressure vessel measuring 18”x24”x47” was constructed for the durability testing experiments (Figure 31). Sealed test plates were mounted to two 11” x 11” holes at the top of the apparatus and held down with toggle clamps. Each test plate contained six 1.2 in^2 slot leaks and only a single slot leak was left exposed for each test.

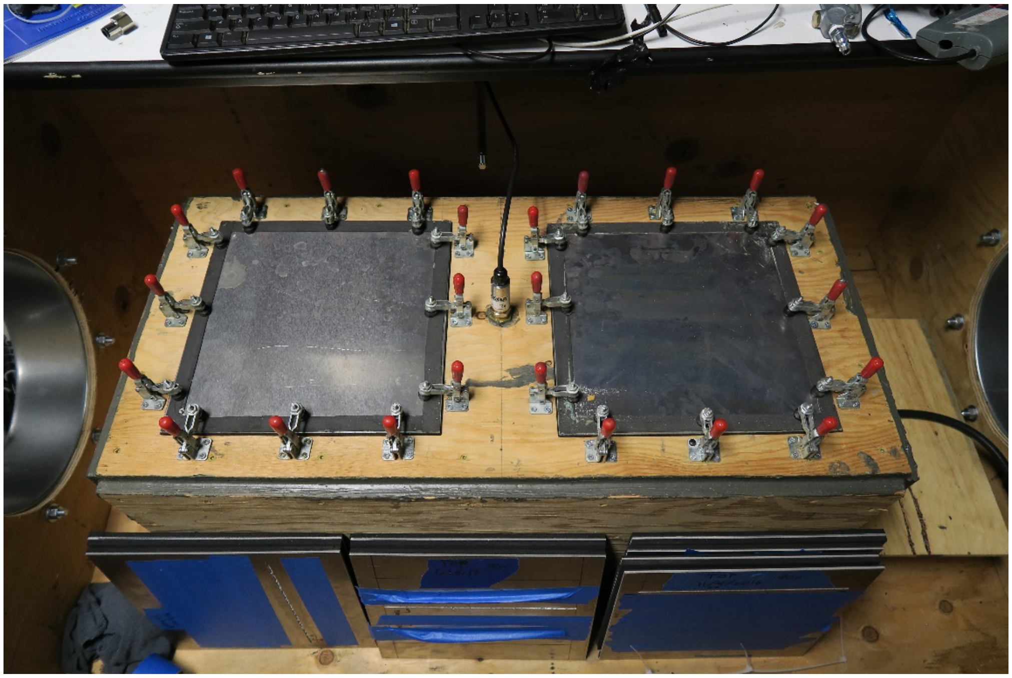


Figure 31: Apparatus for cyclic pressure and temperature testing

To test both positive and negative pressure on the seals, each plate was mounted in a different orientation (Figure 32). The front of one plate faced down in order to apply the pressure to the front of the test plate while the front of a second plate faced upward to test the seal in the opposite direction (the seals form from the inside of the building on the back of the test plates). Compressed air was injected into the pressure vessel through a series of regulators and flow control devices in order to control pressurization rates and magnitudes.

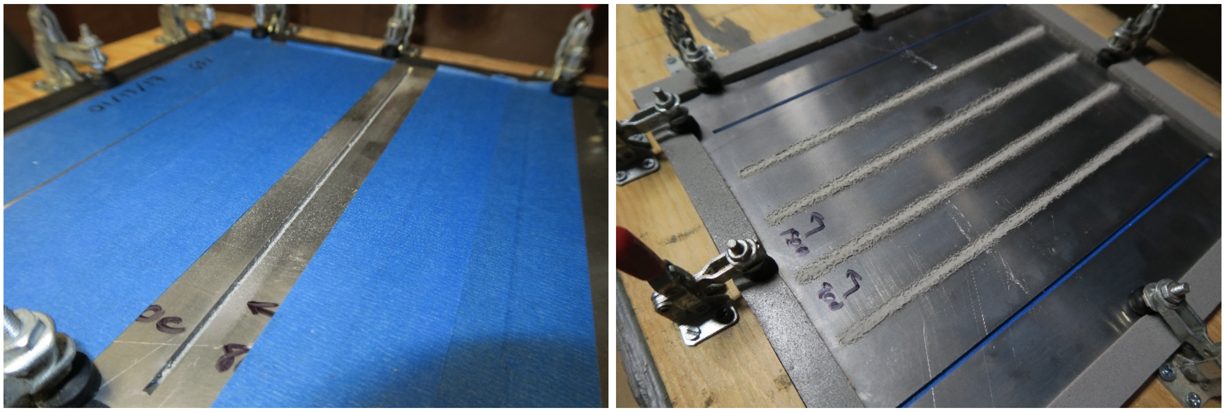


Figure 32: Photos showing top of plate facing up (left), and top of plate facing down (right) on test apparatus

For temperature cycling, the apparatus was placed inside a 58” x 36” x 24” box. A closed loop with a fan, hot water coil, electric resistance heater, and two electronic dampers are used. With the fan recirculating air through the loop, the front of the sealed plates were exposed to the conditioned air loop. To cool the box, both dampers were opened to exhaust hot air and draw in cooler air. Once the lower temp set point was reached, the dampers closed and the heating portion of the cycle began again.

LabView was used to control the apparatus as well as handle data collection. Data was collected at a frequency of 1 Hz. Table 4 lists devices used to record data.

Table 4: Data collection instrumentation

Measurement Type	Device Model	Range	Accuracy	Signal Type
Apparatus Pressure Differential	Omega PX309-001G5V	0 to 1 PSI	±0.0025 PSI	0 to 5 Vdc
Apparatus Pressure Differential	TEC DG-700 Pressure Gauge	0 to 1250 Pa	<1 Pa	RS-232 Digital Output
Apparatus air supply	Alicat MW-250SLPM-D	0 to 5 SCFM	±0.005 SCFM	RS-232 Digital Output
Apparatus airstream temp	Visala HMD70Y	-4 to 176°F	±0.36°F	0 to 10 Vdc
Apparatus airstream humidity	Visala HMD70Y	0 to 100% RH	±2.0% RH	0 to 10 Vdc

7.2.2 Lab Testing Analysis

A mass flow meter was used to measure the baseline leakage of the test apparatus. The leakage of the test apparatus without the presence of a test sample was measured with two plates installed (one facing up, the other facing down), where all slots were taped off. Pressure was raised in 100 Pa increments from 0 to 1,600 Pa while maintaining pressure for 10 seconds at each interval. Measured flow was plotted against pressure and a line was fitted to the data to estimate the leakage of the box at various pressures Figure 33. To correct the measured flow from seal leakage tests for apparatus leakage, the following equation was used.

$$Q_{seal\ leak} = Q_{measured} - (0.000469 * P_{measured})$$

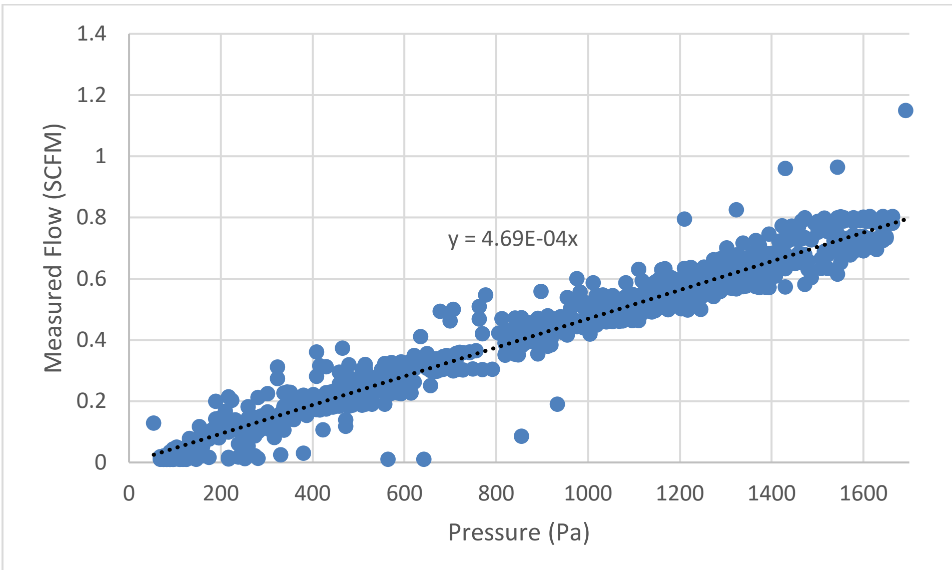


Figure 33: Measured flow vs. pressure of test apparatus

In order to assure that a seal failure would be obvious and measureable, a seal failure was simulated by poking holes in a seal and observing the flow response. Holes were made in the seal while maintaining a constant pressure of 800 Pa. Clear spikes in flow through the seal were seen each time the seals were punctured (Figure 33).

