ESTCP
Cost and Performance Report

(EW-201511)

Automated Aerosol-Sealing of Building Envelopes

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ENVIRONMENTAL SECURITY
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ACRONYMS AND ABBREVIATIONS

#	number
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
DoE	Department of Energy
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
IAQ	Indoor Air Quality
IECC	International Energy Conservation Code
in^2	square inch
MCB	Marine Corp Base
NIST	National Institute of Standards & Technology
NSA	Naval Support Activity
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

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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 Depot, Parris Island

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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 several demonstrations on various building types and in multiple climates to show the ability of 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 several 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. 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 cfmat 75 Pa was sealed over the sixteen demonstrations cutting the air leakage of the buildings in half. Figure 1 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.

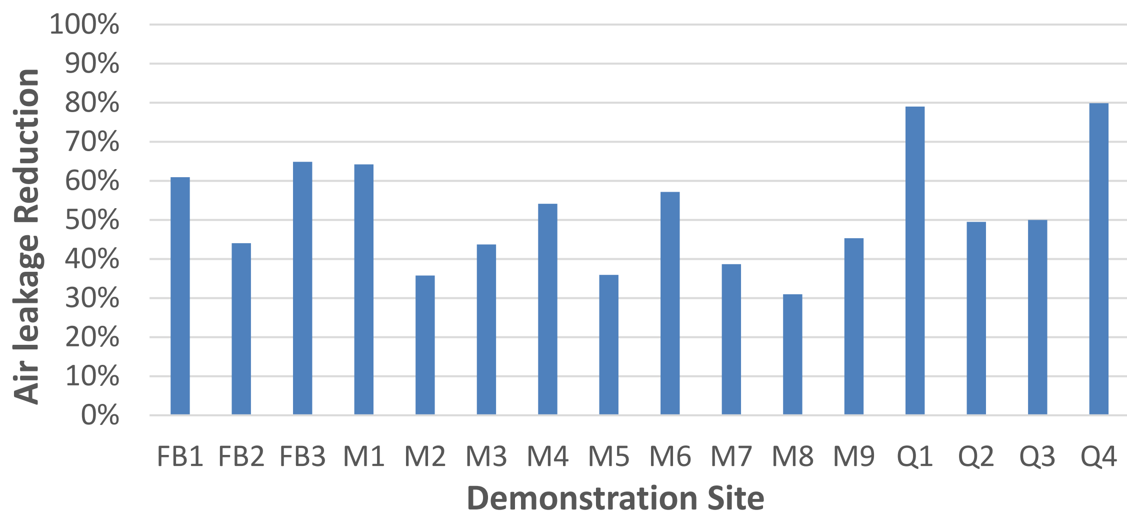

Figure 1. Percent Air Leakage Reduction for All Demonstrations

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 (equivalent 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 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.

1.0 INTRODUCTION

Department of Defense (DoD) facilities consumed 0.2 Quadrillion British thermal units (Btu) 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.

1.1 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.

1.2 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. Prior work has demonstrated excellent results showing the ability to seal 80% of the building leakage in less than two hours. 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.

1.3 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.

1.3.1 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/ft^2. 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.

1.3.2 ASHRAE

American Society of Heating, Refrigerating, and Air-Conditioning Engineers (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/ft^2 of envelope area. Many states have adopted or are guided by the ASHRAE standard 62.2 for their low-rise ventilation code.

1.3.3 IECC

The Department of Energy (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 Air Changes per Hour at 50 pascal (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.

2.0 TECHNOLOGY DESCRIPTION

2.1 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 systems 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, meaning 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.

The aerosol sealing technology was developed over several years by UC Davis primarily through research grants with the DoE 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 Environmental Security Technology Certification Program (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.

2.2 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.

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.

3.0 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 (GHG) reduction as a result of lower heating and cooling requirements. 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[1] require >16 person-hours per 1,000 sq. ft.
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

[1] There are some savings as you go to larger buildings because of the fixed cost associate with setting up and getting equipment and personnel to the site.

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4.0 FACILITY/SITE DESCRIPTIONS

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 between 2,000 and 22,000 square feet. The demonstrations included both residential and commercial buildings, and all buildings were temporarily unoccupied at the time of sealing.

4.1 FACILITY/SITE LOCATIONS, 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.

The condition of the buildings varied from very poor and slated for demolition to building in good shape that were awaiting a new tenant. There was a mix of attic designs with both drop ceilings and exposed roof decks. There were also building with slab-on-grade foundation as well as buildings with subfloors. The majority of buildings had lanolium or concrete floors which reduced the effort required for prepping the buildings.

