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# Recent Applications of Aerosol Sealing in Buildings

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## Abstract

This paper describes two recent applications of aerosol sealing techniques in buildings for improving indoor air quality and reducing energy required for heating, cooling, and ventilation. One application applies a commercially-available duct sealing technology, which has typically been used in single-family applications, to large-building exhaust systems. The initial leakage rates, percent leakage sealed, and issues encountered are presented for several large buildings. The reasons for having this leakage sealed are presented, as are some of the techniques applied when conducting this type of sealing. The average duct leakage for these buildings was 28% of fan flow and the aerosol process sealed over 90% of that leakage. The second application is the use of aerosol sealing techniques for building envelope leaks. The process is similar to that used for sealing leaks in ducts; however it does not depend on injection of the sealant into a carrier flow to transport the sealant to the leaks, and therefore has to address the likelihood of particles settling to the ground, as well as the possibility of particles depositing on vertical surfaces. Laboratory tests investigating the impacts of pressure and particle size on the sealing process are described, as are the results of selected field tests showing how well the process performed when applied at two different stages of new multifamily construction. These tests suggest that the process should be able to achieve better levels of air tightness as compared to manual sealing methods, while including the added benefit of automated air-tightness verification.

**Key words:** aerosol, air-tightness, duct, envelope, sealing.

## 1. Introduction

Heating, cooling and ventilation can account for 50 percent of total building energy use. A significant fraction of this energy use is wasted due to unintended leakage between conditioned and unconditioned spaces. This includes leaks in ducts that are routed through shafts and crawl spaces, as well as leaks in building envelopes to outside or to attics. In addition to the increased conditioning-energy use caused by unintended leaks, leakage in exhaust ventilation systems result in increased fan power requirements that are exacerbated by the fact that the fan power scales with the cube of the increase in volume flow rate.

Over the past 15 years, the subject of duct leakage in buildings other than single-family residences has received considerable attention by various researchers (Cummings et al, 1996; Delp et al, 1998; Delp et al, 1998B; Franconi et al, 1998). This work has included characterizing the stock of duct systems in large commercial buildings (Modera et al., 1999), characterizing duct leakage levels and efficiency metrics for commercial-building thermal distribution systems (Diamond et al., 2003), field testing the impact of supply duct sealing in an office building (Diamond et al., 2003) and a light commercial building (Sherman et al., 2002), as well as the development and application of an aerosol-based sealing technology applicable to large commercial buildings (Diamond et al., 2003).

Duct-system research at Lawrence Berkeley National Laboratory (LBNL) resulted in the development of a technology for sealing duct leaks from the inside by Carrie and Modera (Carrie and Modera, 1998; Modera et al., 1996). This technology seals leaks in ductwork from the inside by pressurizing the duct system with a fog of atomized sealant particles. By temporarily blocking all the intentional exits from the duct system (as well as any coils or fans) the fog is forced to the leaks. The acceleration of the air through the leaks causes the sealant particles to leave the air stream and deposit on the leak edges. By the right choice of particle size, duct flow rate and duct pressure, the particles remain suspended as they travel through the duct system, and thus only a very small fraction of the particles deposit on the duct walls.

The aerosol duct sealing technology was initially applied to single-family residences, becoming commercially available for that market in 1999. The first commercial applications of the technology in large buildings started in 2003 with the introduction of a new atomization technology that significantly increased sealing rates, and allowed the sealant to be atomized inside the ductwork instead of externally.

A similar aerosol sealing process was recently applied to building envelopes, starting in the laboratory and moving into full-scale field testing. Residential building shells are often leaky, causing unintended flows between conditioned and unconditioned spaces that result in additional loads for the heating and air conditioning equipment. Sherman indicates that houses built in the 1990's can have as much as 1160 $cm^2$ of leakage area for a 140 $m^2$ home (Sherman and Dickerhoff, 1994). Significant efforts have been made to reduce the leaks in building shells through improved new-construction practices, but the problem remains one of excess labour costs, constant vigilance and quality control issues. Other research has estimated that reducing envelope leakage to reasonable levels can result in a 30 percent reduction in heating and cooling energy use (Sherman and Matson, 1997; Emmerich et al, 2005). The objective of the aerosol envelope sealing research is to develop and demonstrate a remote aerosolized particle sealing process that simultaneously measures, finds, and seals leaks in a building envelope shell in a cost effective manner.

This paper presents two recent applications of aerosol sealing in buildings: 1) large-building applications of aerosol duct sealing, including field experiences and results related to sealing exhaust systems in large buildings, and 2) aerosol sealing of building envelopes including a sub-set of the laboratory test results, as well as selected field test results.

## 2. Sealing Duct Leakage in Large Buildings

### 2.1 Impetus for Sealing Duct Leakage

The impetus for duct sealing in large buildings can come from several different driving forces: 1) test and balance reports that indicate duct leakage and/or inadequate zone flows, 2) code-driven requirements for flows or pressures for new construction or renovation, 3) comfort and/or pressure control complaints, and sometimes 4) a desire to save energy. These sources are more or less listed by frequency of occurrence. In general, knowing whether the ducts in an existing large building are leaking is considerably more difficult and expensive than uncovering duct leakage in single-family residences. Test and balance reports provide a reasonably certain indication of leakage, however such measurements are generally too expensive to be performed solely to look for duct leakage. Some simplified techniques for quantifying duct leakage in specific applications have been developed, in particular for measuring leakage downstream of