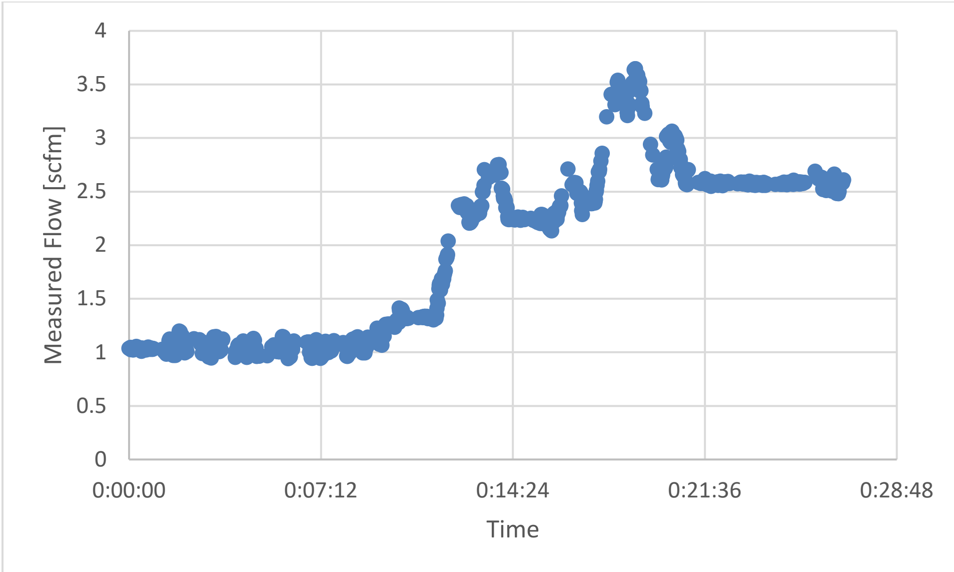


Figure 34: Simulated seal failure showing rapid change in leakage flow

A different failure response was observed depending on which side of the seal was under higher pressure. When the side of the seal exposed to the inside of the envelope during sealing was exposed to higher pressure the effect of a simulated failure was less significant than when the opposite side of the seal was exposed to positive pressure. The most likely explanation for this is that sealant tends to build-up on the interior side of the leak, and when a hole is introduced the excess sealant ends up being pushed into the hole, versus the other side of the leak for which the excess sealant is pushed away from the hole.

7.2.3 Seal Failure Pressure

For the 1,500 Pa tests, no failures were observed during the period when pressure was increased in 100 Pa increments from 0 to 1,500 Pa. Average leakage data was calculated for the first and last five minutes of testing to give the overall change in flow during the one-hour test. The initial and final leakage data is presented in Figure 34. Ultimately, no abrupt seal failures were observed, however a small gradual increase in seal leakage over time was observed.

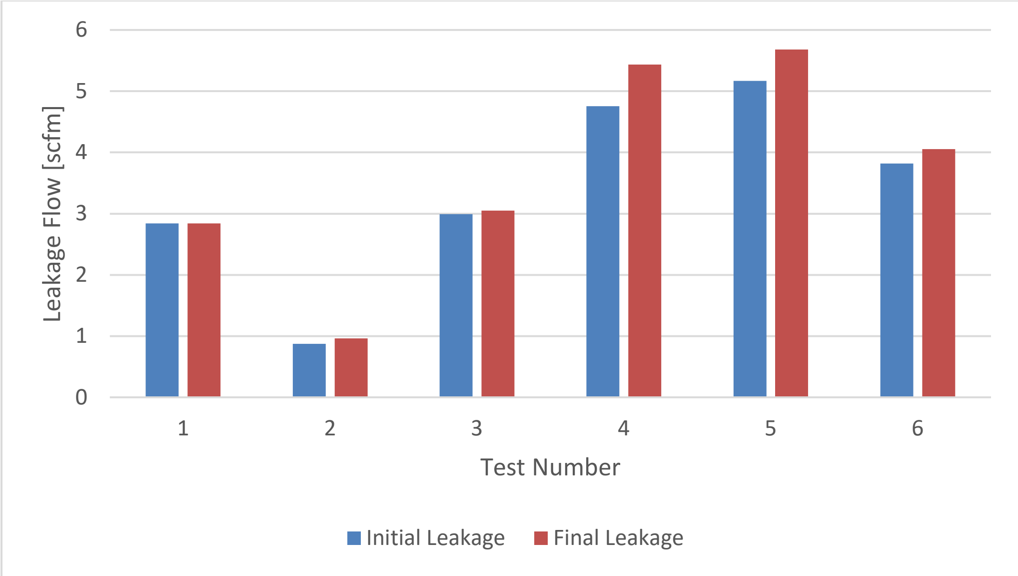


Figure 35: Initial and final leakage flows for each test sample during failure testing

Test plate 1 was used for the ultimate failure test. Pressure was steadily increased from 0 to 5,000 Pa, with no catastrophic failure (Figure 35 and Figure 37).

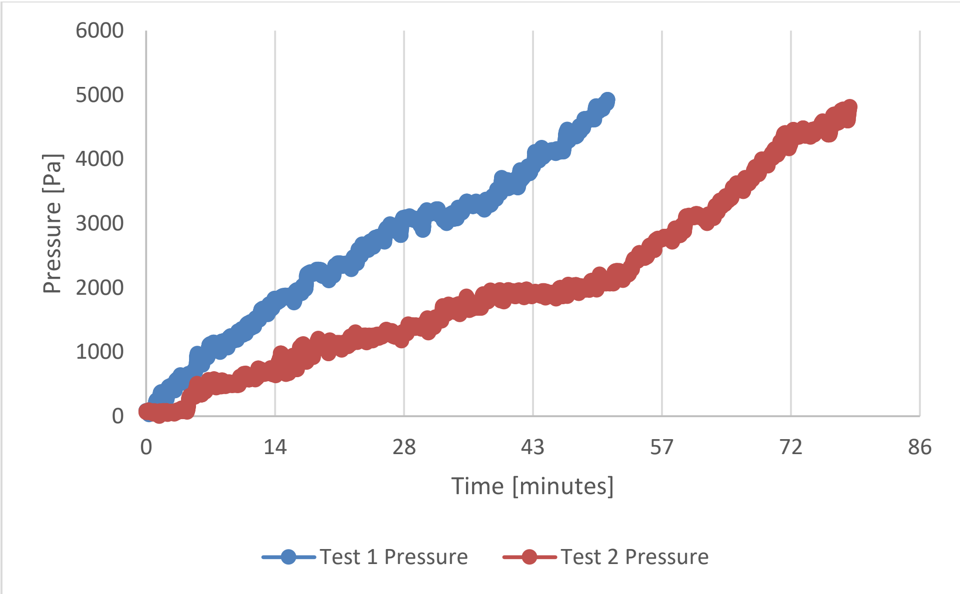


Figure 36: Pressure increase over time for ultimate failure test

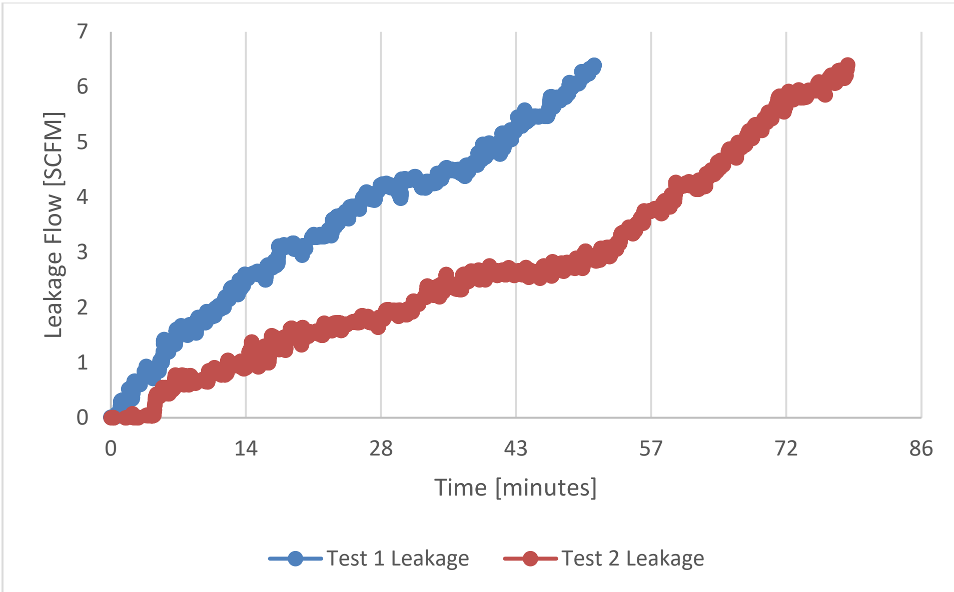


Figure 37: Leakage flow increase over time for ultimate failure test

7.2.4 Cyclic Pressure Loading

During each 800 Pa cyclic test, only a minor change in seal tightness was observed over the duration of the test, which lasted 8-10 hours. Average leakage data was calculated for the first and last 100 cycles of testing to give the overall change in flow over the 1,000 cycles (Figure 37). The increase in leakage was gradual and no sudden increases in pressure suggesting a failure were observed. A final plateau in leakage rates was not observed during the 1,000 cycles. An investigation to find the leakage plateau was carried out and presented below. Test-plate 3, which experienced the most significant increase between beginning and ending leakage, was due to a control system malfunction that caused the pressure to spike to approximately 4,000 Pa for a few seconds, thereby stressing the seal.