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5.0 TEST DESIGN

This project consisted of sixteen demonstrations of the aerosol envelope sealing technology on three 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.

5.1 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 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 will measure 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 closely monitored as well as the cost for materials to develop the cost estimate.

Each test included the following phases: pre-test 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.

5.2 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 used to collect the leakage data for each building.

5.3 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 2): 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 2. Photo of Aerosol Sealing Equipment Setup

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.

5.4 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 3 presents the pre and post air leakage measured in each of the demonstrations and Figure 4 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.

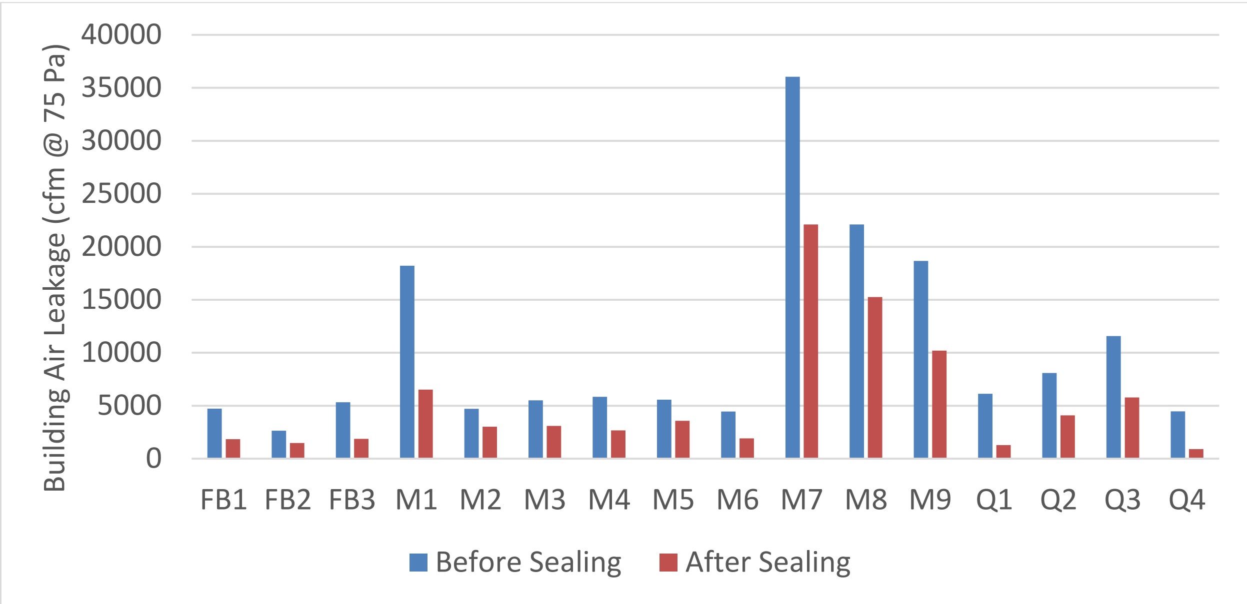