*Table 1. Examples of buildings seeking exhaust duct sealing.*

| Building Type | Bldg. | Bldg. Age | Bldg. Size [$m^2$] | Bldg. Storeys | Location | Exhaust System |
|---|---|---|---|---|---|---|
| **Hotel** | 1 | 2007 | ~150,000 | 57 | Las Vegas, NV | Bathroom |
| | 2 | 2005 | >200,000 | 45 | Las Vegas, NV | Bathroom |
| | 3 | 2008 | >100,000 | 63 | Las Vegas, NV | Bathroom |
| **Condominium/Apartment/Dormitory** | | | | | | |
| Condominium | 4 | 1971 | ~70,000 | 40 | Boston, MA | Bath/Kitchen |
| Dormitory | 5 | 2003 | 4,600 | 6 | Columbus, OH | Bathroom |
| Apartments | 6 | 1979 | ~25,000 | 23 | Camden, NJ | Bath/Kitchen |
| Apartments | 7 | 1960s | N/A | 5 | Bordeaux France | Bathroom |
| **Large Office Bldg.** | 8 | 1958 | 300,000 | 59 | New York City | Toilet (one section) |
| **Hospital** | 9 | N/A | N/A | 6 | San Francisco, CA | General |
| | 10 | 2012 | 29,000 | 3 | Abu Dhabi, UAE | General |
| **Laboratory** | 11 | ~1965 | ~4,000 | 2 | Berkeley, CA | General |

VAV boxes (Modera, 2007), and for estimating leakage in modest-length bathroom exhaust shafts.

The buildings listed in Table 1 represent a modest subset of the large-building exhaust systems that have been sealed over the past several years. There were several different reasons why the building owners decided to have sealing performed. There were two reasons why the hotels needed duct sealing. One hotel (Building 1) was new construction with ducts that did not initially pass the exhaust-duct leakage criteria. The other two hotels (Building 2 and Building 3) needed to assure that the pressure-independent bathroom grilles being installed would have enough pressure to work properly.

The rationale for sealing leakage in exhaust shafts in apartment buildings (Buildings 4-7) included a desire to save energy, provide more uniform (temporal and spatial) ventilation, and in the case of Building 7, to produce the desired ventilation when switching the shafts from naturally driven to fan-driven flow. In other instances, the rationale has been to reduce overall exhaust ventilation rates (e.g. as allowed by code changes in New York City), without risking unreasonably low ventilation rates in some apartments, or under some weather conditions.

In the case of the toilet exhaust in the large office building (Building 8), the building manager wanted to address tenant complaints about odours in the restrooms. For the hospital (Building 9), flow measurements at the grilles indicated that the exhaust flow rates required for an occupancy permit were not being met. For the laboratory building (Building 11), there was a desire to save energy. In a laboratory building, as in a hospital, the HVAC systems are typically single-pass (i.e. 100% outdoor air), which means that any unnecessary exhaust needs to be made up with additional outdoor air that needs to be heated or cooled. In addition, significant fan power savings are made available in such a building by the fact that fan power scales with the cube of the volume flow rate in an exhaust system.

## 2.2 Duct Sealing Process in Large Buildings

In general, sealing ducts in large buildings (exhaust systems or otherwise) with aerosol injection is considerably more complicated than sealing ducts in single-family homes. For example, sealing exhaust shaft/duct leaks in a multi-family apartment building requires simultaneous access to all of the apartments being served by a specific shaft, which means that occupants must be informed in advance. In addition, in such an application, it is essentially impossible to completely vacate the building during injection, which means that extra care needs to be taken to prevent exposing the building occupants to the aerosolized sealant particles. This problem is easier to handle in a hotel, where the management can select the rooms to be left vacant. The standard of care is also elevated in a hospital situation, where vacancy is generally not an option, and neither is dispersion of aerosol particles.

Another issue in tall buildings is the stack effect created by the temperature differential between indoor and outdoor air. The stack effect both creates measurement issues (not being sure exactly where to measure the pressure difference between the ducts and their surroundings), and minimal or even negative pressure differentials across the duct walls (which can make the sealing process slow or even impossible). Both of these problems are reduced or eliminated by performing the sealing process at a larger pressure differential, thereby reducing the relative magnitude of the stack effect.

It should also be noted that there is a distinct advantage associated with sealing vertical ducts/shafts with an aerosol, namely that because the ducts are vertical, the issue of aerosol particles settling onto the bottom of the duct due to gravity essentially goes away. As long as the injection is performed from the top of the ductwork, gravity helps transport the particles to the furthest leaks, as opposed to robbing some particles along the way as in a horizontal duct system.

## 2.3 Duct Sealing Results Summary in Large Buildings

Some of the sealing data from the buildings identified in Table 1 are summarised in Table 2. The estimated average leak pressure provides a general idea of what pressure is seen across the leaks in the duct system during normal operation. The estimated fractional leakage is the fraction of air that either comes from or leaves by the way of leaks in the duct system.

The systems ranged in size from 7300 L/s up to 128000 L/s and the estimated average operating pressure ranged from 25 Pascal to 500 Pascal. In all cases, other than Building 9 that was not sealed, the sealing process reduced leakage in the duct system by more than 80% and in one case by as much as

*Table 2. Exhaust-system sealing results.*

| Building | Nominal Fan Flow [L/s] | Estimated Average Leak Pressure [Pa] | Effective Leakage Area [cm$^2$] | Estimated Fractional Leakage [%] | Fraction Sealed [%] |
|---|---|---|---|---|---|
| 1 | 35,000 (est.) | 100 | 3900 | 16% | 97% |
| 2 | 128,000 (est.) | 50 | 47,800 | 36% | 93% |
| 3 | 48,000 (est.) | 50 | 13,700 | 28% | 92% |
| 4 | 30,000 (est.) | 25 | 11,000 | 24% | 96% |
| 5 | 7,300 | 500 | 512 | 27% | 95% |
| 6 | 14,500 (est.) | 25 | 8190 | 36% | 81% |
| 7 | N/A | 80 | 58 | N/A | 89% |
| 8 | 20,400 (treated section) | 250 | 1630 | 20% (treated section) | 96% |
| 9 | N/A | N/A | N/A | N/A | 0% |
| 10 | 17,900 | 250 | 2340 | 34% | 85% (est.) |
| 11 | 10,400 | 150 | 1670 | 31% | 85% |

97%. In several cases the fractional leakage remaining after sealing took place was less than 1% of the fan flow.