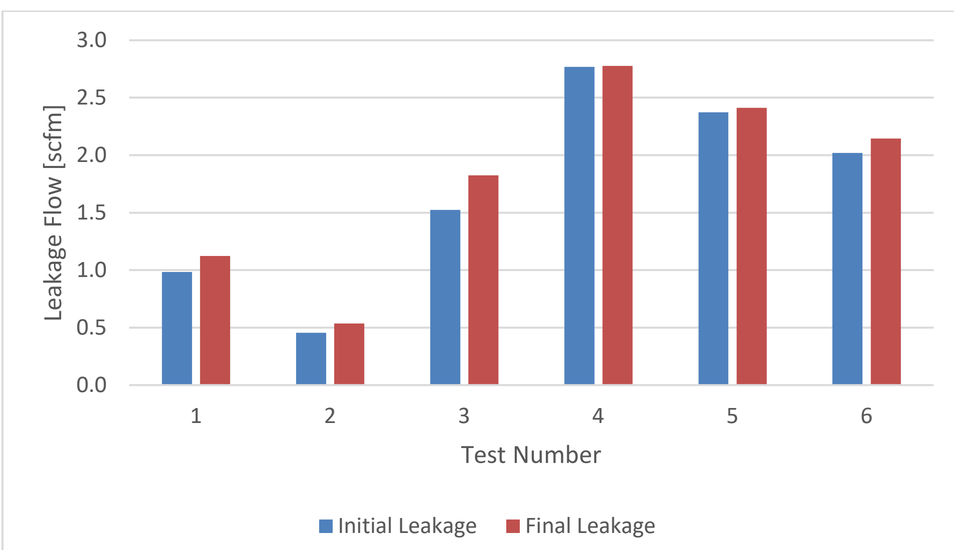


Figure 38: Change in leakage after 1,000 cycles of 800 Pa (note: Test 3 experienced a significant over-pressurization resulting in higher percent change)

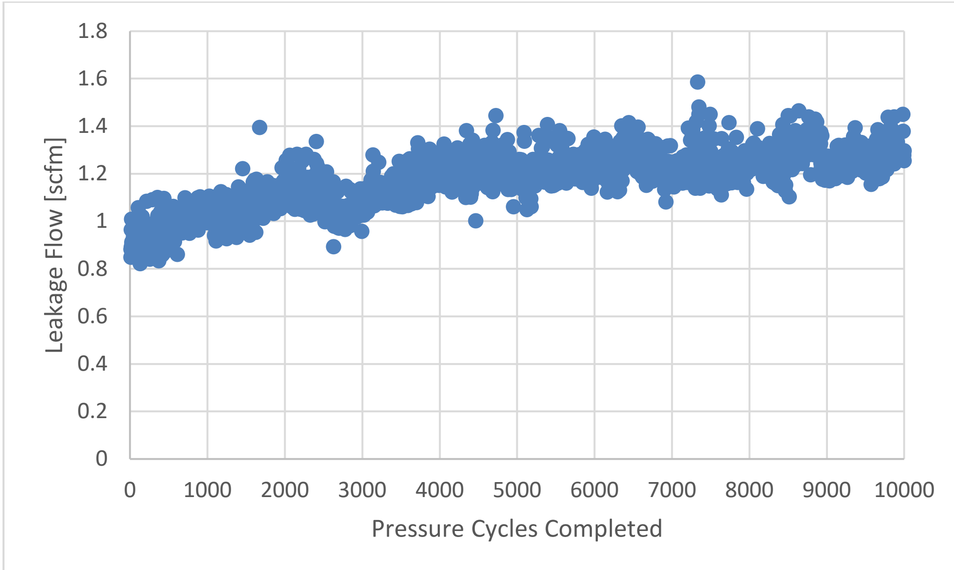


Figure 39: Leakage rates over 10,000 cycles of 800 Pa

An extended 800 Pa cyclic test was performed on Plate 1 to look for a plateau in leakage rate. The extended test followed the same procedures used for the 1,000 cycle 800 Pa test. The leakage appeared to plateau after 4,000 cycles, but modestly increased again after 8,000 cycles, still not reaching an ultimate plateau.

A final test was performed at more reasonable pressures for a building seal, as the wind speed corresponding to an 800 Pa pressure would be more than 80 miles per hour, much higher than a building would typically ever experience. Additional cyclic testing was therefore performed at 100 Pa to see if an observable plateau could be found. Over 1,900 pressure cycles were completed for the 100-Pa cyclic test. Three pairs of slots were tested on Plate 5 to allow for better control of pressure in the apparatus. This cyclic test showed very little change in leakage rates throughout the test period. The overall change in leakage flow between the first and last 100 cycles was 0.0673 scfm for the six sealed leaks tested. This translates to an increase in leakage area of approximately 0.004 in^2. For six sealed leaks each measuring about 1.2 in^2, this represents an overall increase of less than 0.1% in the sealed leakage area, indicating very little change over the course of the testing.

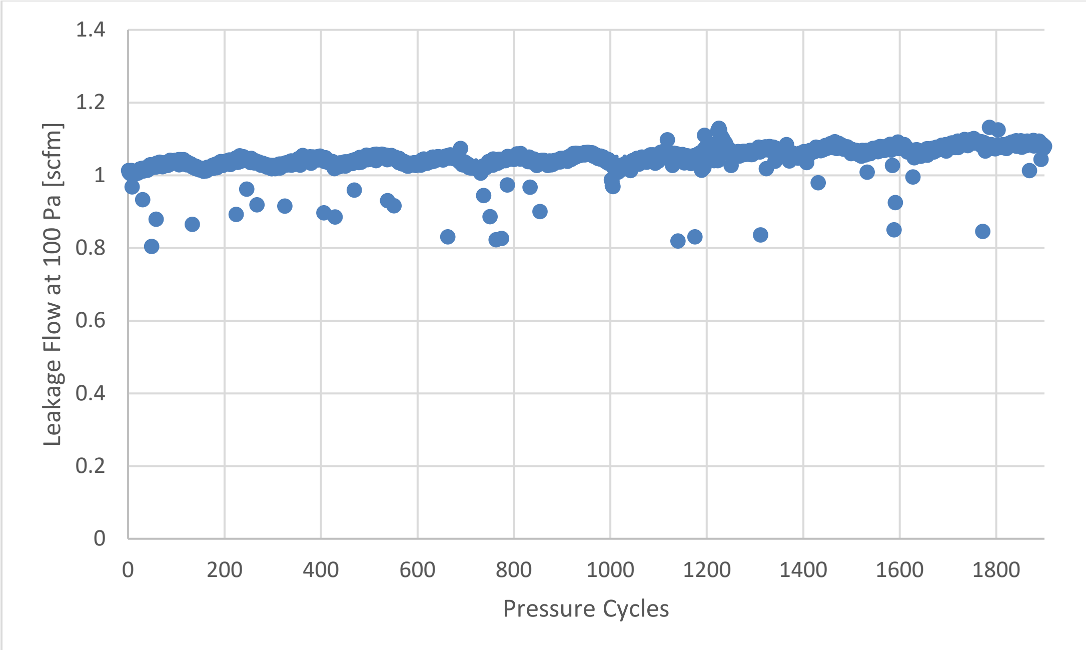


Figure 40: Leakage rates over 1,900 cycles of 100 Pa

7.2.5 Cyclic Temperature Loading

Only one cyclic temperature test was performed for this project due to the time required to complete the test. A total of 1,400 cycles between 80°F to 120°F required nearly three weeks to complete. There were also some issues performing the test according to the test plan. For the first 200 temperature cycles, as well as for cycles 1,000 to 1,100, the pressure in the apparatus was low (<200 Pa) and for cycles 500 to 600 the pressure was high (1200 to 2000 Pa), causing the spike in the leakage flow shown in Figure 41.