Figure 3. Pre and Post Air Leakage Test Results for All Demonstrations

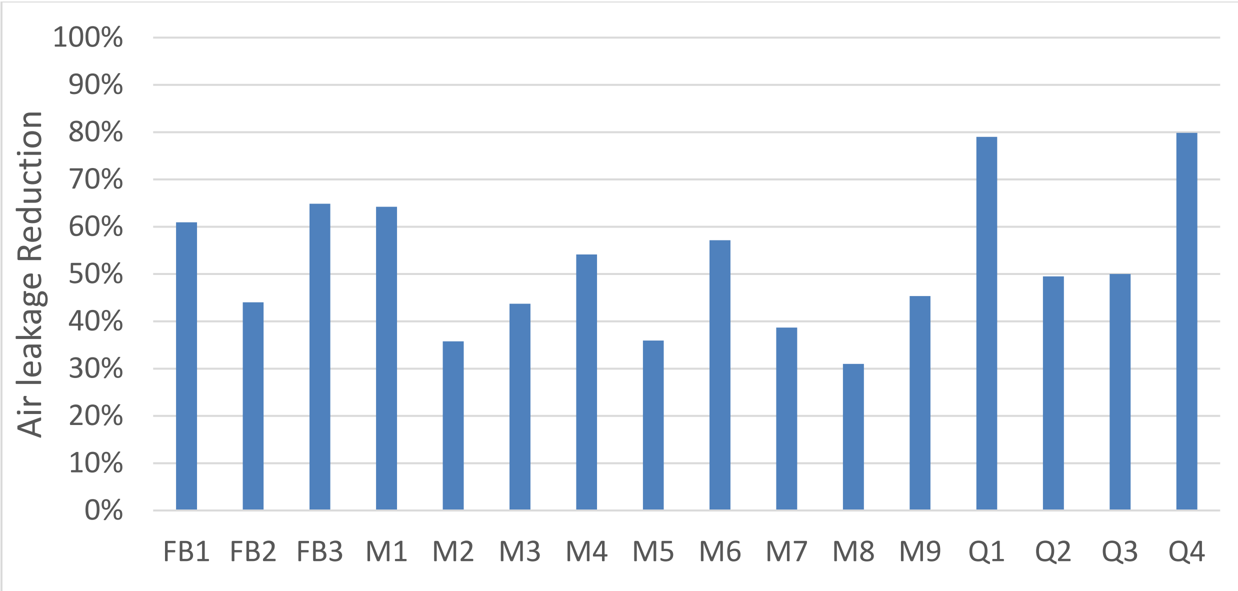

Figure 4. Percent Air Leakage Reduction for All Demonstrations

5.4.1 Example Sealing Demonstrations

One demonstration that took place at Quantico was performed 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 5). The prep work required about 16 person-hours or about one day for a two-person crew.

Figure 5. 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 6 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 demonstration highlights the overall capability of the aerosol sealing approach by showing a 1950s era building getting sealed to the standard outlined for all new military installations in only a couple days of work.

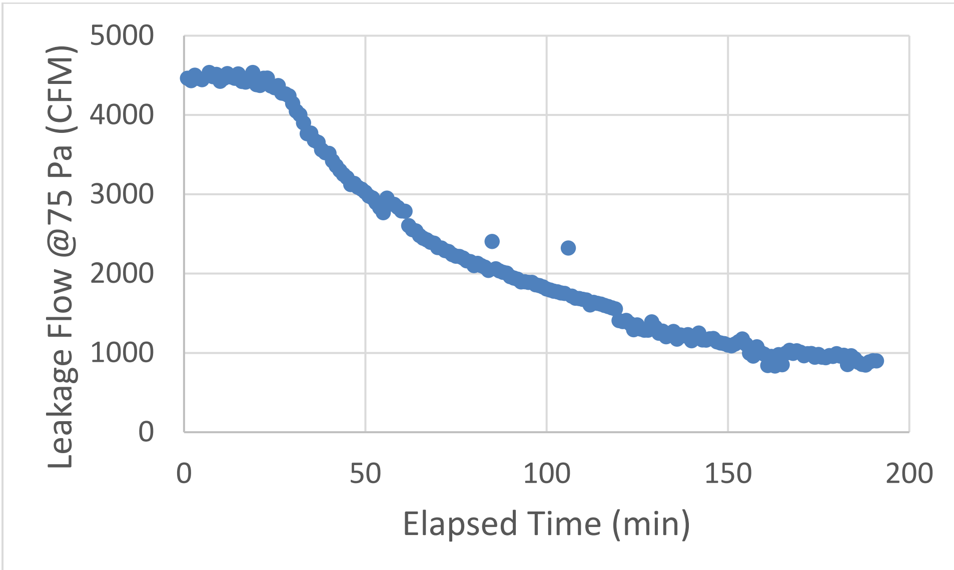

Figure 6. Sealing Profile for Building 2177 at Quantico Marine Corp Base (MCB)

Another sealing demonstrations at Naval Support Activity (NSA) Mechanicsburg in Pennsylvania 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 7), 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 7. 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 8 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.