In the case of Building 9, the sealing process was initiated, and was found not to provide any reduction in leakage. As there appeared to be no good reason for why it did not seal, a camera was dropped down the shaft to look for a gross leak in the system. As it turned out, the problem was an open access door to the duct, one that the long-term building operators claimed did not exist, until it was found with the camera and shown to them. In this case, the size of the opening for the access was estimated to be large enough to account for most of the measured leakage flow (~4000 cm$^2$), and remobilizing to seal the remaining leakage was deemed not to be cost effective.

Building 11 is a laboratory building that had some additional complications. These complications included access issues, such as rooms with biological or radiation hazards, and rooms that potentially had lasers in operation. This necessitated good communication with the individual investigators in the building, in this case through their trusted building manager. Another challenge encountered in this particular building was the fact that the entire exhaust system had to be sealed simultaneously. This process required a large, well-organized crew to assure no grilles were missed, and entailed blocking all 80 grilles which were spread over 4000 m$^2$. The missing block issue is particularly problematic in a large leaky system, as a missing block would change the total leakage sensed by the sealing system by only a few percent.

## 2.4 Large Office-Building Toilet-Exhaust Case Study

Building 8 was chosen to be presented in a bit more detail, as this application involved some previously unencountered issues. The application involved sealing the exhaust ductwork for a large Class-A office building in Manhattan (New York City). The results presented are only for one section of that sealing application, as the remaining data was not immediately accessible. The section reported on is a horizontal run in a mechanical floor of the building, combined with an “express” vertical duct run used to ventilate toilets at least 15 storeys below the mechanical floor. The nice part of this application was that most of the ductwork was vertical (as noted above, vertical sections are inherently easier to seal using the aerosol-based method because there is less concern about particles settling by gravity on the bottom duct surface); however, there was still a long horizontal section on the mechanical floor.

The two key issues associated with sealing a large duct system are: a) assuring that an adequate pressure differential can be produced across all the leaks in the system, and b) assuring that the velocity in the horizontal sections is high enough to keep the particles from settling out by gravity. In general, the minimum pressure differential across the leaks for sealing is 10 Pa, however minimum pressures of 25-50 Pa are desired, particularly for vertical sections in a tall building, where the stack effect can change that pressure differential significantly between the top and bottom of the vertical run. The pressure produced by the sealing equipment is a function of the maximum flow that it can provide and the duct-system leakage. The standard fan on the aerosol system can produce a maximum flow of roughly 300 L/s@25Pa, which translates to about 450 $cm^2$ of effective leakage area. As the leakage of the treated section of Building 8 had more than three times this leakage (Table 2), it was clear that at least four separate aerosol-system fans would be required.

The second constraint is maintaining adequate velocity to avoid gravitational settling. Gravitational settling occurs if there is insufficient mixing in the air stream (i.e. mild turbulence) to maintain particle suspension over the length of a horizontal duct section; however, a high turbulence intensity can result in coating of all the duct walls. For this paper we use a target velocity of 1 m/s for the beginning of the sealing process. The minimum aerosol fan capacity can be determined by the cross-sectional area of the ductwork and the 1 m/s target velocity. In this building the horizontal ductwork had a cross-sectional area of roughly 2 $m^2$, which means that we would needed roughly 2000 L/s, or seven aerosol-system fans to produce 1 m/s. As this was neither a practical nor efficient solution, we chose instead to employ a calibrated "blower-door" fan that can produce up to 4,000 L/s under free-air conditions. The manufacturer provided a special fan calibration for this high pressure application. In the end, a combination of one aerosol system fan and one blower-door fan (Figure 2) was employed, resulting in the sealing plot illustrated in Figure 1. Note that the breaks in the curve correspond to changing the injection point for different portions of the section being sealed.

Although the authors do not know of post-sealing testing of grille flows, the building manager indicated that the sealing addressed the original odour complaints.

## 3. Aerosol Envelope Sealing

### 3.1 Laboratory Test Apparatus

The Western Cooling Efficiency Center (WCEC) at UC Davis has been investigating another application