The temperature cycling test did not lead to a seal failure or cause a rapid decline in seal strength due to temperature cycling. Temperature did have an effect on the seal leakage, causing the seals to expand or contract. For the temperature range 80°F to 90°F, average leakage for the entire duration of the test was 2.36 scfm, and from 110°F to 120°F, average leakage was 1.8 scfm indicating some temperature dependence on leakage rates. A similar trend of gradual increase in leakage after many cycles was also observed.

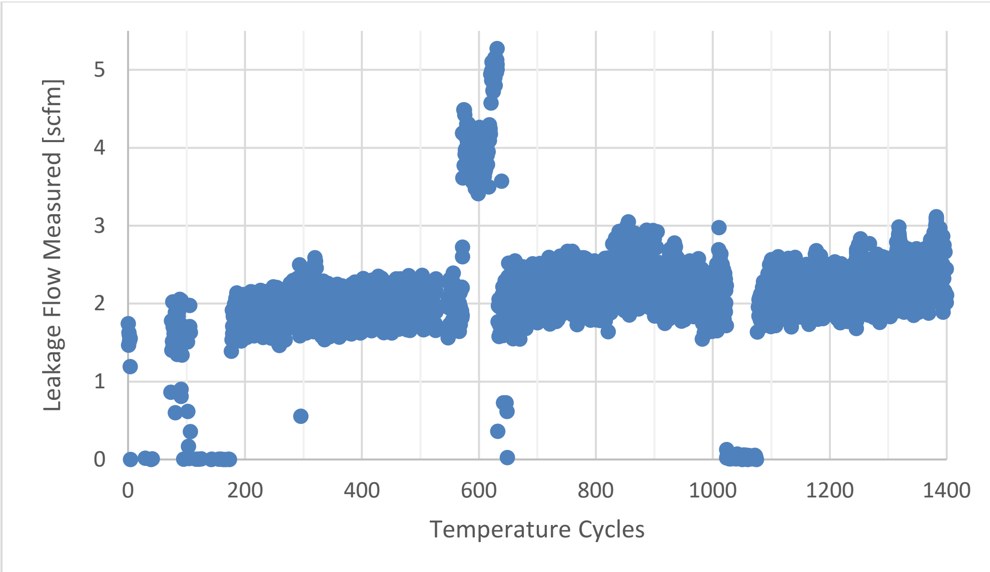


Figure 41: Leakage flow rate during temperature cycling while maintaining 800 Pa

7.3 ENERGY PERFORMANCE MODELING

The objective of this modeling work was to investigate the impact on building energy use due to tightening the building envelope. WCEC modified a Department of Energy standard EnergyPlus model for a commercial buildings developed by the Pacific Northwest National Laboratory. The reference model that was used was a pre-1980 construction small commercial office building. A calculation method derived from DOE-2 was used to model wind driven infiltration, and the infiltration is balanced in the model by simulating exfiltration flows equal to the infiltration. The HVAC system is a balanced central unit that uses a vapor-compression cooling system and a gas furnace for heating. The ventilation system was modeled as a balanced system due to the constraints of the modeling program, with equal exchange of air between the outdoor air and the indoor air. The model was simulated in four climate zones providing total HVAC energy use, as well as ventilation and infiltration flows.

7.3.1 Locations

The locations were chosen to represent the variety of climate zones around the country in order to determine in which climates aerosol sealing technology would be most effective. The locations and the ASHRAE 90.1 climate zones they represent are presented below:

1. Fort Hood, Texas: Climate Zone 2A (Hot/Humid)
2. Fort Benning, Georgia: Climate Zone 3A (Warm/Humid)
3. Grand Forks AFB, North Dakota: Climate Zone 7A (Cold/Moist)
4. Travis AFB, California: Climate Zone 3B (Warm/Dry)

7.3.2 Building Construction

The pre-1980s office building includes five thermal zones, all of which are conditioned (Figure 42). The exterior walls are constructed of wood siding, a layer of R-20 insulation, and ½ inch drywall. The construction has a flat roof, and the ceiling of the conditioned building zones is part of the roof construction. The interior walls separating the zones are constructed of two layers of ½ inch drywall modelled with no gap. The roof is constructed from a roof membrane, R-20 roof insulation, and metal decking.

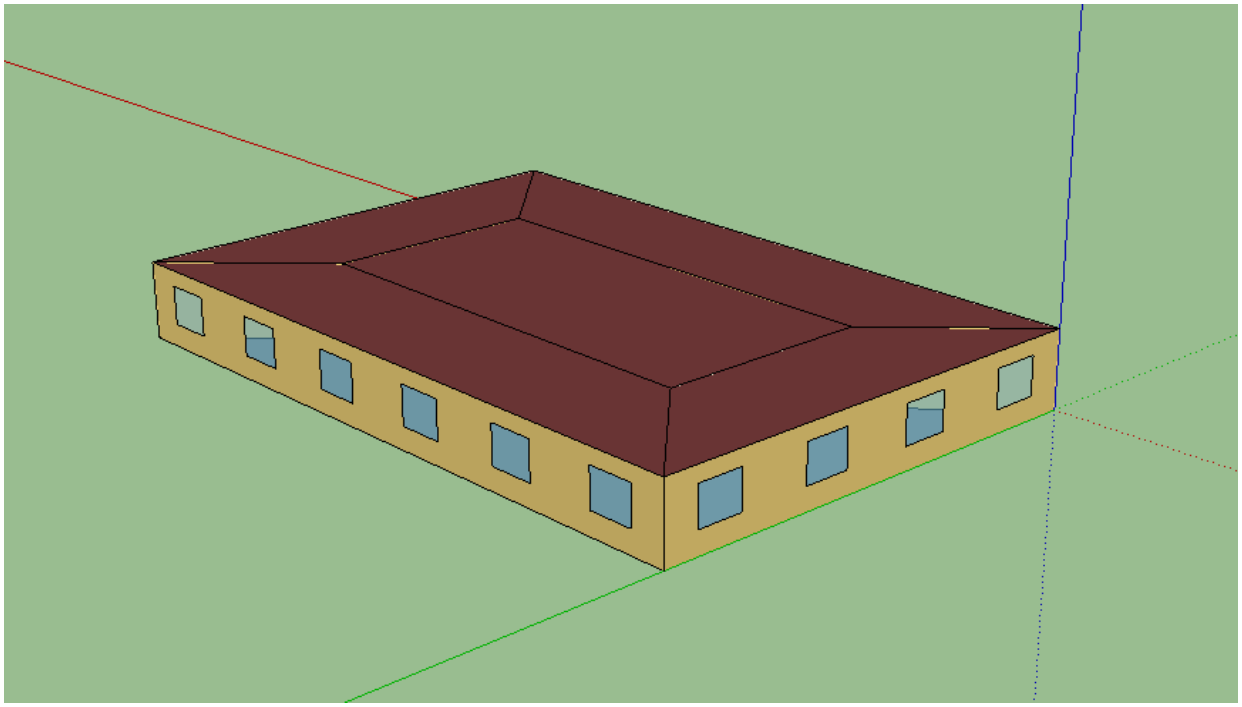


Figure 42: Image of pre-1980s building modeled

7.3.3 HVAC System

Each conditioned thermal zone is independently controlled by a zone thermostat. Each zone has a vapor-compression cooling coil and a natural gas heating coil. The coils were sized according to the climate zone, so that each model within a climate zone would have the same coil sizes as would be expected after an air sealing retrofit. The coil sizing was determined for each climate zone by running all four models within that climate zone with the autosize function, and using the sizing results from the model with the highest loads to size the coils.