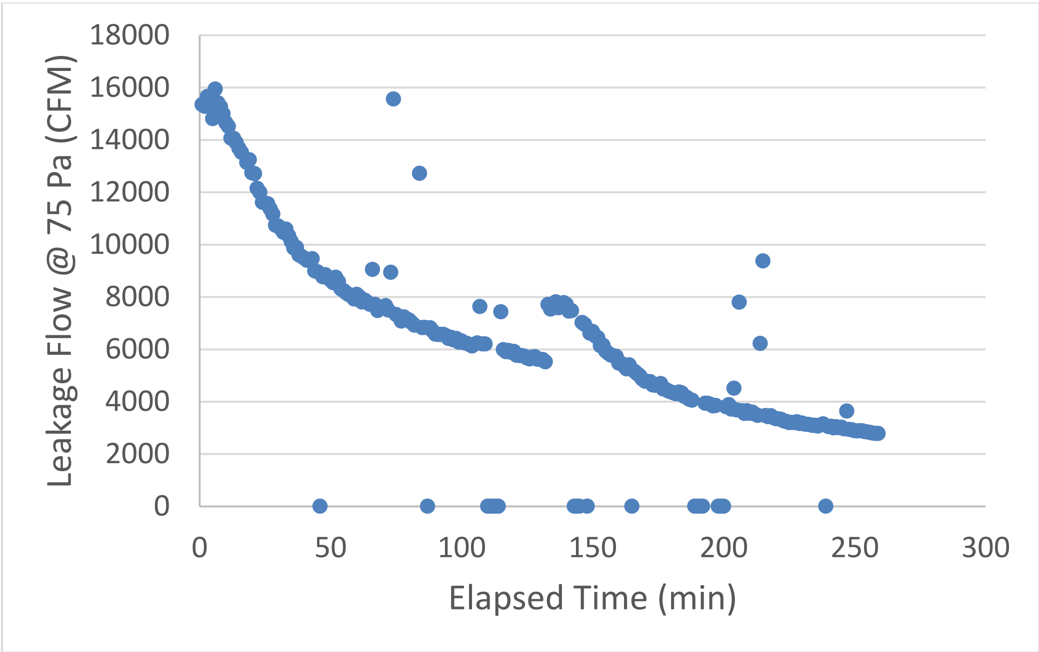

Figure 8. Sealing Profile Showing Both Sealing Events for Building M/608A at NSA Mechanicsburg

6.0 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.

6.1 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 2. 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%

6.2 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.

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 (equivalent 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. 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 0.067 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.

6.3 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 Heating, Ventilation, and Air Conditioning (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.

6.3.1 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)

6.3.2 Modeling Results

The results presented here focus on the HVAC energy consumption of the models simulated in each climate zone. Figure 9 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 10 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.

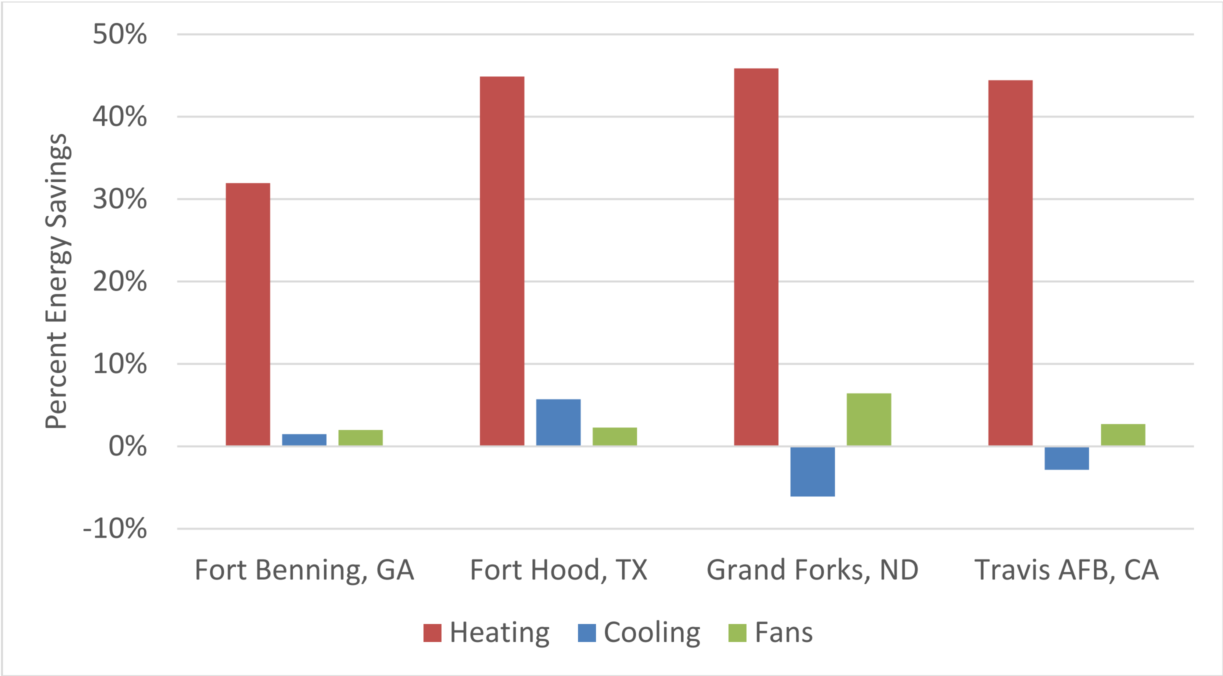

Figure 9. Modeled Percent Energy Savings for Heating, Cooling, and Fan Equipment Due to Air Sealing