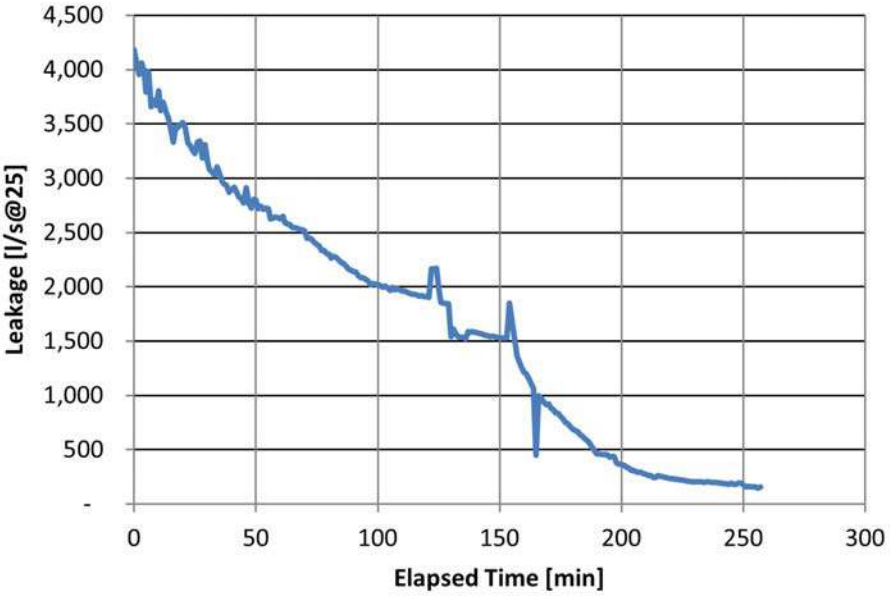


*Figure 1. Leakage versus elapsed aerosol injection time for upper section of office-building toilet exhaust that moves 20,400 l/s (Building 8 in Tables 1 and 2).*

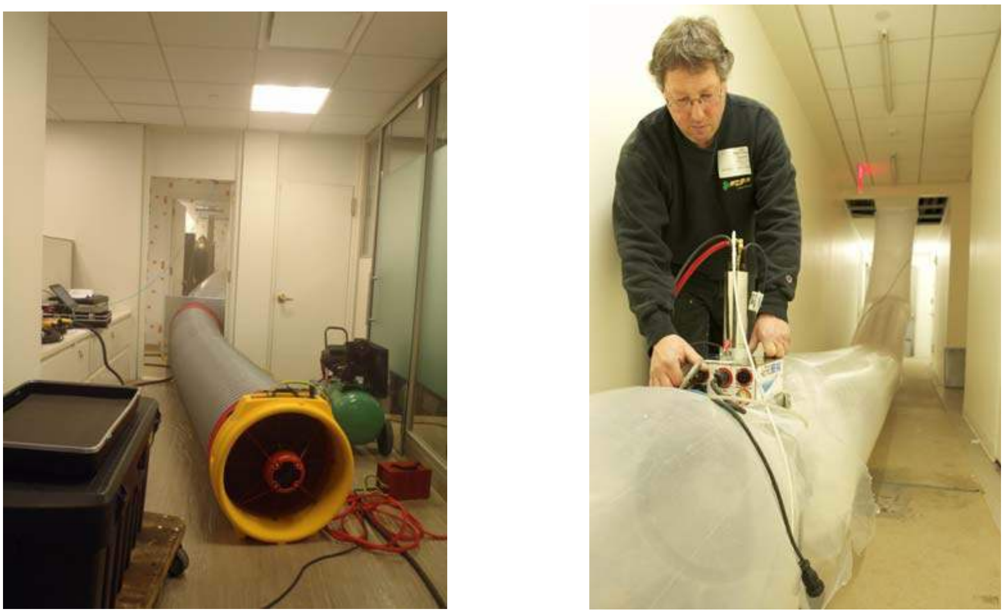


*Figure 2. Blower-door fan being applied in combination with the aerosol sealing system (Building 8 in Tables 1 and 2).*

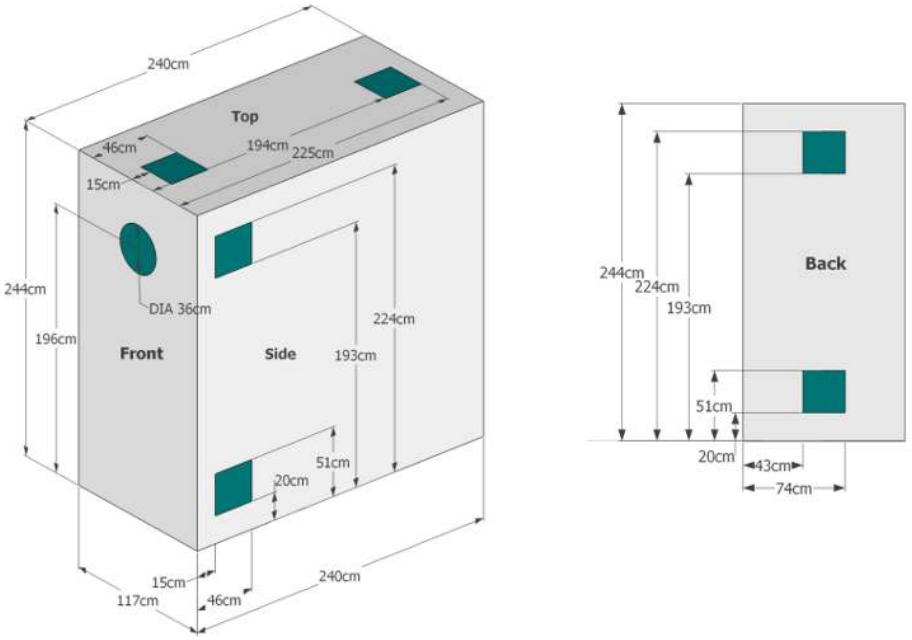


*Figure 3. Dimensioned views of the enclosure showing the various leak locations. Each leak panel, illustrated by the squares, contained six slot leaks, and the sealant was introduced through the injection hole illustrated by the circle on the front of the enclosure.*

of aerosol-sealing techniques which applies the process to building envelopes. Initial proof-of-concept testing of the technology was performed on a 2.4 m by 2.4 m by 1.2 m (8 ft x 8 ft x 4 ft) enclosure with leak panels distributed at various locations around the shell of the enclosure (Figure 2). The approximate size of each leak in a panel was 2.5 to 3 mm by 25 cm by 3 mm (H x W x D), and there were six leaks on each leak panel. The height of each leak was meant to be representative of a typical leak in a building shell, but the depth was much shorter than what is expected to be found in buildings. The total measured leakage for all the panels together is approximately 260 square centimetres of open leakage area. A 36 centimetre diameter hole was used as the injection site to introduce the sealant fog near the top of the enclosure (see Figure 3).