7.3.4 Ventilation

The ventilation systems in each model delivered outside air to the occupied spaces in accordance with ASHRAE Standard 62.1-2007 which outlines the minimum ventilation for commercial buildings. ASHRAE 62.1 prescribes a ventilation requirement based on the expected occupancy of a building as well as the floor area of the building. Table 5 describes the requirements that were used to calculate the ventilation rate:

Table 5: ASHRAE Table of prescribed ventilation by area and occupancy

From ASHRAE 62.1-2013

	People Outdoor Air Rate	Area Outdoor Air Rate	Default Occupant Density	Combined Outdoor Air Rate
Office Buildings	**CFM/person**	**CFM/ft^2**	**#/1000ft^2**	**CFM/person**
Office Space	5	0.06	5	17
Reception Areas	5	0.06	30	7
Telephone/data entry	5	0.06	60	6
Main Entry Lobbies	5	0.06	10	11

This project assumed one person per 110 ft^2 of floor area which for the 5,500 ft^2 building modeled would translates to 55 occupants. The prescribed ventilation rate was calculated to be just over 0.1 CFM/ft^2 using the following formula from ASHRAE 62.1-2013:

$$Q_{vent} = 5 * \left[\frac{CFM}{Person}\right] * \left(\frac{1}{110}\right)\left[\frac{Person}{ft^2}\right] + 0.06[\frac{CFM}{ft^2}]$$

7.3.5 Infiltration

Infiltration can be modeled several ways in EnergyPlus. The model for this project followed infiltration modeling guidelines developed by U.S. DOE for commercial buildings. The infiltration model is based on a calculated reference infiltration (I_{design}) and wind speed coefficient (C). The reference infiltration was developed using known and assumed characteristics of the building, such as air leakage at a reference pressure, flow coefficient of the building, and environmental parameters including terrain, and local air density. The wind speed coefficient was determined using DOE-2 coefficients, which are set such that the $I = I_{Design}$ at a reference wind speed of 10 mph. The effect of the second order wind speed term in the infiltration model was ignored based on the DOE-2 guidelines.

$$Infiltration = Flow_{Factor} * I_{design} * \left[A + B * \left|T_{zone} - T_{DB,OA}\right| + C * V_{Wind} + D * {V_{Wind}}^2\right]$$

I_{design} [m^3/m^2-s]

Table 6: DOE-2 coefficients for infiltration model

A	B	C	D	Reference Velocity
0	0	0.224	0	14.47 [m/s]/ 10 [MPH]

In order to account for increased pressurization of the building when the ventilation equipment is running, there is a flow factor in the infiltration equation. The PNNL reference paper used to guide the infiltration modeling recommends a flow factor of 0.25 when the HVAC equipment is running. This essentially limits infiltration during occupied hours; however, a simple pressurization analysis of a building with typical leakage shows very little building pressurization while a building that meets the USACE leakage requirements would have mild pressurization. For these reasons, no flow factor was applied for the baseline building during occupied hours and infiltration was eliminated during occupied hours in the tightened building.

7.3.6 Modeling Results

The results presented here focus on the HVAC energy consumption of the models simulated in each climate zone. Figure 43 shows the percent energy savings for heating, cooling, and fans associated with air sealing the building. Heating energy use was significantly reduced by at least 30% and up to 45% in some climate zones while cooling energy use and fan energy use was less impacted. Cooling energy use decreased in some climate zones and increased in others indicating that additional infiltration helps to reduce the cooling load. The climate zones that saw reduced cooling energy use were both humid climates. Fan energy use went down slightly in all cases due to fewer operating hours for the heating and cooling equipment.

Figure 44 shows the modeled source energy savings for heating, cooling, and fan equipment. Grand Forks had the largest reduction in source energy consumption reducing building energy consumption by more than 150 GJ annually. The other climate zones showed reductions from 21 to 38 GJ annually.

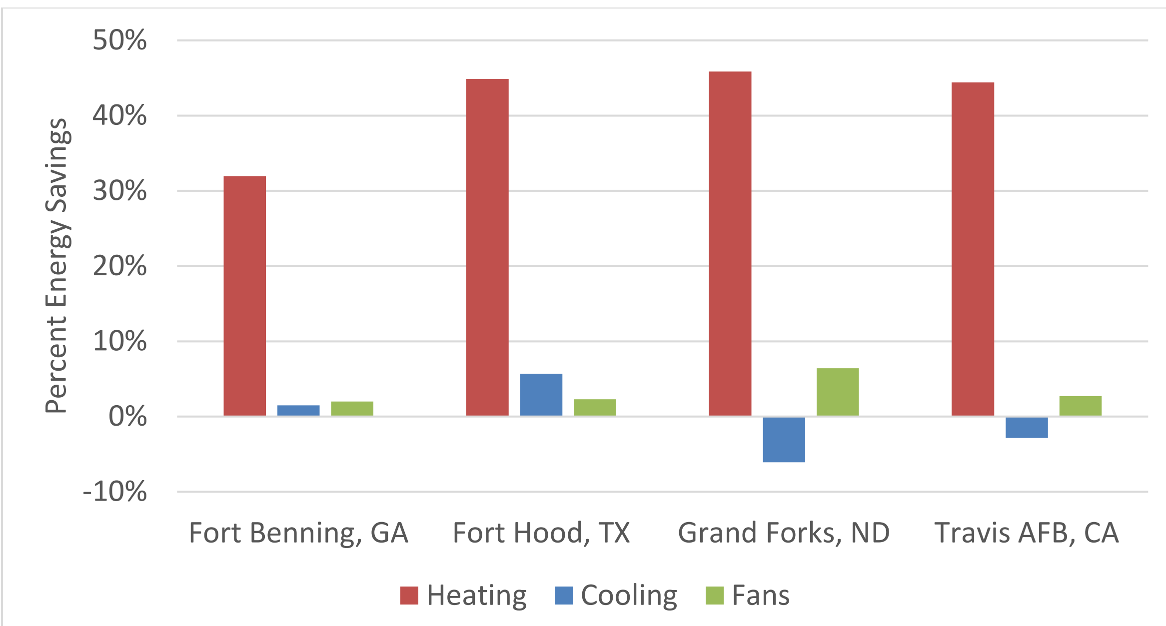


Figure 43: Modeled percent energy savings for heating, cooling, and fan equipment due to air sealing

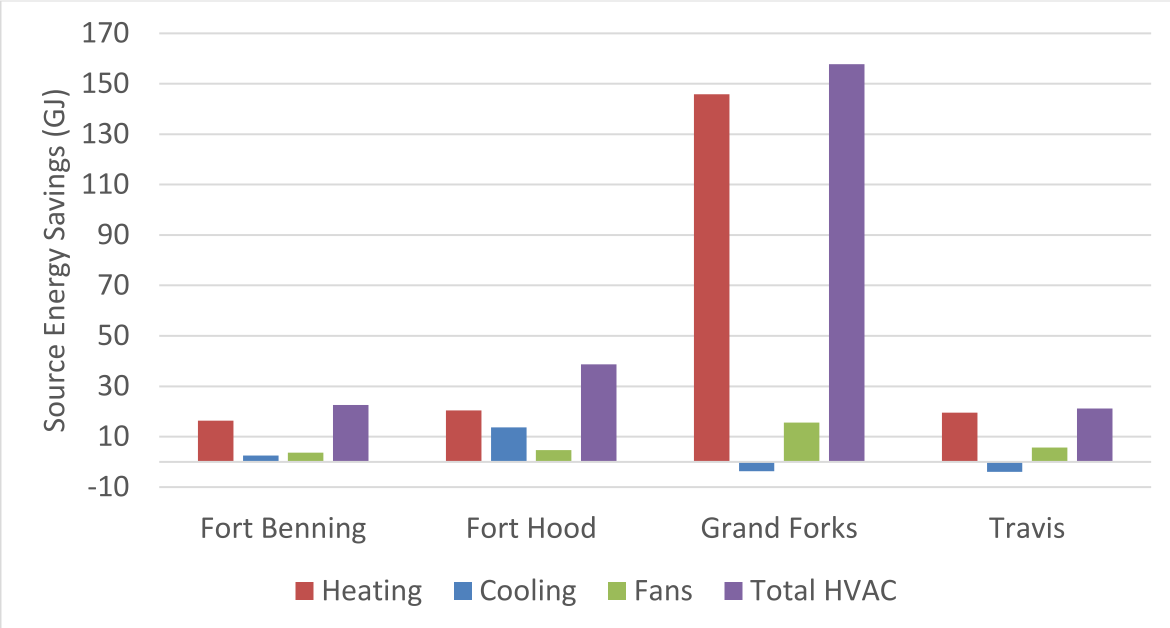


Figure 44: Modeled source energy savings for heating, cooling, and fan equipment due to air sealing

The effect of building pressurization is not included in this analysis but would have a significant impact in buildings with a pressurization target. For mild pressurization of 7.5 Pa, the baseline building would require more than 10-times the ventilation rate to meet that target while the sealed building would only require 2-times the ventilation rate. This additional airflow would introduce a significant load for the building systems to manage. It is likely that the building's equipment would not be able to provide that amount of outdoor air suggesting that the pressurization target in many cases would not be met.

7.4 INSTALLER FEEDBACK ON SAFETY PROTOCOLS FOR INSTALLATION

The application of the aerosol sealing technology does have health and safety considerations for contractors during the application. The sealant used is GREENGUARD Gold Certified, which means that it meets the stricter certification criteria required for use in California schools and healthcare facilities. The toxicity of the sealant used for the aerosol sealing process is well below many other materials used in buildings; however because the sealant is atomized the contractor should wear appropriate personal protective equipment and avoid entering the building if possible. If entering the building during the installation is necessary the contractor should have a fitted respirator to prevent breathing the aerosol. When the installation is complete the aerosol is flushed out by continuing to pressurize the space for several minutes after stopping the sealant injection.