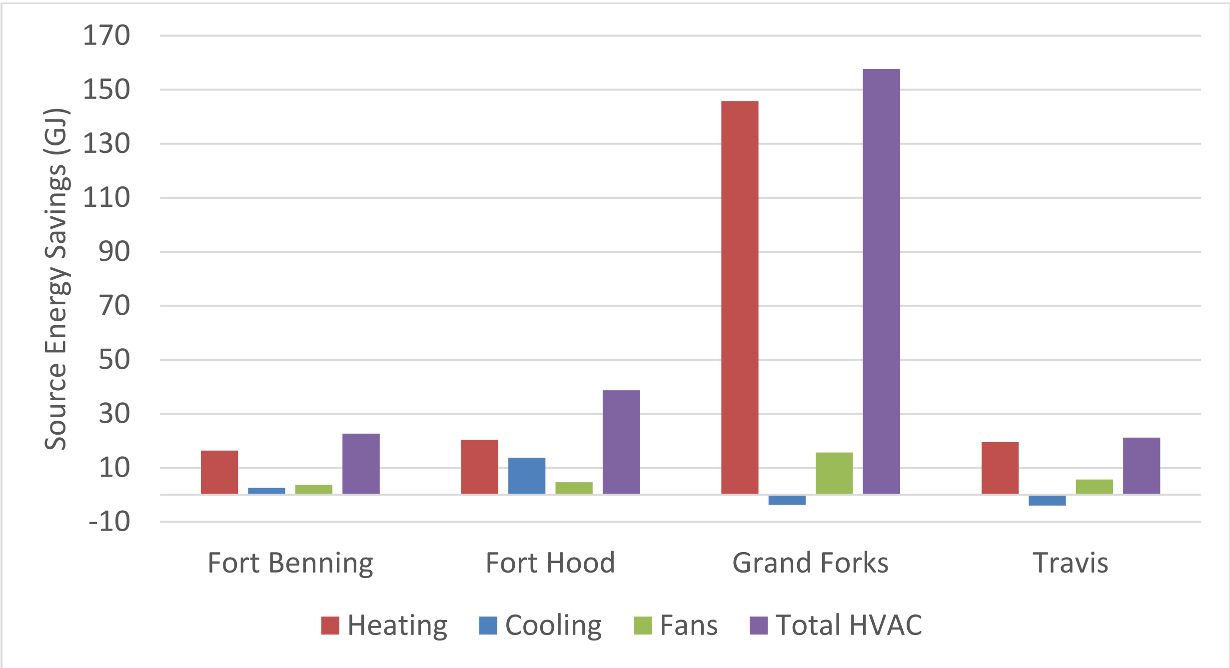

Figure 10. Modeled Source Energy Savings for Heating, Cooling, and Fan Equipment Due to Air Sealing

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.

6.4 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, meaning 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 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.

Finally, feedback was collected from installations staff regarding the safety protocols for the process. The biggest issue that was brought up was that if respirators 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.

6.5 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 11). 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 11shows 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 11. Photo Showing Floor Prepped at Ashurst Elementary at MCB Quantico (left), and Floor Not Prepped at Building 608A at NSA Mechanicsburg (right)

7.0 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.

7.1 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)

7.2 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 3.

The cost model in Table 3 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 3 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 3. 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 + $0.5/ft^2$

7.3 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 USACE 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 4 [6,7]. These EnergyPlus simulations were conducted, the results of which are presented in Table 5. In addition, Table 6 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 4. 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 5. 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 6. 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

Period	Total lifecycle savings		Life Cycle Energy savings		SIR		CO_2 savings
	Tenant Change	Major Renovation			Tenant Change	Major Renovation	
	$	$	kWh	Therm	-	-	kg
Fort Benning, Georgia							
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							
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							
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							
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 7 and Table 8.

Table 7. Building Pressurization for Leaky and Sealed Building with Various Outdoor Air Flow Rates

Outdoor Air Flow [cfm(cfm/ft^2)]	Building Pressurization	
	Leaky (1.8 cfm/ft^2 envelope area)	Tight (0.25 cfm/ft^2 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 8. 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/ft^2)]	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 8 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 8, 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.

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8.0 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 questioned whether the material being applied could potentially have an environmental impact that would affect 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.

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