### 3.2 Laboratory Test Analysis Method

The performance of the aerosol sealing technology was evaluated using three primary metrics: 1) the time needed to seal the enclosure, 2) particle deposition inside the enclosure, and 3) the uniformity of sealant deposition at the leaks. These performance metrics were used to evaluate several independent parameters to understand their effects. The parameters that we believed to be important include the pressure inside the enclosure, the rate of sealant injection, and the size of the particles injected.

The commercialized aerosol-based duct sealing machine, although probably not appropriate for building applications, was used for our initial tests of sealing building shells with aerosols. It included instrumentation for measuring the air flow rate and the differential pressure between the enclosure with respect to the surrounding area. That facilitated continuous monitoring of leakage area during the sealing process. The leakage area was computed using Equation 1 and Equation 2.

$$Q = ELA_{ref} \cdot \sqrt{\frac{2 \cdot \Delta P_{ref}}{\rho}} \cdot \left( \frac{\Delta P}{\Delta P_{ref}} \right)^{n} \tag{1}$$

$$LA = \frac{ELA}{0.6} \tag{2}$$

where

$Q$ = measured airflow rate,

$ELA_{ref}$ = effective leakage area

$\Delta P$ = pressure measured across the leaks

$\Delta p_{ref}$ = a reference pressure (chosen to be 25 Pascals)

$\rho$ = air density

$n$ = flow exponent (typically 0.5 for an orifice)

$LA$ = leakage area

The $ELA_{ref}$ of a leak is the area of a sharp-edged orifice that at some reference pressure will produce the same flow as the leak at that pressure. It has been shown experimentally and theoretically that the $ELA$ of an orifice is related to the actual area by a factor of 0.6 (Batchelor, 1967).

A mass balance was used to determine where the sealant was ultimately deposited. We used a scale with a 0.001 gram resolution to measure the weight of various components before and after sealing to track the fraction of sealant that was lost due to settling or turbulent deposition onto surfaces. These components included: a sheet of plastic placed on the bottom of the test enclosure, the plastic tubing used to transport the sealant from the generation point to the enclosure, and plastic sheets placed on the walls and ceiling. In addition, the sealant deposited in each panel leak was determined by removing the sealant in and around the leak and then weighing the removed sealant. A comparison of the observed deposition for different panels and plastic sheets was used to evaluate the particle distribution inside the enclosure. Errors may have been introduced by: a) not completely removing all sealant from the panels, b) the sample sections of plastic used for measuring wall and ceiling deposition not being representative of the entire surface, and c) the use of the manufacturer's calibration for the sealant flow rates. Assuming the sealant pump calibration was reasonably accurate, the overall error in deposition at particular locations was estimated to be within ±2% of the total sealant mass injected.

We initially expected that the particle size produced by the commercialized aerosol-based duct sealing equipment would be too large to allow for sufficient particle suspension. This was not the case, as the leaks were more than sufficiently sealed in the initial laboratory tests, although it should be noted that the floor area of the test room was rather small (less than 3 $m^2$). Observations in the small-scale tests led to further research on the impact of reducing particle size. In addition to reducing particle size, oscillating fans could be used to assist in keeping the particles suspended and to make the indoor-air particle distribution more uniform in an actual application.

The performance of each test was evaluated using leakage versus time profiles, as well as analyses of sealant use efficiency quantified by the mass balance of sealant materials (i.e. fraction on floor, in leaks, on walls, and lost through leaks).

The independent variables investigated included:

- Average particle size (controlled by sealant dilution);
- Enclosure pressure control;
- Sealant injection rate.

The dependent variables that were used to quantify performance included:

- Sealing rate;
- Sealing uniformity (comparison of the amount of sealant deposited on panels in different locations);
- Sealant use efficiency (fraction that settles on the floor and other surfaces, versus deposited in leaks).

### 3.3 Laboratory Test Results

The envelope sealing tests all showed promising results, sealing the enclosure in as little as seven

*Table 3. Test protocol for each of the nine tests.*

| Test number | Box Pressure (Pa) | Sealant Injection Rate (ccm) | Sealant Dilution | Sealing Time Minutes |
|---|---|---|---|---|
| 1 | No pressure/flow control | 100 | No Dilution | 6.7 |
| 2 | 100 | 25 | No Dilution | 13.5 |
| 3 | No pressure/flow control | 25 | No Dilution | 17.3 |
| 4 | 50 | 25 | No Dilution | 12.6 |
| 5 | 100 | 25 | No Dilution | 15.9 |
| 6 | 50 | 25 | No Dilution | 15.2 |
| 7 | 100 | 25 | No Dilution | 15.3 |
| 8 | 50 | 25 | No Dilution | 14.8 |
| 9 | 100 | 25 | 1 part sealant/1 part water | 27.5 |