Due to the fact that the concept of aerosol sealing of buildings is new, a discussion of the process with Environmental, Safety, and Occupational Health (ESOH) offices at the demonstration sites was carried out. The project team consulted with ESOH staff at each of the demonstration sites to assure that there are no safety concerns with the technology. NSA Mechanicsburg ESOH staff required the project team to provide material data sheets and description of the process prior to allowing the demonstrations. Quantico provided their feedback in a survey indicating that they have no concerns with the process. Lastly, Fort Bragg carried out an environmental study on one of the buildings used for the demonstration and found no issues related to the technology. The completed survey from MCB Quantico staff and the environmental study carried out by Fort Bragg Army Base can be found in Appendix B.

Finally, feedback was collected from installations staff regarding the safety protocols for the process. The biggest issue that was brought up was that if repirators were removed before the aerosol was sufficiently flushed from the building it could cause the installer to feel the affect in their chest. It is recommended that installers wear respirators for at least one hour after installation when working in the building and it was only when respirators were removed early that this seemed be an issue. The reason for removing the respirators was because they can be uncomfortable to wear for extended periods of time.

7.5 IMPACT OF AEROSOL SEALING ON FLOORING (ONLY IF ENCOUNTERED)

The aerosol sealing demonstrations in this project did encounter situations where the floors needed to be protected from aerosol deposition. In these cases plastic and tape were used to cover all horizontal surfaces including floors, table tops, and window sills (Figure 45). This preparation of the building significantly impacted the amount of labor required for the sealing work. While there are no photos showing the floor after sealing, the building operator was generally pleased with the condition of the building. Figure 46 shows a photo of a floor that was not protected during the aerosol installation since the building was slated for demolition. The photo shows a clear layer of sealant deposition on the floor.

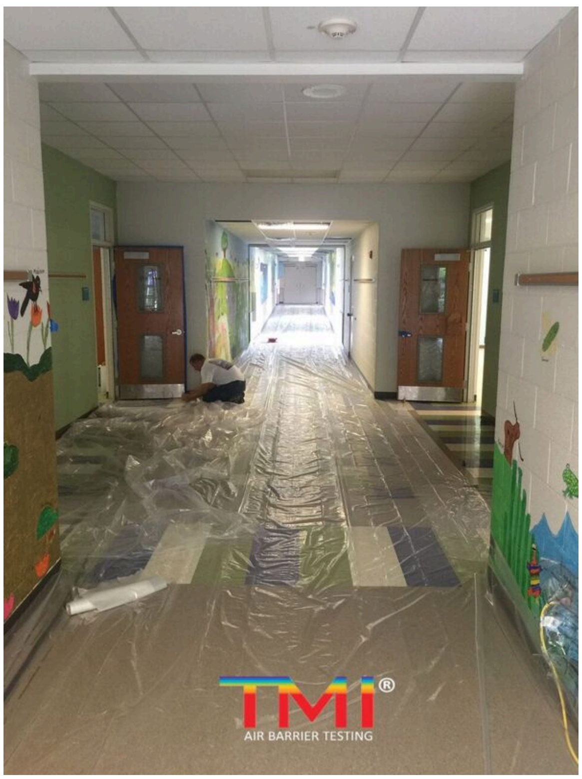


Figure 45: Photo showing floor being prepped at Ashurst Elementary at MCB Quantico

Figure 46: Photo of floor not prepped at Building 608A at NSA Mechanicsburg

8.0 COST ASSESSMENT

This project demonstrated a new technology for sealing building envelopes, the purpose being to determine the overall feasibility of the process. The installations were all performed by research staff, and therefore the cost assessment was based on our best estimates of the costs for a mature technology.

8.1 COST DRIVERS

There are several cost considerations when deciding how much aerosol envelope sealing costs as a retrofit. A primary consideration is the state of the building at the time of sealing. For example, an occupied building full of contents should not be considered at this stage in the technology development. Thus, this project did not test a situation where the contents of the building needed to be protected from aerosol deposition, and there would likely be significant challenges in doing so. On the other hand, two other applications were successfully demonstrated in this project: 1) buildings at the time of tenant changeover (i.e. floors and horizontal surfaces protected), and 2) buildings that were getting the flooring replaced. The latter applications require very little preparation and therefore represent the lowest installation costs, similar to new construction (Note: new construction can require even less preparation if they use tight windows)

8.2 COST MODEL

The cost model is broken out into two potential application points: at the time of tenant changeover, and during major renovation. These two scenarios have very different underlying cost considerations. Installing at the time of tenant changeover assumes that the building is empty of contents and all horizontal surfaces would need to be protected. This scenario requires additional labor and consumables based on the preparation needed. Installing at the time of major renovation assumes that the building is emptied of contents and significant building improvements including replacing flooring is occurring. The preparation of the building at this stage is less time consuming, since floors would not need to be protected from aerosol sealant deposition. These considerations are reflected in the estimated costs for each cost scenario in Table 7.

The cost model in Table 7 was developed based on rough estimates of the time required for setting up, perform the sealing, and breaking down the equipment. Since the pricing of this technology has not fully matured, the estimates account for some streamlining of the process and are reliant on a dealer network of installers to perform the sealing. Ultimately, the cost model was based on an assumed labor rate of $100/hr and the time estimated for a sample of the sealing demonstrations performed.

Table 7 outlines the cost elements relevant to the technology installations. The cost elements that need to be considered are 1) the installation cost, which includes the labor required to install the aerosol sealing product, 2) the consumables used during the installation to protect building contents from sealant deposition, and 3) the energy savings estimates based on energy models.

Table 7: Cost model for aerosol envelope sealing technology

Cost Element	Data Tracked During the Demonstration	Estimated Costs
Installation costs (tenant change)	Labor and material required to install	$1,000 + $1.0/ft^2
Installation costs (major renovation)	Labor and material required to install	$500 + $0.5/ft^2

8.3 COST-BENEFIT ANALYSIS

To perform a cost-benefit analysis for this technology the costs discussed above need to be compared to the benefits provided by the sealing. At the simplest level, the benefit of the technology is to bring DOD buildings into compliance with the Army Corps of Engineering leakage specification. Although a detailed evaluation of the benefits associated with meeting that specification is beyond the scope of this project, there are several metrics by which the value of sealing a building can be evaluated. The main purpose of envelope sealing is to facilitate the control of air flows in buildings, the two key rationales being: 1) reducing energy consumption associated with uncontrolled air infiltration, and 2) controlling where air enters a building, thereby managing Indoor Air Quality (IAQ), providing tactical safety (resistance to chemical warfare), facilitating ventilation energy recovery, and improving thermal control in spaces (no infiltration of humid air).

The most convenient and defensible way to analyze the energy value of building envelope sealing is to perform detailed simulations using well-accepted tools to calculate the impacts. Our investigation indicated that EnergyPlus simulations can be used to perform an analysis of the impacts of sealing in the situation where the building pressure is allowed to float (i.e. pressure and air entry points are not controlled). The energy costs used for the analysis were based on data from the U.S. Energy Information Administration on electricity and natural gas costs for each state which is presented in Table 8 [6,7]. These EnergyPlus simulations were conducted, the results of which are presented in Table 9. In addition, Table 10 presents the life-cycle cost analysis based on these EnergyPlus energy savings, combined with the cost model in Table 7 for the two retrofit scenarios (installing at time of tenant changeover and installing at major renovation). Noting that these results represent the ***bare minimum value of sealing***, according to this analysis of four bases, it appears that the sealing process at tenant changeover is only cost effective in Grand Fork, North Dakota, and is cost effective at somewhere between 10 and 20 years in all climates for major-renovation applications. That said, it is clear that this is not the entire picture.