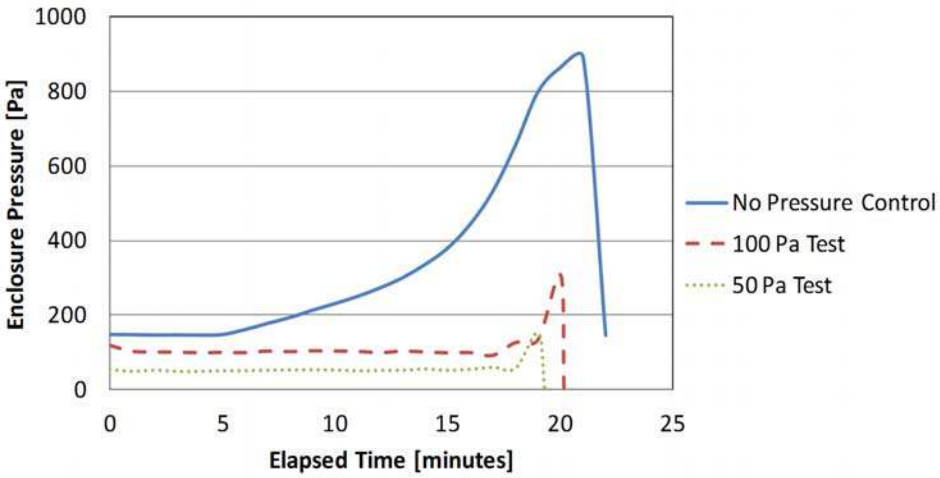


*Figure 4. Typical pressure profiles inside the enclosure during tests with no pressure control, and tests controlled at 100 Pa and 50 Pa.*

minutes. Tests were performed to study the impacts of the independent variables on the sealing parameters (Table 3).

The enclosure pressure differential was regulated by a calibrated fan that controlled the airflow delivered to the test enclosure. Three operating pressures were studied in the small-scale tests: 1) no pressure control (which effectively allows the existing duct sealing software to control the injection flow), 2) manual flow control to maintain 100 Pascal pressure differential, and 3) manual flow control to maintain 50 Pascal pressure differential. Due to the very low absolute leakage level achieved by injecting aerosol sealant, the pressure inside the enclosure became difficult to control as the flow approached the minimum achievable by the equipment (Figure 4).

Figure 5 shows the leakage profiles for each of the nine tests in the enclosure. All tests successfully sealed the enclosure to nearly zero leakage in less than 30 minutes. Note that, at the beginning of each test, the sealant lines were first purged of water before sealant reached the injection nozzle, causing a slight delay at the beginning of each test, which for 25 ccm tests was about 5 minutes and for 100 ccm test was about 2 minutes.

The leakage profiles show that the sealant injection rate had a significant impact on sealing time, whereas controlling the pressure inside the enclosure had a less significant impact. Tests performed at a 25 ccm injection rate at various pressures all sealed the enclosure in 13-17 minutes, whereas injecting sealant at 100 ccm sealed the enclosure in less than seven minutes. The results suggest that lower pressure increased sealing time though this result was not completely repeatable, and for this reason the differences in sealing time for tests 2 through 8 were deemed not significant. Reducing sealant particle size by diluting the sealant with water also significantly extended the sealing time. This was due to the reduced solid sealant injection rate associated with diluting the sealant without adjusting the pump flow rate. In the test with diluted sealant, the enclosure sealed in approximately 28 minutes (Figure 5).

The sealant deposition pattern provided a quick indication of the sealant deposition efficiency. Figure 6 shows the sealant deposition pattern observed during three different tests, a) a high-pressure test with 100 ccm sealant injection rate, b) a high-pressure test with 25 ccm sealant injection rate, and c) a test at 25 ccm sealant injection rate, but with the pressure differential controlled to maintain 50 Pa. The high-pressure test at 100 ccm produced the largest spread of sealant around the leak. The spread decreased when the sealant injection rate was reduced and when the pressure

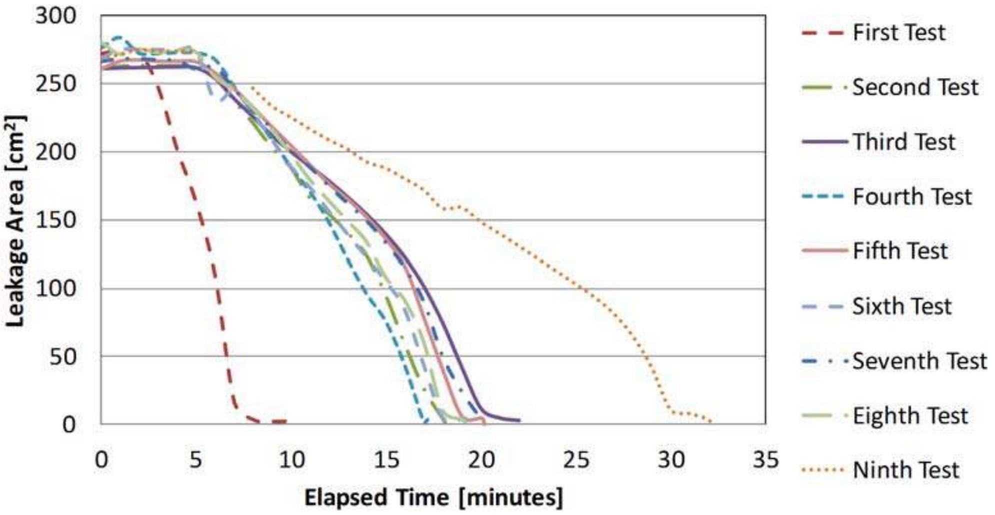
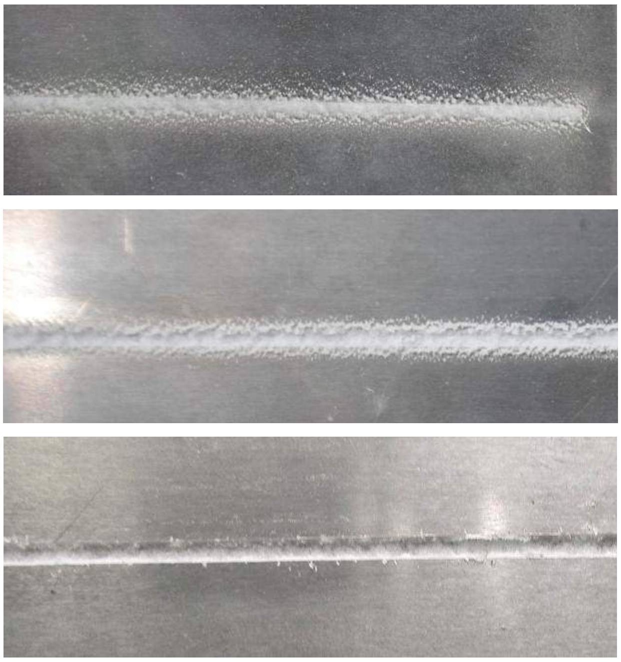


*Figure 5. Leakage profiles for each of the nine tests.*



Deposition at high pressure and
100 ccm injection rate

Deposition at high pressure and
25 ccm injection rate

Deposition at 50 Pa and
25 ccm injection rate

*Figure 6. Sealant deposit pattern on back low panel for tests 1, 3 and 4.*

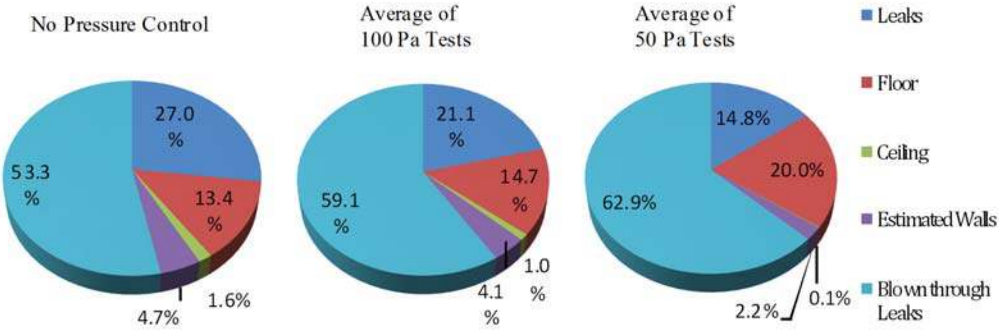


*Figure 7. Average sealant distribution for tests at various pressures and 25 ccm sealant injection rates.*

differential was maintained at 50 Pa. These results suggest that excess deposition is reduced, producing cleaner seals, when the sealant flow rate is reduced, and when the building pressure is reduced. We believe the former may be due to the size of the particles created by the nozzle used for these experiments, and that the latter is due to the lower velocities around the leaks at lower pressures. In terms of spatial uniformity in the lab tests, there was only a 1-2% variation in the mass of sealant deposited between any of the leak panels distributed around the enclosure at any given sealant flow. This suggests very good particle distribution and sealing uniformity for all of the lab tests.

The mass balance analysis allowed for accurate tracking of where the sealant was ultimately deposited. The sealant distributions in Figure 7 show how pressure control affected the sealing process. There is a clear trend, indicating that lower enclosure pressure leads to less sealant being deposited in and around the leaks, more sealant

*Figure 8. Photo of sealant atomization.*

*Figure 9. Multiple aerosol injection system developed by UC Davis.*

being deposited on the floor, less sealant being deposited on the walls and ceiling, and more sealant getting blown through the leaks. Although the majority of sealant injected was blown through the leaks, it is expected that the geometry of leaks in typical buildings will be different than the test enclosure. The longer flow path of typical leaks in buildings is expected to reduce the amount of sealant blown through and, therefore, improve the efficiency of sealant use. We expect that the typical building leaks sealed during this process would be at joints and seams of building enclosure assemblies which are much deeper than the 3 millimetre leaks tested in the lab enclosure.

### 3.4 Field Testing

Several full-scale tests of the aerosol-based sealing technology were carried out at the dry-wall phase of new construction in both single-family detached and multifamily homes, as well as one retrofit test performed on an empty existing home. The initial tests were performed using the existing aerosol duct sealing technology that was used for the laboratory experiments, while the latest application tested a new aerosol injection technology developed by UC Davis. The first full-scale tests demonstrated a lack of sealant transport to adjoining rooms, which required that the atomization nozzle be moved from room to room. The new aerosol injection system is capable of multiple injection points, allowing nozzles to be distributed throughout the building, both expediting the sealing process and eliminating the need to enter the building while applying the aerosol (Figures 8 and 9).

Figure 10 presents the sealing profile observed during two field tests of the aerosol envelope sealing process. These tests were performed on two identical apartments of a new multifamily construction project using the multipoint injection system with four injection points. The 85 m$^2$ apartments were built to LEED Silver standards and were sealed during different stages of the construction process to ultimately determine the most appropriate point to install the aerosol envelope sealing process. The test performed at the "pre-insulation" phase of construction allows the air barrier to be placed at the outside surface of the wall construction, whereas the test performed at the "after texture" phase of construction allows the air barrier to be placed on the inside surface of the wall construction.

Although the tests were performed on two very similar apartments, the initial leakage level differed widely between the two tests indicating that there is far more leakage present on the outer surface of typical multifamily wall construction. In both of these tests the process was stopped before the sealing was complete because of the lack of sufficient materials to complete the sealing and the limited time in which the sealing had to take place. Figure 10 shows that the sealing rate increases when more leakage is present and as the building begins to seal the sealing rate goes down. The test performed at pre-insulation reduced the envelope leakage by about 65% from an initial air change per hour at 50 Pascal (ACH50) of 19 to a final ACH50 of less than 8. The test performed after texture reduced the envelope leakage by about 50% from an initial ACH50 of 7 to a final ACH50 of less than 4.