Table 8: Energy costs used for each model

	Electricity Costs ($/kWh)	Natural Gas Costs ($/Therms)
Fort Benning	$0.1009	$1.050
Fort Hood	$0.0822	$0.858
Grand Forks	$0.0986	$0.791
Travis	$0.1773	$0.872

Table 9: Modeled annual heating and cooling energy savings

	Annual Cooling Energy Savings (kWh)	Annual Heating Energy Savings (Therms)	Annual Cost Savings
Fort Benning	547	143	$206
Fort Hood	1606	178	$285
Grand Forks	1044	1275	$1,112
Travis	147	171	$175

Table 10: Lifecycle cost analysis comparing a building sealed with the aerosol envelope sealing technology to the same building without retrofit air-sealing using 3% discount rate

Fort Benning, Georgia							
Period	Total lifecycle savings		Life Cycle Energy savings		SIR		CO_2 savings
	Tenant Change	Major Renovation			Tenant Change	Major Renovation	
	$	$	kWh	Therm	-	-	kg
5 year	($5,422)	($2,172)	2,733	719.5	0.17	0.33	5,673
10 year	($4,412)	($1,162)	5,468	1,439	0.32	0.64	11,346
20 year	($2,686)	$564	10,939	2,880	0.59	1.17	22,693

Fort Hood, Texas							
Period	Total lifecycle savings		Life Cycle Energy savings		SIR		CO_2 savings
	Tenant Change	Major Renovation			Tenant Change	Major Renovation	
	$	$	kWh	Therm	-	-	kg
5 year	($5,045)	($1,795)	8,020	889.4	0.22	0.45	9,995
10 year	($3,690)	($440)	16,043	1,779	0.43	0.86	19,990
20 year	($1,403)	$1,847	32,096	3,560	0.78	1.57	39,981

Grand Forks AFB/Minot AFB, North Dakota							
Period	Total lifecycle savings		Life Cycle Energy savings		SIR		CO_2 savings
	Tenant Change	Major Renovation			Tenant Change	Major Renovation	
	$	$	kWh	Therm	-	-	kg
5 year	($349)	$2,901	5,216	6,371	0.95	1.89	39,586
10 year	$5,461	$8,711	10,436	12,745	1.84	3.68	79,172
20 year	$15,478	$18,728	20,877	25,497	3.38	6.76	158,344

Travis Air Force Base, California							
Period	Total lifecycle savings		Life Cycle Energy savings		SIR		CO_2 savings
	Tenant Change	Major Renovation			Tenant Change	Major Renovation	
	$	$	kWh	Therm	-	-	kg
5 year	($5,574)	($2,324)	740	854.4	0.14	0.28	4,710
10 year	($4,696)	($1,446)	1,479	1,709	0.28	0.55	9,421
20 year	($3,071)	$179	2,960	3,420	0.53	1.05	18,841

In general, commercial buildings are designed to be controlled to maintain the building at a pressure somewhere between 7.5 to 12.5 Pa above outdoors, so as to eliminate (minimize) infiltration. It should be noted this pressurization facilitates all of the benefits described above. Thus, one way to analyze the impact of sealing would be to determine how much outdoor air needs to be introduced into the building to produce that pressurization for the sealed building versus the existing building. The problem with this type of analysis is that for the existing leakage levels observed in this project (and in many of the buildings tested by the National Institute for Standards and Technology (NIST)), the amount of Outdoor Air (OA) that needs to be brought in approaches outdoor-air supply levels near (or even above) the total flow provided by typical HVAC equipment (i.e. ~100% OA). This problem was addressed by calculating the OA flows required for different levels of pressurization, and then calculating the thermal energy required to heat or cool that air. As detailed building simulation tools such as EnergyPlus are not currently set up to model building pressurization control, this analysis was conducted by using pre- and post-sealing leakage levels to calculate the flows associated with different levels of pressurization, and then using Heating and Cooling Degree Days to calculate the thermal impacts associated with those OA flowrates. The results of those simulations are shown in Table 11 and Table 12.

Table 11: Building pressurization for leaky and sealed building with various outdoor air flow rates

Outdoor Air Flow [cfm(cfm/f²)]	Building Pressurization	
	Leaky (1.8 cfm/ft² envelope area)	Tight (0.25 cfm/ft² envelope area)
582 (0.1) min. vent rate	0.2 Pa	4.7 Pa
1100 (0.2)	0.6 Pa	12.6 Pa
2750 (0.5)	2.5 Pa	51.6 Pa
5500 (1)	7.2 Pa	149.9 Pa

Table 12: Additional annual cooling and heating energy use associated with increased outdoor air flow to maintain pressurization (based upon 785 cfm being required to maintain 7.5 Pa in tight building to avoid all infiltration)

	Leaky-Building Outdoor air flow [cfm(cfm/f²)]	Additional Annual Cooling Energy Use [kWh]	Additional Annual Heating Energy Use [therms]	Additional Annual Energy Cost	Simple Payback [years] Associated with Tightening and Maintaining 7.5 Pa (785 cfm)	
					Tenant Changeover	Major Renovation
Fort Benning	1100 (0.2)	969	105	$ 208	Complicated Vent/Inf. Interactions	
	2750 (0.5)	6044	653	$ 1,296	5.0	2.5
	5500 (1)	14502	1569	$ 3,111	2.1	1.0
Fort Hood	1100 (0.2)	1256	80	$ 172	Complicated Vent/Inf. Interactions	
	2750 (0.5)	7832	496	$ 1,069	6.1	3.0
	5500 (1)	18792	1190	$ 2,566	2.5	1.3

Grand Forks	1100 (0.2)	237	441	$ 373	Complicated Vent/Inf. Interactions	
	2750 (0.5)	1475	2755	$ 2,325	2.8	1.4
	5500 (1)	3539	6612	$ 5,579	1.2	0.6
Travis	1100 (0.2)	544	161	$ 237	Complicated Vent/Inf. Interactions	
	2750 (0.5)	3393	1006	$ 1,479	4.4	2.2
	5500 (1)	8140	2413	$ 3,547	1.8	0.9

The analysis in Table 12 calculates the simple payback for tightening buildings that are intended to meet a pressurization target. This simple payback analysis does not include a discount rate to account for the time-value of money and the results are based on an air conditioning coefficient of performance of 3.0 and an 80% efficient furnace for heating.

It was calculated that 785 cfm of outdoor air is required to pressurize the modeled building that meets the USACE leakage target to 7.5 Pa. The leaky building does not reach 7.5 Pa until 5,650 cfm of outdoor air which would likely be close to the maximum amount of airflow the HVAC systems would be capable of supplying. For this analysis it is assumed that the pressurization achieved by providing additional outdoor air to the leaky building eliminates infiltration when the systems are running. For the case of 1,100 cfm the building would only achieve marginal pressurization of 0.6 Pa which would have an impact on infiltration but certainly not eliminate it, and therefore the simple payback was not calculated for 1,100 cfm of outdoor air. There would likely be some infiltration in the building with 2,750 cfm of outdoor air but it was assumed to be eliminated which means the payback numbers are slightly elevated.

From the annual energy cost savings in Table 12 it is clear that cost effectiveness in all climates is achieved within less than five years for both tenant changeover and major renovation installations if we assume an outdoor air flowrate of 2,750 cfm or above in leaky buildings.

9.0 IMPLEMENTATION ISSUES AND LESSONS LEARNED

This project demonstrated that the aerosol sealing process has significant potential in addressing air leakage in existing buildings. The technology was successful deployed in many different building types, sizes, and conditions, as well as in various climate zones. While the technology showed some great success, there were also many lessons learned along the way.

The most significant challenge that was met during the demonstrations was the presence of significant leakage that was too large for the aerosol to address. This leakage was discovered at the roof-to-wall connection which is a common location for building air leakage since it attaches to continuous air barrier sections. The aerosol sealing process is still advantageous in this situation even though it does require a supplemental manual sealing effort. The manual sealing work performed for this project included adding ridged foam insulation and spray foam to seal the large leak and allow the building to be pressurized. Since the aerosol process was going to be employed, the manual sealing work did not require significant attention to detail allowing the manual sealing to be more efficient. For example, gaps in materials used for blocking the leak did not need to be taped or caulked significantly reducing the detail that is generally required for proper sealing.

Future aerosol sealing installations in commercial buildings should assess the roof-to-wall connection to determine if manual sealing work is required.

Another issue that came up during the demonstrations arose from the fact that most people are not familiar with the aerosol sealing process which led to questions about the safety of its application. It was discovered during this project that it was necessary to engage ESOH staff at each installation very early on in the project to avoid delays in executing the sealing work. ESOH staff at one base was questioning whether the material being applied could potentially have an environmental impact that would effect the process for proper disposal of the building. The demonstration site in this case was slated to be demolished but the concern was whether the material would require a specific disposal method after demolition (like an asbestos abatement process). After providing the safety data sheet and explaining that the amount of material applied to the building is really very small the ESOH staff were satisfied and allowed the demonstration to move forward. For subsequent demonstrations the project team reached out to ESOH to answer any questions they had.

10.0 REFERENCES

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APPENDIX A: POINTS OF CONTACT

The following is the list of key players for the demonstrations.