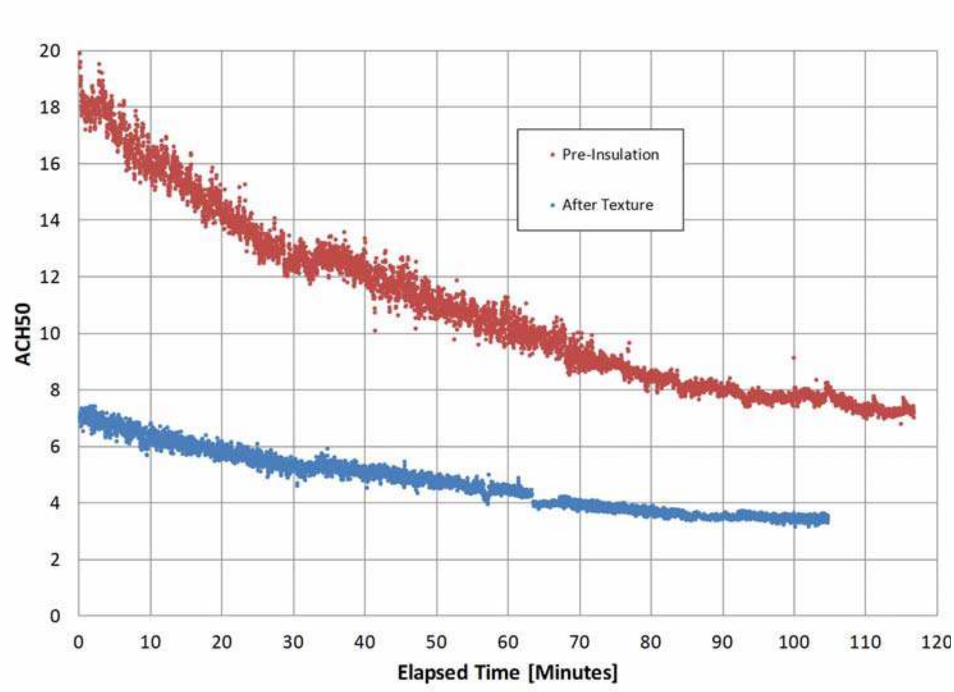


*Figure 10. Sealing profile observed during two installations of aerosol envelope sealing in new multifamily homes during different stages of construction; one before insulation was installed and another after drywall and texture.*

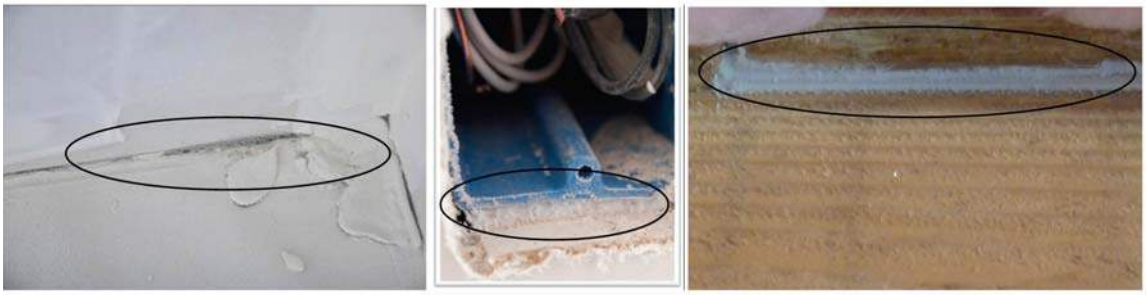


*Figure 11. Photographs of envelope leaks sealed during the field tests (sill plate, electrical box, and header).*

The field tests of the sealing process have shown that the method could seal at least 50% of the leakage observed prior to injection, and also indicated that only minor prepping of the floors and windows is necessary in new-construction applications. The tests also showed that particular care needs to be taken in existing homes, even if they are empty of contents at the time of sealing (e.g. protecting carpeted stairways from more than just particle settling). Figure 11 shows examples of leaks sealed during the field testing, including leaks at sill plates, electrical box, and header. Note that the location of the seal in new construction will depend upon when the sealing occurs during the construction process (e.g. before or after drywall). Also, if there are leaks in series (e.g. a leak into a cavity followed by another leak out of that cavity), the sealing will occur at the smaller openings.

## 4. Conclusions

This paper presented two recent applications of aerosol sealing in buildings: 1) large-building applications of aerosol duct sealing, and 2) aerosol sealing of building envelopes. The two aerosol-sealing approaches, although similar in concept, require very different operating procedures and equipment. For large building exhaust systems, this paper describes some of the reasons for performing the sealing, as well as some of the issues encountered in these applications. Based upon what is presented, it is clear that duct leakage was significant in all these applications (averaging 28% of fan flow), and that the aerosol-based sealing process was able to seal roughly 90% of the leakage encountered in small to very-large exhaust systems. Aerosol envelope sealing was demonstrated to be very promising in both small-scale tests in the laboratory and in the limited full-scale tests that have been performed. In the lab, our tests suggest that lower sealant injection rates result in cleaner seals, we believe due to smaller particles created by the lab-test nozzle at lower sealant injection rates. Our lab tests also suggest that a smaller pressure differential across the leaks creates an even cleaner seal, most likely due to lower approach velocities to the leaks. This needs further investigation. In the field, in both the new construction and existing home applications, the process was able to seal at least 50% of the observed leakage within two hours. For field applications, what remains is to understand and optimize the preparation process required for sealing, to get more experience in field applications of the sealant injection and preparation process, and to turn the multi-point injection system into a viable commercial product.

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