Point of Contact	Organization	Phone & E-mail	Role in Project
Mark Modera	UC Davis	(530) 754-7671 mpmodera@ucdavis.edu	PI
Curtis Harrington	UC Davis	(530) 754-7670 csharrington@ucdavis.edu	Project Manager
Donna Arcidiacono	Thermal Moisture Imaging (TMI)	(215) 355-6141 donna@tmiairbarriertesting.com	Sub-Contractor
John Arcidiacono	Thermal Moisture Imaging (TMI)	(215) 355-6141 jarch362@comcast.net	Sub-Contractor
Michael Perri	NAVFAC – Public Works	215-897-3681 Michael.a.perri@navy.mil	Demonstration POC
Jeromy Range	USMC – Energy Manager	540-446-3086 Jeromy.range.@usmc.mil	Demonstration POC
Lynda Pfau	USACE - Directorate of Public Works	910-396-3597 Lynda.s.pfau.ctr.mail.mil	Demonstraiton POC

APPENDIX B: ESOH TESTING AND SURVEY

DEPARTMENT OF THE ARMY
WOMACK ARMY MEDICAL CENTER
2817 REILLY ROAD
FORT BRAGG NC. 28310

MCXC-DPM-IHS

18 September 2017

MEMORANDUM FOR IMCOM, Directorate of Public Work, (IMBG-PWE-C, Mr. Gary Cullen, Environmental Engineer), Fort Bragg, NC. 28310

SUBJECT: Buildings A-6372 and A-5436 Demonstration Project for Energy Conservation

1. References:

a. Occupational Safety and Health Administration (OSHA), Title 29 Codes of Federal Regulations (CFR), Part 1910.1000, air contaminants.

b. American Conference of Governmental Industrial Hygienists (ACGIH), TLVs and BEIs, Threshold Limit Values & Biological Exposure Indices.

2. General/Purpose: Air samples were taken in buildings A-6372 and A-5436 for the following materials: silica and hydrocarbons, which are ingredients used in an aerosol sealing process.

3. Findings/Deficiencies: The hydrocarbons and silica sample results for both buildings were below the datable Limit of Quantitation (LOQ) for the analytical method.

4. Questions pertaining to this report may be addressed to Mr. Louis DeLaine, Industrial Hygienist at 910-643-6242 or Ms. Damita Y. Reed, Chief, Industrial Hygiene Service, Department of Preventive Medicine, Womack Army Medical Center at 910-396-7595.

Julie E. Lee

JULIE E. LEE
LTC, AN
Deputy Chief, Dept. of Preventive Medicine

DAMITA Y. REED
Chief, Industrial Hygiene Service

TMI® Air Barrier Testing
709 Easton Rd Suite 2A
Willow Grove PA 19090

5 July 2017

Mr. Jeromy Range, Energy Manager
Marine Corp Base Quantico Quantico,
Virginia

RE: Automated Aerosol Building Envelope Sealing Process Environmental Safety and Occupational Health Office Comments Health and Safety Concerns, Survey, and Request for Feedback

Dear Jeromy

As you know, the Department of Defense granted funding to demonstrate an Automated Method of Building Envelope Sealing under its ESTCP program.

Successful demonstrations of this technology were conducted on MCB Quantico at the Ashurst Elementry School Addition classrooms and common area, and at Building 2177, with substantial air leakage reductions and resultant energy savings achieved.

DoD has specifically requested feedback from the Environmental Safety and Occupational Health Office at each DoD demonstration site, to assess any health and safety concerns with respect to the aerosol sealing method.

Since you have been our point of contact and we have not directly interfaced with the EHOS offices, I attached an outline of the process below followed by some general survey questions.

We respectfully request you interface with the appropriate individual in the EHOS office and solicit their comments. Please feel free to call with questions or to add your thoughts; your comments and suggestions are most welcome.

We are grateful to you and to MCB Quantico for supporting the ESTCP demonstrations. We appreciate your cooperation in assisting

Please feel free to contact us with questions.

John Arcidiacono

ESTCP PROJECT #E201511

Automated Aerosol Sealing of Building Envelopes Process Environmental Safety and Occupational Health Office Comments Health and Safety Concerns, Survey, and Request for Feedback

The Department of Defense funded to demonstrations of Automated Method of Building Envelope Sealing under its ESTCP program. DoD has specifically requested feedback from the Environmental Safety and Occupational Health Office at each DoD demonstration site, to assess any health and safety concerns with respect to the aerosol sealing method.

Below is an overview of the process, information on the sealant, and a brief feedback survey.

THE PROCESS:

- We measure the buildings air leakage using the US Army Core of Engineers (USACE) test protocol and the record those results.
- We set up spray nozzles in the area to be sealed.
- We dilute the sealant with 150% water.
- We pump air into the building using ordinary blower door test fans.
- With the building pressurized, we spray diluted sealant through the nozzles, creating a light fog of suspended watery sealant particles in the air in the building.
- The pressurized air carries the fog to the leak locations (cracks).
- The pressurized air accelerates and changes direction as it escapes through the cracks.
- The sealant particles in the fog are heavier than the air and can't change direction as quickly as the air they are suspended in.
- When the air changers direction as it rushes through the cracks, a portion of the suspended particles are slung into the walls of the crack, much like insects in the air are slung into the windshield of a fast moving car.
- The sealant particles stick to the walls of the cracks and each other and accumulate.
- Over time the cracks clog with the sealant particles, with the smaller cracks sealing first.
- The volume of air pumped into the building is measured and automatically reduced as the cracks clog and become sealed.
- At the end of the sealing operation exterior doors are opened and all of the fog is flushed out of the building envelope.
- We measure the building air leakage using the USACE protocol and recorded the results.

Typical air leakage reduction is between 50% and 80%.

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T 215.355.6141 **F** 215.355.0644
Regional: 10411 Motor City Drive, Suite 750, Bethesda, MD 20817 **T 443-228-5970**

THERMAL MOISTURE IMAGING™

THE SEALANT:

The sealant is a commercially available water based acrylic that has been used as an air and water barrier on new construction for more than 15 years. It is listed by the Air Barrier Association of America as an ABAA Evaluated Material and is commonly used on new DoD buildings. It is low VOC and Green Guard Gold certified.

This air barrier material is normally applied to building walls via spray gun (as opposed to pressure propelled aerosol in the ESTCP demonstrations). The fog created by aerosolizing the acrylic smells much like spray applied acrylic paint. The sealant used for the aerosol technology is dilute with 150% water. A copy of the sealant MSD is attached. A copy of the MSD for acrylic paint is also attached for comparison.

Particle Deposition & Surface Protection:

The sealant particles that collect at the leak locations form a gray rubbery texture with good elasticity, (a desired trait where building components might move due to vibration, expansion/ contraction, and pressure variations due to weather events and use of the building, etc).

The particles in the fog within the building slowly precipitate out and land on horizontal surfaces, leaving a fine gray film that may retain slight tackiness. At the demonstrations, surfaces that were intended to be reused were protected with plastic sheeting. Unfinished surfaces such as warehouse floors, or carpets intended to be replaced were not covered. Fog that that leaks through the envelope cracks to the outdoors during the sealing process quickly dissipate and generally are not traceable.

Sealant Quantity:

The quantity of sealant used varies with the size of the envelope being treated and the size of the individual leaks. Most of the demonstrations were performed on buildings between 2000 and 8000 square feet and used between 10 and 30 gallons of sealant. These quantities are not radically different from the quantities of acrylic paint that might be used on similar sized buildings.

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ESTCP PROJECT # E201511

Automated Aerosol Sealing of Building Envelopes

SURVEY QUESTIONS:

DoD has indicated interest in using this method on it's facilities in the future and requires ESOH office comment. So that we may comply, kindly circle the applicable response and include comments if applicable:

Given the information provided above:

1. Does your ESOH office have any concerns with the overall process?

a. We would have no environmental safety or occupational health concerns and see no problem implementing this process. ✔

b. We are concerned over environmental safety or occupational health in this method and would not want to implement this process for the reasons stated below:

c. We would need additional information requested below before making a decision:

2. What details would your ESOH office need to know before authorizing installation of aerosol-applied building envelope seals?

a. We would not need further detail before authorizing installation of aerosol applied building envelope sealing operation. ✔

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b. We would need the following details:

3. What concerns would your ESOH office over the materials used in the sealing process?

a. We have no concerns. ✔

b. We have the following concerns:

4. What concerns might your ESOH have regarding outside installers i.e. use of appropriate personal protection equipment (PPE):

a. We have no concerns as long as the PPE called out in noted in the manufacturers installation instructions are followed. ✔

b. We have the following concerns:

5. What concerns might your ESOH have regarding occupancy of the building after the sealing treatment:

a. We have no concerns. ✔

b. We have the following concerns:

10.1 DOES USE OF THE PRODUCT RESTRICT ANY OCCUPANCY CLASSIFICATIONS OR FACILITY USE (I.E. SCHOOLS, MEDICAL FACILITIES, ETC